The Pennsylvania State University
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ROTORCRAFT NOISE PREDICTION SYSTEM VALIDATION
AND ANALYSIS FOR GENERATING NOISE ABATEMENT PROCEDURES

A Dissertation in
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by
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Abstract

The main contribution from the current work is the enhancement of a comprehensive noise prediction system for rotorcraft and a methodology to analyze flight test procedures in the interest of understanding the noise source generation mechanisms and aid development of noise abatement procedures. This dissertation describes a rotorcraft noise prediction system and its development to incorporate time-dependent information—including trajectory, attitude, blade loads and rotor thrust—for predicting noise generated during a complex maneuver. The validation process is carried out by comparing the predicted noise levels (SELdBA, OASPL and A-weighted SPL) and processed flight test data. The examples considered are: level flight; descent flight; level turns; level, decelerating turns; and descending turns. This range of operations is considered to analyze the prediction system and understand its capabilities and deficiencies for future work. Overall the predicted noise levels were able to match the trends and levels within a 2–4 dB of that measured during the flight test. The time histories are studied in detail to understand the influence of events (such as steady flight conditions, with constant speed, roll angle or descent rate, and transient flight conditions, including roll-in and roll-out of turn, start and end of deceleration or acceleration) occurring during the flight procedure on noise levels and directivity. The key takeaways are that the noise prediction system was able to capture the noise levels but missed blade-vortex-interaction (BVI) noise directivity during some complex maneuvers. Transient maneuvers generate higher-harmonic loading and BVI noise and the intensity depends on the rate of change of flight conditions. The tail rotor not only contributes the thickness noise below the flight path but has significant contribution at sideline observer locations during a maneuver. The radiation distance and directivity have shown a stronger effect on noise levels than the harmonic noise sources. Lastly, the broadband noise dominates the A-weighted SPL for the steady maneuvers (except descent) and its importance is less during the transient flight segments. A final thing to note is that the noise generated during a 6° steady descent (the standard descent angle for approach) was much higher than any other complex procedures studied in the current work.
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List of Symbols

$\alpha_{TPP}$  Angle of attack of the tip path plane

$A_b$  Total blade area

$acc = \frac{dV}{dt}$  Acceleration of the helicopter

$c$  Speed of sound

$C_T$  Coefficient of thrust

$F_x$  Auxiliary $x$–force

$D_f = \frac{1}{2}\rho V^2f$  Frontal drag

$f$  Frontal drag area

$f = 0$  Function that describes source surface

$\gamma$ or FPA  Flight path angle

$g$  Acceleration due to gravity

$\dot{l}$  Time derivative of the blade loading vector

$M_\infty$  Freestream Mach number

$M_{AT}$  Advancing side tip Mach number

$\dot{M}$  Time derivative of the Mach vector incident on the blade

$N_b$  Number of blades

$p'$  Acoustic pressure
$p_{ref}$ Reference pressure, $2 \times 10^{-5}\text{Pa}$

$r$ Distance between observer and source time

$\phi$ Roll angle of the helicopter in degrees (°)

$\dot{\phi}$ Roll angle in degrees/seconds

$\rho$ Density of medium

$R$ Rotor blade radius

$\Psi$ Azimuthal angle on the rotor disk

$\psi$ Yaw angle of the helicopter in degrees (°)

$\dot{\psi}$ Yaw angle rate in degrees/seconds

$\tau$ Source time

$t$ Observe time

$T$ Rotor thrust

$\theta$ Pitch angle of the helicopter in degrees (°)

$\dot{\theta}$ Pitch angle rate in degrees/seconds

$U$ Freestream velocity

$V_{Tip}$ Rotor tip speed

$W$ Helicopter weight

$\Box^2$ Wave operator

$\vec{x}$ Observer position vector

$\vec{y}$ Source position vector

**Abbreviations**

ASCENT AViation Sustainability Center (FAA center of excellence for alternative jet fuels and environment)
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tr>
<td>BVI</td>
<td>Blade-vortex interaction</td>
</tr>
<tr>
<td>BWI</td>
<td>Blade-wake interaction</td>
</tr>
<tr>
<td>CHARM</td>
<td>Comprehensive Hierarchical Aeromechanics Rotorcraft Model</td>
</tr>
<tr>
<td>EPNL</td>
<td>Effective perceived noise level</td>
</tr>
<tr>
<td>FAA</td>
<td>Federal Aviation Administration</td>
</tr>
<tr>
<td>FPA</td>
<td>Flight path angle</td>
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<tr>
<td>HAI</td>
<td>Helicopter Association International</td>
</tr>
<tr>
<td>HSI</td>
<td>High-speed impulsive</td>
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<tr>
<td>MRTR</td>
<td>Main rotor and tail rotor</td>
</tr>
<tr>
<td>MR</td>
<td>Main rotor</td>
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<tr>
<td>OASPL</td>
<td>Overall sound pressure level</td>
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<tr>
<td>PNL</td>
<td>Perceived noise level</td>
</tr>
<tr>
<td>PNLT</td>
<td>Tone corrected perceived noise level</td>
</tr>
<tr>
<td>ROC</td>
<td>Rate of climb</td>
</tr>
<tr>
<td>ROD</td>
<td>Rate of descent</td>
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<tr>
<td>SPL</td>
<td>Sound pressure level</td>
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<td>TR</td>
<td>Tail rotor</td>
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<tr>
<td>TOGW</td>
<td>Takeoff gross weight</td>
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<td>TPP</td>
<td>Tip path plane</td>
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Acknowledgments

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Lastly, to my family, friends and colleagues at Penn state thank you for your encouragement and support.
Dedication

To my parents for their unconditional support, encouragement and for never stopping in believing me. This was impossible without you.
1 Introduction

1.1 Motivation and goals

Helicopter noise is the focus of the current dissertation. The aim of aircraft has always been to reduce transportation time and be able to reach locations where the other modes of transport are not feasible. Fixed-wing aircraft are suitable for long range transportation but they lack maneuverability. The helicopter, on the other hand, has a limitation on speed, but it is capable of performing maneuvers that are impossible for a fixed-wing aircraft. The capability to perform hover, vertical takeoff and landings, and perform sideward and backward flight procedures are in the range of the helicopter’s abilities. This performance is of utmost importance for operations like search and rescue, emergency services, law enforcement activities, and to navigate in city or residential areas. The maneuverability requires a complex system with multiple points of control to change flight operation in the middle of the procedure, as may be the requirement.

The complex helicopter system generates disturbances in the quiescent medium, which propagate as noise. Considering the helicopter operations requiring maneuverability are performed close to the human population, noise has gained significant importance. It is one of the significant hurdles for reaching the full potential of the helicopter service industry. The lack of community acceptance has impeded the
helicopter industry by limiting the number of allowable flight operations.

Every helicopter needs to pass a rigorous noise certification test. These noise certification rules and regulations are placed by the Federal Aviation Administration (FAA), a government organization. This was done to regulate noise exposure in the residential and commercial areas. Even then, certain cities like New York and Los Angeles needed to adopt voluntary restrictions to reduce community complaints resulting in lower helicopter operations. In the interest of helping the helicopter manufacturers, operators, pilots and communities, several organizations were formed with the goal of reducing helicopter noise. The Helicopter Association International (HAI), along with some government organizations, such as the International Civil Aviation Organization (ICAO) and Federal Aviation Administration (FAA), have been investigating the concern with helicopter noise [1]. These committees have organized a “Fly Neighborly Guide” with the help of operators and pilots to fly helicopters quietly and increase the community acceptance of the helicopter operations.

The work presented in this dissertation aims to further the goal of flying quietly by enhancing a noise prediction system to predict the noise during a maneuver and bridging the gap between theoretical understanding and the events occurring during the flight. Although this work is focused on civil helicopters and civil applications, it has the potential of translating to military helicopter operations and the noise generated by unmanned aerial vehicles and urban air mobility.

1.2 Introduction to helicopter noise sources

A helicopter has various components generating noise: engine, airframe, empennage, main rotor, or rotors, and tail rotor. The noise generated by the engine is typically of high frequency with amplitude lower than the other noise sources. The interaction of the main rotor wake with the fuselage and empennage generates a broadband
Figure 1.1: Schematic of rotor noise sources and their directivity [5].

noise source. Among all the components, the main rotor and tail rotor noise contribution to the total noise is maximum. Therefore, the primary focus of the current work is the main rotor and tail rotor.

The noise source components are thickness noise, which radiates in the plane of rotor and occurs due to motion of blade in the medium; loading noise, which radiates below the plane of rotor and is a function of forces acting on the rotor blades; blade-vortex-interaction noise (BVI), which is a highly directional and type of loading noise. The harmonic noise sources: thickness noise and harmonic loading noise occur due to rotation of the blades and are primarily influenced by the blade design, velocity and loads acting on the blade. BVI noise occurs due to the interaction of the tip vortex with the blades. The factor determining BVI noise is the orientation of the main rotor (angle of attack of the tip path plane) with respect to the rotor wake. If the main rotor operates in the wake, BVI occurs and resulting in high-intensity noise. The intensity of interaction depends on the strength of the tip-vortex, wake trajectory and impinging angle of the tip-vortex on the incoming blade. If the interaction is parallel, the major portion of blade
experiences a sudden change in inflow velocity and thus results in fluctuation of blade loads and consequently increases noise level. (For more details on BVI noise refer to Chapter 2.) Broadband noise is also a type of loading noise, which is stochastic and occurs due to fluctuations in blade loads due to the turbulent flow field. The primary broadband sources are: self-noise, i.e., noise generated by the interaction of the turbulent boundary layer with trailing edge, vortex shedding due to bluntness of the trailing edge, tip vortex formation noise, laminar-boundary-layer vortex-shedding; inflow turbulent noise due to ingestion of the previously present wake with the blade, atmospheric turbulence and other such sources. Lastly, there is high-speed impulsive noise (HSI), which radiates in the plane of the rotor and occurs due to the compressibility effect at high tip-Mach numbers. The directivity of the rotor noise sources is shown in Fig. 1.1. The details of the rotor noise sources are discussed in Chapter 2.

1.3 Literature review

The goal of achieving lower helicopter noise is conceivable by performing design changes or changing the flight procedure. In the following section, a brief review of previously conducted research and gaps in the research are addressed. The first subsection addresses the design changes in blade and helicopter to reduce noise generated by the helicopter. A detailed review of the effect of operational changes to reduce noise levels is addressed in the second subsection.

1.3.1 Design changes

In recent years, helicopter manufacturers have been interested in adopting new technologies to reduce drag, vibration, and noise generated by the helicopter. The design changes to reduce noise are primarily achieved by either increasing the aerodynamic performance, constraining specific design parameters, that are
known to be responsible for higher drag or noise, or implementing technology that would reduce a targeted noise source. A status report “Helicopter Noise Reduction Technology,” published in April 2015 [49], is used as the basis for the review on noise reduction using design changes. The contributors to the reports are International Coordinating Council of Aerospace Industries Associations (ICCAIA): Snecma, Airbus Helicopters, Sikorsky Aircraft, Bell Helicopter, Augusta Westland, Turbomeca, Marenco Swiss helicopter and research centers: NASA, DLR, ONERA, JAXA. This section will give a brief overview of the design changes mentioned in the above report. The design changes are focused on reducing a specific type of noise source. Therefore the review is structured to focus on design changes for individual noise sources such as BVI noise, thickness and HSI noise, noise generated by the anti-torque device.

**BVI noise:**

The technologies geared towards reducing the BVI noise operate by reducing the tip vortex strength with changes in the tip design or blade planform or by using active rotor techniques such as the active flaps, active twist, individual blade control (IBC) and higher harmonic control (HHC) of rotor blades. The techniques work by either reducing the blade tip vortex strength or increasing the BVI miss distance in order to reduce the interaction.

NASA has been actively working on reducing noise generated by rotorcraft, either through design changes or operational changes. In 2015, NASA organized a committee called Research of Vertical Lift Technology (RVLT) [2] to enhance the noise reduction technology by changes in design or operational changes. These technologies have shown a significant reduction in BVI noise at the cost of added complexity and a penalty of increased vibration. Though the technologies were initially developed to reduce the rotor vibration, the potential exists to find a frequency at which a reduction in noise and vibration is possible. The HHC
technique controls the blade pitch angle by moving the swashplate at a fixed frequency. HHC pitch inputs for lower noise results in higher induced downwash velocity and blade tip deflection. The increased BVI miss distance results in lower BVI noise. A noise reduction of 6 dB was achieved during various flight tests and wind tunnel tests. While the HHC inputs for lower vibration results in higher BVI noise [60]. Thus a trade-off between lower noise or vibration will determine the frequency and amplitude of the HHC pitch inputs. The IBC controls individual blades by using pitch actuators located above the swashplate. A wind tunnel test showed 12 dB noise reduction and also a reduction in rotor vibration [60]. A comparison between the acoustic pressure with and without IBC showed a reduction in the peak values when the IBC was applied for a 6° descent case as such lower noise can be achieved with active blade controls. The major disadvantage of using HHC and IBC is the weight, mechanical complexity, and the power requirement. Currently, research is done to develop smart structures and actuators to overcome the drawbacks of using the active blade controls.

The use of an active rotor concept for reducing the noise has potential. In work conducted by Straub et al. [50], the use of smart material to control trailing edge flap deflection on a full-scale rotor resulted in reducing the noise and vibration. The active flap actuation reduced BVI noise by increasing the miss distance between the tip vortex and the blade. The BVI noise was reduced by 6 dB, and with a better aerodynamic performance, the system vibration was reduced by 80 %. The actuated flap was tested for 60 hours in a wind tunnel to determine the reliability. Norman et al. [35] demonstrated the advantages of individual blade control (IBC) to reduce noise and vibration. The active twist of the rotor blade was tested during a hover test.

Another methodology implemented to reduce the BVI noise is by changing the blade geometry. Changes in the blade tip shape have shown promise in redistributing blade loads at the tip and induce vortex instability and shows capacity to reduce
noise levels by 5 dB [34]. France developed a quiet helicopter program where
tapered and parabolic shape blade tips have been shown to reduce noise by 3.3
dB [3]. The parallel interaction of the tip vortex with the blade is significantly
reduced by using swept blades and thus reduces BVI noise. Increasing the BVI
miss distance can also be achieved by implementing anhedral and dihedral tips.

The harmonic loading noise can be reduced by increasing the number of blades,
which results in lower loads per blade and thus reduced the harmonic loading noise
(when BVI is not considered). Research is ongoing on active trailing edge flaps to
reduce the in harmonic loading noise [50].

**Thickness noise and HSI noise:**

Thickness noise radiates in the plane of the rotor and is proportional to the speed of
the blade surface. Thickness noise can be reduced by lowering the rotation speed of
the rotor and, in turn, reducing the advancing side tip speed. HSI noise occurs due
to the compressibility effects at high tip-Mach numbers, and with reduced the blade
tip speed, this noise source can be negligible (below approximately 0.7 advancing-
tip-Mach number). Changes in blade geometry can also achieve lower thickness
and HSI noise. The thickness and HSI noise are reduced with swept, tapered and
thinner blade sections, which all are responsible for reducing compressibility effects.
Using anhedral and dihedral blade tips, the HSI noise is found to be reduced.

**Anti-torque devices**

The anti-torque device is another significant noise generator. The high blade
passage frequency of a tail rotor results in annoyance due to the sensitivity of the
human ear about 500 Hz and up to maximum noise sensitivity around 3000–4000
Hz. A ducted tail rotor has shown promise in reducing the noise generated due to
the interaction of the main rotor wake with the tail rotor and potential shielding
effect. However, the presence of the duct results in higher noise levels at sideline
observer locations. The thickness noise generated by the tail rotor radiates below the helicopter, and towards the observer; as such, reducing the rotation speed of the tail rotor has been found to reduce the noise levels. In the project “Helicopter Noise and Vibration Reduction (HELINOVI),” [59] conducted in Europe, tail rotor noise reduction of about 5–8 dBA was achieved by changing the rotor rotation direction. Here, the advancing side of the tail rotor was switched from down to up. With this switch, the first quadrant from $\psi = 0^\circ - 90^\circ$ faces away from the ground. In this quadrant the resultant velocity on the blade increases or the blade is under accelerated flow field. This potentially led the blade radiation vector (or Mach vector) when the blade tip is under accelerated flow field (incoming flow velocity of the blade increases from the azimuth angle of $0^\circ$ to $90^\circ$) to radiate away from the ground. (It is important to note that the feature of rotor orientation resulting in the Mach vector and the noise directivity away from the ground could be used during helicopter turns–Chapter 5). Other techniques for reducing the tail rotor noise are increasing the number of blades, changes in the blade geometry, position of the tail rotor relative to the fuselage and main rotor wake, and reducing the tail rotor thrust requirement.

The techniques, as mentioned earlier, are the current state of the art for noise reduction by implementing design changes. In summary, these changes are focused on reducing a particular type of rotor noise source or increasing aerodynamic performance. For the thickness and HSI noise, reducing the rotor rotation speed and blade design was found to be effective. For reducing the harmonic loading noise increasing the total number of blades in a rotor. The BVI noise could be reduced using an active rotor or by changing the blade design (operational changes are ignored in this section). The major drawback of the active rotors could be overcome using the new smart material technology and reducing the reliance on mechanical actuators [50].

One example that demonstrates the noise reduction by changing the blade
design is the BERP rotor blade (British Experimental Rotor Programme) [10]. The rotor blade was developed to increase rotor lift, forward speed, and reduce vibratory loads. This is primarily achieved with the blade tip design. The blade has thin airfoils, a swept blade tip with a leading-edge notch. The blade tip is swept backward to reduce the formation of shock waves or the compressibility effects on the advancing side. This results in pitching moments, and other such force unbalances. The leading edge notch is formed by the blade close to the tip, being moved forward, resulting in a notch between the tip and the remaining blade, which is required to balance these moments. This notch had an added advantage of generating a vortex from the leading edge at a high angle of attack that would divide the separated flow from the tip vortex and would result in delaying stall at a higher angle of attack. With a combination of the sweep, thin airfoils, and a leading-edge notch to reduce the shock waves and delay stall, a 13.5 dB noise reduction at high speed, and about 5 dB in low-speed descent flight is reported. Thus, noise reduction is possible by implementing blade designs changes.

The rotor design changes for reducing noise and increasing performance is a vast topic and not addressed in detail as it is outside the scope of the dissertation.

1.3.2 Operational changes

Helicopter noise sources are directional and depend on the flight conditions. Flying low noise flight procedure requires understanding the parameters influencing the noise sources, the effect on directivity, and the distance between the observer and the helicopter. The previous research has focused on conducting experiments and flight tests to demonstrate the low noise flight procedures and perform parametric studies of flight conditions [17,23,57]. Another area of research that has gained significant importance due to the available resources is using the computational method to design low noise flight procedures. The first step in using the computational method is to utilize tools to predict noise generated at given flight conditions and then use
tools and the knowledge from previously conducted experiments or computational studies to develop low noise flight procedures. The following literature review presents previous work in this area.

HAI’s ‘Fly Neighborly Guide’ [1] identified parameters responsible for high noise levels and has provided guidelines for pilots and operators to fly quietly. For quiet level flight, it is advised to fly at a higher altitude and a lower speed. However, flying at higher altitude results in increased noise in the sideline distance as the noise directivity changes for those observer positions. Further, it is advised to change the flight condition slowly to minimize noise radiation slowly. A helicopter flying at a lower speed (above the forward speed required for minimum power or thrust requirement) has lower tip-speed, and lower main rotor and tail rotor thrust requirement (propulsive force required for helicopters to fly decreases with speed and is lowest when the velocity required for minimum power and thrust is reached). This leads to lower thickness noise, loading noise, and broadband noise. However, the slow helicopter speed results in higher sound exposure time and increases the annoyance caused due to the flight procedure [29,54]. The time duration, which is a psychoacoustic effect, is captured in sound exposure level (SEL) and effective perceived noise levels (EPNL). It is done so by integrating A–weighted SPL and PNLT, respectively, over a time interval when the noise levels are within 10 dB from the peak noise level. These noise metrics show that the low-speed helicopter could have the same levels as seen for a high-speed flight [29,54].

During a descent or an approach flight procedure, the BVI noise could dominate the total noise generated by the helicopter. This noise source is important because not only are the noise levels generated much higher than most other flight conditions, but also the distance between the helicopter and the observer typically decreases with the flight time. For BVI noise reduction, the ‘Fly Neighborly Guide’ guidelines advises pilots to not operate at certain flight conditions by referring to a plot that describes the maximum A–weighted SPL noise as a function of the rate of
climb/descent and helicopter speed (shown in Fig. 1.2). For those flight conditions in the region of maximum impulsive noise, or the “hot spot”, the noise levels are significantly higher. For example, in Fig. 1.2 the noise levels are maximum around 60 to 80 kts when the descent rate is approximately 300–500 ft/min. This is a BVI flight condition. The flight path angle for the maximum BVI zone is approximately around 6°, which is a typical flight angle used during the approach. The development of a noise abatement procedure would require avoiding the intense noise region in Fig. 1.2 by either changing the descent rate or forward speed. Although noise reduction is desirable, the pilots must not compromise safety using a severe descent rate, too steep flight, or flight path angle or descending at a very high forward speed.

These safety concerns and avoiding ‘hot spot’ region flight conditions are just some of the guidelines generally used by the researchers in their attempt to develop noise abatement procedures. In this literature review, some of the relevant flight test and tools developed with the focus on noise abatement procedures are studied to understand the state of the art, computational tools available, and highlight the
gaps in the research.

First, a brief review of select flight tests that were conducted either to demonstrate the possibility of flying low noise flight procedures or to generate a database for understanding the influence of flight conditions on the noise generated by the helicopter is given. These flight tests were conducted to understand the effect on noise levels by changing the flight procedure. An acoustic flight test focusing on the Sikorsky S76 helicopter was conducted by U.S. Industry/NASA/FAA [27, 28]. This flight test showed the effect on noise levels caused by varying the rate of descent, true airspeed, deceleration, and altitude. Constraints such as flight safety, maximum true airspeed, and altitude were applied when flying a multisegmented flight procedure. The procedures aimed to reduce BVI and to increase the distance between the observer and the helicopter by operating at a higher altitude, which would eventually result in lower noise on the ground plane. The acoustic pressure was measured using microphones and processed to generate EPNL dB.

Key observations from the flight test are: 1) Parameters are interdependent, and therefore there is a limitation on the extent of noise reduction. For example, some of the parameters conflicted with each other—descent from a higher altitude requires a higher rate of descent. Hence a compromise is required to generate a maximum low noise flight path procedure. 2) In the flight test, an array of microphones located on the ground captures the noise footprint of the multisegmented approach flight. The noise contours are compared to demonstrate the sensitivity of the noise levels to the flight path. 3) A multisegment flight path was capable of reducing the noise levels more than 6 dB compared to the flight procedures based on HAI’s guidelines; 80 kts steady descent at the rate of 800 fpm, where noise reduction is around 1–2 dB. 4) This flight test demonstrated that the noise abatement procedure could be realized during an actual flight test and is not just a theoretical concept.

The next flight test considered is the XV-15 tiltrotor flight test [17]. NASA Langley Research Center (NASA LaRC) and Bell Helicopter Textron, Inc. (Bell)
conducted the acoustic flight test. The key findings of the flight test were the potential for achieving noise reduction by changing the noise source directivity. Sound exposure level was reduced by 10 dBA by changing the nacelle angle from 90° to 60°. For analyzing different flight procedures, the measured acoustic pressure was processed to calculate the sound exposure level. The area on the ground plane above a threshold sound exposure levels (102 dB) is then used for comparing the effective low noise flight procedure. Each approach case generates different noise levels on the ground, and the area exposed to noise levels is different from case to case. A quiet case means that the total exposed area is small, and the maximum noise level is low. The flight test demonstrated the need to understand different flight parameters to optimize the low noise flight path procedure. Another observation made during the analysis was that the noise-sensitive areas should be kept towards the left or the retreating side of the rotor—contrary to the HAI’s guidelines.

Flight test data is always valuable for developing and validating empirical tools. One such flight test is the Bell 430 acoustic flight test conducted by NASA, Bell, and the U.S. Army [57]. The flight test included steady flight procedures, such as level flight, decent, climb, and steady turns; and time dependent flight procedures, such as accelerating or decelerating in combination with a steady flight procedure. For maneuvering flight procedures, a multisegmented approach combining various steady states with acceleration or deceleration was considered. For analyzing different flight procedures, a blade-vortex-noise noise metric (BVISPL) was used on a ground plane and a hemisphere. This analysis helped to characterize the BVI noise and also served as a database for future tool development and validation of prediction tools. In the FAA ASCENT Project 6 [29,46], the Bell 430 flight test data was extensively used for coupling and validation of the steady PSUHelosim/CHARM/PSU-WOPWOP noise prediction system. This system is further enhanced in the current work under FAA ASCENT Project 38. Partially in
support of Project 38, NASA and the FAA, along with several other organizations, conducted a series of flight tests for six light helicopters: Bell Helicopter 206L and 407, Robinson R44 and R66, and Airbus Helicopters AS350 and EC130 [58]. This flight test data has been used extensively for developing the current noise prediction system capability for predicting the noise generated for the same flight procedures flown during the flight tests. The objective of the flight test program was to study various flight procedures and develop noise abatement procedures using the flight test data.

Before going into details of the comprehensive noise prediction system developed for low noise abatement procedure development, a brief review of the various tools available for either predicting the noise levels or generating a low noise flight procedure is provided in the following paragraphs.

**Integrated Noise Model (INM) [18]:** INM is used to predict noise levels in the FAA’s Aviation Environmental Design Tool (AEDT) tool (which evaluates the impact of aviation on air quality, noise, fuel consumption, and emissions). The tool is based on the acoustic noise measurement at the centerline and two on either side of the flight procedure and is based on Noise Power Distance (NPD) curves. It is widely used to assess the noise at a given region (airport, national park, residential area surrounding the airport) due to flight procedures, or the cumulative effect of flight operations. The use of INM is limited for rotorcraft operations as the effect of directivity, and crude modeling of the noise levels at different flight conditions are not able to provide thorough insight in developing low noise flight procedures.

**Rotorcraft Noise Model (RNM) [33]:** RNM was developed by NASA, the DoD, and Wyle Laboratories. The deficiency of the INM tool in accounting for the directivity of the helicopter noise sources is addressed in the RNM. This is done by generating noise hemisphere data for a centrally located helicopter operating at a given flight condition. This hemispherical data is obtained by flying a rectilinear flight procedure over a straight array (1D array) of microphones located on the
ground. The noise levels are then calculated at a distance from the hemisphere by inverting the spherical spreading of the noise. The noise hemisphere database was generated through variation in airspeed and flight path angle. During the maneuver, this noise hemisphere now changes along the desired flight path and flight conditions (airspeed and flight path angle), and the noise levels are propagated to the observer. This is how noise levels from multisegmented flight procedures are captured. One major drawback of the tools is its incapability of predicting noise during maneuvering flight. For a maneuver, the flight conditions are continuously changing, and this results in changes in the rotors orientation and thrust. RNM does not account for these transient effects.

**HELicopter Environmental Noise Analysis (HELENA) and Sound Exposure Level starting from the Emitted Noise Evaluation (SELENE):** These European tools are similar to RNM except that the microphone array used to develop the database is spread over the ground is not a straight 1D array (it includes observers located below the flight path and as well as the sideline observer locations) resulting in better capturing the effect of noise directivity.

**Quasi-Static Acoustic Mapping (Q-SAM)** [23]: It is an extension of the processing used in RNM. Here, the noise hemispheres are function of angle of attack of the main rotor tip path plane ($\alpha_{TPP}$) and the advance ratio ($\mu$) instead of airspeed and flight path angle. These two non-dimensional parameters are a function of flight path angle, acceleration or deceleration, drag force and $x$–rotor forces, rotor rotation, and airspeed or helicopter speed. Therefore, the changes in the rotor orientation and the wake trajectory due to unsteady flight conditions, such as the acceleration/deceleration, are accounted for when using the noise hemisphere. A schematic of the Q-SAM process is shown in Fig. 1.3 (from Ref. [23]).

For a maneuvering flight, Q-SAM calculates $\alpha_{TPP}$ and the advance ratio along the flight path and chooses the associated noise hemisphere accordingly. The multiple noise hemispheres along the flight path act as the noise source and, when
Figure 1.3: Flowchart describing Q-SAM [23]

propagated to the observer, gives an estimation of the noise generated during a maneuvering flight procedure. The advantage of the tool appears in capturing the BVI noise during an unsteady flight procedure.

BVI noise occurs due to the interaction of the tip vortex present in the rotor wake with an oncoming blade. For such a condition to occur, the difference between the angle of attack of the rotor tip path plane and wake trajectory skew angle is very small. This decreases the vertical distance between the tip vortex and rotor (BVI miss distance) and generates BVI noise. The rotor orientation, defined by $\alpha_{TPP}$, is positive (nose up) during descent; for level flight or a climb procedure, $\alpha_{TPP}$ is negative, or rotor is tilted forward (nose down). For a very high (positive) $\alpha_{TPP}$, the average rotor inflow is positive (upwash), in which case the induced
velocity pushes the wake above the plane of the rotor. For a negative $\alpha_{TPP}$, the rotor inflow is negative (downwash), and thus the induced velocity pushes the rotor wake far below the plane of the rotor. The condition when the average inflow is almost zero (rotor operating in its wake) results in high BVI and radiates BVI noise. These changes due to unsteady flight conditions are captured in the noise hemisphere used by Q-SAM.

$$\alpha_{TPP} = -\frac{D_f}{W} - \gamma - \frac{1}{g} \left[ \frac{dV}{dt} \right] - \frac{F_x}{W}$$  \hspace{1cm} (1.1)

where $D_f$ = rotor drag = $\frac{1}{2} \rho V^2 f$, $f$ = frontal flat plate area, $W$ = helicopter weight, $\gamma$ = flight path angle, $g$ = acceleration due to gravity, $dV/dt = A_x$ = acceleration parallel to flight path, $F_x$ = auxiliary $X$ force – due to propulsive devices or addition of drag force of the system.

Schmitz et al. effectively used this Q-SAM’s ability to predict BVI noise for an unsteady flight condition [47,48]. The SELdBA ground contour plots were used to analyze the noise generated at a different angle of attack of the rotor tip path plane and advance ratio. This analysis led to developing low noise multisegmented trajectories for the AH-1 helicopter.

**Fundamental Rotorcraft Acoustic Modeling From Experiments (FRAME)** [24]: This tool was developed at the University of Maryland [24] and is an extension to Q-SAM. Here, the noise hemispheres in the Q-SAM are determined for different rotor noise sources by using an analytical model that was calibrated with experimental data using a parameter identification technique. FRAME was thus able to predict noise levels at different quasi-steady flight conditions than what were used to calibrate the analytical model.

**Fundamental Rotorcraft Acoustic Modeling From Experiments (FRAME)-QS**: FRAME-QS integrates the FRAME code with an optimization framework to generate low noise flight procedures. The flowchart is shown in Fig. 1.4. The FRAME-QS hybrid was used to predict noise from different flight maneuvers such
as turns, approach climbs, deceleration/acceleration, and combinations of the above maneuvers. The noise predicted by FRAME was passed on to the optimizer where the optimizer checks the cost function and changes the flight path procedure, within constraints, to achieve a low noise flight procedure.

Greenwood [25] used FRAME-QS to predict noise for a maneuvering AS350 SD1 helicopter. The observations after conducting the study were as follows. Deceleration should be avoided during turn and pull-ups. For level flights, BVI noise is quite low, and acceleration does not show any significant improvement. However, for a level flight with a roll-in turn, acceleration can increase the BVI miss distance but can also increase the noise radiation due to the increment in speed. Turns increase the noise levels for descending or level flight operations with a much higher increase in the noise level seen outside the turn. This occurs due to a change in the directivity of the main rotor loading, broadband noise, and tail rotor thickness noise with the roll of the helicopter. Deceleration during the roll-in or roll-out and advancing-side turn increases BVI noise levels. Any maneuver should be avoided with advancing-side turns, though the retreating-side turns with acceleration or climb results in noise levels close to advancing-side turns. The rate
of a climb does not affect the noise levels significantly, but with the steeper climb, the distance between the noise source and the observer increases, reducing the noise levels due to spherical spreading.

With the results as guidelines for designing low noise flights, three flight procedures are optimized—a level turn, a straight line approach to hover taxi, and a turning approach to a hover taxi. The optimizer, under previously defined constraints, was used to design the flight procedure by seeking to reduce the average SEL. The optimizer tries to separate deceleration from other flight maneuvers by undergoing an aggressive deceleration at the start of the flight procedure, maintaining low bank angle, and low deceleration rate near the approach area. The three abatement procedures are briefly described below.

1) For a level turn, the helicopter decelerates before the onset of BVI and rolls into the turn. As the speed is low, the roll rate and the bank angle is reduced by half. Then the helicopter accelerates midway through the turn and eventually rolls out of the turn. The optimized flight shows 5 dBA reduction in averaged SEL. 2) For a straight approach to hover taxi, the initial approach is to maintain constant deceleration while the optimizer decelerates aggressively, descends, and maintain low speed in the first segment of maneuver. With lower speed the deceleration rate is much lower in the approach area and helicopter has to descend steeply near the approach area. This optimized flight procedure results in 7 dBA averaged SEL noise reduction. 3) For the turning approach to hover taxi flight procedure, the flight initially decelerates, resulting in a low bank angle. In the middle of the roll-out the deceleration is reduced and the helicopter descents at a shallow angle. This trajectory reduces the average SELdBA by 10 dBA. During cases 2 and 3, the optimized flight path, near approach, was at higher altitude than the initial flight path and had to undergo steep descent near the approach area.
1.4 Limitations of previous research

The previously designed low noise flight procedures are primarily focused on reducing BVI noise during approach and flying at a higher altitude to reduce noise exposure on the ground. This was achieved by using a multisegmented approach procedure. The goal of the flight procedures was to either lower the peak noise levels or reduce the total area exposed to sound. The flight procedure design ignored information on noise levels during the transient phase and the lateral motion of the helicopter. When designing a sophisticated multisegmented flight procedure and undertaking a flight test to assess the noise abatement procedure, the knowledge of the events happening during the flight test and its relation to the changes in the blade loads, and consequently the noise, is severely lacking. This is because of the tools used for analysis, such as the Q-SAM, RNM or FRAME-QS, are semi-empirical and based on steady hemispherical noise data. The radiation spheres were calculated using empirical models based on numerical methods or using experimental/flight test data. The noise radiation sphere, though, is calculated for certain flight trim conditions, the transient effects and the lateral motions are not accounted. When using the multisegmented approach, the flight condition changes from one segment to another. During this change, the azimuthal changes in blade loads generate a large increase in loading noise and, in some situation, the BVI noise. Those effects are not captured using the tools mentioned above. One example is a steady turn maneuver; the change in the heading angle of the helicopter results in a roll in motion followed by a constant roll angle turn and then roll out motion. All these components of the turn are transient and cannot just be defined by the rotor thrust or the forward speed. In summary, these tools lack a way of connecting the flight trim to the blade loads and motion and the noise sources. They thus are incomplete when designing a noise abatement procedure where the effect of directivity and flight conditions must be included.
Another important thing to note from the previously designed noise abatement procedure is dependence on the HAI’s ‘Fly Neighborly’ guidelines. These guidelines do not account for the total sound exposure time, and as such, annoyance caused due to the flight procedure is not considered.

In summary, a comprehensive tool is required to generate the noise abatement procedures. The tool should be able to calculate the helicopter trim during complicated maneuvers along with the blade loads and be able to use the rotor trim and blade load information to calculate the noise generated during the flight procedure. The next important area of research is in understanding the noise generated during a flight test by relating the motion of the helicopter to the rotor trim and blade loads and, eventually, the noise generation mechanism. This would be important to generate effective low noise abatement procedures. With a comprehensive tool, a study of the geometric flight path, without significant influence of the noise sources, is required to analyze the effect of the relative distance between helicopter and observer, directivity, and total sound exposure time on the noise levels observed on the ground. Finally, to design low noise procedures, the development of the function that includes the effect of the geometric flight path and the noise sources is necessary before an optimization technique and other machine learning techniques can be utilized. With the advent of neural networks and high computational speed, the potential of using the entire system to guide the pilot exists, as shown by Greenwood [25].

1.5 Dissertation objectives

This dissertation focuses on addressing the critical gaps mentioned in the previous sections. The enhancement of the previously coupled noise prediction system [45,46], validation of the system, and analysis to aid in understanding the events occurring during the flight test procedure in the interest of studying the noise source generation
mechanism and for developing noise abatement procedures is the main contribution from the current work.

The noise prediction system couples [29, 45, 46, 54] a flight simulation code (PSUHeloSim), a high-fidelity rotor aeromechanics model with free wake (CHARM Rotor Module) [39–44, 55, 56], and an industry-standard noise prediction tool (PSU-WOPWOP) [5, 6, 6, 7] to predict noise generated during a flight procedure. The tools used are physics-based models that can be adapted to predict flight dynamics, rotor loads, and noise from various rotorcraft configurations. The flight simulation code PSUHeloSim trims the aircraft for the given flight conditions. After an initial transient phase, the simulation results are then used to predict the flight path, attitude, and rotor loads throughout the maneuver. The CHARM Rotor Module takes the flight trim condition and computes detailed airloads and wake data. The high-fidelity CHARM module and PSUHeloSim can be coupled entirely, i.e., flight simulator trim is used directly for the airloads calculations and main rotor and tail rotor forces and moment data is given as a feedback to PSUHeloSim code. The computational power requirement is reduced with a quasi-periodic blade load assumption; the periodic rotor load data (one rotor revolution for each rotor: main rotor and tail rotor, even if the rotor speeds are different) are used throughout a 0.5 seconds period, and then is updated for the next period. This process is repeated throughout the entire flight procedure. The airloads data is used in PSU-WOPWOP to compute the acoustic pressure from both the main and tail rotor at the desired observer locations. The description of the rotor noise sources and the formulation used to compute the acoustic pressure time history is provided in Chapter 2. A variety of spectral metrics can be computed by PSU-WOPWOP, such as overall sound pressure level (OASPL), A-weighted sound pressure level, effective perceived noise level (EPNL dB), sound exposure level (SEL dB), etc. A simple broadband noise model developed by Pegg [37], is used in PSU-WOPWOP to calculate the 1/3 octave broadband noise. The computation calculates the spectrum for every
0.5 seconds (used as a window in Fast Fourier transformation) of the flight time. The rotor thrust is calculated and updated every 0.5 seconds to get an accurate prediction. The comprehensive noise prediction system is then validated with the flight test data. The details of the comprehensive noise prediction system are provided in Chapter 3.

The flight test data reported in NASA Technical Report [58] detailing the NASA and FAA flight test of the six light weight helicopter, was obtained and used for validation of the noise prediction system. The six helicopters are; Robinson R44 and R66, Airbus AS350 and EC130, and Bell 206L and Bell 407. In this work, helicopters models were developed for each of the helicopters. The computational models were developed using data available only from publicly available sources, and the parameters that were not available but necessary for the simulation are based on engineering judgment. The noise prediction system predicts the noise for the microphone array used during the flight tests by simulating the exact flight trajectory flown. The comparison of the flight test data with the predicted noise levels is further used to assess the noise prediction system and to understand its limitations. More importantly, the noise source generation mechanisms of the flight tests are better understood with the help of the noise prediction system. This validation is carried out for 8 flight conditions; steady level, steady descent, level left and right turns, level decelerating left and right turns, and descending left and right turns. The detail of the validation process and analysis is provided in Chapters 4 and 5. The dissertation concludes with Chapter 6, and the scope for future work is discussed in Chapter 7.

**Summarizing main contributions from current work:**

- Enhancement of the noise prediction system to develop capabilities for predicting the noise generated during a maneuver (previous tools has limitations due to use of using steady-state flight conditions for generating noise hemispheres).
• Development of the helicopter model for validation and analysis of the noise prediction system.

• Validation of the comprehensive noise prediction system by simulating the flight test trajectory.

• Analyzing the simulated flight trajectory to understand the effect of transient flight conditions (such as a change in helicopter attitude and velocity) during the flight test on the noise generation mechanism.

• Developing understanding for generating noise abatement procedures by accounting for transient effects.
Rotor noise

In the previous chapter, the different helicopter noise sources were briefly noted. The rotor noise is the dominant noise source generated by the helicopter and is the primary focus of the present chapter. The helicopter creates a complex flow field during its operation. Unlike fixed-wing aircraft, the helicopter main rotor is responsible for providing the necessary lift and propulsion required for the flight procedure. The tail rotor provides the torque required to counterbalance the reactive moment generated due to the rotation of the main rotor. The main rotor and the tail rotor have similar mechanisms responsible for noise generation; however, the intensity and the directivity of noise source differs due to the rotor orientation and the total thrust requirement. In this chapter, a brief study of the different rotor noise sources and the tools available to predict the rotor noise sources are discussed.

2.1 Rotor noise theory

The formulation of the wave equation for predicting the noise generated by the rotor starts with the continuity and momentum equations (Navier-Stokes equations). The wave equation is derived by combining the partial time derivative of the continuity and the divergence of the momentum equation. An inhomogeneous wave equation
is obtained by rearranging the terms such that the wave operator is on the left-hand side and the remaining terms on the right-hand side. The inhomogeneous terms on the right-hand side are the mathematical representation of the physical quantities that generate pressure fluctuations in the quiescent medium. Lighthill’s acoustic analogy \([30, 31]\) treats these terms as the fictitious sources which provide the same outcome as the physical source mechanisms. The analogy is used to predict the noise generated due to the motion of the fluid. It is widely used in understanding noise generation mechanisms in various applications like jet noise. It is important to note that in Lighthill’s acoustic analogy that the acoustic medium (fluid) is stationary and the sources are time dependent. However, to predict rotor noise, generalization of Lighthill’s acoustic analogy is required to account for the interaction of the fluid with surfaces in arbitrary motion, i.e., rotor blades. Ffowcs Williams and Hawkings (FW-H) \([22]\) extended Lighthill’s acoustic analogy for the case of moving surfaces in the paper “Sound Generation by Turbulence and Surfaces in Arbitrary Motion”. In the formulation, the wave equation was written using generalized functions with the discrete blade surface being the functional surface for the Dirac delta and Heaviside function. Eqn. 2.1 is a form of the FW-H equation.

\[
\Box p'(x, t) = \frac{\partial}{\partial t} \left[ \rho_0 v_n \delta(f) \right] - \frac{\partial}{\partial x_i} \left[ P_{ij} \hat{n}_j \delta(f) \right] + \frac{\partial^2}{\partial x_i \partial x_j} \left[ T_{ij} H(f) \right]
\]  

(2.1)

where \( P_{ij} \) is the compressive stress tensor and \( T_{ij} = \rho v_i v_j - P_{ij} - c^2 (\rho - \rho_0) \) is the Lighthill stress tensor.

The acoustic pressure is preceded by the d’Alembertian operator \( \Box^2 \) to represents the wave equation on the left-hand side of Eqn. 2.1. This is the acoustic pressure representing the fluctuations relative to the mean quiescent medium pressure, and when perceived by the human ear is termed as noise. The equation \( f = 0 \) is an implicit function that represents the acoustic data surface, permeable (a fictitious
surface in the fluid) or impermeable (coincident with the actual blade surface), on which the Dirac delta $\delta(f)$ operates. For an impermeable surface, $f = 0$ is the surface of the blade; $f < 0$ is inside the blade, and $f > 0$ is outside the blade. The term $v_n$ is the component of velocity on the surface in the direction of the local outward normal to the blade surface. Eqn. 2.1 has three terms on the right-hand side, each representing different rotor noise sources. The first term mathematically represents noise due to a monopole and is the thickness noise source. The second term is related to the forces on the blade surface and mathematically represents a dipole, and is known as the loading noise source. The first and second terms on the right-hand side of the Eqn. 2.1 are the extra source terms introduced by Ffowcs Williams and Hawkings (FW-H) and they are only present on the support of the Dirac delta function—the surface $f = 0$ (e.g., on the blade surface). The last source term is a volumetric term with double divergence of the Lighthill stress tensor and is known as the quadrupole term. The three noise sources are additionally subgrouped depending on the frequency content, intermittency, and stochastic nature and intensity. This is discussed in detail later in the current chapter.

A significant advantage of using the generalized functions was that the free-space Green’s function can be used to find an integral representation of the solution, as is done by Farassat [6,19–21] to get an analytical solution of the integral form of the FW-H equation (Eqn. 2.1). One formulation is the retarded integral form of the FW-H equation shown in Eqn. 2.2–Farassat’s Formulation 1A. Equations 2.2–2.4 shows the analytical form of the first two terms of the FW-H Eqn. 2.1. The first term $p'_T$ (Eqn. 2.3) is the thickness noise and the second term $p'_L$ (Eqn. 2.4) is the loading noise. The integral is calculated at the observer time and location by evaluating the integrand at each point on the surface at the retarded time or emission time, represented by $[\cdot]_{\text{ret}}$ in Eqns. 2.3 and 2.4. The retarded time is found by considering the relation between the observer time and source time: $r = c(t - \tau)$. 

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p'(x, t) = p'_T(x, t) + p'_L(x, t) \quad (2.2)

where:

\begin{align*}
4\pi p'_T(x, t) &= \int_{f=0} \left[ \frac{\rho_0 (\dot{v}_n + v_n)}{r(1 - M_r)^2} \right] dS + \int_{f=0} \left[ \frac{\rho_0 v_n (r \hat{M}_r + c(M_r - M^2))}{r^2(1 - M_r)^3} \right]_{ret} dS \\
4\pi p'_L(x, t) &= \frac{1}{c} \int_{f=0} \left[ \frac{l_r}{r(1 - M_r)^2} \right]_{ret} dS + \int_{f=0} \left[ \frac{l_r - l_m}{r^2(1 - M_r)^3} \right]_{ret} dS + \frac{1}{c} \int_{f=0} \left[ \frac{l_r r \hat{M}_r + c(M_r - M^2)}{r^2(1 - M_r)^3} \right]_{ret} dS \quad (2.3)
\end{align*}

\begin{align*}
2.2 \text{ Rotor noise sources} \\
\text{Thickness noise} \\
\text{The first source term of the FW-H equation (Eqn. 2.1) is a monopole term and}
\text{represents the thickness noise source. The quiescent fluid or air is displaced due to}
\text{the motion of the rotor blades, and this generates a disturbance that travels as a}
\text{sound wave, and it is characterized as the thickness noise. The velocity component}
\text{normal to the blade surface (v_n) in the term } \frac{\partial}{\partial t} \left[ \rho_0 v_n \delta(f) \right] \text{is the strength of the}
\text{thickness noise source. This makes the noise source proportional to the helicopter}
\text{speed and the rotation rate of the rotor. The Dirac delta function } \delta(f) \text{restricts}
\text{the term on the blade surface. The noise source is periodic and is analytically}
\text{determined in the current work using Farassat’s Formulation 1A (Eqn. 2.3). The}
\text{term } \frac{1}{(1 - M_r)} \text{is the Doppler amplification factor, where } M_r \text{ is the Mach number in}
\text{the radiation direction. The amplitude of the term is higher in the plane and front}
\text{of the rotor resulting in the thickness noise directivity, as shown in Fig. 1.1.}
\end{align*}
Loading noise

The second source term of the FW-H equation (Eqn. 2.2) is a dipole source known as the loading noise source. The rotor blades are the lifting surfaces for the helicopter. The blades motion generates pressure difference on the upper and lower surfaces, and this pressure difference provides the necessary lift and propulsion required for helicopter flight. The loaded blades, in turn, exert force on the surrounding medium, which results in a disturbance that propagates as sound waves. The Dirac delta functions $\delta(f)$ restricts the loading source to the blade surface ($f = 0$). The term $(P_{ij}\hat{n}_j)$ term is the local forces on the blade surface. Of the three components, the local blade force component in the lift direction is largest; hence, the directivity of the loading noise primarily out-of the plane of the rotor. The directivity of the noise source is shown in Fig. 1.1. Farassat’s retarded-time formulation IA loading noise component is comprised of three integrals as shown in Eqn. 2.4.

The characteristic of load distribution on the rotor blade is significantly different from that observed in the fixed-wing aircraft. One significant distinction is the difference in relative velocity along the azimuth and blade span for a helicopter in a forward flight compared to the relative velocity on a fixed-wing aircraft. For the rotor blades, the relative air velocity impinging on the blade increases along the span with highest speed at the blade tip. During hover, the helicopter rotor blade only has the rotation speed and no incoming air due to helicopter forward flight velocity. This results in a force distribution that is independent of rotor azimuth, but varies along the blade span. In forward or a maneuvering flight, the rotor blades are loaded with both spanwise and azimuthally varying loading that is not symmetric. This is because the relative velocity seen by the blade is a combination of the aircraft speed and the blade rotation, resulting in high tip velocity on the advancing side of the rotor disk and a reverse flow region at the root on the retreating side of the rotor.

To offset the azimuthal variation of velocity on the rotor disk, helicopters have
cyclic pitch control to change the angle of attack of the blades around the azimuth. The variation of forces acting on a blade due to the changing velocity and local angle of attack results in significant time variation in loading and the loading time derivative in the first integral of Eqn. 2.4 becomes a significant noise source. In the Eqn. 2.4, the term $\dot{l}_r$ accounts for the temporal variation of the forces acting on the blade surface and it is significant in the radiation direction. This term is important when the loading changes rapidly, as happens during impulsive loading events such as BVI, and also because the term is a far-field noise term (divided by $r$-radiation distance and not $r^2$). When BVI noise occurs this noise source is usually dominates the total noise and is essential when considering maneuvers. BVI noise is so important that it will be discussed later in detail. The other far-field term in the Farassat Formulation 1A for loading noise is the third term in the Eqn. 2.4. The term includes the effect of time rate of change of the Mach velocity (in the radiation direction) and thus is important when helicopter is maneuvering. Both of these terms are important when the flight trajectory is a function of time and is not following a steady flight procedure either due to time derivative of the blade loads or the Mach velocity. The broadband noise is another type of loading noise and is considered separately due to the noise generation mechanism and the high frequency content seen in the noise spectrum. The broadband noise is generated due to the unsteadiness in the blade loads caused by unsteady flow velocity impinging on the blade.

**Blade-vortex-interaction (BVI) noise**

BVI is a type of loading noise as the interaction is characteristic of changing the inflow velocity results in a sudden change in blade loads at that location which subsequently results in a higher time derivative of the blade loads ($\dot{l}_r$-term in Eqn. 2.4) and thus generating higher loading noise. The parameters determining the strength of BVI noise are the tip vortex trajectory, strength, and structure, miss
distance (distance between the tip vortex and the rotor plane), interaction angle of the tip vortex with blade leading edge [32]. If the interaction is parallel to the rotor blade, i.e., the leading edge of the rotor blade is parallel to the tip vortex, the sudden change in blade loads occurs across the entire blade span resulting in multiple sources of BVI occurring instantaneously and therefore higher amplitude of acoustic pressure in steady descent.

BVI varies along the span and azimuth and typically occurs around 55° to 70° on the advancing blade side and 300° to 330° on the retreating blade side [60]. The change in blade loads amplitude is larger, with the BVI observed on the retreating side. Still, as the angle of interaction is smaller or more parallel on the advancing side, the BVI noise generated by the advancing side is significantly higher. The BVI miss distance \(d\) is the separation between the tip vortex and the rotor blade. This parameter is an implicit function of the rotor skew angle and is dependent on; blade airloads at the time of vortex formation, induced downwash, and blade tip flapping deflections. If the miss distance is small, the rotor is operating in its wake and stronger BVI results. Thus the interaction depends on the wake trajectory, it is an impulsive phenomenon, and depends on various dynamic parameters for the interaction to not only occur but also determine the intensity. The rotor blades generate wake in the downstream direction. During hover, this downstream direction is below the rotor (skew angle of the rotor wake close to 90°–angle made by the slipstream of the wake with the rotor tip path plane). As the helicopter transition into forward flight, the wake is pushed behind the rotor, and the wake skew angle is lower than 90°. When this wake skew angle is equal to the rotor tip path plane angle of attack, the rotor operates in its wake. During such a condition, the blade tip vortex interacts with the incoming blade generating an impulsive and annoying noise source called the BVI noise.

BVI noise is a significant noise contributor during an approach flight procedure. Low noise helicopters or flight path procedures requires low BVI noise emission.
Farassat’s Formulation 1A [6,19–21] is capable of predicting BVI noise provided that the load distribution on the blade is accurate and has high temporal resolution. (The current research work uses PSUHelosim to calculate the rotor states and state derivatives, CHARM rotor module to calculate the blade loads and wake trajectory and PSU-WOPWOP for predicting the noise levels—details are provided in Chapter 3.) Farassat’s Formulation 1A is implemented for calculating and for calculating the CHARM rotor module, calculates the rotor blades and wake trajectory.

**Broadband noise**

Broadband noise is a type of loading noise. The broadband noise is generated due to the interaction of the turbulent flow with the blades or the fuselage and other surfaces. Turbulence is characterized as stochastic, intermittent, and small length scale fluctuations of the fluid properties, like velocity, pressures, and so forth. This results in a spectrum of frequency content higher than seen in the thickness and harmonic loading noise (approximately higher than 300 Hz) and, subsequently, the resulting fluctuating pressures disturbance occurring at higher frequencies. The rotor broadband noise sources are the turbulence ingestion, self-noise, i.e., the turbulent boundary layer interacting with the blade surface, formation of tip vortex, and fluctuations caused because of the shed vortex and wake in the fluid field. The stochastic and random nature of the turbulence leads to a wide range of frequencies in the acoustic spectrum. The frequency content is higher than seen in the thickness and harmonic loading noise. At higher frequency, human ear sensitivity increases resulting in significant importance of the noise source. The sound is directed above and below the helicopter, with the directivity shown in Fig. 1.1. The noise source prediction requires prior knowledge of the fluctuating blade forces due to turbulent flow. Resolving the turbulent flow or, in other words resolving the small scale fluctuations and modeling the closure of the problem is computationally expensive and could be done using CFD based computational aeroacoustics (CAA) to get a
decent prediction. It is currently just at or beyond the state of art to do a direct simulation or large eddy simulation to predict broadband noise and the quality of predicted noise levels is not guaranteed. Therefore, empirical or semi-empirical models are needed/used. Pegg’s empirical broadband noise model [37] and the Brookes, Pope, and Marcolini (BPM) broadband model [11–15] (only predicts self-noise) are among the more widely used for predicting broadband noise. In the current work, Peggs’s empirical model is used because of its simplicity and robustness required for predicting the noise generated during a flight test. The model accounts for self-noise generated due to interaction of the turbulent boundary layer with the blade surface, vortex formation noise, ingestion noise, includes the effect of blade interacting with wake, inflow turbulence. The limitation of the models are discussed during validation process in Chapters 4 and 5.

**High speed impulsive (HSI) noise**

The last term of the FW-H equation (Eqn. 2.1) is known as the quadrupole term, and it accounts for high-speed-impulsive (HSI) noise. The quadrupole term (the last term of Eqn. 2.1) is a volumetric noise source as the Heaviside function $H(f)$ is zero inside the surface $f = 0$, and is equal to one outside the surface. The quadrupole noise source is significant when the helicopter is operating at a transonic tip speeds, when the tip Mach number on the advancing blade is close to the speed sound HSI noise propagates primarily in the plane of the rotor ahead of the helicopter (similar to thickness noise and as shown in Fig. 1.1 for the directivity). HSI noise is not considered in this work because it is usually not an issue with civil helicopters.

**2.3 Prediction of rotor noise in the current work**

PSU-WOPWOP [5–7] uses a time domain integral of the generalized Eqn. 2.1 to estimate the acoustic pressure using Farassat’s Formulation 1A 2.2. PSU-WOPWOP
calculates the thickness, loading, and BVI noise using first principle-based physics. The accuracy of the prediction depends on the aerodynamic calculation for the blade loads and the capability to trim the helicopter. The quadrupole term requires extensive computation power and is ignored in the PSU-WOPWOP calculation. An empirical method, such as Pegg’s empirical model [37], is used to calculate the broadband noise. PSU-WOPWOP is used to calculate different noise metrics for a maneuvering helicopter on the ground plane. The details of the noise prediction system are discussed in Chapter 3.
Development of a comprehensive noise prediction system

Acoustic noise is the undesirable end product of any flight procedure. Accurate prediction of noise levels at a given observer position requires the simulation to fly the aircraft and calculate aircraft attitude, rotor blade loads, and motion. Therefore, the noise prediction system necessitates the use of a controller to trim the aircraft for a given flight procedure, a tool to calculate the rotor wake, blade loads, and motion at the trim condition. The noise prediction requires this information on aircraft motion, and blade loads and motion to predict the noise using some integral form of Ffowcs Williams and Hawking’s equation [22] (e.g., Farassat’s Formulation 1A as introduced in chapter 2).

The noise prediction system developed in this project consists of three different codes. A flight dynamics and simulation code, PSUHeloSim [26], developed at Penn State; a high-fidelity aeromechanics free wake and rotor analysis code, CHARM (Comprehensive Hierarchical Aeromechanics Rotorcraft Model), developed by Continuum Dynamics, Inc. (CDI) [55, 56]; and a noise prediction tool, PSU-WOPWOP, also developed at Penn State [8, 9, 38]. A schematic of the noise prediction system is presented in Fig. 3.1 followed by details of the three codes in section 3.1.
3.1 Description of the noise prediction system

The noise prediction system was developed to analyze and generate noise abatement procedures. The coupling of the three codes was carried out in Refs. [29, 46, 54].

3.1.1 PSUHelosim

PSUHelosim [45, 46] was built as first-order state-space form model and is developed in MATLAB/Simulink environment. This facilitates easier numerical integration, trimming and linearization. The model is nonlinear with 21 first order state equations; 1) 6-degree of freedom (DoF) nonlinear equations to calculate the 12 the states of fuselage \((u, v, w, p, q, r, \phi, \theta, \psi, x, y, z)\); 2) seconds-order blade flapping dynamics equation to calculate the 3 states of flapping motions and its derivatives \((\beta_0, \beta_{1c}, \beta_{1s}, \dot{\beta}_0, \dot{\beta}_{1c}, \dot{\beta}_{1s})\); and 3) a 3-state Pitt-Peters inflow model (to calculate \(\lambda_0, \lambda_{1c}, \lambda_{1s}\)). The equation of motions are solved using the Runga–Kutta method and trim algorithm uses the Newton-Rhapson method to calculate the state and
state derivatives. The main rotor, tail rotor, fuselage, and empennage are modeled separately with a simple aerodynamic model for fuselage and empennage and a static Bailey model [4] for the tail rotor. The state and state derivatives are the output to an external code for high fidelity rotor blade loads calculation.

For the current work, PSUHelosim is tailored to simulate a prescribed flight trajectory and calculate the rotor blade loads by coupling with the CHARM rotor module. The first step to trim a helicopter requires setting up the helicopter model. The model requires information on the helicopter; center of gravity, weight, moment of inertia and other such parameters, information on the various components; main and tail rotor (number of blades, radius, chord length, blade twist, hinge offset, Lock number (non-dimensional number–ratio of blade flapping aerodynamic forces and inertial forces), position with respect to the helicopter CG and other such parameters), fuselage, vertical and horizontal tail plates (position from the vehicle CG, frontal, side, and flat plate area), and engine (maximum power available). These parameters are kept constant when simulating a flight trajectory and are presented in more detail later in this chapter in Table 3.3. Prior to running the coupled PSUHelosim/CHARM rotor module, the trim solutions and controls are calculated for an array of helicopter velocities and rate of descent/climb. This database is used to initialize the PSUHelosim/CHARM rotor module for the starting steady state flight condition. After initialization the trim solution and controls are calculated for desired flight trajectory. The desired flight trajectory is provided as the three velocity components and heading angle. The controller calculates the error in the simulated flight trajectory and provides a feedback based on the control law. The trim solutions and controls are then provided to the coupled CHARM rotor wake module for calculating wake trajectory and rotor blade loads. The calculated rotorcraft state vector, state derivatives, and control inputs are provided to the CHARM rotor module at regular time steps to predict high-fidelity rotor forces and moments. The coupling is started 3 seconds after the simulation starts.
This time is required for the wake to develop in CHARM rotor module. After 10 seconds of simulation time, the state and state derivatives are used to predict the blade loads, wakes, aircraft dynamics, and blade dynamics. The CHARM rotor loads and motions is used directly to calculate the high-fidelity blade loads. In the open loop coupling the blade load information is not feedback to PSUHeloSim as is done for a closed-loop coupling. In closed-loop coupling, the system effectively replaces the main and tail rotor module of the PSUHelosim code with the one in CHARM rotor module.

### 3.1.2 CHARM rotor module

In the current work, CDI’s Comprehensive Hierarchical Aeromechanics Rotorcraft Model (CHARM) \[39–44,55,56\] is used to determine the blade loads and predict the BVI. CHARM is a software developed by Continuum Dynamics, Inc. The strength of the tools lies in analyzing aeromechanics and aerodynamics of the rotary wing aircraft design. The tool couples “a full-span, free-vortex wake model with a vortex lattice, lifting surface, blade aerodynamics model, an elastic blade structural dynamics model that accounts for fully-coupled flap/lag/torsion modes, and a fast doublet panel fuselage model which together provide a capability for modeling complete aircraft aeromechanics for combinations of rotors, props, wings, ducts, tails, and airframes.” The wake model can be implemented as a prescribed or free wake model with multiple or a single trailed vortices from the full span of each rotor blade. The roll up of the vortex sheet or the trailed vortex filament eventually forms a single trailed tip vortex whose core size and structure can be determined analytically using the Vatistas equation \[51–53\]. This tip vortex model and its trajectory is further used to determine BVI airloads. Determining BVI airloads requires a high azimuthal resolution, i.e., azimuthal spacing less than 1° (\(\Delta\psi \leq 1°\)). This is computationally expensive. A feature called ‘Reconstruction’ is utilized to reduce the computational time by recalculating the rotor wake trajectory to determine
the inflow velocity at a very high temporal discretization before the airloads are determined at high temporal resolution. This post-processing calculation results in reducing the computational time while still achieving high temporal resolution airloads. The reconstructed BVI airloads are then used to calculate the loading noise using Farassat’s Formulation 1A (used in PSU-WOPWOP). The coupling of PSUHelsons and CHARM [39–44,55,56] yields the necessary information needed for the first principle-based thickness and loading noise prediction and other information required to predict broadband noise. After the initial coupling transient phase, starting the simulation at the desired flight trajectory, and coupling with the CHARM rotor module has passed, the high-fidelity rotor blade loads, rotor thrust, helicopter trajectory, and attitude are calculated. This information is used in PSU-WOPWOP to compute the acoustic pressure for the main and tail rotors at the desired observer locations. PSU-WOPWOP uses this information to calculate the thickness, loading, and BVI noise using Farassat’s Formulation 1A.

### 3.1.3 PSU-WOPWOP

PSU-WOPWOP predicts the acoustic pressure time history by a numerical implementation of Farassat’s Formulation 1A [6,21]. The formulation was derived from the Ffowcs Williams and Hawkings equation [22] (details of the formulation available in Chapter 2). The formulation uses a retarded time algorithm. This entire system comprises a first principle, physics-based model for calculating the thickness and loading noise of the rotor blades. PSU-WOPWOP computes a variety of spectral metrics, such as overall sound pressure level (OASPL), A-weighted overall sound pressure level (L_A), effective perceived noise level (EPNL), sound exposure level (SEL), and so forth. The broadband noise in this work is calculated using an empirical model developed by Pegg [37]. The Pegg model calculates 1/3-octave broadband noise sound pressure levels. The formulation requires information about the rotor (radius, blade area), flight condition (blade velocity), and rotor
thrust. The blade loads (higher azimuthal resolution), and motion, and helicopter flight trajectory and attitude information are provided by the coupled PSUHelosim and CHARM rotor module. PSU-WOPWOP also has an atmospheric attenuation model and hard wall reflection models to account for these propagation effects.

The noise prediction system capability and limitations for the current implementation are demonstrated in section 3.2.

3.2 Example to demonstrate the noise prediction system

In the previous work (Refs. [29, 46, 54]) a Bell 430 helicopter model was developed for the noise prediction. To develop the helicopter model, information such as the number of blades, blade radius, engine power, helicopter physical dimensions, rotor dimensions, including blade radius and chord, the moment of inertia, and much more were necessary. As the starting point for the current work, the model was used in the noise prediction system to predict noise levels generated by a Bell 430 helicopter operating at 8000 lbs gross weight in 95.0 kts, level flight. The noise was measured at an observer located directly below the aircraft (the aircraft was 190 ft above the ground). This flight condition was chosen to match the flight test data. Therefore, a direct comparison can be used to judge the noise prediction system.

The flight test data used for comparison is collected from the acoustic flight test conducted by NASA, Bell Helicopter, and the U.S. Army in 2008 [57]. The measured acoustic pressure was processed through PSU-WOPWOP to calculate the noise levels at a given microphone location. This was done to eliminate any differences in the post-processing of the acoustic pressure data. As such, the only difference in the comparison comes from measured and predicted acoustic pressure.

The noise levels used to compare the flight test data and noise prediction system are overall sound pressure level (OASPL, dB), A-weighted sound pressure level
(L_A, dBA), sound exposure level (SEL, SELdBA), and effective perceived noise levels (EPNL, EPNLdB). The OASPL and L_A (A-weighted overall sound pressure level) are shown in Fig. 3.2.

![Graphs showing OASPL and L_A](image)

(a) Overall sound pressure level  (b) A-weighted sound pressure level

Figure 3.2: Example case: Bell 430–95.0 kts level flight.

In Fig. 3.2, the y-axis represents the noise levels and the x-axis represents the distance of the helicopter from the observer (located at position [0, 0, 0]). The noise prediction has captured the peak of the A-weighted SPL and the noise levels for more than 10 dBA down from the peak value (as this range is used to integrated to calculate the sound exposure level (SEL), which is used for noise certification by the FAA). However, the OASPL is underestimated by 2–3 dB. The SEL and EPNL comparisons are shown in Table 3.1. The noise levels compare well with those obtained from the flight test data.

<table>
<thead>
<tr>
<th>Flight test (PSU-WOPWOP processing)</th>
<th>SEL dBA</th>
<th>EPNL dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight test</td>
<td>97.5</td>
<td>100.0</td>
</tr>
<tr>
<td>Predicted</td>
<td>97.3</td>
<td>99.1</td>
</tr>
</tbody>
</table>

Table 3.1: Comparison of noise levels at the overhead microphone (Microphone 11–Ref. [57]).
The preceding example shows that the noise prediction system can be used to accurately predict noise levels of a helicopter operating in a steady flight condition. As the ultimate goal of the project is to be able to generate a noise abatement procedure, the capability to do so is best demonstrated by the examples shown in the next section 3.3.

### 3.3 Considerations for noise abatement

A comprehensive noise prediction system that incorporates the flight dynamics, aerodynamics and aeroacoustics of the helicopter, is required to predict noise of a maneuvering aircraft and to design low noise flight procedures. Special considerations must be made when implementing the noise prediction system to address the challenges of noise abatement. The noise prediction system should be capable of evaluating different helicopter models, operating in various flight conditions, and different geometric flight paths. To illustrate the challenges, simple examples are presented for discussion.

As examples of noise abatement procedures, two proposed noise abatement procedures are described here along with initial SEL noise predictions when the procedures are used.

<table>
<thead>
<tr>
<th>Segment</th>
<th>Procedure 1</th>
<th>Procedure 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>[a]</td>
<td>Constant speed (100 kts) descent and increasing flight path angle (FPA)</td>
<td>Decelerating at constant descent rate (1400 fpm)</td>
</tr>
<tr>
<td>[b]</td>
<td>Decelerating at constant flight path angle (-10°)</td>
<td>Decelerating at constant descent rate</td>
</tr>
<tr>
<td>[c]</td>
<td>Decreasing the descent rate at constant speed</td>
<td>Decreasing the flight path angle and descent rate</td>
</tr>
<tr>
<td>[d]</td>
<td>Decreasing flight speed at lower descent rate before landing</td>
<td></td>
</tr>
</tbody>
</table>
Figure 3.3: Flight path and velocity description of noise abatement procedures for Bell 430 aircraft.

(a) Noise abatement procedure 1.

(b) Noise abatement procedure 2.

Figure 3.4: SEL contours for Bell 430 operating in 80 kts, 6° descent and noise abatement procedures 1 and 2.

The procedures are each comprised of four segments, described in Table 3.2, and shown in Fig. 3.3. Figure 3.3 shows the time history of the aircraft altitude and the velocity profiles for these noise abatement procedures. (Notice, these procedures are only designed for the aircraft to descend to 200 ft above the ground and at \( x = 0 \), in these examples.) Figure 3.4 shows the predicted SEL contours on the ground for the reference case of an 80 kts, 6° descent and the two noise abatement procedures for the Bell 430 aircraft. Notice in both cases the SEL level is much lower than the reference case except near \( x = 0 \). The major difference between the two noise abatement procedures is segment \([b]\), shown in Table 3.2. By descending at constant rate of descent, the flight path angle increases with decrease in aircraft
speed and the flight condition results in lower noise. Thus, the noise abatement procedures were effective, although they were not necessarily optimal. Further analysis is required to consider the flyability of these approach procedures.

The noise abatement achieved in the procedures can be best explained by studying the effect of acceleration/deceleration and flight path angle on the noise levels. For this case study, the noise prediction system was run for a Bell 430 helicopter. Here, 5 different flight configurations are considered: 80 kts with 3°, 6° and 9° descent flight path angle and zero acceleration [Figs. 3.5, and 3.7] and 80 kts with 6° descent angle and -0.05g, 0.0g, and 0.05g acceleration [Figs. 3.6 and 3.8].

Figure 3.5: Bell 430: Comparison of OASPL dB levels for 3°, 6° and 9° steady descent flight path angle

Figure 3.6: Bell 430: Comparison of OASPL dB levels for 6° descent flight path angle with -0.05, 0, and 0.05g acceleration (acc)

The result shows OASPL and A–weighted SPL contours on a hemispherical grid.
The helicopter is located at the center (0.00, 0.00, 30.48 m) of a hemisphere grid with a radius of 100 ft (30.48 m). The helicopter travels in the positive x direction and positive z-axis is the altitude. Figures 3.5–3.8 shows the tilted top view of the hemisphere. A more detailed description is provided in Appendix A.1. The case is run for only 0.5 seconds with the hemisphere moving with the helicopter.

When comparing Figs. 3.5 and 3.6, it is obvious that though the flight conditions are different the resultant noise levels are essentially the same. The noise levels are maximum for an 80 kts, 6° steady descent flight (middle contour in Fig. 3.5). These higher noise levels are due to the rotor blade operating in its wake and thus producing higher BVI noise. A steady descent flight with 3° or 9° flight path angle (FPA) has a different rotor orientation from that observed for 6° (FPA) steady descent flight. For these rotor orientations, the rotor blades do not operate in the wake and this increases the BVI miss distance. Ideally, a steady descent flight with 3° or 9° flight path angle (FPA) would result in a quieter flight. However, a 3° steady descent has a very shallow descent, and when flying at 9° flight path angle, the descent is steep with the risk of going into autorotation. Also, pilots prefer to fly at 6° descent flight path angle.

The rotor orientation can be changed for the 6° steady descent flight by accelerating or decelerating the aircraft. This changes the effective flight path and thus reduces the BVI noise. Figure 3.6 shows that the pilot can choose to fly at 6° descent FPA and also minimize the noise by accelerating or decelerating (term acc in Eqns. 3.1) the vehicle by 0.05g (g = 9.81 m/s²). The transient flight conditions results in the same noise levels as 3° and 9° steady descent FPA. This occurs because, when accelerating or decelerating at 80 kts and 6° FPA, the rotor changes its orientation such that the angle of attack (α_{TPP}) of the rotor remains same as that for 3° and 9° descent angle, respectively and thus increasing the BVI miss distance. This means that the effective flight path angle has changed for the transient flight.

45
Effective FPA = FPA − acc × sin(FPA) \hspace{1cm} (3.1)

Equation 3.1 explains why the 80 kts, 3° steady descent flight (left contour in Fig. 3.5) and 80 kts, 6° descent with acceleration of 0.05g (left contour in Fig. 3.6 have almost identical noise contours. The effective flight path angle for 3° steady descent case is 3°, and for the 6° descent case with 0.05g acceleration, the effective flight path angle is 3.062°. Similarly, for the 80 kts, 9° steady descent case the effective FPA is 9° (right contour in Fig. 3.5) and for 80 kts, 6° descent with deceleration of 0.05g (right contour in Fig. 3.6), the effective FPA = 8.94°.

Figure 3.7: Bell 430: Comparison of A–weighted SPL for 3°, 6° and 9° steady descent flight path angle

Figure 3.8: Bell 430: Comparison of A–weighted SPL for 6° descent flight path angle with -0.05, 0, and 0.05g acceleration

Figures 3.7 and 3.8 shows the contour of A–weighted SPL. A similar trend, as observed for OASPL contours, is seen for the A–weighted SPL contours. The flight
condition of $6^\circ$ steady descent has a strong BVI noise. The center contour in Fig. 3.7 shows the advancing (left part of the contour and right of the flight direction shown in the Figs. 3.7 and 3.8) and retreating side (behind the helicopter) BVI. The advancing side BVI (‘red spot’) has higher strength when compared to the retreating side BVI.

Therefore, the primary reason for lower noise generated on the ground plane by the two procedures (Figs. 3.3 and 3.4) is the avoidance of the BVI by operating at higher rate of descent or flight path angle with deceleration, which make the effective flight path angle much higher that the one actually flown during the procedures.

The noise abatement procedures mentioned above work only for approach as they target BVI noise reduction by changing the rotor orientation, so that the rotor does not operate in its wake. Thus, there is a necessity to understand different noise sources and perform a parametric study of flight conditions for various rotor noise sources. Also, the hemispherical results indicate that the directionality of the noise is not isotropic. This will play a significant role in trying to manipulate the noise directivity such that sensitive areas are much quieter than other areas.

**Limitation of the existing noise prediction system**

The noise was predicted for these noise abatement procedures using the unmodified noise prediction system, described above. However, the prediction system was not capable of handling a time-dependent maneuvering flight. An approximate approach was used to predict the results for the above cases. At every 0.5 seconds of the flight time, the noise for the observers on the ground was predicted using the flight position and blade loads at that time. An observer time history of the A-weighted SPL is calculated for the observers on ground and then integrated to calculate the SEL noise levels (shown in Fig. 3.4). This “manual” approach assumed constant blade loads and linearly interpolated flight positions for a given observer.
time segment. For a maneuvering helicopter, the flight path is not rectilinear and the difference between the source time and the observer time can be very different based on the actual distance between the observer and the aircraft. Thus the noise prediction system needed some additional features to become a comprehensive noise prediction system for evaluating noise abatement procedures. These changes are further explored in the current chapter in section 3.5 and details of developing helicopter models is presented in section 3.4.

### 3.4 Development and description of helicopter models

In the current work, six helicopter models corresponding to the aircraft flown in the FAA/NASA noise abatement flight test [58] have been developed, following the approach set forth by Saetti et al., [46]. The six helicopters include the Robinson R44 and R66, Bell 206L and 407, and Airbus AS350 and EC130 helicopters. These helicopters were chosen based on availability, technology level, weight, number of blades, type of tail rotor, and the direction of rotor rotation.

The Robinson R44 and R66 are a similar size and have two-bladed main rotors with the same diameter, but the main rotor blade chord and twist are different. In addition, the R44 has a piston engine while the R66 has a turbine engine. (Note: the current noise prediction system does not predict engine noise.) The Bell 407 is a newer technology helicopter that is a larger replacement for the Bell 206L. The Bell 407 has a heavier maximum gross takeoff weight and has a four-bladed main rotor as opposed to the 206L, which has a two-bladed main rotor. The AS350 and EC130 helicopters are also closely related with a three-bladed main rotors and clockwise rotor rotation. The EC130 has a ten bladed Fenestron anti-torque device rather than the standard two-bladed tail rotor found on the AS350. The different helicopter configurations provide a good range of data for parametric analysis. The
Table 3.3: Helicopter specifications used for this work.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Robinson</th>
<th>Bell</th>
<th>Airbus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R44</td>
<td>R66</td>
<td>B206L</td>
</tr>
<tr>
<td>Maximum gross weight (lbs)</td>
<td>2500</td>
<td>2700</td>
<td>4150</td>
</tr>
<tr>
<td>Estimated flight weight (lbs)</td>
<td>1950</td>
<td>1900</td>
<td>3300</td>
</tr>
<tr>
<td>Engine Power (hp)</td>
<td>245</td>
<td>224</td>
<td>650</td>
</tr>
<tr>
<td>Main rotor number of blades</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Tail rotor number of blades</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Main rotor diameter (ft)</td>
<td>33.00</td>
<td>33.00</td>
<td>37.00</td>
</tr>
<tr>
<td>Tail rotor diameter</td>
<td>4.8</td>
<td>5.0</td>
<td>5.4</td>
</tr>
<tr>
<td>Tip velocity (main rotor) (m/s)</td>
<td>215</td>
<td>215</td>
<td>210</td>
</tr>
<tr>
<td>Tip velocity (tail rotor) (m/s)</td>
<td>183</td>
<td>193</td>
<td>216</td>
</tr>
<tr>
<td>Blade twist (deg)</td>
<td>-6</td>
<td>-10</td>
<td>-10</td>
</tr>
<tr>
<td>Lock number</td>
<td>6</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Flat plate area (ft²)</td>
<td>6</td>
<td>5.5</td>
<td>8.5</td>
</tr>
<tr>
<td>Main rotor rotation direction from top</td>
<td>CCW</td>
<td>CCW</td>
<td>CCW</td>
</tr>
</tbody>
</table>

helicopters considered are light to intermediate weight. A few of the key parameters for these helicopters are shown in Table 3.3.

The noise prediction system can determine the trim of the helicopter for a wide range of flight conditions. To do so requires helicopter configuration information, such as the parameters shown in Table 3.3 (and many more). Some of the parameters – like the number of blades, blade radius, engine power, and physical dimensions of the helicopter – are readily available from the manufacturers; however, other
important parameters like the blade chord, flat plate area, hub axis tilt, moment of inertia and others are not always available and may be proprietary. Scaled drawings of the helicopters and engineering judgement about blade structural properties were used to provide a rough estimate of the unknown parameters in this work. The rotor Lock number is approximated based on the class of the vehicle.

An incorrect trim of the helicopter may result in erroneous predicted noise. This error will depend on the sensitivity of the noise generation mechanism to the aircraft trim state. An analysis of the sensitivity of the noise source to the various parameters used to determine the aircraft trim was conducted and is described in this section.

Some helicopter parameters indirectly affect the noise generated by the helicopter. These parameters have a significant influence on the rotor trim, which in turn has a significant influence on the noise generation mechanisms. One of the rotor trim parameters is the angle of attack of the rotor tip path plane, $\alpha_{TPP}$. This trim variable is an important parameter not just for the performance characteristics of the helicopter but also for the BVI noise generation. If the angle is close to the skew angle of the wake, a significant noise contribution arises from the blade-vortex interaction (BVI), i.e., a tip vortex of the blade interacts with the oncoming blade. The amount of the noise generated due to the BVI noise source depends on the angle, and if incorrect, then the peak BVI noise for the helicopter will be either missed or calculated with a wrong flight condition. This offset can change the understanding of noise characteristics of the helicopter operating at various flight conditions.

The frontal drag force (function of flat plate area), flight path angle, rotor tilt angle, acceleration or deceleration, and propulsive force defines the angle of attack of the tip path plane ($\alpha_{TPP}$). The flat plate area and rotor tilt angle are fixed helicopter inputs that remain the same for all flight conditions. The flat plate area (FD) is assumed to be in the range of 6 ft$^2$ to 15 ft$^2$ depending on the class of the
helicopter and are primarily based on the suggestions made based on the flight test data. As FD increases, the tip path plane angle increases, and the peak BVI noise occurs at a higher rate of descent (higher approach glide slope angle). Table 3.4 shows how the assumed flat plate area affects $\alpha_{TPP}$ for a Bell 407 operating at 80 kts and descending at 6° flight path angle.

Table 3.4: Bell 407 helicopter trim

<table>
<thead>
<tr>
<th></th>
<th>FD=5</th>
<th>FD=15</th>
<th>FD=20</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_{TPP}$</td>
<td>0.684</td>
<td>1.21</td>
<td>4.455</td>
</tr>
</tbody>
</table>

The flat plate area also directly affects the helicopters performance characteristics by changing the drag of the vehicle. As the drag increases, the power requirement and the thrust required for forward speed increases proportionally. The hub axis tilt is important as it will affect the thrust vector necessary for broadband noise calculation and during a descent flight determines the angle of attack of the tip path plane at which the BVI noise occurs. The approximated flat plate area could be improved by matching the flight test data and predicted result at the peak BVI flight condition.

Some parameters, like the weight of the helicopter, change for every flight run. To avoid complexity, the weight of the helicopter was originally chosen to be 90% of the maximum gross weight. This weight turned out to be higher than the actual helicopter weight in the flight test (for most cases), and this led to higher noise levels predicted for aircraft like the Bell 407, for which the maximum SEL contribution comes from the broadband noise. Figure 3.9 shows the comparison between the broadband SEL contours for the helicopter with 90% of maximum weight and actual weight during the flight test (3600 lbs). The broadband noise is empirically calculated using the Pegg model [37] and is a function of the rotor thrust. Higher helicopter weight requires a higher rotor thrust. After additional
Figure 3.9: Parametric study of weight for Bell 407: Contour of broadband sound exposure level (SELDBA) for a 80 kts, level flight [Top figure: Helicopter weight=4200 lbs and Bottom figure: Helicopter weight=3600 lbs].

Flight test information became available, the weight of the helicopter was modified, and the trim was recalculated, and the noise levels were predicted. Here the weight of the helicopter is reduced by 1800 lbs (to 3600 lbs). The comparison with the flight test data has improved by changing the weight of the helicopter. In all the validation predictions, the estimated weight of the helicopter during the flight test is used. This value is recorded in Table 3.3. This change will help to reduce the differences between the flight test and predicted noise levels and will help to validate the prediction system.

The sensitivity to the parameters increases for flight conditions which are near the boundary of the flyable envelope, such as a very high forward speed or high rate of descent. For these flight conditions the dynamic inverse controller in PSUHelosim often is not able to calculate the state and state derivatives below the tolerance set for error. However, as long as the helicopter model data is in a reasonable range, for the current scope of the project, the approximation appears to be reasonable.

The helicopter models developed in this work are further used to enhance and validate the noise prediction system. For more detail on PSUHelosim and setting up the helicopter models please refer to work done by Saetti et al., [46] and Padfield [36].
3.5 Important features analyzed or implemented into the noise prediction system

Numerous modifications to the original noise prediction system were made for the validation of comprehensive noise abatement procedures. In the following subsections, each new feature is explained along with the rationale for the implementation decision. Each newly added feature directly enables prediction of noise abatement maneuvers or improves the noise prediction. The subsequent descriptions emphasize the impact on different noise sources and the overall effect seen in total noise.

3.5.1 Time-dependent aircraft position and attitude

The first requirement for noise prediction of abatement procedures is that the noise prediction system must be able to include time-dependent changes in velocity and direction. Acceleration due to either changes in velocity or changes in heading result in changes in the blade motions and loading, thus changing the noise generation. Velocity and direction changes also change the directivity of the noise relative to observers on the ground. In maneuvering flight, it is fundamental that the time-dependent aircraft position, attitude, and airloads are included in the flight simulation and noise prediction.

In the updated noise prediction system, the simulation of time-dependent maneuvers (transient maneuvers) proceeds in the following manner. The flight simulation code PSUHeloSim begins the simulation. After a time interval used to ensure any startup transients have passed, the commanded flight procedure (maneuver) begins. In the commanded flight procedure, heading velocity and heading angle of the desired flight path are used to direct the flight simulation. The CHARM rotor module, coupled with PSUHeloSim, uses the flight simulation state data and computes detailed blade loads.
Figure 3.10: Flight trajectory information of a Robinson R66 performing a level, decelerating turn (at a target roll angle $35^\circ$, and decelerating at -0.05g from 80 kts to 60 kts), considered for demonstrating the necessity of a time-dependent noise prediction system.

The flight trajectory information, (i.e., $x - y - z$ position as a function of time), attitude (roll-pitch-yaw as a function of time) and blade loads are the new inputs to PSU-WOPWOP. (PSU-WOPWOP already has the ability to compute the noise of transient maneuvers, but the previous version of the noise prediction system did
not implement the transfer of this information to PSU-WOPWOP.) To speed up
the computation, the rotor loads data are extracted every 0.5 seconds as periodic
data (one rotor revolution for each rotor, even if the rotor speeds are different –
this quasi-periodic approximation is described in section 3.5.5). Only the airloads
are assumed to be periodic – the aircraft position, attitude, and noise prediction
are computed continuously throughout the maneuver. The airloads data from
CHARM are then used in PSU-WOPWOP to compute the acoustic pressure from
both the main and tail rotors at the desired observer locations. PSU-WOPWOP
also computes different metrics (OASPL, SEL, etc.) for further analysis.

As an example to show the time-dependent nature of the aircraft position and
attitude, the Robinson R66 helicopter model is used in a simulation of a level,
decelerating right turn. Figure 3.10a shows the flight trajectory (East position
vs. time, altitude vs. time, and absolute velocity vs. time) for the R66 helicopter
performing a 90° right turn and Fig. 3.10b shows the aircraft attitude (roll, pitch
and yaw) as a function of flight time. The aircraft pitch and roll attitudes peak
around 3 seconds as predicted by the PSUHelosim and CHARM codes, followed
by a period of steady level flight (until approximately 15 seconds) after which the
helicopter performs the combination of deceleration, roll-in, and roll out of the turn.
Figure 3.10 has points marked from 1–5. Point 1 represents an 80 kts level flight
condition, Point 2 represents the beginning of the roll into the turn and start of
deceleration, Point 3 represents maximum roll angle of 40° and heading angle of
45°, Point 4 represents the roll out of the turn, and Point 5 represents steady, 60
kts level flight. PSUHelosim coupled with the CHARM rotor module generates
these time-dependent parameters (after simulation time 10 seconds), which are the
input to the PSU-WOPWOP noise prediction code. As the noise levels decrease
with distance and change rapidly with directivity, the aircraft position and attitude
are important inputs to predict the noise accurately. Figure 3.11 shows sound
exposure level (SEL) noise contours (individual components and total) for the
example Robinson R66 time-dependent flight maneuver. PSU-WOPWOP uses a problem dependent, user specified set of coordinate transformations to model all the details of the aircraft flight position and motion in order to predict noise.

Figure 3.11: Sound exposure level (SEl_{dBA}) contours calculated using a time-dependent noise prediction system, for a Robinson R66 performing a level, decelerating turn (at a target roll angle 35°, and decelerating at -0.05g from 80 kts to 60 kts).

In Fig. 3.11, the aircraft starts flying from the bottom of the figure (x = 0 m, y = 0 m) toward the top, and then the aircraft turns to the right 90° at about x = 500 m. Note that the noise computation in PSU-WOPWOP starts from 10 seconds so that the transient that occurs at the initialization of the coupling is not included in the noise prediction. The SEL contour directivity reflects the right turn. The broadband noise is the dominant component of the SEL metric, which accounts for annoyance by using noise duration. The time-dependent position and
attitude of the helicopter are crucial parameters to include in this case because the helicopter state is changing significantly throughout the turn and deceleration. The transient segment of the flight procedure, start/end of the deceleration, rate of change in roll angle, can be observed in Fig. 3.10b, result in higher rate of change of blade loads along the azimuth (\( \dot{l} \)–shown in Fig. 3.16) and consequently, higher-harmonic loading noise.

This capability of noise prediction to follow a predefined flight trajectory is utilized when validating the system with the flight test data. The different flight procedures analyzed and used for validation closely follow the flight trajectory flown during the flight test.

### 3.5.2 Importance of time-dependent loading

Time-dependent blade loading is important to correctly predict the loading noise, and time-dependent rotor thrust is also important for the broadband noise prediction. In the current section and section 3.5.6, predictions are presented to demonstrate this assertion. Figure 3.12 shows a comparison between loading noise SEL contours on a ground plane \((x - y)\) with constant blade loads and quasi-periodic blade loads (varying every 0.5 seconds–described in detail in section 3.5.5) for the level, decelerating turn (described in section 3.5.1). Note that both predictions include a time-dependent flight trajectory, and helicopter attitude. In Fig. 3.12a, the loading from the level flight before the turn is used throughout the noise computation, thus the increased rotor thrust due to the centrifugal force and BVI are not included. Figure 3.12b shows SEL contours with the expected increase in noise levels generated by a maneuvering flight during a turn. As the vehicle transitions from a steady level flight to a decelerating turn \((x = 400 \text{ to } 600 \text{ m})\), BVI has increased resulting in an overall increase in noise levels.
3.5.3 Closed and open loop coupling

In this section, the coupling of the PSUHelosim flight simulation and CHARM aerodynamics module are described. PSUHelosim needs initial velocity components and the information of changes in desired heading velocity and heading angles during the flight procedure to calculate the helicopter state vector, state derivatives, and control inputs. These values are passed to the CHARM rotor module at regular time steps. CHARM calculates rotor loads and moments that can be used directly (open loop coupling) for the noise prediction or passed back to PSUHelosim (closed loop coupling - dotted blue line connection shown on Fig. 3.1) so that the flight simulation uses the high-fidelity blade loads. Once converged, the blade loads and motion are passed to the noise prediction (PSU-WOPWOP).

One significant difference between the closed and open loop coupling is the tail rotor model. PSUHelosim uses a simple model to calculate the tail rotor collective and power requirement. If closed loop coupling is used, the main rotor wake effects are captured in the tail rotor inflow, and the main and tail rotor flapping motion

(a) Constant blade loads
(b) Quasi-periodic blade loads

Figure 3.12: Comparison of loading sound exposure level (SELdBA) contours for a constant periodic and quasi-periodic blade loads calculated for a Robinson R66, level, decelerating turn (at a target roll angle 35°, and decelerating at -0.05g from 80 kts to 60 kts).
accounts for these changes. However, during open loop coupling, the influence of wake on the two rotors goes unnoticed and results in different trim for blade loads calculation.

Figure 3.13: PSUHeloSim-CHARM rotor coupling for a Robinson R66 performing a level, decelerating turn with a roll angle of 35° and deceleration of -0.05g from 80 kts to 60 kts (x-axis is simulation time).
To illustrate the difference between open and closed loop coupling, consider the level, decelerating 90° turn in section 3.5.1. The flight trajectory and attitude information are provided in Fig. 3.10. The coupled PSUHelosim and CHARMM codes calculate aircraft state for the flight procedure. In Fig. 3.13 the controls (collective, longitudinal, and lateral cyclic pitch for the main rotor, and collective pitch for the tail rotor) and flapping angles of the trimmed solution using closed and open loop coupling are shown. The controls (Fig. 3.13a) jump at 3 seconds as the closed loop coupling starts from this point. The transient jump settles down after a few seconds. The tail rotor collective ($\theta_{0T}$) for this case does not show a significant difference when computed using a closed loop or open loop coupling. This is one of the checks for approximating helicopter parameters. Another point to note is the tail rotor collective ($\theta_{0T}$) decreases during a right-hand turn for a counterclockwise rotating main rotor. The cyclic flapping angles (Fig. 3.13b), which would affect the thickness noise computation, show a significant difference as the effect of the wake are not available for open loop coupling, but are accounted for during the closed loop coupling. The expected advantage of using a closed loop coupling is in calculating the state of the helicopter with the consideration of the detailed wake effects on the inflow and use of a detailed tail rotor instead of a simple model. This result in the CHARMM rotor module to calculate the blade loads with more accurate trim. A closed loop coupling forces the CHARMM model to calculate the However, the validation of the noise prediction system was carried out using open loop coupling. The robustness of the open loop coupled PSUHelosim/CHARMM was essential for trimming the helicopter to follow a very transient flight procedure flown during flight test. The helicopter models developed for validation were purely based on engineering judgment and lacked the sophistication needed for a closed loop coupled solution.
3.5.4 Resolving issue with CHARM reconstruction

(a) Discontinuity in the periodic blade loads in $z-$direction.

(b) Error in loading acoustic pressure due to discontinuity in blade loads.

Figure 3.14: Demonstrating the discontinuity in the periodic blade loads in $z-$direction for a Bell 407 performing a level flight.

CHARM rotor module calculates the time-dependent or azimuth angle-dependent blade loads required for noise prediction. These blade loads are typically discretized
for every 15° or 7.5° azimuth of blade rotation, depending on the chosen discretization. However, for BVI noise prediction, the temporal resolution required is typically at least 1°. To overcome this lack of azimuthal resolution, the CHARM rotor module uses a feature called reconstruction (RECON). Here, at the time of calculating periodic blade loads for predicting noise the reconstruction resolves the wake and calculates the blade inflow for every 1° rotor azimuth (i.e., between the two previously calculated azimuth angle. So for example, if blade loads were calculated for every 15°, then reconstruction calculates the wake and inflow for each 15° azimuth segment to generate periodic blade loads for higher temporal resolution). However, the reconstruction feature results in a discontinuity every 15° azimuth angle (shown in Fig. 3.14a) and this adds numerical noise in the loading noise calculation which can be seen in the loading acoustic pressure time history (shown in Fig. 3.14b). The jump in loading acoustic pressure circled as ‘red’ in Fig. 3.14b, occurs at the same frequency as that of the discontinuity.

First, a more detailed examination is conducted to understand the significance of error in the loading acoustic pressure calculation. The first term of the loading acoustic pressure (p′<sub>L</sub>) calculated using Farassat’s Formulation 1A (described in detail in Chapter 2 and shown in equation 3.2) contains the surface integral of the source time derivative of the blade loading in the radiation direction and the Doppler amplification factor. The time derivative of the loading vector (̇l) is calculated using the blade loads. This has a numerical error due to the discontinuity, seen above, and results in a nonphysically high value in the time derivative of the loading vector and, if used for in Formulation 1A calculation, results in an error in loading noise. This error exists for both the rotors: the main and tail rotor.

\[
4\pi p'_L(x, t) = \frac{1}{c} \int_{f=0}^{f} \left[ \frac{\hat{l}_r}{r(1-M_r)^2} \right]_{ret} dS + \int_{f=0}^{f} \left[ \frac{l_r - l_m}{r^2(1-M_r)^2} \right]_{ret} dS + \frac{1}{c} \int_{f=0}^{f} \left[ \frac{r\hat{M}_r + c(M_r - M_r)^2}{r^2(1-M_r)^3} \right]_{ret} dS
\]

(3.2)
An attempt is made to resolve the error seen when calculating the time derivative of the loading vector for the main rotor. Here, the jump in time derivative is removed by changing the value of the azimuth derivative at the angles before and after the jump to the value of the derivative from the previous or later angles, such that the jump is not included in the derivative calculation (i.e., assume the jump occurs at 15th azimuth angle then to reduce numerical error; change the time derivative of the blade load at 14th and 15th azimuth angle to that of 13th azimuth angle and 16th azimuth angle same as 17th azimuth angle). The azimuthal derivative of the loading vector at these three angles does not show the erroneous jump, and this is seen in the acoustic loading pressure shown in Fig. 3.15. Here, the acoustic loading pressure for a single rotor blade is calculated for random flight time, with and without resolving the reconstruction (RECON) error. The results show a significant decrease in the amplitude of the error, though small fluctuations are still observed.

During the tail rotor loading noise calculation, the blade azimuth resolution is kept 15° and not 1°. The main reason for doing this is the small-time step required for 1 azimuthal increment of the tail rotor blade. This time step is an order of magnitude lower when compared to the main rotor. As such, even a small jump or error in blade load calculation results in amplifying the numerical error in time derivative of the blade loads and subsequently, the loading noise generated by the tail rotor. Therefore, the reconstruction is not applied when calculating the tail rotor blade loads. This may result in not capturing certain tail rotor and main rotor wake interaction effects when predicting the tail rotor loading noise.

This is an improvised approach to remove this numerical error. The correct fix is that the reconstruction process be corrected so that no artificial jump occurs in blade load calculation. For now, this method is used to resolve the reconstruction error when validating the noise prediction system using the flight test data.
3.5.5 Quasi-periodic blade loads

Noise abatement procedures often will involve maneuvering flight, where the aircraft attitude and blades loads change continuously throughout the maneuver. The level, decelerating turn in section 3.5.1 is a good example of such time variation. The blade loads for that maneuver are shown in Fig. 3.16 at the five distinct times shown in Fig. 3.10. The loads are the component of force per unit length acting on the fluid in the $z$–direction (top view of the rotor) where the flight direction is left to right in the figure. The individual load plots are numbered 1–5 corresponding to the flight conditions described in section 3.5.1. For flight condition 1, the blade loads reveal there is less thrust than for the next three flight states. An increase in rotor thrust and BVI is observed as the helicopter goes through the turn in flight states 2 to 4, with a maximum seen during flight state 3 (maximum roll angle and centrifugal force on the helicopter) and a decrease for the 60 kts level flight condition. Figure 3.16 also shows the presence of strong BVI blade loads at flight states 2, 3, and 4. So to capture the noise generated during a maneuver – like the level, decelerating turn – the noise prediction system needs to account for the
continuously changing blade loads.

The noise prediction system is capable of calculating the blade loads as a continuous function of time. However, there are computational considerations in dealing with time-dependent data. The most straightforward approach is to predict the aircraft motion, blade motion, and blade loading at every time step, and pass it to the noise prediction program. While this should be the most accurate, it is also computationally very demanding because significant amounts of data and computational time are required. An approximation currently used to reduce the computational demands is for the airloads computations on each rotor to be computed for one rotor revolution and then used for 0.5 seconds. This quasi-periodic blade loads assumption is based upon the observation that for maneuvers that are not too aggressive, the blade loading only changes slowly and is approximately periodic for each rotor revolution.

The quasi-periodic approximation reduces the computational effort, especially for the tail rotor, but it does eliminate some of the potential interactions between the main rotor wake and tail rotor.

Figure 3.16: Periodic blade loads in $z$—direction at 5 instances of flight path shown in Fig. 3.10 for a Robinson R66 performing a level, decelerating turn.
Impact of “jump” in blade loads

The quasi-periodic assumption changes blade loads every 0.5 seconds, which is not an integer multiple of a rotor revolution period. Furthermore, when the loading changes from one period to the next, there can be a “jump” in blade loads, which can be more or less severe depending upon the flight condition. Initially, there was a concern that this “jump” would add numerical noise in the prediction due to an erroneous calculation of the time derivatives of the loading variable, similar to the error seen during reconstruction. However, this jump occurs at a single source time, which gets smeared out on the acoustic planform of the blade, and also the

Figure 3.17: “Jump” in blade loads for a steady and BVI flight condition.

Figure 3.18: Impact of “jump” in blade loads on overall sound pressure level (OASPL, dB) contour calculated over a hemispherical grid.
frequency of jump is much smaller (jump occurs approximately every 2.5–3 rotor revolution) than seen during error caused by reconstruction (jumps occurs at 1/24th of a rotor revolution). To examine if this numerical error can increase the noise intensity, two periodic blade loads with a rather extreme jump are considered for an 80 kts flight of a Bell 407 helicopter (for ease of understanding, noise levels are calculated for a single main rotor blade). The first periodic blade loading exists from 0.0-0.5 seconds of the source time. This blade loading is calculated for an 80 kts level flight condition, while the seconds blade loading for 0.5–2.0 seconds of the source time is calculated for an 80 kts, 6° descent flight condition. The “jump” between the two blade loads is circled with a dotted blue line in Fig. 3.17. In this figure the loading for one blade is shown on the path the blade traverses over four rotor revolutions. These are two very different conditions and are only used to demonstrate the potential error if a quasi-periodic blade assumption is adopted.

The OASPL are predicted for an 80 kts level flight using these two blade loading conditions, and the results are shown in Fig. 3.18. Here, the helicopter is located at the center (0, 0, 100 ft) of the hemisphere that travels in the positive $x-$direction with the helicopter. The radius of the hemisphere is 100 ft with (0,0,0) location is directly beneath the aircraft. For each hemisphere, the OASPL is computed using 0.5 seconds of predicted acoustic pressure data with a “Hanning” window applied. The grid is used to look at the noise directivity to see if the jump in the blade loading results in “hot spots” that don’t exist during the previous and later times; times that don’t have any jump in the loading.

The hemisphere at observer time 0.0 seconds only uses the first blade loads (steady level flight–80 kts) for a -0.25 to 0.25 seconds observer time window. For the time window of 0.25–0.75 seconds or observer time 0.5 seconds, the blade loads are switched between the two blade loadings, and the results are shown in Fig. 3.18 for the hemisphere marked as 0.5 seconds. The results show a small elevation of noise levels when compared to hemisphere marked as 0.0 seconds. The hemisphere plots
for the observer time 1.0, 1.5, and 2.0 seconds uses the BVI blade loads observed during a 6° steady descent flight. In these results, no obvious “hot spots” due to the jump in loading are observed. The smoothing effect in a time window for which the blade loads are switched can be explained by retarded time and lower frequency of jump. In the noise computation, the noise from each segment on the rotor blade at the same source time, arrive at the observer at different observer times. Thus the actual blade planform at any source time can be quite different from the one seen by an observer (the acoustic planform). Because the jump in blade loads is localized to a single source time on the blade, its effect at any observer point is minimal.

The loading acoustic pressure time history of the flight procedure with two distinct periodic blade loads is shown in Fig. 3.19. The loading acoustic pressure for the time 0.0–0.5 seconds is calculated with only the blade loads observed for a steady level flight while for the time window 0.5–1.0 seconds the blade loads change suddenly. The impact of the jump in blade loading is very small at this observer position. Upon detailed examination, there is some difference in the signal as the loading changes from the level flight loading to BVI loading. After 0.6 seconds, the acoustic pressure signal is just due to the BVI loading. Thus, this simple implementation of the quasi-periodic blade loading does not seem to result
in any significant errors and provides the noise prediction system with capability of predicting loading noise during a maneuver at much less computational cost.

### 3.5.6 Implementing time dependent and wall reflected broadband noise computation using Pegg’s empirical model

The broadband noise is a significant rotorcraft noise source in noise certification metrics. In the noise prediction system, PSU-WOPWOP uses an empirical broadband noise model developed by Pegg [37]. The broadband noise has higher frequency content (than thickness and loading noise), which is weighted more heavily in metrics that represent human hearing. As such, the broadband noise can be a dominant contributor in noise levels, like SEL – especially when the aircraft flies overhead and downrange. The broadband noise prediction in PSU-WOPWOP was not able to handle time-varying rotor thrust or ground reflections at the beginning of this work, so modifications were required for noise abatement predictions. These modifications will be described in the next two subsections.

**Importance of time-dependent rotor thrust for broadband noise**

The empirical model developed by Pegg [37] for broadband noise computes the $1/3$rd-octave SPL noise spectrum. The formulation requires the following input: total blade area, rotor thrust component in the direction of hub axis or average blade lift coefficient ($\bar{C}_l$), rotor tip speed, angle between the negative thrust axis and vector between the hub and observer, and distance between the source (rotors) and the observer. Some of the input parameters, like total blade area and rotor tip speed, are constant for a rotor. The distance between the source and the observer is computed in the broadband noise calculation with the implementation of time-dependent helicopter position. Two time-dependent parameters not previously modeled in the PSU-WOPWOP calculation are the angle between the negative thrust axis and the vector from the hub to the observer, and the rotor thrust.
Both of these change during a maneuvering flight and depend on components of rotor thrust. Hence, a modification to PSU-WOPWOP was performed to include a time-dependent thrust vector. In the code, the rotor thrust components are provided as a continuous function of time. For an observer time window of 0.5 seconds, the rotor thrust components are averaged to calculate the resultant rotor thrust and the angle between the resultant thrust and the vector from the hub to the observer.

For the level, decelerating 90° turn case described in section 3.5.1, the blade lift coefficient averaged over a rotor revolution ($\bar{C}_l$) is calculated throughout the entire flight maneuver and is shown in Fig. 3.20a. $\bar{C}_l$ ranges approximately from 0.12–0.19 and is maximum during the turn maneuver (time: 15-27 seconds in Fig. 3.20a). A comparison of broadband SEL contours computed using constant rotor thrust (at the beginning of the flight time) and a time-dependent rotor thrust in the Pegg broadband noise model is performed to emphasize the importance of the current modification. The results are shown in Fig. 3.20. Rotor thrust increased during the turn maneuver and this effect is clearly seen by comparing the two contours shown in Fig. 3.20. The roll of the helicopter changes the directivity of the broadband noise but increases the noise levels due to the increase in rotor thrust. These factors are now implemented in the noise prediction system.
(a) Averaged blade lift coefficient $\bar{C}_l$ for the main rotor of a Robinson R66 helicopter performing a level, decelerating turn (at a target roll angle 35°, and decelerating at -0.05g from 80 kts to 60 kts), $x-$axis is the simulation time.

(b) Constant rotor thrust

c) Time-dependent rotor thrust

Figure 3.20: Comparison of broadband sound exposure level (SE$$\text{l}_{\text{dBA}}$$) contours at a constant and time-dependent rotor thrust, for a Robinson R66 performing a level, decelerating turn (at a target roll angle 35°, and decelerating at -0.05g from 80 kts to 60 kts).

**Ground reflection of broadband noise**

The full applicability and limits of the Pegg broadband noise model [37] are not well understood; therefore, the model needed to be evaluated before utilizing it for designing noise abatement procedures. This evaluation was enabled by comparing flight test data, obtained from the acoustic flight test conducted by NASA and the
FAA [58], with the predicted results. The measured data provides acoustic pressure time histories for this wide range of flight conditions over a large microphone array placed on the ground. The comparison provides important insight into the noise in general, and by inference the broadband noise.

The comparison with flight test requires the noise prediction system to account for the real effects of noise propagation to the observer. In many actual situations, the noise is reflected off the ground and heard by the observer. The flight test data was taken with microphones placed on ground boards on the ground. The need to model broadband noise reflection became clear when comparing the level flight test data with the predicted noise. The broadband noise reflection was assumed not to be correlated with the direct broadband signal (i.e., uncorrelated) because the propagation path can be significantly different for the reflected signal (although when the microphone is placed on a hard ground board, the reflection is correlated). The uncorrelated broadband noise sources were summed by adding the mean squared acoustic pressure spectrum of the observer and the image observer. In particular, the 1/3-octave SPL levels computed by the Pegg noise model were converted to mean squared pressure, summed, and then converted back to 1/3-octave SPL levels.

As an example, a comparison between the validation results for the Robinson R66 and the Bell 407 – with and without the broadband wall reflection model – is performed and shown in Fig. 3.21. Figure 3.21a on the left shows the comparison for the Robinson R66, while the right-hand side Fig. 3.21b is for the Bell 407. In the case of the R66, the broadband noise is the dominant noise source, and hence, it was important to have a wall reflection model in the broadband noise prediction. The Bell 407 helicopter has significant thickness, loading, and broadband noise contributions. In both cases the SEL levels increase with the broadband wall reflection, but to differing degree. Hence, when the broadband noise is only comparable to other noise sources (i.e., it is not dominant), there is a smaller difference between the cases with and without broadband wall reflection, and when...
broadband noise is small compared to other sources, the reflection typically does not impact the total noise.

Figure 3.21: Comparison of sound exposure level (SELdBA) contours, for an 80 kts level flight, with and without ground reflection of the broadband noise.

3.5.7 Time-dependent blade flapping dynamics for thickness noise

During a maneuver, the blade coning, longitudinal, and lateral flapping angles are time-dependent; thus, the orientation of the rotor tip-path plane can vary relative to the rotor shaft throughout a maneuver. In the noise prediction system, PSUHeloSim and the CHARM rotor module determine both the aircraft and blade
dynamics. The time-dependent aircraft position and attitude are passed directly to PSU-WOPWOP, where it computes the aircraft motion and rotor rotation based on this information. The blade geometry information required for computing thickness and loading noise is passed separately to the PSU-WOPWOP code. The loading noise calculation is based on lifting line theory (compact chordwise assumption) and, as such, only requires the blade geometry information at the quarter-chord of the blade (shown in Fig. 3.22). The blade motions relative to the rotating hub frame are passed by CHARM to PSU-WOPWOP as a time-dependent blade deformation file, which can also include time-dependent blade bending. This information is included in the loading noise calculations. However, for the thickness noise computation, the shape of the blade is required. For this reason, the computational surface of the entire blade is made of a 2-D airfoil along the span. An unstructured grid (shown in Fig. 3.23) defines the 3D blade for thickness noise calculation. The blade flapping and bending motions that were included in the lifting line used for loading noise calculation are not accounted for thickness noise prediction. As such the blade surface, though undergoes the rotor rotation and other motions associated with the helicopter, is constant throughout the flight. In the future work, the rotor flapping motions need to be added as some function of the rotor coning, longitudinal, and lateral flapping coefficients ($\beta_0$, $\beta_1c$, $\beta_1s$) for improving the prediction of thickness noise.
3.6 Concluding remarks

In this chapter, the noise prediction system (developed by [29, 46, 54]) is described and demonstrated in section 3.2. The system was not fully capable of modeling low noise flight procedures in its original implementation. In this work, the deficiencies in the initial implementation were identified and analyzed. Then modifications necessary for analysis and design of low noise flight procedures were implemented. By comparison of the predicted noise levels with the flight test data (obtained in the acoustic flight test conducted by FAA/NASA in 2017 [58]), some existing numerical errors have been addressed and new features (described in this chapter like wall reflection for broadband noise, quasi-periodic blade loading, source motion and so forth) were implemented in the noise prediction system.

The total simulation time depends on the number of observer, number of blades and rotors and total flight time. The PSUHelosim/CHARM calculation takes approximately 20–25 minutes to simulate a flight trajectory of about 30 seconds. The inputs are provided to PSU-WOPWOP for calculating noise. PSU-WOPWOP is capable of performing parallel computing over the number of observers. The computational time can be tremendously reduced by using a single processor for
each observer. The computation time for calculating noise for a single observer depends on the discretization of the source time array, total flight time and number of rotors and blades. A general rule of thumb used for discretizing the source time array is to use 1024 time steps ($nt$) for duration of 1 rotor revolution. For example:

To compute noise level generated by Bell 407 (2 rotors with 4 bladed main rotor and 2 bladed tail rotor) over a single observer and for a total observer time of 55 seconds, the total computation time is approximately 12–13 minutes.

The noise prediction system with the newly implemented features is validated in Chapters 4 and 5. This validation is done to not only give confidence in the current system but also to provide new insight into the noise levels generated by the flight procedures. The improvement of the noise prediction system is an ongoing process, and any issues found will be the future work for the current project (ASCENT Project 38).
Validation and analysis of steady flight conditions

A comprehensive noise prediction system is required to predict helicopter noise and develop potential noise mitigation strategies. It requires capability of predicting noise generated during a complex maneuver. Understandably, it is necessary to validate and understand the limitations of the noise prediction system before it can be used to develop noise abatement procedures. In this chapter, the validation process is carried out by comparing the predicted acoustic pressure and noise levels of microphones on ground boards to the acoustic data obtained during the flight test [58]. The FAA and NASA conducted a acoustic flight test with six different helicopters in coordination with the FAA Center of Excellence ASCENT Project 38. The flight test includes various flight operations: such as steady level flight, steady descent, steady turns, deceleration/acceleration with descent or turns, and other flight profiles. The flight profiles are achieved by varying velocities, the rate of descent or climb, bank angle, and deceleration. The measured data provides acoustic pressure time histories for this wide range of flight conditions over a large microphone array placed on the ground. Details about the flight test can be found in [58].

The examples considered are; level flight, descent, level right and left turns,
level, decelerating turns, and descending turns. This range of flight conditions was necessary to analyze the prediction system and understand its capabilities and deficiencies for future work. The comparison of flight test data and predicted noise using the noise prediction system will give confidence in the noise prediction system’s capability in the development of noise abatement procedures and also help to improve the current prediction system.

4.1 Validation process

The validation process to conduct the comparison between the predicted noise levels and the flight test data is provided in this section. Certain modifications were necessary for the noise prediction system to make a direct comparison. These modifications are discussed here. Another thing that is addressed in this section is the processing of the measured acoustic pressure time history obtained during the flight test.

4.1.1 Using noise prediction system for validation

The comprehensive noise prediction system described in Chapter 3 is validated by directly comparing the flight test data with the predicted noise. The main requirement is simulating the flight trajectory so that it will follow the actual flight test trajectory. The aim when conducting validation is to minimize differences between experiment and prediction so that any discrepancies in the theoretical modeling or numerical implementation may be found. This is difficult when using flight test data for validation because flight test data always includes transients in the desired flight trajectory and aircraft attitude due to continually changing variables like wind gusts and piloting uncertainty, which is usually not accounted for in the flight simulation. Care must be taken to account for simple transient changes during a flight, like a temperature and wind changes, fuel burn, etc. to
ensure the flight test data and predictions represent the same conditions. However, for the current scope of the work, only the flight trajectory is simulated. Effects due to wind gusts, changes in temperature and wind direction are ignored.

The flight trajectory information is available in the flight test data [58]. In the flight simulation, the controller tries to mimic the actual flight procedure and calculates the states and state derivatives required by the CHARM rotor module for calculating high-fidelity blade loads and motion. The simulation for each flight run proceeds in the following manner. The flight simulation code PSUHelosim begins the simulation. After a short segment of steady flight condition the commanded flight procedure (maneuver) begins.

The recorded information on flight trajectory ($x, y, z$ coordinates as a function of flight time) and the aircraft attitude (pitch, roll, yaw as a function of flight time) during the flight test is transient and is shown in Fig. 4.1 in the ‘black’ line.

For the validations process the difference between a real and simulated flight trajectory is achieved by using the flight trajectory information. In order to do so, the controller requires more flight information such as; helicopter trajectory; $x, y,$ and $z$, helicopter velocity components; $v_x, v_y,$ and $v_z$, acceleration components; $a_x, a_y,$ and $a_z$, and heading angle with its first and second time derivatives; $\psi, \dot{\psi},$ and $\ddot{\psi}$. These 12 input commands to the controller are able to simulate the actual flight trajectory, as shown in Fig. 4.1–black line. One point to note is that the aircraft heading angle and its first and second derivatives are the inputs to the simulation, while the pitch and roll angles are only calculated during the simulation—the flight controller does not follow roll and pitch excursions in the flight test data at this time.
Figure 4.1: R44, 80 kts, level flight - comparison between flight test data, simulated steady flight path and simulated transient flight path using flight test data.

The coupled PSUHeloSim/CHARM flight simulator uses the flight simulation state data and computes detailed blade loads, flight trajectory, and aircraft attitude along the flight path. To speed the computation, the rotor loads data are extracted every 0.5 seconds and treated as periodic data (one rotor revolution for each rotor).
Although the system can operate in a fully coupled mode (closed loop), here the high fidelity CHARM airloads are fed back to controller. However, for the validation purpose the coupling is one way (open loop); i.e., no feedback of the airloads to the simulator. The airloads data from CHARM are then used in PSU-WOPWOP to compute the acoustic pressure generated by both the main and tail rotors at desired observer (microphone) locations (the system is described in Chapter 3, and the schematic of the noise prediction system is shown in Fig. 3.1). PSU-WOPWOP can compute different noise levels from the predicted acoustic pressure; however, sound exposure level (SEL), overall sound pressure levels (OASPL, dBA), A-weighted sound pressure levels (L_A, dBA), and acoustic pressure time history are used for validating the noise prediction system with the flight test data. The first metric chosen for validation was the sound exposure level (SEL). This metric takes into account the duration of the noise event and is the metric used for helicopter noise certification for the aircraft used in the NASA/FAA flight test.

4.1.2 Flight test data processing

The flight test data available for this study contains the measured acoustic pressure time history data for each microphone in a microphone array. These microphones were flush-mounted on the ground with ground boards. The actual microphone locations used in the flight test are also used for observer locations in the noise predictions. The flight test data includes other flight information; flight trajectory (X, Y and Z position of the helicopter), attitude (ψ, θ and φ), three velocities (v_x, v_y and v_z in feet and knots), acceleration of the helicopter (a_x, a_y and a_z) helicopter weight, uncertainties of these variables, reference temperature, wind direction, and other such values. The acoustic data was recorded with NASA and Northrop Grumman Aerospace Systems (NGAS) acoustic measurement. The six helicopters were installed with an Aircraft Navigation and Tracking System (ANTS) unit for capturing helicopter flight trajectory. The unit receives Global Positioning System
(GPS) signal, processes and uses Kalman filtering to determine the helicopter state. Details of the flight test can be found in [58].

The direct comparison of the acoustic pressure measurements with predicted acoustic pressure is awkward due to a large number of individual microphones and unavoidable transient effects of flight test. Therefore, the validation process starts by post-processing measured acoustic pressure data into SEL contours using PSU-WOPWOP; thus, the only difference between the prediction and the measured data is the acoustic pressure time history and not the details of the algorithm used to compute sound exposure level (SEL). Certain microphones (or observers) shown on the SEL contour plot are chosen for detailed validation of the noise level time history. This microphones selection was based on interesting features seen in the SEL contour plot, or if the helicopter was performing complex maneuvers around the microphone location. Some comparison of the acoustic pressure time history and the sound pressure level is shown to further understand the validation results.

The comparison process is automated in the following manner. The acoustic pressure time history obtained from the flight test data is converted into the input format required for PSU-WOPWOP for post-processing. The input data to PSU-WOPWOP is different for every microphone location. Each microphone has different range of measured time history (variation in the total time of measured time history) and a different start and end time at which the data was measured. Thus, every microphone for a given flight run requires a separate set of PSU-WOPWOP input files. PSU-WOPWOP runs over all the microphone/observer pressure data and calculates the noise levels, which are then written in Tecplot format for further analysis. Any microphones in the experiment that did not capture the acoustic pressure time history are excluded from the computation. After the noise prediction system is used to predict the noise levels for a given flight run, a comparison between the flight test data and the predictions is shown as the 2D contour plot of the ground plane ($x$–$y$ plane) or a time history plot at the chosen observer position.
The last general point that should be made about the noise prediction system is that a unique helicopter model is required for each aircraft. Several details are required for the flight simulation, airloads and trim analysis and the noise predictions. In this work, detailed descriptions of the flight test aircraft were not available; therefore, parameters from online, public sources were used along with engineering judgment to provide the missing parameters. More details on the specific helicopter models and how they were developed is given in section 3.4.

4.1.3 Processing the simulated flight trajectory to define the helicopter position and attitude in PSU-WOPWOP

The simulated flight trajectory, obtained with using the newly improved controller (described in section 4.1.1) used to simulate the transient flight trajectory flown during the flight test [58], is processed to reduce the numerical error caused by the small timestep used for discretizing the flight information. The updated controller in the PSUHelosim/CHARM rotor module can simulate the flight trajectory and generates source motion (helicopter motion) information required for noise prediction in the PSU-WOPWOP noise prediction code. The simulated flight trajectory or source motion was discretized with a time step of 1 period of tail rotor revolution (approx 0.001 seconds). This small discretized time step was thought to be small enough to capture the transient effects due to the time derivative of the helicopter trim states. However, it was found that the thickness noise prediction was much higher than seen during a constant speed flight procedure. Initially, it was expected that due to the transient velocity and the roll of the vehicle, the noise estimated for the simulated flight trajectory would be higher (2–4 dBA) than seen during a constant velocity level flight procedure. However, the noise levels seen were more than 6–8 dBA greater than the noise predicted. This led to further investigation by analyzing the noise generated by the Bell 407, 80 kts level flight procedure.

The Bell 407 helicopter is flown at 80 kts level flight. The controller uses
the flight trajectory information obtained during the flight test to simulate the flight trajectory. The noise prediction system generates the blade loads, helicopter trajectory and noise levels. The SEL contours are shown in Fig. 4.2. The results on the left, shown in Fig. 4.2a, show a comparison of the total SEL predicted with the flight test data on the ground plane (x – y plane with the microphones marked as black circles).

(a) Demonstration of the error in the thickness noise calculation by validating and analyzing components.

(b) Comparing SEL thickness noise generated by the main rotor and tail rotor.

Figure 4.2: Analyzing error in thickness noise calculation for a Bell 407, 80 kts level flight.
The total predicted SEL contour shows overprediction when compared to the SEL calculated after post-processing the flight test data [58] (Fig. 4.2). When looking at different noise source components (right contours in Fig. 4.2a), the maximum noise is due to thickness and broadband. The broadband noise is relatively constant below the flight path, as expected for a level flight (even a transient flight). On the other hand, the thickness SEL contour (Fig. 4.2a) shows a ‘red’ spot below the flight path and that is contributing to the excess noise seen in the total predicted SEL shown in Fig. 4.2—shown by the red arrows. This ‘red’ spot (a bit out-of-place high noise level especially for a relatively constant velocity, level flight procedure) suggested that further investigation of the overpredicted thickness noise was warranted. By calculating the thickness noise from the main rotor and tail rotor separately (shown in Fig. 4.2b), it is seen that the main rotor is responsible for the overprediction of the total SEL.

The two microphones from the SEL contour, shown in Fig. 4.2b, are further used to analyze the A-weighted noise. Figure 4.3a shows the microphones located on the grid used during flight test [58] for analysis. The microphone 36 (located at [-1142.6 m, 0.0 m, 0.0 m]—shown in Fig. 4.3a) is located directly underneath the helicopter during flyover and the microphone 32 is located at a sideline location (on flight test grid – [853.4 m, -320.0 m, 0.0 m]). The noise levels estimated using the simulated flight trajectory (discretized every 0.001 seconds) are shown on the left in Figs. 4.3b and 4.3c.

During approach, an obvious overprediction of the thickness noise when compared to the flight test data was thought to be a numerical simulation issue due to the characteristic of the overpredicted thickness noise (very weird trend). This is seen as the helicopter approaches the observer position or microphone and is circled with a cyan colored line in Figs. 4.3b and 4.3c.
(a) Microphone grid used during flight test [58]—microphone 32 and 36 marked in blue.

(b) Overhead microphone (36): Left subfigure—non-smooth unfiltered flight trajectory, and Right subfigure—non-smooth unfiltered flight trajectory.

(c) Sideline microphone (32): Left subfigure—non-smooth unfiltered flight trajectory, and Right subfigure—non-smooth unfiltered flight trajectory.

Figure 4.3: Comparison of A-weighted noise level for a simulated and filtered flight trajectory of Bell 407, 80 kts level flight.

The primary reason for the overprediction of the thickness noise during approach is the small-time step used for discretization of the flight path, which was thought
to be important to capture all the information of the source motion in predicting noise, but resulted in a non-smooth flight trajectory. One major issue that arose was the calculation of the first and second time derivative of the source position, i.e., velocity and the acceleration of the vehicle (error shown in Fig. 4.4b), in the PSU-WOPWOP thickness noise calculation. Here, a central differencing scheme is used for calculating the time derivatives. Any small discrete non-continuous change in the source motion gets amplified due to the small discretized time interval. Any outliers or discontinuous jumps in this high temporally resolved source motion can lead to significant error in the first time derivative (position difference is multiplied by $10^3$) or the second time derivative (position difference is multiplied by $10^6$), i.e., velocity and the acceleration of the vehicle.

![Acceleration graph](image)

(a) Acceleration calculated using the simulated flight trajectory

(b) Acceleration calculated using the filtered flight trajectory

Figure 4.4: Demonstration of the error (for 0.2 seconds during approach) in calculating acceleration using the highly discretized and filtered flight trajectory for Bell 407, operating at 80 kts level flight.

Figure 4.4b shows the error observed when calculating the acceleration. This
erroneously calculated acceleration used to calculate the term $\dot{M}_r$–time derivative of the Mach vector in the radiation direction, as described in Chapter 2. This term is used in calculating thickness and loading noise, as shown in Eqn. 2.2.

The error in calculating the acceleration and, subsequently, the thickness noise prediction is due to the non-smooth flight trajectory. A smooth filtering (using MATLAB) of the flight trajectory and increasing the discretized time step of the source motion $(x(t), y(t), z(t))$ (from 0.001 to 0.2 seconds for the case considered), is thought to be small enough to capture the transient motions during the flight test without undergoing any numerical implementation issues. This results in a higher value of $dt$ when using a central differencing scheme in PSU-WOPWOP for calculating the helicopter acceleration. This provides a buffer when considering the outliers or discrete, discontinuous jump when simulating an actual flight trajectory. The calculated acceleration for the filtered flight path is shown in Fig. 4.4b–bottom figure. Figures 4.3b and 4.3c shows the noise levels for the filtered flight trajectory–on the right side. The trend in the predicted A-weighted SPL seen during the approach (seen in figures on the left in Figs. 4.3b and 4.3c ) is no longer seen for the A-weighted SPL predicted with the filtered flight trajectory (shown on the right in Figs. 4.3b and 4.3c). However, the thickness noise is overpredicted, with a ‘serrated’ pattern seen for microphone 32 (explained later) and the overprediction of the broadband noise after the helicopter has passed over the observer. Nonetheless, the numerical error in predicting thickness noise has mostly disappeared. This smooth filtered flight trajectory information is used for validation to remove the numerical error due to the implementation.
4.2 Comparison of predicted noise levels to flight test data for steady flight conditions

In this section, noise predictions are performed for six different flight conditions and compared with the flight test data, followed by a brief explanation of the results. The helicopter model information is provided in Table 3.3. For the comparison between the flight test data and the predicted noise, the SEL, overall sound exposure level (OASPL), A–weighted sound pressure level (L_A), and sound pressure level (SPL) are considered suitable. The SEL contours show the differences in the noise levels at various microphone locations and include the time duration effect of the flight trajectory. (The duration of the noise event, in addition to its absolute level, are important aspects of annoyance.) The SEL contours are easier to compare among the different flight procedures and to illustrate the significance of the flight trajectory for generating low noise flight procedures. Another important reason for using SEL for validation is that noise levels are used by FAA for noise certification of the helicopters. The OASPL and A-weighted SPL provide more details at a given observer position because the temporal variation of the noise components can be evaluated. Sound pressure level (SPL) has too much detail for general comparison (spectrum is calculated every 0.5 seconds of the flight time and the total flight duration is higher than 40 seconds, for the most flight procedures considered for validation) and is thus only utilized for analysis and not for validation. For the same reason the comparison of the raw flight test data (acoustic pressure) with the predicted acoustic pressure is hard to analyze or comprehend due to the large number of data points, and as such is only utilized for explaining the observed noise levels for a very short time interval (usually 1 rotor revolution). Because the ultimate focus of this work is on the development of noise abatement procedures and it is important to consider aspects relating to annoyance and time duration; therefore, SEL, OASPL, and A–weighted SPL (L_A) were thought to be appropriate
measures for comparison with the flight test data.

The validation results compare predicted and measured noise level contours for the microphone array deployed on the ground during the flight test. In the SEL contour plots, the helicopter is flying in the positive $x$ direction nominally along the path $y = 0$ (the ground plane is the $x – y$ plane). The grid locations, marked as black circles, are the microphone locations used during the flight test. The microphones are flush mounted to the ground boards (as described in [58]) to remove the complexity due to the ground reflections (a flush-mounted microphone on a ground board effectively measures double the free-field pressure). As described in Chapter 2, the noise prediction takes into account the ground reflection and atmospheric attenuation. For the ground reflection model, the observer is considered to have an image located at equal distance from the ground as the observer and at radiation distance and emission angle of the reflected ray. The thickness and loading noise are coherent noise sources, and as such, the acoustic pressure time of the observer and image are added to account for ground reflection (for an observer located on the ground, the acoustic pressure time history is doubled). The broadband noise is considered incoherent, and as such, the mean squared acoustic pressure of the observer and the image are added. Note that, though the microphones are located on the ground, the broadband noise source is considered an incoherent noise source for validation of the noise prediction system.

In this chapter, comparisons are performed for the following steady flight configurations: 80 kts level flight and 80 kts in 6° descent.

4.2.1 Validation 1: 80 kts, level flight

The first case considered for comparison between the flight test data and predicted noise is 80 kts, steady level flight flying at an altitude of around 200 ft or 61 m. The comparison is made for the Robinson R44 and R66, the Airbus AS350, and the Bell 206L and 407 helicopters. As the Fenestron was not modeled for Airbus
EC130, this helicopter is not included in this validation. The flight configuration was chosen because the blade-vortex-interaction (BVI) noise is unlikely, and the flight condition is nominally steady. Initially, the noise calculations were performed without the broadband wall reflection model. However, after comparing it with the flight test data, the need for the wall reflection was clear, and it was included in the system. The broadband noise is calculated using Pegg’s empirical model [37] and is a function of rotor thrust, blade area, and tip velocity and with empirical constants based on experimental data.

4.2.1.1 Sound exposure level validation

Figure 4.5 shows the SEL contours on the ground plane for an 80 kts, level flight. For each helicopter, the contour on left is the SEL calculated by processing flight test data (refer to section 4.1.2 in the current chapter), and the right contour is the SEL contour predicted using the noise prediction system. The noise levels are well captured for the R44, R66, Bell 407 and AS350 (Figs. 4.5a, 4.5b, 4.5d, and 4.5e) and are overpredicted for the Bell 206L (Figs. 4.5c). The noise levels are higher for heavier helicopters and those with higher rotor tip speed. Although the Bell 407 (Fig. 4.5d) was tested at a lower weight than the AS350 (Fig. 4.5e), the SEL values are very close. This could be due to the higher rotor blade tip speed for the Bell 407. The R44 (Fig. 4.5a) and R66 (Fig. 4.5b) predictions agree well with the flight test data with relatively similar levels and directivity.
Figure 4.5: Total sound exposure level (SEL) for a 80 kts, level flight. (For each subfigure: left–flight test data; right–prediction)
Considering the predicted noise levels compares well with the flight test, the system is then used to analyze different noise sources. Examination of the noise components for the 80 kts level case shows significant broadband noise contributions (Figs. 4.6a–4.8a) followed by loading noise for all the helicopters.

The noise components for the Robinson R44 and R66, shown in Figs. 4.6a and 4.6b, demonstrates the differences between the noise generated by two very similar helicopters and shows the contribution of the individual noise source to the total predicted SEL noise. The weight of the two helicopters flown during the flight test was similar. One of the major differences between the two helicopters is the tip speed of the tail rotor. Robinson R66 helicopter has higher tail rotor tip speed, and the effect of this can be seen by comparing the higher thickness and loading noise seen in Fig. 4.6b with Fig. 4.6a.
Figure 4.6: Sound exposure level (SELdBA) of noise components for a Robinson R44 and R66 performing 80 kts, level flight.
Figure 4.7: Sound exposure level (SEL_{dBA}) of a noise components for a Bell 206L and Bell 407 performing 80 kts, level flight.
The Bell 206L and Bell 407 noise sources are shown in Figs. 4.7a and 4.7b respectively. The weight of the two helicopters flown during the flight test was almost the same (the Bell 407 is 400 lbs. heavier than Bell 206L). Bell 407 main rotor has blades (4 vs. 2), and higher main rotor tip speed (231 m/s vs. 210 m/s) than Bell 206L helicopter. These differences result in thickness and loading noise (Fig. 4.7b) of the Bell 407 that is higher than the Bell 206L (Fig. 4.7a). As for Bell 206L helicopter, noise levels (Fig. 4.5c) are higher than observed during the flight test–and the dominant noise contribution is due to broadband noise (Fig. 4.7a). The overprediction of the broadband noise could potentially be due to an error in the empirical constants–a lower number of blades resulting in higher lift coefficient across the blade and/or wrong assumed main rotor tip speed ($1/3^{rd}$ octave SPL proportional to $V_{tip}^3$). Considering that for the level flight, the total A–weighted SPL peak is dominated by the broadband noise and this noise dominates the total predicted A–weighted SPL, any error in its prediction results in error in the total predicted SEL.

Figure 4.8a shows the noise components for AS350 helicopter operating at 80 kts level flight. Here, the dominant noise source is also the broadband noise (Fig. 4.8a). Comparing the noise levels for the Bell 407 and AS350 helicopter shows that though the helicopter has almost same weight (AS350 is 400 lbs heavier than Bell 407) the thickness and loading noise (Figs. 4.7b and 4.8a) are higher for Bell 407. This is due to the higher rotor tip speed of the Bell 407 helicopter. Overall the noise trends for the SEL contours are captured, if not the exact noise levels. The lighter weight helicopters have lower noise levels due to lower rotor thrust and therefore lower broadband noise.
Figure 4.8: Sound exposure level (SELdBA) for a Airbus AS350 performing 80 kts, level flight.

The SEL provides a direct comparison between the predicted and measured noise levels, but the time evolution of the noise and finer details are not evident. Consequently, an examination of the OASPL and A-weighted SPL time histories are required for further analysis. This is provided in the next section, followed by the comparison of the acoustic pressure time history and sound pressure level for a particular microphone location.

4.2.1.2 Time history validation

The OASPL and A-weighted SPL time histories provide much more detail about the noise generated during the total flight operation time. Considering the two noise levels are function of time, the richness of detail is higher than SEL but lower than the acoustic pressure time history and sound pressure level (SPL). Therefore, the OASPL and A-weighted SPL time histories are first used to analyze the flight
procedure at a selected microphone, then the acoustic pressure time history is considered for a limited time period. The comparison here is focused on the Bell 407, and the Airbus AS350 helicopters. These two helicopters generate higher noise levels during level flight as compared to the other helicopter and they have different main rotor blade number (4 and 3 respectively), rotor tip speeds, and direction of rotation.

For this comparison a single row of microphone from the flight test array is chosen; located along \( x = -304.8 \text{ m} \) and \( y \) ranging from \(-304.8 \text{ m} \) to \(304.8 \text{ m} \). These microphones show variation in the noise propagated at various sideline positions, shown in Fig. 4.9 (microphones 7–11). For the first case considered, microphones 7–8 are on the port (left) side of the helicopter, microphone 9 is on the centerline of the helicopter flight path, and microphones 10–11 are on the starboard (right) side of the helicopter. For the Bell 407, the advancing blade side of the rotor is on the starboard side, while for the Airbus AS350 the advancing blade side is on the port side of the helicopter. The time history of noise levels is analyzed for the Bell 407 followed by Airbus AS350 helicopter.
Figure 4.10: Overall sound pressure level along $x = -304.8$ m for Bell 407 operating at 80 kts level flight.
4.2.1.2.1 Bell 407: Time history validation

Figures 4.10 and 4.11 show the comparison between the OASPL and A–weighted SPL. The predicted peak of both the OASPL and A–weighted SPL matches well with the flight test data (compare Flight test–with Predicted Total in Figs. 4.10 and 4.11). The noise levels
are highest for the microphone located directly below the helicopter (microphone 9) and the levels decrease with increasing sideline distance. The loading noise is dominant contributor to the peak OASPL - when the aircraft is overhead. Thickness is dominant as the aircraft approaches and broadband contributes along with loading after the aircraft flies over (all along the centerline). The broadband noise is higher beneath the helicopter (microphone 9 - Fig. 4.10c) and does not contribute as significantly at the sideline positions. For the sideline microphones, the thickness noise peaks before loading noise peaks, and the thickness and loading are a little higher on the advancing blade side (starboard side - microphones 10 vs 8, and to a lesser degree microphone 11 vs 7). The noise levels at the sideline locations also have a significant contribution from tail rotor and this is analyzed later in this section. As the helicopter approaches the centerline microphone, the thickness noise (‘black’ line - in Fig. 4.10–4.11) dominates and is higher than that observed during the flight test. However, the levels are much lower than the peak, therefore the overprediction of the thickness noise levels is not registered in the SEL calculation. (Note: The thickness noise calculation does not include the blade flapping motions and this in one of the future scope for the current work.)

The broadband noise source is the dominant noise source in the A–weighted SPL time histories, especially closer to the flight path. The loading noise is also significant underneath the helicopter (Fig. 4.11c), but still lower than the broadband noise. The noise levels steadily decreases with increasing sideline distance. With the absence of BVI noise, the loading noise directivity is primarily below the helicopter as seen in Figs. 4.10–4.11.

Similar observations are made for a second row in the contour plot (along \( x = -579 \text{ m} \)). The results are available in Appendix B.

The OASPL and A–weighted SPL provides more detailed analysis of the data included in the SEL contour plots. The noise sources provides an explanation of the different directivity and frequencies associated with the noise source generation.
mechanisms. Further analysis is conducted to understand the noise generated by the main rotor and the tail rotor. This analysis was done using a sideline observer location–microphone 8, located at (-304.8 m, 152.4 m, 0 m) on the $x - y$ ground plane. This microphone was chosen because it was off to the side of the flight path and also shows the noise contribution from the tail rotor.

Figures 4.12 and 4.13 shows the comparison between the flight test and the noise generated by the main rotor and tail rotor and the different noise components of the two rotors, using OASPL and A–weighted SPL. Figures 4.12a and 4.13a shows the comparison between the total noise generated by the main rotor and tail rotor. The contribution from the tail rotor is significant due to the position of the microphone 8. As the helicopter approaches the microphone location, the thickness noise dominates the total noise generated by the main and tail rotor. The thickness OASPL (Fig. 4.12c) generated by the main rotor is higher than the noise levels seen in the flight test data. Further analysis is required to understand the effect on noise levels due to the lack of flapping motion of the blades in thickness noise calculation. The A–weighted SPL is dominated by tail rotor noise as the helicopter approaches the observer position. The noise levels are overpredicted and this could potentially due to the absence of scattering effect or shielding from the fuselage. The OASPL or lower frequency loading noise generated by the main rotor and the tail rotor are comparable to each other, while the high frequency or the A–weighted loading noise shows that the tail rotor noise dominates the total A–weighted loading noise generated by the helicopter. One thing to note is that the interaction effect of the main rotor wake with the tail rotor is absent due to the quasi-periodic assumption used for the tail rotor loading noise calculations. As for the broadband noise, the A–weighted main rotor broadband noise dominates the peak of the total noise generated by the helicopter. The broadband noise generated by the tail rotor is significantly lower.
Figure 4.12: Comparing the main rotor and tail rotor overall sound pressure level generated by Bell 407 80 kts level flight at the location of microphone 8.
Figure 4.13: Comparing the main rotor and tail rotor A–weighted SPL generated by Bell 407 80 kts level flight at the location of microphone 8.
The overpredicted A-weighted thickness SPL during approach is further analyzed using acoustic pressure time history and is discussed here and shown in Fig. 4.14. For microphone 8 (shown in the flight test grid in Fig. 4.9), the acoustic pressure time history is compared with the flight test data. A much broader outlook in the noise levels is achieved by calculating and analyzing the SEL, OASPL, and A-weighted SPL, and this helps in narrowing the times when the acoustic pressure time history is considered directly. Otherwise, the amount of data for a single microphone is too high to make any relevant observation. However, certain peculiarities seen in the two time histories (Figs. 4.10b, 4.11b, 4.12 and 4.13) are not explained. These features can be explained by analyzing the acoustic pressure time history.

First note the overprediction of the thickness noise in the OASPL and A-weighted SPL (Figs. 4.10b, 4.11b, 4.12 and 4.13) and the ‘serrated’ pattern as the helicopter approaches the observer position. The total pressure time history has too many data points to effectively show in a single plot; therefore, the pressure time history is assessed for two separate rotor revolution periods to demonstrate the kinds of observations conducted. To understand this feature of the noise prediction, 1 rotor revolution during the approach, starting a little after 25 seconds of the flight time, is used for analysis. The direct comparison between the measured and predicted acoustic pressure is shown in Fig. 4.14. The measured acoustic pressure time is adjusted to match the peaks with the predicted noise. This was required as the actual azimuthal location of the main rotor blade, and tail rotor during the flight test is unknown and could be different from the prediction. In the current work, an attempt is not made to match the phasing between the main rotor and tail rotor blade with the flight test data, i.e., the relative position of the tail rotor blade compared to the main rotor blades.
Figure 4.14: Comparison of predicted acoustic pressure time history with flight test for 1 rotor revolution as the helicopter approaches the microphone 8; for Bell 407 operating at 80 kts level flight.
Figures 4.14a–4.14c show the comparison between the measured acoustic pressure \( (p') \) with the predicted noise from the helicopter (main rotor and tail rotor combined) and its noise components. At this microphone location, most of the noise contribution to the total noise is from the thickness noise, as is shown in Fig. 4.14b. Though the predicted acoustic pressure matches all the peaks seen in the measured acoustic pressure, it has a higher amplitude. The negative peak in the measured acoustic pressure matches well with the thickness acoustic pressure generated by the main rotor is demonstrated in Fig. 4.14e. The smaller negative peak in the measured acoustic pressure occurs at the same frequency as the noise generated by the tail rotor. However, the predicted tail rotor noise is overestimated. This overestimation could be due to the absence of the fuselage resulting in the lack of scattering and shielding of the noise by the fuselage body. The approximate angle of emission (angle made by the vector from the tail rotor to the observer on the \( x-y \) plane) is 2.6°. At this angle, a direct view of the tail rotor by the observer is obstructed by the fuselage. This hypothesis could be tested by adding a fuselage in the noise prediction, but such a prediction is out of scope for the current study.

Another way to support the hypothesis is a comparison of the predicted and measured acoustic pressure when the helicopter is overhead or close to the observer. At an emission angle close to tail rotor thickness noise directivity (90°), the tail rotor thickness noise would not be obstructed by the fuselage. This is demonstrated in Fig. 4.15. The measured acoustic pressure time history is compared with the predicted thickness noise. The figure on the right shows that not only the negative peak in the measured acoustic pressure, occurring at the main rotor blade passage frequency, matches with the flight test data, but the small peaks occurring at the tail rotor blade passage frequency are very close to the small negative peaks in the measured acoustic pressure. This indicates that the hypothesized overprediction of the tail rotor thickness noise during approach due to lack of scattering or shielding of the noise from the fuselage has some validity.
Another feature studied is the serrated pattern seen on in OASPL and A-weighted thickness noise seen in Figs. 4.10b and 4.11b. After analyzing the thickness noise generated by the main rotor and tail rotor, one thing is obvious that the ‘serrated’ pattern is not seen in predicted thickness noise generated by either the main rotor or tail rotor (Figs. 4.12 and 4.13). This pattern can only be explained by the superposition of the two noise sources. Considering the thickness noise emitted by the main rotor and tail rotor are comparable to each other, the in-phase and out-of-phase results in constructive and destructive interference and hence the ‘serrated pattern’ seen in the predicted noise. Two such instances when the main rotor and the tail rotor thickness noise are out of phase and in phase are shown in Fig. 4.16. When the main rotor and tail rotor are out of phase the thickness acoustic pressure is much smaller (Fig. 4.16a) compared to the in-phase acoustic pressure, shown in Fig. 4.16b which generates the ‘serrated’ pattern.
Figure 4.16: Acoustic pressure time history for demonstrating the effect of out of phase and in phase of the thickness noise at the microphone 8, for a Bell 407, operating at 80 kts level flight.

Figure 4.17 shows the comparison of the measured acoustic pressure and the predicted acoustic pressure with its components for microphone 8 and when the helicopter was close to the flight path. The total acoustic pressure compared in Fig. 4.17a, shows that the system is capable of of capturing the level and the peak as seen in the measured acoustic pressure, with the peak negative pressure due to the main rotor thickness noise (shown in Figs. 4.17b and 4.17e) and the peak positive acoustic pressure due to the main rotor loading noise (shown in Figs. 4.17c and 4.17f). The loading noise directivity is primarily below the helicopter. Though, the microphone is at a sideline location, the effect of the radiation distance between the source and observer and the directivity shows the increase in loading noise in Figs. 4.10b and 4.11b. Considering the microphone used for analysis is located at a sideline position, the contribution of the tail rotor noise to the total noise can be seen as the directivity of the tail rotor thickness is primarily below the helicopter and tail rotor loading noise is in the sideline due to the rotor axis being parallel to the ground and not towards the ground, like the main rotor, for a level flight.
Figure 4.17: Comparison of the acoustic pressure time history for 1 rotor revolution around the peak noise levels at the microphone 8, for Bell 407 operating at 80 kts level flight.
4.2.1.2.2 Airbus AS350: Time history validation  The next case considered for detailed analysis is the Airbus AS350 operating at 80 kts level flight. This case was chosen due to the direction of the rotor rotation. The rotor rotates in the clockwise direction (seen from above or top). Due to this the advancing side is on the left side of the flight trajectory and the retreating side on the right. The flight trajectory information (shown in Fig. C.1) and time histories for all the microphone is provided in Appendix C and Figs. C.3–C.10.

Five microphones considered here are located at constant $x = -304.8$ m (locations of the microphones on the flight test grid are shown in Fig. 4.9), with the microphone 7 (Figs. 4.18a and 4.19a) and 8 (Figs. 4.18b and 4.19b) on the advancing side, microphone 9 (Figs. 4.18c and 4.19c) on the centerline beneath the flight trajectory, and microphone 10 (Figs. 4.18d and 4.19d) and 11 (Figs. 4.18e and 4.19e) on the retreating side.
Figure 4.18: Overall sound pressure level at $x = -304.8$ for Airbus AS350 operating at 80 kts level flight.
Figure 4.19: A–weighted sound pressure level at $x = -304.8$ m for Airbus AS350 operating at 80 kts level flight.

For the centerline microphone 9 (Figs. 4.18c and 4.19c) the total predicted noise level is higher than the flight test levels and is dominated by the thickness noise as the aircraft approaches. Once the aircraft is nearly overhead - corresponding to the
peak OASPL level - the predicted noise is dominated by the loading noise and the total predicted OASPL levels agree with the flight test quite well. The A–weighted SPL also agrees quite well with the flight test for the centerline microphone, but in this case the broadband noise is the dominant contributor. The predicted noise on the advancing side, microphones 7 (Fig. 4.18a) and 8 (Fig. 4.18b), matches at the times near the peak value of the flight test data. Similar to centerline microphone 9, most of the contribution to the total OASPL is from the thickness noise as the aircraft approaches and then loading noise during flyover and during the peak level. As for the microphones located on the retreating side, microphones 10 (Fig. 4.18d) and 11 (Fig. 4.18e), the peak OASPL levels are overpredicted somewhat, due to overprediction in loading and broadband noise. Microphone 10 is analyzed in more detail later in this section to understand the overprediction.

The broadband noise dominates the A–weighted SPL for the microphones 7–11 shown in Fig. 4.19. The peak of the A–weighted SPL is captured by the noise prediction system for the microphones 8–12 (Figs. 4.19b–4.19e). For the two sideline location microphone 8 (Figs. 4.18b and 4.19b) and 10 (Figs. 4.18d and 4.19d) the total peak noise level has decreased resulting in lower SEL for these microphone locations. Here, the broadband noise is the dominant noise source and the peak matches well with that measured during the flight test. The loading noise on the other hand shows lower levels compared to the broadband noise but the trends seen in the time history of the loading A–weighted SPL are very similar to that seen during the flight test (check the A–weighted SPL for the microphone 8–the small dip in A–weighted SPL calculated using flight test around 72 seconds is also seen in the loading A–weighted SPL). The A–weighted loading noise and thickness noise (shown in Fig. 4.19) are much lower than the broadband noise and as such they do not have significant influence on the SEL contours shown in Fig. 4.5e. The A–weighted broadband noise dominates and is overpredicted at the microphone location 7 and 11 (Figs. 4.19a and 4.19d respectively).
One more thing to note is the contribution of the main rotor and the tail rotor to the total loading noise. As the helicopter approaches microphone 9, the noise levels at the sideline microphones are reduced and the total noise has significant contributions from both the main and tail rotors. The noise from tail rotor and main rotor are compared for the sideline microphone 10 (Figs. 4.20 and 4.21).

Figure 4.20a shows that the peak noise levels are overestimated. This overprediction in the peak noise comes from both the main rotor and tail rotor (shown in Fig. 4.20b). The OASPL for the microphone 10 (Fig. 4.20a) shows two peaks in the loading noise and this is also seen in the flight test data. The main rotor loading noise (shown in Fig. 4.20d) shows the two peaks and the levels match that seen during the flight test. It is speculated that the two peaks occur either due to small variation in the helicopter attitude (shown in Fig. C.1) and consequently, changing the blade loads that generates higher harmonic loading noise, or due to change in directivity as the helicopter nears the centerline microphone 9 (first peak) and then flies over (second peak—at same radiation distance as the first peak). The tail rotor loading noise, shown in Fig. C.1 has a similar peak value as that of the main rotor loading noise. The overprediction of the peak OASPL, occurring due to contribution from the main and tail rotor, is analyzed using acoustic pressure time history, shown in Fig. 4.22. The analysis was primarily conducted to understand if the main rotor or the tail rotor is responsible for the overpredicted peak OASPL.
Figure 4.20: Comparing the main rotor and tail rotor overall sound pressure level generated by Airbus AS350 80 kts level flight at the location of microphone 10.
Figure 4.21: Comparing the main rotor and tail rotor A-weighted SPL generated by Airbus AS350 80 kts level flight at the location of microphone 10.
Figure 4.22: Comparison of the acoustic pressure time history for 1 rotor revolution around the peak noise levels at the microphone 10 location, for Airbus AS350 operating at 80 kts level flight.
The acoustic pressure time history for the microphone location 10 (grid shown in Fig. 4.9) is shown in Fig. 4.22. The first thing to note is the extremely transient nature of the acoustic pressure measured during the flight test. This microphone is located at the retreating side of the flight path. For this microphone the lower frequency noise is dominated by the loading noise and the high frequency noise is dominated by the broadband noise. This can be easily seen when comparing the total acoustic pressure generated by the main rotor (Fig. 4.22c) and tail rotor (Fig. 4.22e). Here, the acoustic pressure is shown for 1 rotor revolution around the peak noise levels seen in Figs. 4.20a and 4.21a. From Figs. 4.22c and 4.22d it seen that the three peaks seen in the measured flight test data corresponds to the loading noise generated by the main rotor (3–bladed rotor). However, the loading noise predicted for the tail rotor, shown in Figs. 4.22e and 4.22f, is very high compared to the that observed during the flight test and occurs at higher frequency due to the blade passage frequency of the tail rotor. Therefore, the total predicted acoustic pressure is overestimated and results in overprediction of the peak OASPL (Fig. 4.18). Though the A–weighted SPL for the tail rotor (Fig. 4.21d) is higher than main rotor loading noise, the effect is not seen as the broadband noise (Fig. 4.21a) dominates the total A–weighted SPL.

There could be several reasons for overprediction of the tail rotor loading noise. First, the tail rotor operates under the influence of the main rotor wake and this affects the tail rotor blade loads. This could amplify the loading acoustic pressure. The noise prediction system discretized the tail rotor blade loads every 15° azimuth and as such it is highly unlikely that the self BVI of the tail rotor is captured. Second, the simulated helicopter roll angle has an offset with that observed during the flight test (shown in Fig. C.1). This could result in change in noise directivity and any error in the helicopter attitude could result in higher thrust requirement from the tail rotor. This offset in roll angle occurs due to the assumed parameters, such as hinge offset, moment of inertia, center of gravity and so forth, based on
engineering judgment are used in building the helicopter model. Therefore some errors are to be expected. As of now a concrete conclusion cannot be made of why the tail rotor generates higher loading noise.

4.2.2 Validation 2: 80 kts, 6° descent

The second case considered for comparison of flight test data with predicted noise is 80 kts, 6° steady descent. This flight condition is associated with high BVI noise. The validation of this flight condition will help to assess the tip-vortex strength and geometry, blade loading data, and the PSU-WOPWOP noise prediction. For the noise prediction, PSU-WOPWOP uses periodic blade loads updated every 0.5 seconds; however, the position of the aircraft relative to the microphones is modeled correctly throughout the flight trajectory. The helicopter begins with a level flight followed by a descent (the aircraft altitude is approximately 1000 ft when it is 10,000 ft uprange) and pulls up at the end of the flight segment (at an altitude of approximately 50 ft). The approximate flight path was used to command the simulation to “fly” the aircraft successfully through the three transient segments.
4.2.2.1 Sound exposure level validation

(a) Robinson R44

(b) Robinson R66

(c) Bell 206L

(d) Bell 407

Figure 4.23: Contours of total sound exposure level (SEL) for a 80 kts 6° descent flight. (For each subfigure: left—flight test data; right—prediction)
Figure 4.23: (continued) Contours of total sound exposure level (SEL) for a 80 kts 6° descent flight. (For each subfigure: left–flight test data; right–prediction)

Figure 4.23 shows a comparison between the SEL contours computed from the flight test data and from the predicted noise for the 80 kts, 6° steady descent case. Figures 4.23a and 4.23b are for the R44 and R66 helicopters, respectively. Recall these helicopters both have two-bladed main rotors, but with different blade designs (chord and twist), and they have different power plants (piston and turbine, respectively). Because the weight of the R44 and R66 were significantly lower than the other helicopters considered, the total main rotor thrust and blade loads were lower. As a result, the SEL levels for the R44 and R66 (Figs. 4.23a and 4.23b) are somewhat lower than the other aircraft. The predicted SEL values are quite close to the flight test data for both of the Robinson aircraft—with a very small underprediction. Comparing noise levels generated by Robinson R44 and R66 shows that the R66 helicopter has slightly higher SEL values and this difference is captured by the noise prediction system.

Figures 4.23c and 4.23d are for Bell 206L and Bell 407 helicopters, respectively. The Bell 206L also has a two-bladed main rotor, while Bell 407 has a four-bladed main rotor with higher tip velocity (which may increase the thickness noise). The Bell 407 produced significantly larger contours of higher intensity noise, although the peak level was only a few dBA higher than the Bell 206L. Here, the predicted
contour levels are close to that observed during the flight test with a slight shift in the contour shape. The main features of the contour are captured quite well. More analysis is needed to determine if the shape discrepancy is due to variations in the aircraft attitude in the flight test that were not directly modeled in the flight simulation and noise prediction.

Figure 4.23e shows the comparison for the Airbus AS350 helicopter. The AS350 has a three-bladed main rotor that rotates clockwise (observed from above). The clockwise rotation effect is seen in both the predicted and flight test noise contours (the noise has moved towards the positive $y$—axis because the advancing rotor blade is on that side). Overall the trend is well captured by the noise prediction system for the AS350.

The overall conclusion based on the comparisons between prediction and flight test data for the six helicopters is that the prediction system has been able to perform well. Both the absolute levels and shape of the SEL contours agree quite well with the test data. So with this conclusion, it is instructive to consider the individual noise sources for each of the aircraft and see how they compare to each other and how the noise sources from one helicopter compare in level and directivity with the other helicopters. The three noise sources considered for the different helicopters are thickness noise, loading noise, and broadband noise, shown in Figs. 4.24a–4.26a. Main rotor and tail rotor contributions to each source will be considered together (although they can be separated in the predictions).

The thickness noise, shown in Figs. 4.24a–4.26a, is not the dominant noise source mechanism for the descent flight condition. The noise levels are higher for the helicopter with highest rotor tip speed (i.e., Bell 407). The loading noise, shown in Figs. 4.24a–4.26a, increases with number of blades and the broadband noise dominates the total noise levels for the lighter and 2–bladed rotors (R44, R66 and Bell 206L), shown in Figs. 4.24a–4.25a. The thickness noise levels are higher for a helicopter with higher rotor thrust and rotor tip velocity (i.e., Bell 407). (It should
be noted that Pegg’s empirical relation [37] used to calculate the broadband noise has these two terms in the formulation.) Thus, the heavier helicopter generates more noise than the lighter helicopters (due to increase in main rotor thrust).

The major noise contribution for the Robinson R44 and R66 is the broadband noise (Figs. 4.24a and 4.24b). The loading noise is higher for R66 helicopter (Fig. 4.24b) when compared to loading noise generated by the R44 helicopter (Fig. 4.24a). Although the noise is predicted for the main rotor and tail rotor only, the trend and the levels are well captured by the noise prediction system. This indicates that the engine noise contribution to the total helicopter noise is not significant and can be ignored for these cases.
Figure 4.24: Sound exposure level (SEL) for the noise sources, for Robinson 44 and R66 performing 80 kts 6° descent flight.
The Bell 407 has higher noise levels than the Bell 206L. The major difference in
the noise generated by the two helicopters comes from the loading noise seen in Figs. 4.25a and 4.25b. One of the reasons for this level difference might be due to the number of blades. Increasing the number of blades reduces the bound circulation or lift coefficient across the blade, for helicopters with similar weight, resulting in lower blade loads and strength of the trailing vortices and the tip vortex. However, as the frequency of interaction between the tip vortex and the blade has increased, the resulting changes in the interaction geometry could increase BVI noise with an increase in number of blades. This is a speculation made based on the observation made by comparing the SEL contours of AS350 and Bell 407 helicopter. This suggestion requires further examination because the overall trend and the levels are well captured by the noise prediction system. It should also be noted that the flight is close to the ground at the end of the flight run resulting in higher SEL levels, highlighting the effect of the distance between the observer and helicopter on the noise levels. The noise levels for the AS350, though slightly underpredicted relative to the flight test data, show a similar trend, with a major contribution from the loading noise (Fig. 4.26a).

By comparing the loading noise (Figs. 4.25a–4.26a) of the three helicopters, Bell 206L, Bell 407, and AS350, the effect of the number of blades on the BVI noise generation mechanism can be seen. Here, with an increase in the number of blades the BVI noise levels ($6^{th} - 40^{th}$ blade passage frequency increases with the number of blades for relatively constant rotation rate) have increased for helicopters with the relatively similar weights. The next step in the validation process is to compare different noise levels with that generated using flight test data. The loading noise predicted for Bell 407 and AS350 helicopter is higher (Figs. 4.25b–4.26a) than the broadband noise, indicating that the loading noise has higher frequency content (SEL based on time integration of A–weighted SPL). From the literature [1] the 6° descent flight has a significant BVI noise contribution. Thus, it is speculated that the loading noise is a large contributor due to the presence of BVI. The prediction
system is capable of capturing the high noise region on the ground.

(a) Airbus AS350

Figure 4.26: Sound exposure level (SEL) for the noise sources, for an Airbus AS350 performing 80 kts 6° descent flight.

4.2.2.2 Time history validation

Validation of the SEL contours for 6° descent flight showed good comparison with the flight test data. One important difference seen during this comparison was a very dominant loading noise on the advancing side of the flight trajectory. The flight test data shows small shift in higher noise levels on the advancing side. However, the predicted data shows slight overprediction of the noise levels on the advancing side. This is further studied in this section.

The two helicopters considered for study are the Bell 407 and Airbus AS350. These two helicopters have 4-bladed and 3-bladed main rotors rotating with counterclockwise and clockwise rotation directions, respectively. As such the effect of the BVI noise on the advancing side and the retreating side occurs on the different sides.
A single row of microphones is chosen; located along $x = -579.1$ m (microphone 14–24; centerline microphone is 19). These microphones shows variation in the noise propagated during the 6° descent on both sides of the flight path, as shown in Fig. 4.27.

4.2.2.2.1 Bell 407: Time history validation  First, consider the Bell 407 helicopter. The OASPL metric is shown in Fig. 4.28 for the microphones 14–24 (marked on grid shown in Fig. 4.27).

Figure 4.27: Microphone grid used during flight test [58]–microphone 14–24 marked in blue.
Figure 4.28: Overall sound pressure level at $x = -579.1$ m for Bell 407 operating at 80 kts, 6° descent flight.
Figure 4.29: A-weighted SPL at \( x = -579.12 \) m for Bell 407 operating at 80 kts, 6° descent flight.

The results shows that the noise levels and trend for the microphone 15 (Fig. 4.28b) to 23 (Fig. 4.28j) are well predicted. The peak shows an underprediction of 2 dB but overall the results compares well with the flight test data. The dominant noise source is the loading noise. The loading noise increases from the retreating side or the left side of the flight trajectory (flying in positive \( x \) direction) to the
centerline microphone 19 and then decreases as the sideline distance increases. This is similar to that seen during an 80 kts levels flight. Though one difference exists is that the noise levels on the advancing and retreating side of the flight path, at the same sideline distance, is not symmetric and skewed towards the advancing side, i.e., the noise levels are higher for the advancing side. Here, the BVI noise dictates the directivity primarily in the advancing side and as such a noise level on the advancing side is higher than the retreating side.

For the microphone 14 located on the retreating side of the flight path (Fig. 4.28a), the predicted total noise peak is lower and occurs earlier than observed during the flight test. The underestimation of this noise levels could be due to lower loading noise. On the other hand the microphone (microphone 24–Fig. 4.28k) located on the extreme sideline distance on the advancing side of the flight path, shows higher a sharp peak in the total predicted noise levels and 2–3 dB overestimation compared to the flight test data. This overprediction in the noise levels appears to be due to loading noise and can be seen in Fig. 4.28k. It is speculated that to compensate the roll-offset, occurring due to the assumed effective hinge offset for the hingeless rotor, the rotor disk tilts toward advancing side. With the rotor tilted aft and towards advancing side, the Mach vector when the rotor blade is in the first quadrant (azimuth 0°–90°) points towards the sideline microphones located on the advancing side of the flight path and the directivity results in lower levels towards the sideline microphones located on the retreating side of the flight path. In other words, the dot product of the Mach vector ($\hat{M}_r$) with the radiation direction is higher for sideline microphones on the advancing side of the flight path when compared to the sideline microphones on the retreating side of the flight path. This dot product is used for calculating the loading noise in Farassat’s Formulation 1A. The advancing side BVI interaction occurs in this first quadrant, and as such, the BVI noise in the loading noise is slightly overestimated for the sideline microphones on the advancing side and underestimated for the retreating side microphones.
The thickness and broadband noise are much lower than the loading noise around the peak noise levels on the OASPL plot. However, thickness noise is dominant as the helicopter approaches the microphone position with overprediction at the sideline microphones. This observation is similar to that seen during the 80 kts level flight.

The A-weighted SPL for the Bell 407, 80 kts 6° descent is shown in Fig. 4.29. The peak of the predicted noise levels matches well with the flight test data for all the microphones, except microphone 24 (Fig: 4.29k). The major noise contribution to the peak noise levels comes from the broadband noise on the retreating side (microphone 14–18 shown in Figs. 4.29a – 4.29e), and equal contribution from the broadband noise and loading noise at the centerline microphone location (microphone 19 shown in Figs. 4.29f) and dominant loading noise on the advancing side (microphone 20–24 shown in Figs. 4.29g–4.29k). This shows that the directivity of the BVI is towards the advancing side and dominates the total noise generated by the helicopter. The broadband noise does not show a significant directivity on the advancing or retreating side. The thickness noise is dominant as the helicopter approaches the microphone location and is overpredicted at the sideline position (microphone 21–24, Figs. 4.29h–4.29k). This overprediction is due to higher tail rotor thickness noise and the explanation is similar to that explained for the Bell 407, 80 kts level flight.

After examining at the OASPL and A-weighted SPL, the loading noise is found to have interesting characteristics. The low frequency loading OASPL, shown in Fig. 4.27, is underpredicted at the retreating sideline microphone 14 (shown in Fig. 4.28a) and overpredicts the loading OASPL and A-weighted SPL for the advancing sideline microphone 24 (shown in Figs. 4.28k and 4.29k). Further analysis is conducted for the microphone 24 by assessing the 1/3rd octave sound pressure level.
The overpredicted total OASPL and A-weighted noise is expected due to the BVI noise generated by the main rotor. Further analysis is conducted by comparing the 1/3rd octave spectrum at the peak noise level with the predicted levels and is shown in Fig. 4.30. From the literature it is expected that the BVI noise occurs in the frequency range of 6th–40th blade passage harmonics. For the Bell 407 helicopter this frequency range is 165 Hz – 1100 Hz. Figure 4.30 shows that around the BVI frequency range, the loading noise is overestimated. One reason could be that the BVI predicted for 1 rotor revolution was constant for 0.5 seconds of the flight time and so if the transient flight path resulted in moving the tip vortex away from the blade (changing the BVI miss distance) would not be captured and this perhaps resulted in a very high noise levels. This cannot be verified. BVI noise occurs when the tip vortex interacts parallel to the blade. As the flight is transient this phenomenon may not occur at the same frequency as seen in the current prediction. These noise levels are higher only at the sideline position where it appears a specific directivity of the BVI noise is in play and is potentially amplified due to the rotor tilt in the advancing side to compensate for the roll-offset. The
second reason for overprediction may be in calculating the blade loading noise due to the reconstruction feature used in CHARM.

4.2.2.2 Airbus AS350: Time history validation  The second helicopter considered for analyzing and validating 80 kts 6° descent flight is the Airbus AS350 helicopter. The helicopter has clockwise rotating rotor when seen from above. As such the retreating side of the helicopter is the right side of the flight path and the advancing side of the helicopter is the left side. In Fig. 4.23e, the left side of the flight path is the one where the sideline distance \( y \) is positive. In the grid shown in Fig. 4.27, the microphone 14–18 are on the advancing side of the flight path, microphone 19 is at the centerline and the microphone 20–24 are on the retreating side.
Figure 4.31: Overall sound pressure level at x = -579.1 m for Airbus AS350 operating at 80 kts, 6° descent flight.
Figure 4.32: A-weighted SPL at $x = -579.12$ m for Airbus AS350 operating at 80 kts, 6° descent flight.

Figures 4.31 and 4.32 show the OASPL and A-weighted SPL for the microphone from 14–24 respectively. Overall the predicted OASPL compares well with that obtained using flight test data. Approximately 2–4 dB overprediction of the peak noise levels is seen on the advancing side of the helicopter, similar to that seen for the Bell 407 helicopter. This overprediction occurs due to loading noise generated
by the main rotor. Figure 4.33 shows that the main rotor generates higher noise levels and these noise levels are a little overpredicted. Similar to that seen for Bell 407, the loading noise dominates the OASPL with a 2–4 dB overprediction on the advancing side (Figs. 4.31b–4.31e).

Figure 4.33: Comparing the main rotor and tail rotor noise level generated by Airbus AS350, 80 kts 6° descent flight at the location of microphone 16.

The thickness OASPL dominates as the helicopter approaches the microphones. The broadband noise has much lower contribution to the OASPL but dominates the A–weighted SPL on the retreating side of the helicopter (microphones shown in Figs. 4.32g–4.32k).

The thickness OASPL dominates as the helicopter approaches the microphones. The broadband noise has much lower contribution to the OASPL but dominates the A–weighted SPL on the retreating side of the helicopter (microphones shown in Figs. 4.32g–4.32k).
The OASPL at microphone 23 and 24 (Figs. 4.31j–4.31k) shows peak noise levels at two instances. The predicted total OASPL follows a similar trend and matches the flight test data. Near the peak OASPL, loading OASPL matches the flight test data and follows the trend as the helicopter flies over. This occurs because the noise prediction system accounts for the directivity of the loading noise generated by a rotor, for which the angle of attack of the tip path plane is equal to the wake trajectory, and changes in the radiation distance between the observer and the helicopter. As a similar peak is not seen for the A-weighted SPL, this loading noise is generated primarily by the main rotor (shown in Fig. 4.34) and at lower frequency.

![Graphs showing OASPL noise](image)

(a) Total OASPL noise  
(b) Loading OASPL noise

Figure 4.34: Comparing the main rotor and tail rotor noise level generated by Airbus AS350, 80 kts 6° descent flight at the location of microphone 23.

In conclusion, the two helicopters Bell 407 and Airbus AS350 considered for the study show variation of the total noise in the advancing and retreating sides. The OASPL (Figs. 4.28 and 4.31) and A-weighted noise levels (Figs. 4.29 and 4.32) compare well with the flight test data. The results shows that, though the noise levels for the microphones located on the advancing side are overpredicted by 2–3 dB or dBA, the levels are higher than that seen for the retreating side. The
broadband noise dominates the total noise levels on the retreating side. The major contribution to the total noise is only from the main rotor.

Certain limitations of the noise prediction were seen when validating the 80 kts level and 80 kts 6° descent flight conditions. This is the scope for future development and is discussed in the Chapter 7.

4.2.3 Understanding the importance of following the flight trajectory for analyzing flight conditions

In the previous sections, validation for the steady flight conditions was done using a simulated flight trajectory. Here, the differences with flying a nominal flight trajectory and a simulated flight trajectory for Bell 407 80 kts level flight and 80 kts 6° steady descent are shown in Fig. 4.35 and the SEL contours are shown in Fig. 4.36. The nominal flight trajectory has no variation in velocity and helicopter attitude. The roll rate, yaw rate, and pitch rate are zero.

The SEL contours show that for level flight (Fig. 4.36a), the difference with the simulated flight trajectory and nominal flight trajectory is negligible. For this flight condition, the broadband noise dominates the total peak levels (2 dBA overprediction). The Pegg empirical model used for predicting the noise levels is not sensitive to small changes in the flight conditions. Another thing to note is that at 80 kts level flight, the loading and thickness noise are mostly harmonic noise sources and are not very dependent on a small-time rate of change in flight conditions.

For the 6° steady descent flight condition 4.36b, the BVI noise generated by the main rotor dominates the total levels. Here, the noise levels generated with the simulated flight trajectory underpredict the total levels, while with the nominal flight trajectory, the total noise levels are overpredicted. The BVI noise source is a strong function of flight conditions. (Changes to the velocity, pitch, and roll angle changes the blade-vortex-interaction.) With the simulated flight, the helicopter
experienced deceleration and changes in roll angle and pitch angle. These transient effects moved the wake trajectory away from the rotor. The rotor was continuously operating in the wake for the nominal flight procedure, which resulted in the noise levels higher than the observed with simulated flight trajectory.

This analysis shows the importance of simulating the flight trajectory. Here, the effect of transient flight conditions is better captured. With the further enhancement of the noise prediction system, the SEL contours are more likely to match the flight test data with the simulated flight trajectory than with a nominal flight trajectory.
Figure 4.35: Comparing flight test trajectory with simulated and nominal flight procedures for Bell 407 performing 80 kts level flight and 80 kts 6° descent.
Figure 4.36: Comparing sound exposure level contours generated for a simulated and nominal flight procedures for Bell 407 performing 80 kts level flight and 80 kts 6° descent.
4.3 Concluding remarks

This chapter describes the development and validation of a helicopter noise prediction system and discusses the sensitivity of the acoustic characteristics to the helicopter configuration parameters and flight condition. A detailed overview of the post processing of the flight test data, noise prediction system and validation was provided. The noise prediction system is validated against new acoustic flight test data for two steady flight conditions. Overall, the noise prediction system was able to capture the trends of the noise contour plots, and the predicted noise levels were close to the flight test data—usually within a few SELdBA. The use of SEL contours of the various noise components (thickness, loading, and broadband) provided some explanation and understanding of flight test data and what aspects of the prediction system that might need to be improved. The noise prediction system was able to differentiate relatively small differences in the helicopter configuration and accurately predict the resultant changes in noise levels—even though “engineering judgement” to estimate the detailed aircraft information was sometimes required. The different noise levels were also used to validate and assess the noise prediction system. Observations from the results are demonstrated and analyzed. A few important points made during this process are:

1. Tail rotor thickness noise is overpredicted as the helicopter approaches the microphone location. This is thought to occur due to lack of scattering or shielding effect from the fuselage.

2. The flapping motion of the blade is missing in the thickness noise calculations.

3. Tail rotor loading noise does not include the effect of interference with the main rotor wake and has lower temporal resolution.

4. Main rotor loading noise is overall predicted well by the system. An overprediction of the loading noise levels on the advancing side of the rotor could
be due to error in trimming the helicopter or could be result of the error in selecting the tip vortex core limit. This parameter is required for blade load calculation by the CHARM rotor module.

The entire chapter focused on development of the validation process and validating and analyzing the noise levels generated by relatively steady flight conditions. In the next chapter, the same noise prediction system and validation process are used to validate complex maneuvers performing a level turn, decelerating turn, and descending turn.
In the previous chapter, the validation of the system was focused on analyzing and understanding the noise levels generated by relatively steady flight conditions. Different noise levels and noise sources were analyzed to understand the physics of the noise generated during flight procedures. That analysis highlighted the advantage of a comprehensive noise prediction system and displayed its weakness for the future scope of development. The weaknesses observed in steady flight conditions, including 1) the overpredicted tail rotor noise as the helicopter approaches, 2) the overprediction of the BVI noise in some cases, and 3) issues with calculating broadband noise, are also likely to exist when validating a complex maneuver. With that in mind, turn maneuvers are assessed to understand the noise levels generated during a maneuver and the current noise prediction system for turns and transient flight conditions.

The examples considered in this chapter are level turns, decelerating turns, and descending turns in the left and right directions. This range of flight conditions showcases the potential noise mitigation that could be achieved by using turn maneuvers in a flight procedure and understand the capabilities of the current noise prediction system and deficiencies that can be addressed in the future work.
From the literature review, analysis of a complex maneuver using a comprehensive noise prediction system is lacking. Such analysis would not only help explain the mechanisms responsible for noise generated during a turn but could eventually help in building an empirical model for analyzing a maneuvering flight procedure.

For the comparison between the flight test data and the predicted noise, the sound exposure level (SEL), overall sound exposure level (OASPL), A–weighted sound pressure level, and sound pressure level (SPL) noise metric are used.

The major differences between any steady level or descent flight with a turn maneuver are: 1) the changes in the thrust requirement either during the transition period (more energy required to overcome any inertial motion) or increase in thrust levels to balance the centrifugal force experienced by the helicopter during a turn maneuver; 2) change in noise level directivity due to the roll of the helicopter; and 3) changes in the blade-vortex interaction as the trajectory and strength of the wake and tip vortex changes significantly during transition.

The validation results compare predicted and measured noise level contours for the microphone array deployed on the ground during the flight test. In the figures, the helicopter begins flying in the positive $x$–direction nominally along the path $y = 0$ (the ground plane is the $x – y$ plane). The grid locations, marked as black circles, are the microphone locations used during the flight test.

### 5.1 Validation 3: Level turns

The previous validation cases were steady or approximately steady. For a maneuvering case, like a level turn, the time-dependent flight trajectory, blade loads, and moments change in a time-dependent manner. Validation of the noise prediction system with time-dependent, transient flight conditions would give confidence in the system’s capability for maneuver noise prediction, which is important for developing noise abatement procedures. The flight trajectory for this validation case can be
described as a constant 80 kts level flight followed by a 90° turn, executed with a roll angle of 25° and the heading change—either to the left or to the right. The flight speed and altitude (152.4 m or 500 ft) is nominally maintained throughout the turn. Figure 5.1 shows a pictorial representation of the position of microphone array and the flight path of the procedure considered.

![Figure 5.1: Pictorial representation of an 80 kts level turn flight procedure.](image)

### 5.1.1 Sound exposure level validation

The noise prediction system results are compared with the flight test data for the Robinson R66, Airbus AS350, and the Bell 407 aircraft for both left and right turns in Fig. 5.2. Overall the prediction agrees reasonably well with the flight test data, but the predicted levels are consistently higher than the measured levels (typically 2–4 dBA).

The thickness, loading, and broadband noise components are shown in Figs. 5.3, 5.4 and 5.6, where the broadband noise components are higher than the thickness and loading noise for all the aircraft.
Figure 5.2: Total sound exposure level (SELaBA) for a 80 kts, level turn; final roll angle 25°. (For each subfigure: left–flight test data; right–prediction)
When compared to the 80 kts level flight (e.g., AS350 level flight–noise levels shown in Fig. 4.5e), the noise generated by level left (Fig. 5.2e) and right turn (Fig. 5.2f) seems lower due to the difference in the flight altitude. The level flight operates approximately 100 ft (60.96 m) while the level turns operate at 500 ft (152.4 m). The peak SEL for the AS350, 80 kts level flight is about 94 dBA, and for level, turn is about 88 dBA. If the noise levels were adjusted for only spherical spreading and the 80 kts level fight was operating at an altitude of 500 ft, the peak noise levels would roughly be 86 dBA. As such, a noise penalty is incurred for the level turn maneuvers. However, the advantage of the level turn flight procedure would come if the noise sensitive zone is around [0,0,0,0,0] (on the SEL contour shown above) and avoiding the noise sensitive zone is advantages than the incurred penalty of 2 dBA.
Robinson R66: SEL validation

Figure 5.3: Sound exposure level (SEL[BA]) for the noise sources for a Robinson R66 performing 80 kts, level retreating-side and advancing-side turn flight procedures.
The Robinson R66 helicopter has much lower noise levels (shown in Figs. 5.2a–5.2b and 5.3) than the other two helicopters. The flight trajectory information is shown in Appendix D and in Figs. D.31 for retreating-side (left) turn and for advancing-side (right) turn. This is due to lower helicopter weight and lower blade tip speed.

**Airbus AS350: SEL validation**

For the Airbus AS350 helicopter, the peak noise levels are similar for the advancing side (Fig. 5.2e) and the retreating-side turn (Fig. 5.2f). However, the noise spreads more in the sideline microphone positions for the retreating-side turn (Fig. 5.2f) compared to the advancing-side turn (Fig. 5.2e). The noise prediction system captures this feature. As for the advancing-side turn (Fig. 5.2e), the peak noise occurs only below the flight path. This feature is captured by the predicted noise, though the noise levels are overestimated by 2 dBA. This overestimation is due to the broadband noise shown in Fig. 5.4a. The major contributions to the total noise are from the main rotor (results are shown in the Appendix C in Figs. C.22 and C.32). On the retreating side, the tail rotor generates higher loading noise compared to that generated by the main rotor. This is the reason for the noise to be more spread out in the sideline position and inside the turn. This occurs due to an increase in the tail rotor thrust requirement. The comparison between the loading SEL generated by the main rotor and tail rotor is shown in Fig. 5.5.
Figure 5.4: Sound exposure level (SEL_{dBA}) for the noise sources for a Airbus AS350 performing 80 kts, level advancing-side and retreating-side turn flight procedures.
Figure 5.5: Comparing loading SEL generated by the main rotor and tail rotor for Airbus AS350 performing 80 kts, level turn.

Bell 407: SEL validation

For the Bell 407 helicopter, the noise levels (Figs. 5.2c and 5.2d) are overpredicted by 2–4 dBA. The Bell 407 also has higher loading SEL levels than the other aircraft (although loading does not appear to be a major contributor in this maneuver). The broadband noise (Fig. 5.6 dominates the total noise generated by the helicopter. The thickness noise for the Bell 407 (Fig. 5.6) is significantly higher than the other helicopters (due to higher main rotor and tail rotor tip-speed), but the broadband noise magnitudes of the AS350 and Bell 407 are comparable. As such, the overpredicted total noise is due to predicted broadband noise levels that are too high and potentially thickness noise from the tail rotor (that should be shielded by the fuselage). Figure 5.7 shows for the advancing-side turn that the broadband noise of the main rotor is dominant, followed by the tail rotor thickness noise, and then the loading noise from both the main and tail rotors.
Figure 5.6: Sound exposure level (SEL\textsubscript{dBA}) for the different noise sources generated by Bell 407 performing 80 kts, level turn flight procedures.
In both the turns, the SEL contours (seen in the flight test data and noise predictions) have approximately the same magnitude. Therefore, it is not surprising that the main rotor rotation direction (AS350–CW vs. R66 and Bell 407–CCW) does not seem to have much impact in this case.

(a) Main rotor thickness noise
(b) Tail rotor thickness noise
(c) Main rotor loading noise
(d) Tail rotor loading noise
(e) Main rotor broadband noise
(f) Tail rotor broadband noise

Figure 5.7: Comparing dominant noise sources for the Bell 407 performing 80 kts, level advancing-side (right) turn.

The SEL contours did give an overall outlook for the noise generated by the helicopters. The noise levels showed the dominant noise source generated by the tail rotor and main rotor. However, it is important to note that though two noise
sources may have the same SEL, the noise source contributing to the total SEL is the one with the highest A–weighted peak levels. This occurs due to time integration effect. So if, for example, the broadband noise generated by the main rotor and thickness noise generated by the tail rotor of a Bell 407 operating in a 80 kts level advancing-side (right) turn (shown in Fig. 5.7) has comparable levels, the main rotor broadband noise has higher noise levels and shorter time duration while the tail rotor thickness noise has longer duration and smaller peak A–weighted SPL. Furthermore, for the Bell 407 8kts advancing-side (right) turn, the total SEL is dominated by the main rotor broadband noise. This can be found by analyzing the time histories of noise levels for the entire flight procedure. Thus the next section focuses on the time history of the noise levels.

5.1.2 Time history validation

The time history of the noise levels shows the effect of changes in the flight condition, directivity and the relative distance between the helicopter and observers at different microphone locations. Again the cases considered are level retreating-side and advancing-side turns at a maximum roll angle of 25°. It is interesting to study the noise levels during the transition period as the helicopter ‘rolls in’ the turn and then as it ‘rolls out’ of the turn. Another feature to study in these maneuvers is the effect of the helicopter roll on the advancing and retreating side and the changes in the noise levels due to expected increase in main rotor thrust as the helicopter rolls.

5.1.2.1 Bell 407: Time history validation

The first helicopter considered is the Bell 407 helicopter. The maneuvers considered for analysis are retreating-side (left) and advancing-side (right) turn maneuvers. A brief observation based on all the microphones is presented in Appendix B from Figs. B.23–B.30 for the retreating-side (left) turn and from Figs. B.33–B.40 for the advancing-side (right) turn. The flight procedure starts with a steady level flight
and then rolls into the turn. The flight trajectory information is provided in Fig. 5.8.

Figure 5.8: Comparing flight trajectory and attitude information of the simulated flight procedure with the flight test data for a Bell 407 performing level advancing-side (right) and retreating-side (left) turns.
Retreating-side (left) turn:  First consider the level, retreating-side (left) turn. The following summary is based on the noise levels at all the microphone positions used during the flight test, and is provided in Appendix B from Figs. B.23–B.30. The dominant noise source depends on the microphone location. Initially, the helicopter is operating at 80 kts level flight. For this segment of flight procedure the thickness noise during approach and loading OASPL underneath the flight trajectory are major contributors to the peak noise levels. The OASPL time history during approach compares very well with the flight test data (Figs. B.23–B.30 in Appendix B and Fig. 5.10 in this section). This thickness OASPL is primarily generated by the main rotor (Figs. 5.10c and 5.10d. The predicted A–weighted SPL is overpredicted as the helicopter approaches the microphone, when compared to flight test data. The overpredicted thickness noise is generated by the tail rotor (Figs. 5.11c and 5.11d). This is a common feature seen through out the predicted noise for different microphones and potentially occurs due to the absence of the scattering or shielding effect from the fuselage.

The second thing to note is the peaks seen in the OASPL and the A–weighted SPL occurring at observer time. When the helicopter is closest to the microphone the loading OASPL dominates the peak. The A–weighted SPL peak occurs either during the roll-in or roll-out (increase in rate of change in roll angle) when the helicopter generates higher-harmonic loading noise or when the helicopter is closest to the microphone resulting in broadband noise dominating the A–weighted SPL. As the helicopter rolls to perform a turn maneuver, the rotor thrust requirement increases to balance the centrifugal force experienced by the helicopter. The rotor tilts in a way that the advancing side is at higher altitude than the other three side and the thrust vector has a significant component in the $x – y$ plane and not just $x – z$ plane as seen during a forward flight (the thrust vector is required not to just balance the weight of the helicopter but also to balance centrifugal force). During this roll-in motion, i.e., increase in rate of change of roll angle, the blade loads are
continuously changing and are not very periodic. This result in higher loading noise as the helicopter rolls in. The blade loads don’t show confirmation that this is BVI noise. However, the changes in the blade loads are continuously happening and as such have higher \( \dot{l}_r \) term. After this the helicopter undergoes a turn at a peak roll angle of 25°. This roll angle is kept relatively constant before roll-out of the turn.

During the turn, the main rotor thrust vector components points toward the center of the turn and the tail rotor thrust requirement is higher to balance the additional torque required during the turn. This results in an increase in tail rotor loading noise with higher contribution to the total loading noise (seen in the loading noise time history at the sideline microphone locations (Fig. B.29)). As the frequency content of the harmonic tail rotor loading noise is larger than the main rotor loading noise, its contribution to the total A–weighted loading SPL is comparable and at certain locations higher than main rotor loading noise.

After this the helicopter rolls out of the turn. During this transient period the rate of change in blade loads increases resulting in higher loading OASPL and higher A–weighted broadband SPL dominating the total OASPL and A–weighted time history. The noise levels are well captured by the noise prediction system. These observations are made by analyzing all the microphones used during the flight test. The observations made above can be best demonstrated by analyzing the noise level of microphones 15 and 23. The microphones location with respect to the flight path is shown in Fig. 5.9.
Figure 5.10: Comparing overall sound pressure levels for the two microphones located at the same distance on either side of the flight trajectory of a Bell 407 performing level, retreating-side (left) turn.
Figure 5.11: Comparing A–weighted sound pressure levels for the two microphones located at the same distance on either side of the flight trajectory of a Bell 407 performing level, retreating-side (left) turn.
The first thing to note from the retreating-side turn (left turn) is that thickness noise follows the same trend as seen during a level flight (shown in Figs. 5.10a–5.10b and 5.11a–5.11b). During the turn maneuver the relative distance and Mach vector in the radiation direction \( M_r \) between the microphone 15 and helicopter decreases as it is located directly below the flight path, while it increases for the microphone 23. The loading noise shows two peaks; first during the roll-in of the helicopter and second when the helicopter is closest to the microphone location and about to roll-out of the turn. At this observer time, around 36–40 seconds, the helicopter initially has a peak roll angle of 25° and is about to perform roll-out of the turn after 40 seconds. The loading OASPL results are shown in Figs. 5.10e–5.10f) and for A–weighted loading SPL are shown in Figs. 5.11e–5.11f).

When comparing the two microphones, 15 and 23, the noise levels are higher for the microphone 23 during the roll-in (around 26–30 seconds of the observer time) and the OASPL matches the levels observed during the flight test but the A–weighted SPL is overpredicted. Microphone 23, at the instance of roll-in, lies on the advancing side and has some BVI noise and higher-harmonic loading noise. The noise levels are higher for microphone 15 around 36–40 seconds of the observer time as the helicopter is closer to microphone. The A–weighted broadband SPL dominates the peak for the microphone 15 and A–weighted loading SPL noise for the microphone 23 (Fig. 5.11) and the higher noise levels are observed when the helicopter is closest to the microphone and is about to roll-in. These observations can be made for other microphones used in the test grid that are not shown in detail because the two selected microphones best represent the case considered.

**Advancing-side (right) turn:** The Bell 407 level, advancing-side (right) turn is analyzed to determine the differences between turns. A brief observation based on all the microphones is presented in Appendix B from Figs. B.33–B.40 for the advancing-side (right) turn. The flight procedure starts with a steady level flight
and then rolls into the turn. The flight trajectory information is provided in Fig. 5.8. Similar to level flights and level retreating-side (left) turn, the thickness noise is dominant during the approach and follows the same trends. The loading OASPL shows a peak around the roll-in of the helicopter and a second peak when the helicopter is close to the microphone. Here, the rotor during roll-in is turned such that the advancing side is below and retreating side is above and eventually during the turn the rotor disk is tilted backwards and towards right. This is to provide the necessary thrust in the $y$–direction and toward the center of the radius of the turn. At the sideline locations the loading OASPL has significantly higher contribution from the tail rotor and at certain locations is higher than the loading noise generated by the main rotor. As the helicopter turns at a peak roll angle of $25^\circ$ the helicopter accelerates and as such shows a sharp peak of noise levels (shorter duration seen in the time history of the noise levels) compared to level left turn.

The roll-out of turn is more gradual for the case considered as it occurs after 45 seconds of the flight time (actually a bit longer when accounting for sound propagation time). For the microphones located at the sideline positions and on the advancing side of the turn (due to change in heading angle of the helicopter, these microphones are now located inside the turn), the loading noise is well captured within 1–2 dB and the time history shows almost constant noise levels as the helicopter turns (almost same radiation distance). The peak predicted OASPL is dominated by the loading noise generated by the main rotor and tail rotor. The thickness noise follows similar trend as seen before for other flight conditions.

For the case considered the broadband noise dominates the peak A–weighted SPL and is overestimated by the 2 dBA. This noise is primarily from the main rotor. The A–weighted loading SPL shows multiple peaks, the peaks are associated with the higher-harmonic loading noise levels generated during the transient period as the helicopter roll angle changes (increase in roll rate), second peak due to
the directivity of the main rotor loading noise and the helicopter is closest to the observer position. Note, that the noise levels seen for the second peak are due the increase in rotor thrust and radiation distance and not higher-harmonic loading noise as this is seen during the first peak.

The third peak, if distinct, is due to the loading noise generated by the tail rotor. For this case the sideline microphones show higher tail rotor loading OASPL and A-weighted SPL, due to increase in thrust requirement during the turn, directivity of loading noise and higher frequency content. The A-weighted thickness SPL is dominated with the tail rotor noise and is higher on the sideline microphone locations. This noise level is comparable to the flight test data. The observations conducted above were made by analyzing the noise levels at different microphone locations and analyzing the contribution from the main rotor and tail rotor. The above described analysis can be best represented by understanding the two microphones; 10 and 24.

Figure 5.12: Microphone location with respect to the flight trajectory for Bell 407 performing 80 kts level advancing-side (right) turn.
Figure 5.13: Comparing overall sound pressure levels for the two microphones located on either side of the turn of a Bell 407 performing level, advancing-side (right) turn.
Figure 5.14: Comparing A-weighted sound pressure levels for the two microphones located on either side of the turn of a Bell 407 performing level, advancing-side (right) turn.
The microphone 10 is located on the retreating side and out of the turn while microphone 24 is located inside the turn and on the advancing side. The microphones location with respect to the flight path is shown in Fig. 5.12.

During the turn maneuver the Mach vector in the radiation direction ($M_r$) between the helicopter and microphone 10 increases as it is close to the centerline or $y = 0$ m. For microphone 24, located at a sideline position, during the roll the directivity of the thickness noise is more towards the microphone 10 than microphone 24. The A–weighted SPL shows that thickness noise generated by the tail rotor is slightly overestimated and is dominant. At the microphone location 10, this thickness noise generated by the tail rotor matches the levels measured during the flight test and is higher than seen for microphone 24 as the microphone is located at the sideline and ahead of the helicopter flight trajectory. The loading OASPL dominates the total OASPL noise.

For the microphone 10 located outside the turn and on the retreating side during the turn, the loading noise contribution is from both the main and tail rotor with the main rotor thickness noise contributing to the peak. The loading OASPL results are shown in Figs. 5.13e and 5.13f and the A–weighted loading SPL are shown in Figs. 5.14e and 5.14f. The microphone located inside the turn shows higher loading noise generated by the main rotor and is observed for a longer period of time. While outside the turn the loading noise generated by the tail rotor has a higher peak but a shorter duration of noise generation. This primarily happens due to the distance between the helicopter and the observer. As the helicopter turns, microphone 24 is inside the turn and closer to the radius of the turn and as such has higher noise exposure than microphone 10. As mentioned previously the A–weighted SPL shows multiple peaks due to roll-in, operating at peak roll angle and with helicopter closest to the observer and higher tail rotor loading noise. For microphone 10, these three peaks are distinct (Fig. 5.14e) and for the microphone 24, though the main rotor loading noise shows these three peaks, the tail rotor
loading noise dominates through the entire duration of the turn and contributes the most to the total A–weighted SPL.

The A–weighted broadband SPL dominate the peak level for the microphone 10 and the noise levels is observed when the helicopter is closest to the microphone and is about to roll-out of the turn. The noise is overestimated at the peak for this microphone. For the microphone 10 (Fig. 5.14a), located outside the turn, the broadband noise peak is comparable to thickness and loading noise and thus results in overprediction of the total A–weighted SPL. These observations can be made for other microphones used in the test grid, but they are not shown here. The time history for all the microphones used during the flight test are provided in Appendix B from Figs. B.33–B.40.

5.1.2.2 AS350: Time history validation

The next helicopter considered is the Airbus AS350 helicopter. The two cases considered are with the helicopter operating at a relatively constant altitude and speed and turning either towards left (advancing side of the helicopter) or on the right (retreating side of the helicopter); with peak roll angle around 25°. The maneuver starts with a steady level flight and then performs a turn by changing the roll angle and the collective pitch of the tail rotor. Any turn maneuver requires higher disk loading to balance the centrifugal force experienced by the helicopter. An advancing-side turn results in the main rotor disk tilted towards the left and reduced thrust requirement from the tail rotor to maintain the flight trajectory while a retreating-side turn results in the rotor disk tilted towards the right and with increase in thrust requirement from the tail rotor to maintain the flight trajectory. After the maximum roll angle is achieved the main rotor reduces the tilt in the lateral direction and follows the turn procedure. Figure 5.15 shows the flight trajectory information for the turns.
Figure 5.15: Comparing flight trajectory and attitude information of the simulated flight procedure with the flight test data for an Airbus AS350 performing level advancing-side (left) and retreating-side (right) turns.
Advancing-side (left) turn: For the first case considered, a level advancing-side (left) turn flight trajectory is shown in Figs. 5.15a and 5.15c. The helicopter flies steady level flight for the first 26 seconds of recorded flight time, and rolls in when the flight time is approximately 26 seconds. The helicopter achieves a peak roll angle of approximately 25° around 29 seconds of flight time and proceeds with this relatively constant roll angle for the rest of the flight procedure. The noise prediction system follows this complex maneuver with one distinct difference between the flight test trajectory and the simulated trajectory. The offset of the roll angle by about 5°, i.e., the simulated flight trajectory shows higher roll angle approximately around 30°. This error needs to be registered for identifying and analyzing the time history of the noise levels.

A deeper analysis is conducted by examining select microphones located directly below the flight trajectory. This analysis is conducted using microphones 42, 36, and 29 in the flight test microphone array; Fig. 5.16b and the results are shown in Figs. 5.16–5.17.
Figure 5.16: Overall sound pressure level at microphone located below the flight trajectory of an Airbus AS350 operating at 80 kts, advancing-side (left) turn.
The first thing to note is the overprediction of peak loading OASPL, which is higher than the flight test data for microphones 42 and 36, as shown in Fig. 5.16. This overprediction is the result of higher noise levels generated by the main rotor (based on the directivity and verified by calculating the noise levels for main rotor only, results shown in Figs. C.23–C.30 in Appendix C). This overprediction of noise levels is largely due to overprediction of the lower frequencies (note the difference between the loading OASPL peak and A-weighted SPL peak for the microphone 42, shown in Figs. 5.16a and 5.17a, is about 12 dB). One reason for the overprediction could be the difference in the weight of the helicopter simulated (3750 lbs.–average weight of the helicopter during the flight test was considered to avoid
further complications) and actually flown during the flight test (3565 lbs). Directly overhead of the microphone 29 the helicopter starts turning towards the advancing side (left) and the loading noise directivity changes and this overprediction in the loading OASPL has decreased (Fig. 5.16d). For the case considered, the simulated flight has higher roll angle and this could potentially change the directivity of the noise levels or the error in estimating the sideward flat plate area (assumed to be 35 ft²). These parameters are assumed using engineering judgement so the exact value was not known.

The A-weighted loading SPL peak matches the flight test, but due to over-prediction of broadband noise, the total A-weighted SPL predicted at the three microphones (Fig. 5.17) is too high. This overprediction results in higher SEL compared to the flight test as shown in Fig. 5.2e. The thickness OASPL (Fig. 5.16) dominates the total OASPL only when the helicopter approaches. The A-weighted SPL (Fig. 5.17) shows there is a very small contribution from the thickness noise. The time history of noise levels at these microphone locations demonstrated the effect of the changes in flight condition as the helicopter flies steady and then starts the turn maneuver when the helicopter is approximately overhead of microphone 29. Similar observations were made for the Airbus AS350 operating an 80 kts right turn for microphones 36 and 29; and hence, they are not shown here.

A microphone located on the sideline would show different noise characteristics due to the effect of noise source directivity. Consider microphones 26 and 32 located on the advancing side and the retreating side of the flight path, respectively, for the 80 kts level advancing-side (left) turn (Fig. 5.18a). The two microphones are located at the same sideline distance of 320.04 m and at $x-$location of -853.4 m. For the advancing-side turn (left turn), shown in Fig. 5.18a, around 25 seconds of flight time helicopter is at the same $x-$location (-853.4 m) and is undergoing roll, and reaches a peak value of 25° around flight time 29 seconds.

For the retreating-side turn (right turn) (Fig. 5.18b), the helicopter is near the
same $x-$location (-853.4 m) around flight time 15 seconds and is undergoing roll that reaches a peak value of 25° around flight time 20 seconds. As such the effect of change in roll angle and subsequently, the heading angle can be observed by analyzing the time history of the noise levels at these two microphone locations. The results are shown in Figs. 5.19–5.22. These figures also show the noise from the main rotor and tail rotor separately. These two microphone are considered to understand the effect of a level turn at sideline observer locations.

First consider the 80 kts level advancing-side (left) turn maneuver, with microphone 26 located on the advancing side and inside the turn and the microphone 32 located on the retreating side and outside the turn. For microphone 26 (Fig. 5.19a and 5.20a), the total OASPL peak is dominated by the loading noise generated by the main rotor and by thickness noise as the helicopter approaches the microphone location. Both the microphones shows a peak around flight time 24–25 seconds. This peak in noise levels is observed due to transient blade loads as the wake and tip vortex trajectory is continuously changing resulting in higher fluctuation (as the helicopter rolls in) and also due to the lowest distance between the microphone and the helicopter (at flight time 25 seconds the distance from the helicopter to the microphone is around 850 m). As the helicopter rolls in towards the advancing side the loading OASPL is matches the peak OASPL for the microphone 26 (Figs. 5.19a and Fig. 5.20a) and does not reduce for rest of the observer time ($t > 30$ seconds) in the simulation. The flight test data shows a similar trend, though the levels are approximately same after the peak level. The constant value of the noise levels is due to relatively constant directivity (thrust vector points inside the turn) and the distance between the helicopter and the observer (circular flight path results in same radiation distance). The contribution to the loading OASPL is primarily from the main rotor with a small contribution from the tail rotor (shown in Fig. 5.20a). Since the microphone is located inside the turn and in the sideline location, the effect of the directivity and geometric distance between the helicopter and the
observer location generates this peculiar trend seen in the total and loading OASPL time history.

A similar trend is observed for the total A–weighted SPL (shown in Fig. 5.21a); however the flight test and simulation A-weighted noise level is slightly underpredicted after the peak (during turn procedure). The A–weighted loading SPL peaks around 33 seconds and is higher than the broadband noise. Prior to this observer time, the helicopter is changing the flight procedure from steady level to steady turn and includes the transient flight condition. During the transition period the wake trajectory and blade tip vortex trajectory and strength changes rapidly and could result in BVI and higher-harmonic loading noise. For the case considered, higher-harmonic main rotor loading noise is seen around 200–300 Hz.

The next case is for the microphone 32 (Fig. 5.19b), which is located on the retreating side and outside the turn and at the same sideline distance as the microphone 26. Here, the total OASPL shows two peaks dominated by the loading OASPL (shown in Fig. 5.20b). The first peak occurs because the helicopter is at the same $x$–location as the microphone and starts to turn towards the advancing side (roll-in motion), similar to microphone 26 (shown in Fig. 5.20a). Here, both the main rotor and the tail rotor contribute to the noise levels. The second peak occurs because prior to the observer time, $t <32$ seconds, the helicopter has reached a peak roll angle resulting in the maximum blade loads or thrust requirement for the turn maneuver. After this the geometric or the radiation distance between the helicopter and the microphone increases as the helicopter turns left of the flight path and the microphone is on the right side of the flight path. Only the main rotor has the double peak characteristic and the tail rotor loading noise decreases as the helicopter moves away from the microphone. As for the A–weighted SPL, the broadband noise dominates the total noise levels with the main rotor and tail rotor generating similar levels of broadband noise as the helicopter approaches the microphone and then the broadband noise generated by the main rotor dominates.
the total noise levels (shown in Figs. C.26 and C.30 in Appendix C).

(a) Level left turn  
(b) Level right turn

Figure 5.18: Grid points considered for analyzing OASPL and A-weighted SPL

(a) Microphone 26 (on advancing side of level advancing-side turn)  
(b) Microphone 32 (on retreating side of level advancing-side turn)

(c) Microphone 26 (on advancing side of level retreating-side turn)  
(d) Microphone 32 (on retreating side of level retreating-side turn)

Figure 5.19: Comparing overall sound pressure level at microphones located on the advancing and retreating side of the flight path of an Airbus AS350 operating at 80 kts, level advancing-side (left) and retreating-side (right) turn.
Figure 5.20: Comparing loading overall sound pressure level at microphones located on the advancing and retreating side of the flight path of an Airbus AS350 operating at 80 kts, level advancing-side (left) and retreating-side (right) turn.
Figure 5.21: Comparing A–weighted sound pressure level at microphones located on the advancing and retreating side of the flight path of an Airbus AS350 operating at 80 kts, level advancing-side (left) and retreating-side (right) turn.
Figure 5.22: Comparing A–weighted loading sound pressure level at microphones located on the advancing and retreating side of the flight path of an Airbus AS350 operating at 80 kts, level advancing-side (left) and retreating-side (right) turn.

Retreating-side (right) turn: For the second case considered, i.e., the Airbus AS350 performing a level, retreating-side (right) turn shown in Figs. 5.15b–5.15d. In this case the helicopter flies a level flight for the first several seconds and then rolls in at approximately 10 seconds and achieves a peak roll angle of approximately 25° around flight time of 20 seconds. Then the helicopter proceeds with this relatively constant roll angle for the rest of the turn. Similar to the advancing-side turn, the simulated trajectory has a roll-offset about 5°, i.e. the simulated flight trajectory shows maximum roll angle approximately around 20°.
The time history of the noise levels is shown in Figs. C.33–C.40 in Appendix C. The results for the two microphones considered are shown in Figs. 5.19c, 5.20c, 5.21c, and 5.22c for microphone 26 and Figs. 5.19d, 5.20d, 5.21d, and 5.22d for microphone 32. During the maneuver the roll is initiated around 10 seconds and at approximately 15 seconds the helicopter $x-$position is the same as the microphones 26 and 32. As such, the peak in noise levels are seen for an observer time of approximately 15–17 seconds. This peak is dominated by the loading noise in the OASPL time history (Figs. 5.19c, and 5.19d) and by broadband noise in the A–weighted SPL time history (Figs. 5.21c, and 5.21d). As the helicopter approaches the microphone the thickness noise dominates the total noise levels. After 20 seconds of the flight time, the helicopter has achieved a peak roll angle of 25° (due to roll offset the simulated flight trajectory has roll angle of 20°). The helicopter turns and the distance between the microphone 26 and the helicopter increases (similar to microphone 32 during a level advancing-side (left) turn maneuver). The distance between the microphone 32 and the helicopter reduces slowly as the helicopter turns right. This results in slower reduction in the noise levels as the helicopter turns. As for the A–weighted SPL, the broadband dominates and sometimes is overestimated for both the microphones together with some contribution from the loading noise. The A–weighted flight test data shows a very ‘jagged’ curve in Fig. 5.19d. This is not captured by the noise prediction system.

5.1.2.3 Comparison of noise levels generated by AS350 performing level turns

Comparing the two microphones located inside the turn of the level turn flight procedure shows that the noise levels are higher for a level advancing-side turn as (Fig. 5.19a, microphone 26) compared to level retreating-side turn (Fig. 5.19d, microphone 32). In both cases, the simulation overpredicts the OASPL levels after the peak level in the flight test data. The main contributor to the overpredicted
OASPL (Fig. 5.20d) is the loading noise generated by the main and tail rotor. Both the noise levels seem high and is unclear which rotor contributes to the most error seen in the predicted OASPL. For the case considered, the tail rotor thrust requirement has increased and as such generates higher loading noise during the entire turn procedure (compare Figs. 5.20b and 5.20c), which is comparable to that measured during the flight test. The A-weighted loading SPL is primarily generated by the tail rotor (higher frequency noise and directivity to the sideline) with a slightly higher contribution from the level advancing-side (left) turn when compared to level retreating-side (right) turn (Fig. 5.21). A comparison of the two microphones outside of the level turns shows that while the levels and behavior are different, they both agree quite well with the flight test data (see Figs. 5.19b, microphone 32, and 5.19c, microphone 26).

Of the two flight cases and the two microphones, microphone 26 located inside the level advancing-side (left) turn (Fig. 5.21a) and microphone 32 located inside the level retreating-side (right) turn (Fig. 5.21d) show slightly higher A-weighted loading noise compared to the broadband noise around observer time 32–36 seconds. This is further analyzed by comparing the OASPL and A-weighted loading noise generated by the main and tail rotor for the microphone 26 located inside the level advancing-side (left) turn, shown in Figs. 5.21a and 5.22a, respectively.

### 5.1.3 Comparison of noise levels generated by Bell 407 and AS350

A final note on these comparisons: For the Bell 407, the peak noise levels have significant contributions from thickness and loading noise while for the Airbus AS350 helicopter the noise levels are dominated by the loading noise at the peak. Generally, the Bell 407 helicopter generates higher noise levels than the Airbus AS350 helicopter. BVI noise was only observed during the roll-in of the helicopter. These observations are evident in Figs. 5.23 and also shown in Appendices B-C.
These microphones are located outside the turn of the advancing-side and retreating-side turns performed by AS350 and Bell 407. Another feature to notice is that the microphones located outside the turn for an advancing-side flight procedure has a distinct peak or the peak occurs for a shorter duration (microphone 15 for AS350 advancing-side turn and microphone 23 for Bell 407 advancing-side turn).

**Remarks:** The loading noise generated by the main rotor is overestimated for level turns. A few hypotheses for this are: 1) The helicopter is simulated (3750 lbs–average weight of the helicopter during the flight test) has higher weight than the one flown during this particular set of test flights (starting weight 3548 lbs); 2) The roll offset observed during both level left and right turns–could be due to higher sideward flat plate area assumed or as the hingeless main rotor was never able to produce the same lift from the advancing side and the retreating side and thus required the fuselage to have a roll off-set to compensate for the moment about the $x-$axis (higher roll angle required for the turn on the advancing side and lower roll angle required for the retreating side and the roll was negative during a level flight). These hypotheses require further investigation and are outside the scope of the dissertation.
Figure 5.23: Comparing total overall sound pressure level to demonstrate the effect of roll angle; for the Airbus AS350 and Bell 407 helicopter performing both advancing-side and retreating-side turns.
Figure 5.24: Comparing total A-weighted sound pressure level to demonstrate the effect of roll angle; for the Airbus AS350 and Bell 407 helicopter performing both advancing-side and retreating-side turns.
5.2 Validation 4: Level, decelerating turns

In this section, the helicopters perform a complex maneuver that starts with 80 kts level flight and then executes a level turn with a maximum target roll angle of 35° while simultaneously decelerating at 2 kts/seconds. For the analysis and validation both left and right turns are considered. The turns were executed such that the initial heading was changed by nominally ±90°, so the aircraft final heading was in the ±y—direction and the flight speed was reduced from 80 kts to approximately 60 kts.

Figure 5.25: Pictorial representation of an 80 kts level right-turn procedure.

Figure 5.25 shows the pictorial representation of the level, decelerating right-turn over the flight test grid. The altitude for the flight procedure is kept relatively constant around 500 ft (152.4 m). The velocity, initially constant at 80 kts during level flight, decelerates as soon as the helicopter starts to roll to achieve the target maximum roll angle of 35° and heading angle of 90° in either direction. As compared to the level turn case, the decelerating-turn maneuver has higher complexity. The
decelerating-turn maneuver has a higher target roll angle of 35° when compared to the previous case where the maximum target roll angle was 25°. This results in a sharp turn or small radius during the turn—in fact, the black line representing the actual flight path shows that the pilot was not always able to complete the turn at 90°, but rather the helicopter turned more than 90°. During the transition from level to level turn, transient noise is expected due to the addition of the roll rate. Another change in the maneuver is the deceleration from 80 kts to about 60 kts at approximately 2 kts/seconds. During such a maneuver the total sound exposure time would also increase resulting in higher annoyance and sound exposure level. Also when turning and decelerating the wake characteristics are continuously changing resulting in continuous change in periodic blade loads and sometimes in BVI interaction. All of these transient effects add to the noise generated by the flight procedure and prediction of the noise generated would help to validate and assess the current noise prediction system and to identify which aspects of the maneuver are most important. The validation is performed for the Robinson R66, Airbus AS350 and Bell 407 helicopters performing both advancing-side and retreating-side turns.

5.2.1 Sound exposure level validation

The sound exposure level contours for the three helicopters (Robinson R66, Airbus AS350, and Bell 407) is shown in Fig. 5.26
Figure 5.26: Total sound exposure level (SEL_{dBA}) for a level, decelerating turn; final roll angle 35° and deceleration from 80 kts at 2 kts/seconds.
(e) Bell 407, Retreating-side (left) turn

(f) Bell 407, Advancing-side (right) turn

Figure 5.26: (continued) Total sound exposure level (SEL dBA) for a level, decelerating turn; final roll angle $35^\circ$ and deceleration from 80 kts at 2 kts/seconds.

The prediction system captured the magnitude and directivity of the SEL contours quite well for all three aircraft. The predicted total noise levels were off by a maximum of 2 dBA for the three helicopters considered. This is encouraging for such a complex maneuver—especially when it is understood that the noise prediction system uses a quasi-periodic blade load assumption, an empirical broadband noise model, and the helicopter model was designed purely through engineering judgement to provide many missing parameters. During the maneuver, maximum noise is generated around the transient flight condition. Any transient motion results in unsteady, aperiodic blade motion and loading (increased $\dot{l}_r$ term in the Farassat’s Formulation 1A for loading acoustic pressure calculation). The helicopter begins the turn and decelerates around $x = -1000$ m. This maneuver results in unsteady blade loading and generates significant noise. The noise levels are higher than that observed in a level turn seen in Fig. 5.2.
Robinson R66: SEL validation

Figure 5.27: Sound exposure level (SELdBA) for the noise sources for a Robinson R66 performing 80 kts, level, decelerating retreating-side (left) and advancing-side (right) turn flight procedures.
The Robinson R66 helicopter, which is lighter than the other two helicopters, generates lower noise levels than the Airbus and Bell helicopters. The flight trajectory information is shown in Appendix D and in Fig. D.1 for the retreating-side (left) turn and Fig. D.51 for the advancing-side (right) turn. Figures 5.26a, 5.26b and 5.27 shows the total SEL contour and its components for Robinson R66 helicopter performing left and right turn. (Also note that the R66 helicopter turns nearly 180° rather than the desired 90°. The broadband noise dominates the two turns and is shown in Figs. 5.27. The loading noise is higher during the transient phase or during the turn as is shown in Figs. 5.27. One distinct difference between the two turns is the loading noise generated is most intense inside of the advancing-side (right turn), while for the retreating-side turn the loading noise is outside of the turn, and continues over a larger area. This noise is generated by the main rotor. For this helicopter the noise contribution from the tail rotor is very small and is not shown.
Airbus AS350: SEL validation

Figure 5.28: Comparing flight trajectory and attitude information of the simulated flight procedure with the flight test data for an Airbus AS350 performing level, decelerating advancing-side (left) and retreating-side (right) turns.
Figure 5.29: Sound exposure level (SELdBA) for the noise sources for Airbus AS350 performing 80 kts, level, decelerating decelerating advancing-side (left) and retreating-side (right) turn flight procedures.
For the AS350, the ground contour plot of SEL values (Figs. 5.26c and 5.26d) shows a region of high noise. This region occurs in the region where the flight is turning at approximately 70 kts. This localized increase in SEL levels is not only due to the turn maneuver but also because of the increase in annoyance due to the increase in flight time. When comparing the retreating-side (right) turn and advancing-side (left) turn performed by the AS350, it is clear that for the advancing-side (left) turn the “hot spot” is close to the center of the turn (inside the turn), and for the retreating-side (right) turn the “hot spot” has moved towards the end of the flight segment and outside of the flight track. This can be explained by examining the flight trajectory shown in Fig. 5.28. The two turns start at different flight times. Acceleration is not shown in Fig. 5.28 but it can be deducted from velocity vs. flight time plot.

![Noise Prediction System](image1.png)

(a) Main and tail rotor

![Noise Prediction System](image2.png)

(b) Main rotor

![Noise Prediction System](image3.png)

(c) Tail rotor

Figure 5.30: Loading sound exposure level(SELdBa) for the noise sources for Airbus AS350 performing 80 kts, level, decelerating advancing-side (left) flight procedure.
For the advancing-side turn (left) (Fig. 5.26c), the noise levels are higher during the roll-in motion of the helicopter and during the turn. Comparison with the flight test data shows that the predicted noise levels have different directivity, with the noise levels more spread out during the turn part of the flight procedure. The noise levels outside the turn and when the helicopter is experiencing maximum roll angle, the total SEL contour (around $x = -400 \text{ m} - -300 \text{ m}$ and $y = -100 \text{ m} - 100 \text{ m}$) doesn’t show the trend seen during the flight test. Though the noise levels are much lower, the thickness noise shows this trend. So either the thickness noise is underestimated (noise is radiated ahead of the helicopter) or the error in directivity due to roll angle offset by about $5^\circ$ has resulted in error in predicting the trend. Further analysis is conducted in the current chapter by analyzing the time history.
of the noise levels.

The retreating-side turn (right turn) shows that the noise levels are higher during a decelerating turn and peaks as the helicopter rolls out of the turn. The results are shown in Fig. 5.26d. The noise components show (Fig. 5.29b) that the contribution to the total noise level is primarily from loading and broadband noise, with peak loading noise occurring outside the turn during roll-in (towards the advancing side and transient flight condition) and peak broadband noise occurring as the helicopter is experiencing maximum roll (maximum thrust required). When comparing the loading noise generated by the advancing-side (left) turn (Fig. 5.30) and retreating-side (right) turn (Fig. 5.31) it is clear that the noise levels peak on the advancing side of the rotor, irrespective of the turn direction, and are primarily generated by the main rotor (shown in Figs. 5.30 and 5.31). However, the tail rotor shows higher noise levels during a retreating-side turn (right turn), but since the levels are much lower than the peak loading noise this effect is not observed. The broadband noise prediction shows that the noise levels are higher during a retreating-side turn (right turn). This could be the result of the roll offset observed by the vehicle due to error in modeling the helicopter (based solely on engineering judgment—error in sideward flat plate area and center of gravity). Overall the noise levels compare well for the Airbus AS350 helicopter with an error of 2 dBA.

**Bell 407: SEL validation**

The Bell 407, Figs. 5.26e and 5.26f, show good agreement between the flight test data and the prediction. Here, the high noise region seen in the total SEL noise contour for an Airbus AS350 helicopter performing level, decelerating turns, is absent when the Bell 407 is at maximum roll angle during the turn. The helicopter turns left around 65 kts and rolls out of the turn with small acceleration (this is due to the pilot’s variation from the planned flight procedure). The acceleration at the end of the flight procedure resulted in lower sound exposure time and as
such lower SEL values. The flight trajectory is shown in Fig. 5.32. During the roll-in operation the helicopter experiences change in velocity and roll angle. These two distinct actions result in a very transient wake trajectory, a higher rate of change in blade load around the azimuth and more potential for BVI. As such, higher loading noise is generated and is shown in Figs. 5.33. The thickness SEL is primarily generated by the tail rotor and the loading and broadband noise are primarily generated by the main rotor (shown in Appendix B in Figs. B.43 and B.54). The characteristic nature of noise generation during a transient maneuver is further analyzed by examining the time history of the OASPL and A-weighted SPL levels, as the SEL contours provide a limited understanding.
Figure 5.32: Comparing flight trajectory and attitude information of the simulated flight procedure with the flight test data for a Bell 407 performing level, decelerating advancing-side (right) and retreating-side (left) turns.
Figure 5.33: Sound exposure level (SEl_{dBA}) for the noise sources generated by Bell 407 performing 80 kts, level, decelerating retreating-side (left) and advancing-side (right) turn flight procedures.
Remarks: The various noise components for the level, decelerating turn are shown in Figs. 5.27a–5.29b. The loading noise has increased during the decelerating turn for each of the three helicopters. This increase in noise is associated with the BVI noise, i.e., the rotor operating in its wake and increase in rate of change in blade loads along the azimuth and higher-harmonic loading noise (more pronounced during decelerating turns than level turns). The increase in rotor thrust during a turn produces lesser effect on loading noise when compared to the transient processes mentioned above. The direct effect of the change in rotor thrust can be seen in the broadband noise; however, the relationship between the transient rotor thrust and broadband noise is unclear because most of the empirical constants were designed for steady flight procedures. Nonetheless, the noise prediction system was capable of capturing many transient effects – as seen in the trends of the noise contour plots. Furthermore, the system identifies that different noise components have different levels of contribution in the total SEL depending upon the aircraft and flight maneuver. Even though this case is considered to be a level, decelerating turn flight, the flight trajectory information, shown in Figs. 5.28 and 5.32, reveals the actual maneuver is more complicated in each instance. As such, it is hard to be definitive in the comparison between different helicopters or to draw general conclusions from the differences seen in the SEL contours.

5.2.2 Time history validation

The time history should further help to analyze the effect of turning into the turn, and out of the turn, and deceleration rate. Considering the multiple flight conditions during the maneuver, the validation process should be able to assess the prediction system for different flight conditions.
5.2.2.1 Bell 407: Time history validation

The time history of the Bell 407 helicopter performing a level, decelerating turn is examined first in this section. The limitations described when analyzing the steady level, steady descent and level turns are still present when validating and assessing the current flight conditions.

Retreating-side (left) turn: First consider the level, decelerating retreating-side (left) turn flight procedure. The flight trajectory information is provided in Fig. 5.32. The helicopter starts decelerating at a simulation time of approximately 20 seconds, reaches the lowest speed of 67 kts at 32 seconds and accelerates to 86 kts around 48 seconds. This reduction in flight speed would result in a longer time to complete the turn as compared to the level turns. Thus during the decelerating turn the total sound exposure time increases and with it the annoyance experienced by the observer would increase. The flight also undergoes a level turn adding an additional complexity to the transient maneuver. When the helicopter has reached the lowest speed at simulation time 32 seconds it starts the roll-in motion at about 33 seconds and then reaches a maximum target roll angle of 35° around 36 seconds, heads towards the retreating side of the flight track (left turn) and starts a roll-out maneuver around 47 seconds.

A summary of the time history results is discussed here, time history predictions for the Bell 407 are shown for all of the microphones in Appendix B, Figs. B.44–B.51. As the helicopter approaches the microphone (observer position), the low frequency noise generated by the main rotor is well predicted and the high frequency noise generated by the tail rotor is overestimated, as is seen in the previous cases. Following the level flight segment, the flight decelerates and reaches a lowest speed during the flight procedure. Next the maneuver starts the roll-in motion. Around this flight time (30–36 seconds), the main rotor generates higher loading noise with BVI. During this transient phase, the blade wake is rapidly changing resulting in a
higher time derivative of the blade loading along the azimuth and as such higher loading noise. The noise prediction system captures this trend with an accuracy of 2 dBA in A–weighted loading SPL. After this segment of the maneuver (flight time from 30–36 seconds) is complete the helicopter accelerates and rolls with a target roll angle of 35°. During this segment of the test run, the thrust requirement of the vehicle increases to compensate for the centrifugal force experienced during the turn and additional force required for accelerating the vehicle. As such, higher loading noise and broadband noise is generated during the decelerating turn segment of the current maneuver (test run).

The noise prediction system follows the trajectory reasonably well but has a higher pitch attitude and roll angle offset (around 5°), which is shown in Fig. 5.32. The rate of change in blade loads along the azimuth increases for these three transient segment; deceleration, roll-in motion and roll-out motion of the helicopter. During these three transient segments higher-harmonic loading noise and BVI noise is generated. This trend is well captured for the microphones located close to the flight path (for example microphones 36 and 29 shown Figs. 5.35 and 5.36). Another important feature seen in the time history plot of Bell 407 performing the level retreating-side turn is the overprediction of the A–weighted broadband SPL microphone located outside the turn and close to the flight path when the helicopter is undergoing a constant roll angle turn and during roll-out motion. This error in the predicted noise is likely due to the higher thrust requirement during the turn resulting in higher broadband noise. This happens for microphones located at \( x = -1000 \) ft or -304.8 m (for example microphones 14 and 19 shown in Figs. 5.35 and 5.36 and the time history plots of all microphones used during the test grid in Fig. B.44–B.51). Around this \( x \)–position the helicopter heading angle has changed and is moving towards the left of the flight path.
Figure 5.34: Microphone location with respect to the flight trajectory for Bell 407 performing level, decelerating retreating-side (left) turn.

(a) Microphone 36  
(b) Microphone 29  
(c) Microphone 19  
(d) Microphone 14

Figure 5.35: Overall sound pressure level for Bell 407 level, decelerating retreating-side (left) turn.
Microphones 36, 29, 19 and 14, on the grid shown in Fig. 5.34, are considered to demonstrate the observation made above. Microphones 36 and 29 are located directly below the flight path where the OASPL and A-weighted SPL are dominated by the loading noise. Around this microphone position, the helicopter is decelerating, then undergoing a turn at a lower velocity of 67 kts. Due to this transient phase and the relative distance between the helicopter and the observer, the loading noise dominates both the lower and higher frequency range (OASPL, Figs. 5.35a and 5.35b and A-weighted SPL, Figs. 5.36a and 5.36b). As the helicopter accelerates and turns after 36 seconds of the flight time, the total OASPL and A-weighted SPL compares well with the flight test data.
Microphone 19 and 14 are on the sideline of the flight path, on the advancing and retreating sides, respectively (OASPL, Figs. 5.35c and 5.35d and A-weighted SPL, Figs. 5.36c and 5.36d). For these microphones the peak OASPL is underestimated during the transient maneuver (24–40 seconds). This underestimation of the noise levels is either due to underestimation of the loading noise generated by the tail rotor or missing the BVI noise directivity. As the helicopter turns the trend and level is well captured. The A-weighted broadband SPL is higher and overestimated as the helicopter accelerates and turn, and it is postulated to occur due to either the wrong flat plate area (frontal drag area) or error in calculating the rotor thrust.

Even with the current deficiencies described above, the noise prediction system is capable of capturing the trend for several noise sources generated by the main rotor. The tail rotor loading noise predicted for the case considered is very small and does not show any significant contribution to the total loading OASPL or A-weighted SPL. One of the reasons could be the large time step used to discretize the tail rotor blade loading data (loading data is available every 15° of the azimuth) or the error in calculating the trim of the tail rotor (the collective of the tail rotor is below 0° for most of the flight time).

**Advancing-side (right) turn:** The next case considered is the level, decelerating advancing-side (right) turn flight procedure. The flight trajectory information is provided in Fig. 5.32. The helicopter starts decelerating around 17 seconds, reaches the lowest speed of 60 kts at 38 seconds and accelerates to 80 kts around 50 seconds. The deceleration occurs with an interval of constant speed of approximately 70 kts from 23 seconds to 32 seconds. The flight also undergoes a level turn adding an additional complexity to the transient maneuver. The helicopter starts the roll-in motion around 29 seconds, reaches a maximum target roll angle of 35° around 33 seconds and then starts the roll-out-of turn around 37 seconds and finishes the turn maneuver around 42 seconds. Since most of the turn happens at low speed the
radius of the turn is higher and comparable to level turn with target roll angle of 25°.

A general summary of the time history of the noise levels for the microphones used during the flight test, shown in Figs. B.55–B.62 in Appendix B, for the Bell 407 helicopter performing level, decelerating advancing-side (right) turn maneuver is provided here. Similar to previous cases, the thickness noise generated by the main rotor or the low frequency thickness noise seen in the OASPL compares well with the flight test data while the high frequency noise levels generated by the tail rotor are overpredicted when compared to the flight test data. After the level flight maneuver the flight decelerates. During this maneuver the noise generated by the rotor decreases. The maneuver has a much lower rate of deceleration than seen for the level, decelerating retreating-side (left) turn performed by the Bell 407 and as such has much lower noise contribution. After this phase of the flight maneuver, the helicopter operates at a relatively constant lower speed. At around 32 seconds the helicopter rolls and decelerates. Due to such a transient flight condition, the time derivative of the blade loading is large and results in higher loading noise and sometimes BVI noise. Eventually during the roll-out and acceleration, the changes in the blade loads and rotor thrust increases and this result in higher loading noise and small overprediction of the A–weighted broadband SPL. As mentioned before for the level, decelerating retreating-side (left) turn, the noise prediction system follows the trajectory to a certain degree, but shows higher pitch attitude and roll angle offset (around 5°) as shown in Fig. 5.32. The trend and levels are well captured for most of the microphones located close to the flight path and before the change in heading angle by 90° (for example microphones 36 and 29 shown in Figs. 5.38 and 5.39). The time history plot shows the A–weighted SPL are underpredicted for the microphones located outside the turn. This is clearly seen for the microphones located at $x = -1000$ ft or $-304.8$ m (the example microphones 24 and 19 are shown in Figs. 5.38 and 5.39). Around this $x$–position, the helicopter
heading angle has changed and is moving towards the right of the flight path. One major difference between the level, decelerating left and right turns is a better validation for the level, decelerating right turn. It is not clear if the predicted noise levels are better for the decelerating right turn due to the flight procedure or lower rate of change in helicopter speed and roll angle (a more slowly changing flight conditions).

Figure 5.37: Microphone location with respect to the flight trajectory for Bell 407 performing level, decelerating advancing-side (right) turn.
Figure 5.38: Overall sound pressure level for Bell 407 level, decelerating advancing-side (right) turn.
Figure 5.39: A-weighted sound pressure level for Bell 407 level, decelerating advancing-side (right) turn.

Microphones 36, 29, 19 and 24 are considered to demonstrate the previous observation. Microphones 36 and 29 are located directly below the flight path and show the OASPL and A-weighted SPL is dominated by the loading noise. Around this microphone position, the helicopter is decelerating, then undergoes a decelerating turn at a lower velocity of 60 kts. This transient phase and the relative distance between the helicopter and the observer results in increased low and high frequency loading noise (OASPL, Figs. 5.38a and 5.38b and A-weighted SPL, Figs. 5.39a and 5.39b). During the roll-in and turn maneuver the total OASPL levels match well with the flight test data. At this time (around 20–24 seconds), the helicopter was decelerating and transitioning to a constant level flight, which
results in the rotor operating in its wake. The predicted OASPL even captures noise levels seen during the roll-out and as the helicopter accelerates at the end of the flight procedure. As for the A-weighted loading SPL, the levels are slightly overestimated during the roll-out for the microphone 36 and 29 (small peak seen around observer time 32–36 seconds for microphone 36 and observer time 40–44 seconds for microphone 29). During the turn maneuver the A-weighted loading SPL is overestimated, potentially due to change in BVI directivity than that observed during the flight test. The noise prediction system is capable of capturing the changes in the noise levels as the flight transitions from one flight conditions to another.

Microphone 19 and 24 are close to the flight path but on the retreating side (OASPL, Figs. 5.38c and 5.38d and A-weighted SPL Figs. 5.39c and 5.39d). For these microphone the total OASPL is well captured during the roll-in and deceleration (32–36 seconds). Similar to microphones 36 and 29, the noise levels are dominated by the BVI noise generated by the main rotor. The A-weighted SPL is well captured for the microphone 24 and is underestimated for microphone 19. Microphone 19 lies outside of the turn and this underestimation for microphones outside the flight path is seen even for level turns performed by the Bell 407 and AS350. Furthermore, the underestimation of the noise levels is either due to underestimation of the loading noise generated by the tail rotor or missing the BVI [the error in capturing the BVI noise levels could be due to an error in calculating the BVI miss distance–this requires a good estimation of flapping motions and is related to the flat plate area of the helicopter]. Underestimation of the BVI intensity could also occur due to the settings used in CHARM rotor module. The minimum vortex core size of the inboard trailing vortices was chosen 0.5 times of chord size and 0.01 times of chord size for outboard vortices, this parameter might need to be tailored for each helicopter and for the advancing and retreating side for better prediction of the BVI noise levels]. The A-weighted broadband SPL is
higher and overestimated as the helicopter accelerates and turns. (Pegg’s empirical model used for calculating broadband noise relies on rotor thrust as a key input parameter, and higher rotor thrust is required to trim the helicopter to follow the flight trajectory).

5.2.2.2 Airbus AS350: Time history validation

The time history plot for the Airbus AS350 level, decelerating turns are considered for analyses and validation. A general summary based on the noise levels observed for the flight test grid (results are shown in Appendix C from Figs. C.43–C.50 for the advancing-side (left) turn and from Figs. C.53–C.60 for the retreating-side (right) turn) is presented here with a focus on the differences between the Bell 407 and AS350, decelerating turns. When comparing the Bell 407 and Airbus AS350 level decelerating left turn (compare Figs. 5.32a and 5.28a), the total flight procedure time of the AS350 is much shorter and has a high rate of change of the flight condition. This results in a large amount of higher-harmonic loading and BVI noise. The left and right turns both show higher noise generated outside the turn during the flight test. The predicted noise shows that the noise is primarily higher on the advancing side, so inside the turn for the advancing-side turn (left) and outside the turn for the retreating-side turn. Another thing to note is the underprediction of the broadband noise and much lower predicted broadband noise levels than seen for the Bell 407 helicopter. Pegg’s empirical model used for predicting broadband noise is a function of blade tip speed and rotor thrust. Considering that the weight of the two helicopters as tested during the flight test and when simulated are close to one another, the difference in the blade tip speed results in higher broadband noise generated by the Bell 407. The OASPL and A-weighted SPL time history (results are shown in Appendix C from Figs. C.43–C.50 for the advancing-side (left turn) and for the retreating-side (right) turn from Figs. C.53–C.60) shows loading noise dominates the peak noise levels while for the Bell 407 the broadband

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noise dominates the A-weighted SPL (results are shown in Appendix B from Figs. B.44–B.51 for the retreating-side (left turn) and for the advancing-side (right) turn from Figs. B.55–B.62). Another major difference between the two helicopters is the higher BVI noise generated by the Airbus AS350 helicopter. For the Airbus level, decelerating advancing-side (left) turn, the deceleration and the turn occurs simultaneously as opposed to a Bell 407 level, decelerating advancing-side (right) turn. As the rate of change in flight condition (velocity and roll angle) is larger for the Airbus AS350 flight procedure, the resulting time derivative of the blade loading is higher and also with the helicopter tilting backwards and sideways the rotor wake trajectory interacts with itself resulting in BVI noise.

**Advancing-side (left) turn:** During the advancing-side turn (left) the helicopter starts decelerating around flight time 14 seconds, reaches the lowest speed of 60 kts around 25 seconds and accelerates to 65 kts from flight time 30–34 seconds. The flight also undergoes a level turn and starts roll-in motion around flight time 17 seconds, reaches a maximum target roll angle of 35° around flight time 23 seconds and then starts the roll-out around 27 seconds and finishes the turn maneuver around flight time 30 seconds. This flight trajectory information is provided in Fig. 5.28.

![Figure 5.40: Microphone location with respect to the flight trajectory for Airbus AS350 performing level, decelerating advancing-side (left) turn.](image-url)
Figure 5.41: Overall sound pressure level for Airbus AS350 performing level, decelerating advancing-side (left) turn.
Figure 5.42: Loading overall sound pressure level for Airbus AS350 performing level, decelerating advancing-side (left) turn.
Figure 5.43: A-weighted sound pressure level for Airbus AS350 performing level, decelerating advancing-side (left) turn.
Figure 5.44: A-weighted loading sound pressure level for Airbus AS350 performing level, decelerating advancing-side (left) turn.

For analyzing the time history of the Airbus AS350 helicopter performing level, decelerating advancing-side (left) turn microphones 36, 29, 19 and 14 are considered (sequence is based on the microphone location in the flight test grid and the flight path and is shown in Fig. 5.40).

Microphone 36 and 29 are located directly on the flight path while the microphone 14 and 19 are located close to the flight path but at sideline positions. These four microphones shows the noise generated during the approach, when the helicopter is overhead, and when BVI noise is generated by the advancing and retreating sides. The results are shown in Figs 5.41–5.44.

For the advancing-side turn (left) the helicopter trim is at a higher roll angle to
follow the same flight trajectory as was flown during the flight test. The higher roll angle of the helicopter results in a higher thrust requirement to balance the centrifugal force and thus requires the rotor tip path plane to pitch forward (but most importantly change in the BVI noise directivity). This results in higher blade loads and higher rate of change in blade loads along the azimuth and consequently higher loading noise, especially for the microphones (36 and 29) located directly below the flight path. The OASPL time history (Figs. 5.41a and 5.41b) for these microphones shows good comparison with the flight test data. This noise is dominated at the peak by the main rotor loading noise (Figs. 5.42a and 5.42b). These noise levels are overpredicted during the turn maneuver (around observer time 20–30 seconds) for the microphone 36 and are well captured for microphone 29. The thickness noise is comparable to loading noise during approach.

The A-weighted sound pressure level for the microphone 36 (Figs. 5.43a and 5.44a) is overestimated during the roll-in of the helicopter by about 2–3 dBA. This overprediction is due to the loading noise generated by the main rotor. The flight test data shows a drop in the noise levels as the helicopter passes but the predicted noise shows large amounts of high frequency loading noise generated by the main rotor (refer Fig. 5.44a). The peaks in the A-weighted loading noise is observed when the helicopter is overhead of this microphone around 10–12 seconds and is associated with the BVI and higher-harmonic loading noise generated during the transient flight conditions. As the helicopter has already flown over the microphone position (after observer time 20 seconds), the predicted peak in the loading noise is associated with the noise generated behind the rotor. This directivity can be assumed to be the retreating side BVI noise. The magnitude of the retreating side BVI is overestimated. Further work is necessary to analyze whether overestimation of BVI noise is due to error in rotor trim or predicting the vortex core size. For microphone 29, the helicopter was overhead around 18–19 seconds of the flight time. When the helicopter was overhead the broadband noise dominated (Fig.
and at the end of roll-in motion (after observer time 20 seconds) the loading noise dominates the A-weighted SPL and is overestimated by 2–3 dBA. The flight test data shows two peaks associated with the start of roll-in motion and end of roll-in motion. The noise prediction system captures this double peak behavior and demonstrates that they are generated due by the main rotor BVI (Fig. 5.44b). Thickness noise is dominant only during approach.

Microphone 14 and 19 are located outside the turn. During approach the thickness noise dominates the OASPL at microphone 19 (Fig. 5.41c). The OASPL time history shows that the loading noise contribute to the predicted peaks and the agreement with good with the flight test data. The loading noise is primarily generated by the main rotor with a small contribution from the tail rotor (this can be seen for the A-weighted SPL in Figs. 5.44c and 5.44d). During the roll-in and deceleration of the helicopter (around 15–20 seconds) the predicted loading A-weighted SPL for the microphone 14 compares well with the flight test data. The A-weighted SPL shows a higher contribution from the loading noise (mostly BVI noise) generated by the main rotor. The broadband noise level peaks when the helicopter is closest to the microphone (microphone 14 is closer than 19) and rapidly decreases at the sideline positions. Another thing to note is the A-weighted loading SPL around observer time 20 seconds for the microphone 19 (Figs. 5.43c and 5.44c). Here, the prediction shows a peak at the same observer time as seen during the flight test but the levels are underpredicted by the prediction system. This peak is thought to be due to BVI, potentially with a different directivity than seen in the predicted noise data. The flight test data shows three peaks associated with three transient stages; start of deceleration, start of roll-in motion and start of roll-out motion. The noise prediction system underestimates these three peaks (noise levels are better captured during the roll-in motion than seen for the other two transient stages). While for microphone 14 (Figs. 5.43d and 5.44d), the A-weighted SPL is captured within 1–2 dBA.
Generally the OASPL shows the trends seen in the flight test data with the loading noise dominating most of the time history. As for the A–weighted SPL, the loading and broadband noise contributes to the total noise with some overprediction. During the decelerating turn, BVI noise generation was stronger than seen for a level turn. The noise prediction is capable of capturing the changes in intensity of BVI noise and higher-harmonic loading noise for different maneuvers, but it has issues with capturing the directivity of the retreating side BVI. The time histories of the noise levels at all the microphone positions used during the flight test for Airbus AS350 performing level, decelerating left turn are provided in Appendix C from Figs. C.43–C.50.

**Retreating-side (right) turn:** After examining the level, decelerating advancing-side turn, the next focus is on the level, decelerating retreating-side turn. The time histories of the noise levels at all the microphone positions used during the flight test for Airbus AS350 performing level, decelerating retreating-side (right) turn are provided in Appendix C from Figs. C.53–C.60. The retreating-side turn starts by decelerating from 80 kts at flight time 15 seconds to 60 kts around 26 seconds and rolls-in from 20 seconds to achieve a peak roll angle around 25 seconds. The helicopter turns at maximum target angle for few seconds before starting the roll-out maneuver at 30 seconds. The flight trajectory information is provided in the Fig. 5.28 and the flight path over the microphone array is shown in Fig. 5.45.

For this maneuver the helicopter requires a lower roll angle (around 5° lower) to follow the flight trajectory flown during the flight test. As such this maneuver also requires less thrust during the roll-in and deceleration of the helicopter. This results in lower frequency harmonic loading noise generated by the main rotor.
Figure 5.45: Microphone location with respect to the flight trajectory for Airbus AS350 performing level, decelerating retreating-side (right) turn.

(a) Microphone 36
(b) Microphone 29
(c) Microphone 19
(d) Microphone 24

Figure 5.46: Overall sound pressure level for Airbus AS350 performing level, decelerating retreating-side (right) turn.
Figure 5.47: Loading overall sound pressure level for Airbus AS350 performing level, decelerating retreating-side (right) turn.
Figure 5.48: A-weighted sound pressure level for Airbus AS350 performing level, decelerating retreating-side (right) turn.
The loading noise dominates the peak noise levels and is highest when the distance to the observer is minimum. In general, during approach the OASPL levels are well predicted with the thickness noise dominating the levels. During roll-out (observer time 32–40 seconds) the noise levels are slightly overpredicted (second peak in loading noise). This overprediction is due to generation of main rotor BVI noise (Fig. 5.47–two loading noise peaks seen for microphone 29). The A–weighted SPL for microphone 36 (Fig. 5.48a), though slightly overpredicted at the peak, is well captured overall. For the microphone 29 (Fig. 5.48b), the A–weighted SPL is underpredicted at some instances. Here, the prediction does not capture the peak during roll-in and start of deceleration around 18 seconds. As the helicopter
achieves maximum roll angle and relatively constant velocity, the noise levels are reduced due to ‘steadiness’ of the maneuver. At this time the noise prediction under predicts the total noise levels potentially due to different directivity due to the roll-offset seen in the simulated flight trajectory. When the helicopter starts the roll-out motion the OASPL is overestimated by 2–4 dB.

Similar to microphones 36 and 29, the OASPL peaks are well captured for the microphones 19 and 24 and are dominated by the main rotor loading noise. For the microphone 19, the flight test data shows that once the A-weighted SPL (Fig. 5.48c) peaks it remains relatively constant during the entire transient flight segment, while the predicted noise shows that the loading noise peaks (mostly higher harmonic loading or BVI, seen as a sharp peak is seen in the A-weighted SPL) during the roll-in and roll-out of the helicopter. The underpredicted loading noise levels during the initial deceleration phase of the maneuver could be because the BVI noise directivity is more towards the advancing side than the retreating side of the flight path. For the microphone 24, the peak noise level is underpredicted when the helicopter is approaching (during transient flight condition) and overhead. The tail rotor generates small amount of loading noise mostly during roll-out of the turn but the peak level is much lower than that generated by the main rotor and this observed even at the sideline distance.

5.2.2.3 Summary of decelerating turns:

In summary, two helicopters are chosen for studying the details of the time history of noise levels. Both left and right turn results are shown for analysis. The noise prediction system is capable of capturing the noise levels during the transient maneuver. The broadband noise model is too simple for using it to analyze the details of such a complex maneuver and its limitations are clearly seen when analyzing the A-weighted time history. The incorrect trim due to roll angle offset has been shown to change the BVI intensity and directivity. However, the system
is still capable of capturing the BVI event during the transition phase, such as roll-in and roll-out with acceleration or deceleration. In the future, analyzing the input parameters to the noise prediction system, such as minimum vortex core size, effective hinge offset, and flat plate area, would provide better insight into predicting BVI noise during a transient maneuver. Thickness noise was more important for the Bell 407 helicopter than for AS350 helicopter. Predicting thickness noise still requires time dependent information on blade flapping motion. The thickness noise generated by the tail rotor shows a contribution to the total thickness noise but the loading noise generated by the tail rotor is of little consequence to the total loading noise generated by the helicopter, especially when compared to the tail rotor loading noise at the sideline position for the steady level and level turn flight maneuvers.

Potential lessons for noise abatement procedures: AS350 helicopter showed higher BVI due to higher rate of change in flight conditions. A deceleration results in the rotor tip path plane to tilt aft and with the roll-in motion and the probability of tip vortex interactions with the blade is higher. Also, during such flight conditions the blade load time derivative increases resulting in higher noise levels. A turn performed at lower speed has shown to generate much lower noise.
5.3 Validation 5: Descending turns

The final flight trajectory considered can be described as 80 kts constant level flight followed by a 90° turn at a roll angle of 35°, while the aircraft also is descending along a 6° flight path angle. The turn and descent of the helicopter occur simultaneously. The nominal flight path for a right descending turn is shown Fig. 5.50. Initially the helicopter begins in level flight nominally 152.4 m (500 ft) above the ground. The helicopter then starts the descent at a constant flight path angle of 6° followed by a turn with a maximum target roll angle of 35°.

One important thing to note is that the noise levels are much lower than seen for the steady descent (Fig. 4.23). During a steady descent maneuver the rotor is continuously operating in its wake and the intensity of interaction depends on the rotor tip path plane angle of attack and the wake skew angle, which depends on the inflow or the downwash of the wake. During a descent procedure the rotor experiences upwash and when the upwash is enough to push the wake into the tip path plane angle of the rotor, BVI occurs. However, during a turn the helicopter main rotor tilts and the resulting wake is skewed not only in the $z-$axis but also in the $x$–$y$ plane. The effective inflow determining the wake skew angle relative to the rotor tip path plane is now a function of the heading velocity (resultant $v_x$ and $v_y$) and rate of descent ($v_z$). So even if the motion in the $z-$direction increases the upwash in the $z-$direction, the inflow velocity component in the $x$–$y$ plane, comprising of the forward speed, pushes the wake away from the rotor and as such the effective BVI miss distance is higher during a 6° descending turn than during a steady 6° descent maneuver. Another thing that should be considered is that the exposure time and distance to the observer will be different for the steady descent and descending turn (at least at the same observer locations). In future work, it will be interesting to see if for a combination of flight path angle, forward speed and roll angle, the BVI noise levels are close to that seen during a steady 6° descent, i.e.
the incident inflow velocity in the $x - y$ plane pushes the rotor wake on itself.

Figure 5.50: Pictorial representation of an 80 kts descending turn flight procedure.

### 5.3.1 Sound exposure level validation

The validation using the sound exposure level is carried out for three helicopters performing right and left descending turns. The flight test and prediction SEL contours are shown in Fig. 5.51 for the R66, AS350 and Bell 407 helicopters. The noise prediction system was able to capture the overall trend but has underestimated the noise levels for AS350 (Figs. 5.51c and 5.51d). The noise levels for a descending turn case are higher than those for the level turn (Fig. 5.2) and the level, decelerating turn (Fig. 5.26). This increase in the noise level is primarily due to a decrease in altitude (distance) and an increase in BVI noise.
Figure 5.51: (continued) Total sound exposure level (SE滥BA) for a 80 kts descending turns, at flight path angle of 6° and final roll angle 35°
Robinson R66: SEL validation

The Robinson helicopter is lighter than the other two helicopter and has lower noise levels. The flight trajectory information is provided in Appendix D in Figs. D.61 and D.71. The retreating-side (left) turn (Fig. 5.51a) and advancing-side (right) turn (Fig. 5.51b) show higher noise levels at the end of the flight procedure (lower altitude) and also slightly higher noise levels during the turn. The predicted noise captures the higher noise levels at the end of the turn but underestimates the total noise levels by 2 SELdBA.
Figure 5.52: Sound exposure level (SELdBA) for the different noise sources generated by Robinson R66 performing descending retreating-side (left) and advancing-side (right) turn flight procedures.
The noise component analysis shows that the broadband noise is dominant for the left and right turns with a comparable contribution from the loading noise during the turn procedure (shown in Fig. 5.52a and 5.52b). Other characteristics to note are the higher loading noise levels outside the turn (Fig. 5.52b) for the left side (retreating-side turn) and inside the turn (Fig. 5.52a) for the right side (advancing-side turn). Both of these occur on the advancing side of the rotor indicating that the advancing side matters more for noise generation mechanism than whether the turn maneuver is on the retreating or the advancing side.

**Airbus AS350: SEL validation**

The Airbus AS350 helicopter main rotor rotates in the clockwise direction with the advancing side on the left of the flight path. The flight trajectory information is shown in Fig. 5.53.
Figure 5.53: Comparing flight trajectory and attitude information of the simulated flight procedure with the flight test data for an Airbus AS350 performing descending advancing-side (left) and retreating-side (right) turns.
The sound exposure levels for the left descending turn (advancing-side turn) and the right descending side turn (retreating-side turn) are shown in Figs. 5.51c and 5.51d, respectively. The predicted noise levels captured the trend or the “hot spots” seen during the flight test for both the turns within noise levels up to 2–3 SELdBA of accuracy. Though the maneuver is described as a descending turn, note from the flight trajectory information shown in Fig. 5.53, the flight procedure also has deceleration and acceleration as the helicopter turns and descends, thus adding another complexity in predicting the wake and blade loads and noise generated during the flight.

The total noise levels for the Airbus AS350 helicopter are much higher than the Robinson R66 helicopter and lower than the Bell 407 helicopter. The major contributor to the total SEL is the broadband noise with significant contribution from the loading noise during the descending turn maneuver, with small amount of BVI noise. These results are shown in Fig. 5.54. The loading noise is slightly higher when turning towards the advancing side and is seen inside the turn. The slightly higher loading and broadband noise levels at the end of the right side turn procedure is due to higher roll rate during turning out of the maneuver compared to the left turn (left turn roll attitude shown in Fig. 5.53c and for right turn in Fig. 5.53d). In the Appendix C Figs. C.62 and C.72 shows contributions from the main rotor and tail rotor to the total SEL for the two flight procedures.
Figure 5.54: Sound exposure level (SELdBA) for the different noise sources generated by Airbus AS350 performing descending advancing-side (left) and retreating-side (right) turn flight procedures.
Bell 407: SEL validation

The Bell 407 helicopter SEL are shown in Fig. 5.51e for the descending left or the retreating-side turn and in Fig. 5.51f for the descending advancing-side (right) turn. The prediction captures the “hot spots” seen during the flight test. Here the levels are overestimated by 2-3 dBA. This overestimation is due to large amount of BVI noise generated by the main rotor (shown in Figs. 5.55). Similar overprediction was seen during a steady descent maneuver performed by the Bell 407. The BVI noise is overestimated either due to incorrect trim of the helicopter or the poorly estimated characteristics of the tip vortex of the blade. Nonetheless, even with the deficiency the noise levels are well captured. Comparing the different noise sources shown Figs. 5.55 shows higher loading noise than seen for the previous two helicopters and slightly higher thickness noise. Here the loading noise is primarily generated by the main rotor (BVI) and the thickness noise by tail rotor (high frequency noise content). As the helicopter descends at a flight path angle resulting in maximum BVI noise, the noise levels on the ground plane are higher. Then the turn maneuver starts and during this maneuver the noise levels are reduced for both left and right turns as the BVI miss distance has increased. Also here the helicopter speed was reducing and once the turn is finished, the helicopter starts to roll-out and accelerate and descend. As the altitude is reduced at the end of the flight procedure the SEL reaches maximum for the flight procedure. The flight trajectory information is provided in Fig. 5.56.
Figure 5.55: Sound exposure level (SELdBA) for the different noise sources generated by Bell 407 performing descending retreating-side (left) and advancing-side (right) turn flight procedures.
In summary, the partitioning of the noise components is interesting in this case because it is different for all three aircraft. For the Robinson R66, thickness and broadband noise components are larger than loading noise, while for the Bell 407, the loading noise component is dominant, and for the AS350, loading and broadband noise are both higher than thickness noise. For the AS350 and Bell 407, the loading noise contains more focused “hot spots”, typical of BVI noise. The broadband noise is highest for the AS350, especially during the turn. Overall, the noise prediction captured the trends seen in the flight test contours.

5.3.2 Time history validation

The OASPL and A–weighted SPL time history are predicted and compared with the time history of the processed flight test data using PSU-WOPWOP. Similar to the analysis conducted for the decelerating turns, the analysis for the descending turns would show the noise generated for different flight condition and the noise prediction system’s capability of predicting the noise levels. One particular thing to note of the maneuver is that the helicopter speed never remains constant and is either decelerating or accelerating, thus changing the effective flight path angle.

5.3.2.1 Bell 407: Time history validation

The first helicopter to be examined in more detail is the Bell 407 helicopter. The flight trajectory information for the left and right descending turns is provided in Fig. 5.56.
Figure 5.56: Comparing flight trajectory and attitude information of the simulated flight procedure with the flight test data for a Bell407 performing descending advancing-side (right) and retreating-side (left) turns.
Retreating-side (left) turn: For the retreating-side (left) descending turn maneuver, the helicopter starts descending at about 20 seconds of the flight time with a flight path angle of 6°. For a steady maneuver this flight path angle results in the rotor operating in its wake and generating BVI noise. The helicopter speed is relatively constant for this segment of the flight path and is around 80 kts. The helicopter starts the roll-in motion at about 32 seconds, reaches a maximum target roll angle (around 35°) at 36 seconds and maintains this roll angle and then begins the roll-out procedure from 43–46 seconds. Around 36 seconds the helicopter is accelerating and reaches a speed of approximately 96 kts at the end of the flight procedure. The flight simulator follows the trajectory, but has a roll offset of about 5° (i.e. during simulation the maximum roll angle of the vehicle is around 40°, which requires higher rotor thrust). Also, during the simulation the helicopter pitch angle is higher during the roll-in and roll-out maneuver (i.e. helicopter pitches backwards or nose is up) compared to flight trajectory data. For this flight procedure, the helicopter turns with maximum roll angle and rolls out while descending and accelerating. Thus from the flight time of 36 seconds onward the helicopter is performing three complex maneuvers simultaneously. For a steady descent at a flight path angle generating maximum BVI, the rotor disk tilts backwards. However, if the maneuver is also turning and accelerating, the
tilt of the rotor disk tilt won’t be as large. This effectively changes the angle of attack of the tip path plane and the rotor wake moves away from the disk and thus increases the BVI miss distance. The flight procedure ends at an altitude of 30.48 m or 100 ft above the ground.

Figure 5.58: Overall sound pressure level for Bell 407 performing, descending retreating-side (left) turn flight procedure.
Figure 5.59: Loading overall sound pressure level for Bell 407 performing, descending retreating-side (left) turn flight procedure.
Figure 5.60: A-weighted sound pressure level for Bell 407 performing, descending retreating-side (left) turn flight procedure.
The time history of noise levels is analyzed for microphones chosen based on either the discrepancy in the predicted and flight test data and the relative location with respect to the flight path (Fig. 5.58). The four microphones show that the noise levels during approach are dominated by the thickness noise with the OASPL (shown in Fig. 5.58) being dominated by main rotor thickness noise and the A–weighted SPL by the tail rotor thickness noise (shown in Fig. 5.60). First consider microphones 38 and 29 located on the sideline and below the flight trajectory, respectively. For these two microphones, the loading noise dominates the peak OASPL and A–weighted SPL. This indicates that higher frequency loading noise is generated during the maneuver, which is usually associated with higher-harmonic
loading and BVI noise.

For the microphone 38 (Figs. 5.58a and 5.60a), the loading noise is overestimated. This overestimated noise occurs due to erroneous prediction of BVI noise and the directivity. This could be due to the roll offset observed in the simulated flight trajectory. This directivity of BVI is associated with advancing side BVI (similar to what was seen for the steady descent flight procedure, where the loading noise was skewed towards the advancing side – potentially due to an error in roll angle and resulting in an error in directivity). The A–weighted SPL peak is dominated by the loading noise and is overpredicted indicating the error is due to overprediction of the higher-harmonic loading or BVI noise.

Microphone 29 (Figs. 5.58a and 5.60a), located directly below the flight path, shows the peak in noise levels occur when the helicopter is overhead, and compares well with the flight test data for both the OASPL and A–weighted SPL. For this microphone both the loading and broadband noise contributes to the total A–weighted SPL.

Microphone 19 (Figs. 5.58c and 5.60c) is located outside of the turn and shows underpredicted (by 1–2 dB) noise levels. The flight test data shows a peak around the flight time when the helicopter was undergoing a constant roll angle turn and accelerating. Here, the effect is not fully captured (potentially due to missing the BVI directivity). Microphone 14 (Figs. 5.58d and 5.60d) has the maximum OASPL and A–weighted SPL when compared to other microphones. Similar to the other microphones, here the peaks are dominated by the main rotor loading noise. At the time the helicopter is rolling out of the turn and accelerating, it also has a lower radiation distance between the microphone 14 and the helicopter (due to descending flight). The OASPL and A–weighted SPL peak match well with the flight test data.

In general for the descending retreating-side (left) turn, the noise levels are generated when the helicopter is flying at a maximum BVI noise condition and
transitioning from straight flight to turn, and vice versa. All these flight conditions result in the blade operating in its wake, resulting in high time derivative of blade loading along the azimuth and interaction of the blade vortex with the tip. Also, note the overestimated loading noise levels during the steady descent segment on the advancing side of the rotor and is potentially due to change in directivity caused by the roll offset observed for the simulated flight path. A more detailed parametric study (trim of the helicopter, flat plate area, tip vortex core size and diffusion) is required for matching the peak levels for such a complicated maneuver. The time histories of the noise levels at all the microphone positions used during the flight test for Bell 407 performing descending retreating-side (left) turn are provided in Appendix B from Figs. B.66–B.73.

**Advancing-side (right) turn:** The advancing-side (right) turn maneuver is analyzed next. During this flight procedure the helicopter is initially at 80 kts level flight and starts descending around 20 seconds. The flight procedure ends at an altitude of 34.00 m or 111 ft above the ground, as shown in Fig. 5.56. During the entire flight procedure the helicopter speed is relatively constant, around 80 kts, with deceleration to 73 kts from 30–35 seconds and followed by an acceleration to 80 kts from 35–40 seconds. The helicopter starts to roll-in at 30 seconds, reaches a maximum roll angle of about 35° around 35 seconds, maintains relatively constant roll angle up to 42 seconds, and then starts the roll-out maneuver (from 42–46 seconds). The flight simulator is relatively capable of following the roll angle seen during the flight test but predicts a higher pitch angle (helicopter nose is up) during roll-out and at the start of the descent maneuver.

The time history of noise levels are analyzed for microphone 38, 29, 19, and 24 and are shown on the flight test grid in Fig. 5.57. The results are shown in Figs. 5.62–5.64. Similar to the previous case of the descending left turn, the main rotor thickness and tail rotor thickness dominates the OASPL and A-weighted SPL
during approach, respectively. The peak of the noise levels is dominated by the loading noise with some contribution from the broadband noise in the A–weighted SPL.

For microphone 38 (shown in Figs. 5.62a and 5.64a), the predicted OASPL time history is in very good agreement with the flight test data, but there is a slight overprediction in the peak of the A-weighted SPL around the flight time 20 seconds, when the helicopter starts steady descent. The skewed directivity of BVI noise on the advancing side is seen only in the prediction and not during the flight test. Similar observations were made for steady descent and a descending left turn.

Microphone 29 (shown in Figs. 5.62b and 5.64b) is located directly below the flight path and the helicopter is overhead during the roll-in flight procedure. At this microphone location, the OASPL and A–weighted SPL peaks are dominated by the loading noise. For this microphone location the peak of time histories compares well with the flight test data. A slight underprediction during the constant roll angle is observed in the A–weighted SPL.

Microphone 19 was also considered for analysis; it lies outside the turn (shown in Figs. 5.62c and 5.64c) and shows small underpredicted OASPL and significant underprediction of the A–weighted SPL peaks. This underprediction is also seen during level, decelerating turns and descending retreating-side (left) turn and occurs when the helicopter rolls in and turns at a constant roll angle. The flight test data shows the acoustic pressure time history has characteristic BVI pulse, which is missing in the noise prediction system. So either the BVI directivity or the lower temporal resolution of the tail rotor blade loading is affecting the loading noise at this sideline position. For this microphone the predicted broadband noise and loading noise contribute to the total A–weighted SPL, but are underestimated.

The last microphone considered for time history analysis is microphone 24 (shown in Figs. 5.62d and 5.64d). The peak of the OASPL and A–weighted SPL are dominated by the loading noise and compares well with the flight test data. This
peak is seen during the roll-out flight procedure. The A–weighted loading noise shows a small peak during roll-in and as the relative distance decreases, the noise level steadily increases and peaks during roll-out and when the helicopter is closest to the microphone. The A–weighted broadband SPL peaks when the helicopter is closest to the microphone but the levels are substantially lower than the A–weighted loading SPL. The time histories of the noise levels at all the microphone positions used during the flight test for Bell 407 performing descending advancing-side (right) turn are provided in Appendix B from Figs. B.77–B.84.

Figure 5.62: Overall sound pressure level for Bell 407 performing, descending advancing-side (right) turn flight procedure.
Figure 5.63: Loading overall sound pressure level for Bell 407 performing, descending advancing-side (right) turn flight procedure.
Figure 5.64: A-weighted sound pressure level for Bell 407 performing, descending advancing-side (right) turn flight procedure.
Summary of Bell 407, descending turns: In summary, comparing the retreating-side (left) and advancing-side (right) descending turn flight procedure, the noise levels are seen to be higher for advancing-side (right) turn. Though its not a fair comparison as during the retreating-side (left) turn the helicopter was decelerating and accelerating adding additional complexity and influencing the wake trajectory. (These differences in implementation of the desired descending turn maneuver are likely typical of the variability in real piloted flight.) The peak noise levels are dominated with the loading and BVI noise generated by the main rotor. The noise prediction does a better job in predicting the advancing-side (right) turn maneuver due to lower rate of change in roll angle and velocity.
5.3.2.2 Airbus AS350: Time history validation

The second helicopter considered for the analysis is the Airbus AS350 helicopter. The flight trajectory information for the advancing-side (left) and retreating-side (right) descending turn is provided in Fig. 5.53.

![Microphone grid used during flight test](image)

Figure 5.66: Microphone grid used during flight test [58]– microphone marked in blue used for analyzing time history of noise levels for Airbus AS350 descending turn flight procedures.

**Advancing-side (left) turn:** For the advancing-side (left) turn maneuver the helicopter starts descending at about 8 seconds of the flight time at a flight path angle of 6°. The helicopter speed is relatively constant for this segment of the flight path and is around 80 kts. The helicopter starts the roll-in at around 14 seconds, reaches a maximum target roll angle (around 35°) at 18 seconds and maintain this roll angle and then begins the roll-out procedure from 24–27 seconds. Around 15 seconds the helicopter is decelerating and reaches a speed of approximately 67 kts and starts accelerating from 22–34 seconds. The flight simulator follows the trajectory; however, has a roll offset of about 5° (i.e. during simulation the maximum roll angle of the vehicle is around 40°, and therefore, higher rotor thrust is required). Also, during the simulation the helicopter pitch angle is higher during the roll-in and roll-out than the flight test trajectory data (i.e. the helicopter pitches backwards or nose is up). The flight procedure ends at an altitude of 70.0 m above the ground.
Figure 5.67: Overall sound pressure level for Airbus AS350 performing, descending advancing-side (left) turn flight procedure.
The time history of noise levels is analyzed for the microphones shown in Fig. 5.66. The thickness noise is much lower during the flight procedure than seen for the Bell 407 helicopter and is shown in Figs. 5.67 and 5.69. First consider the two microphones 38 and 29 located on the sideline and below the flight trajectory respectively. For these microphones, the loading noise dominates the peak OASPL and broadband noise dominates the A-weighted SPL with the loading noise peak closer to the broadband noise. This indicates that higher frequency loading noise is generated during the maneuver and is usually associated with unsteady loading due to BVI.

For the microphone 36 (Figs. 5.67a and 5.69a), the loading noise peak is well
captured and occurs when the helicopter is overhead. Around this flight time the helicopter is descending along a constant flight path. Note there is another peak in the noise levels around the 20 seconds. This is generated due to roll-in motion of the helicopter. Here the loading OASPL and A-weighted broadband SPL are overestimated.

Microphone 29 (Figs. 5.67b and 5.69b) is located underneath the flight trajectory. The total OASPL is dominated with the loading noise. The peak loading noise occurs when the helicopter is overhead, descending and about to start the roll-in motion. After this flight time, the helicopter reaches a maximum roll angle and starts a descending decelerating turn. The noise prediction predicts the main rotor loading OASPL well. The A-weighted SPL shows that the total noise levels are due to both the loading and broadband noise and is underpredicted by 2 dBA.

Microphone 19 noise levels are shown in Figs. 5.67c and 5.69c, microphone 19 is located outside of the turn. The OASPL peak is captured well, but the A-weighted SPL reveals an underprediction of noise levels when the helicopter is in the transient phase (during the roll-in of the descending turn). This trend is similar to that seen for Bell 407 helicopter and other turn flight procedures, indicating that the noise prediction system is not capturing the BVI noise directivity for this microphone.

Microphone 14 noise levels are shown in Figs. 5.67d and 5.69d. The main rotor loading OASPL and A-weighted SPL show three distinct peaks. This peaks are seen during the start of the descending roll-in maneuver, at the start of constant roll angle, decelerating descending segment of the maneuver, and during the accelerating descending turn. (Note, this was the maneuver flown during the test, though it was intended to be only descending turn maneuver at constant speed.)

These three transition periods result in larger time derivatives of the blade loading and BVI. The increase in levels of these peaks is due to the decreasing distance between the helicopter and the microphone with the last transition phase closest to the microphone location. The broadband noise dominates the peak of
the A–weighted SPL but overall the total noise level is underestimated during approach for the microphone location. The time histories of the noise levels at all the microphone positions used during the flight test for Airbus AS350 performing descending advancing-side (left) turn are provided in Appendix C from Figs. C.63–C.70.

Figure 5.69: A–weighted sound pressure level for Airbus AS350 performing, descending advancing-side (left) turn flight procedure.
Retreating-side (right) turn: The retreating-side (right) turn of the Airbus AS350 is analyzed next. During this flight procedure the helicopter is initially at 80 kts level flight and starts descending around flight time 17 seconds. The flight procedure ends at an altitude of 50 m above the ground. During the entire flight procedure the helicopter speed is relatively constant, around 80 kts, with deceleration to 60 kts from 22–33 seconds and followed by a constant speed flight procedure and then acceleration from 60 kts to 80 kts from 40–48 seconds. The helicopter starts to roll-in at 25 seconds, reaches a maximum roll angle of about 35° around 30 seconds, maintains relatively constant roll angle until 35 seconds and then starts the roll-out maneuver (from 35–39 seconds). The aircraft trajectory
and attitude information is shown in Fig. 5.53.

The time history of noise levels is analyzed for microphone 36, 29, 19 and 24 and are shown on the flight test grid in Fig. 5.66. The results are shown in Figs. 5.71–5.73. Similar to the previous case of descending retreating-side (right) turn, the main rotor thickness dominates the OASPL during approach. The peak of the noise levels is dominated by the loading noise. The peak is well captured by the noise prediction system. This peaks occurs when the helicopter is closest to the microphone location and around this time the helicopter is also performing transient maneuver. The noise levels for microphone 19 compares well with the flight test data and this is one major differences between this flight procedure and the previous results. For the Bell 407 and other flight procedures performed by AS350, the A–weighted SPL for the microphone located outside the turn was always underestimated. The A–weighted SPL peak for the four microphones is dominated by the contribution from the loading and broadband noise. The noise levels are well captured for this flight procedure. The time histories of the noise levels at all the microphone positions used during the flight test for Airbus AS350 performing descending retreating-side (right) turn are provided in Appendix C from Figs. C.73–C.80.
Figure 5.71: Overall sound pressure level for Airbus AS350 performing, descending retreating-side (right) turn flight procedure.
Figure 5.72: Loading overall sound pressure level for Airbus AS350 performing, descending retreating-side (right) turn flight procedure.
Figure 5.73: A-weighted sound pressure level for Airbus AS350 performing, descending retreating-side (right) turn flight procedure.
Figure 5.74: Loading A–weighted sound pressure level for Airbus AS350 performing, descending retreating-side (right) turn flight procedure.

5.3.2.3 Summarizing descending turns

In summary, the descending turn maneuver is more complicated than any other maneuver previously analyzed. During the maneuver, the helicopter is sometimes descending, decelerating and turning. The noise prediction captured the subsequent increase in loading noise either due to high rate of change in blade loads along the azimuth or BVI for certain microphone location and misses the directivity for microphones located outside the turn. The thickness noise is a large contributor during approach for the Bell 407 helicopter but shows lower significance for the AS350 helicopter during the same flight procedure. The broadband noise was relatively less significant for the Bell 407 flight procedure when compared to the
level turn and level, decelerating turn. For this flight procedure the BVI noise dominates the A-weighted SPL. As for the AS350 flight procedure, the broadband and loading contributes to the total A-weighted SPL.

One final comment about the flight procedure is that though the complexity was much higher than a 6° steady descent flight analyzed in the previous chapter, the noise levels generated are generally lower. For a steady 6° descent the rotor is continuously operating in its wake but during transient flight conditions the wake trajectory moves away from the rotor and generates lower BVI noise.
Conclusion

In the current work, a comprehensive noise prediction system is developed. The system is validated with the flight test data obtained for 5 helicopters: Robinson R44 and R66, Bell 206L and Bell 407, and Airbus AS350. The results were analyzed to understand the events happening during the flight test and to address the current limitations of the system. A summary and conclusions are provided below:

6.1 Development of noise prediction system

The noise prediction system developed in this project consists of three different codes. A flight dynamics and simulation code, PSUHeloSim; a high-fidelity aeromechanics free wake and rotor analysis code, CHARM (Comprehensive Hierarchical Aeromechanics Rotorcraft Model); and a noise prediction tool, PSU-WOPWOP. New features are added to the noise prediction system to develop capabilities required for predicting noise generated by maneuvering flight procedures. The current system is equipped to handle time-dependent flight path, quasi-periodic blade loads changing every 0.5 seconds of the flight time for calculating loading noise and time-dependent thrust vector to calculate broadband noise using the Pegg’s empirical model. An example of a Robinson R66 performing level, decelerating turn is used to demonstrate the necessity and current limitations of the system.
The system is able to follow the maneuvering flight trajectory and the differences between the open-loop and closed-loop system were demonstrated.

6.2 Validation and analysis

A general summary for all the helicopters and flight runs

The noise prediction system tracked the flight trajectory performed during the flight test, calculated the rotor states and state derivatives, calculated the blade loads and used them to determine the noise levels. The noise levels are lower for lighter helicopters (Robinson R44 and R66) used in the validation process. The noise levels are higher below the flight path and decreases with increasing sideline distance. During approach the thickness noise dominates the total noise levels with the main rotor loading noise dominating OASPL. The Bell 407 generated maximum thickness noise (among the helicopters considered) due to higher main rotor and tail rotor tip-speed. The loading noise dominates the peak OASPL and usually occurs when the helicopter is overhead. This peak is well captured for most of the microphones and helicopters. Sometimes two peaks close to one other (one maybe smaller than other) can be seen in the OASPL time history due to the contribution from thickness and loading noise, demonstrating the effect of directivity could amplify the total noise levels. The tail rotor generates high-frequency thickness noise below the flight trajectory and is overestimated during approach (clearly seen in A-weighted SPL) due to a lack of scattering or shielding effect from the fuselage. Pegg’s broadband noise model scales with the rotor thrust, however the empirical model was not intended for maneuvers or steady turns (higher thrust requirement to balance the centrifugal force acting on the vehicle and to overcome the inertia during the transient period) and may result in excess noise levels. The level turn flight procedures demonstrated the significant effect of the directivity and increased rotor thrust on the noise levels. The noise prediction system was able to fly the
complicated maneuvers and showed reasonably good predictions. The limitations of the current system is the future work and discussed in Chapter 7.

The first flight test considered for validation is the 80 kts level flight. Apart from the summary described above key conclusions are described here. The effect of phasing between the main rotor and tail rotor is seen with the ‘serrated’ pattern generated during approach time histories. The broadband noise dominates the peak A–weighted SPL and matches well for the Bell 407, Airbus AS350, Robinson R44 and R66 helicopters, and is higher for heavier helicopters. The Pegg’s empirical model used to predict broadband noise does a reasonably good job for heavier helicopters with higher number of blades and lighter helicopters with lower number of blades but fails to capture the trend for Bell 206L helicopter which has lower number of blade and is on heavier side (weight is closer to Bell 407 helicopter than Robinson R44 and R66 helicopters). The loading noise generated by the tail rotor is directed at sideline location and has shown to be overpredicted when comparing the acoustic pressure time histories of the loading noise generated by the main rotor and tail rotor with the flight test data. The tail rotor loading noise also dominates the A–weighted loading SPL.

The second validation case considered for analysis is the steady 6° descent flight condition. This flight condition is considered primarily to investigate the BVI noise. The Bell 407, followed by AS350, Bell 206L, R44 and then R66 has the noise level in descending order. The SEL is well captured by the noise prediction system. For this flight condition, the heavier helicopters (Bell 407 and AS350) shows maximum contribution from loading SEL and followed by broadband SEL. For the lighter helicopters, the maximum contribution to the total SEL is from the broadband noise. The A–weighted SPL is dominated by the loading and broadband noise for the overhead microphone, on the advancing side of the rotor by loading noise and on the retreating side by broadband noise. The peak levels seen during the flight test are measured and predicted when the aircraft is overhead, however the noise
levels at the sideline observer locations can be overestimated on the advancing side and underestimated on the retreating side when the helicopter has a roll-offset and is tilted on the advancing side (seen for the AS350 helicopter flight case). The system controller, which uses substantial engineering judgment to choose unknown parameters—including an assumed effective hinge-offset, CG of the vehicle and with the rigid blades and a controlled heading angle—the controller seems to compensate with some residual roll-offset compared to the trajectory flown during the flight test. This has resulted in the loading noise skewed towards the advancing side of the rotor. The higher frequency content in the loading noise, seen with significant A-weighted SPL contribution to the total noise for this flight conditions, indicates presence of a strong BVI. One important observation to note about BVI noise is the effect of number of blades. Bell 407 and AS350 are close in weight but the number of blades is different (4 vs. 3 respectively). The BVI noise frequency range, $6^{th}$–$40^{th}$ harmonics of blade passage frequency, is higher for the Bell 407 compared to the other helicopters used in the current work. The BVI frequency range for Bell 407 is 165-1101 Hz and for AS350 is 118-788 Hz. Therefore, even if by increasing the number of blades, the circulation across the blade decreases with reduced tip-vortex strength, the increased frequency of interaction and the number of tip-vortices in the wake trajectory results in higher BVI noise when the helicopter is flying in a BVI noise condition. This results in higher annoyance caused by the helicopter and higher SEL. *When designing low noise rotors, increasing the number of blades would reduce the harmonic loading noise; however, it results in higher noise levels during BVI and transient flight conditions due to the interaction effect from one blade to another.*

The third validation case is the 80 kts, level advancing-side turn and retreating-side turns performed by R66, Bell 407 and AS350 helicopters. The SEL is higher for heavier helicopters and the predicted SEL is overpredicted by 2–3 dBA. This overprediction occurs due to the overprediction of broadband noise and error in tail
rotor thickness noise due to lack of shielding from the fuselage. The increased rotor thrust during the transient maneuver, such as the roll-in and roll-out, steady turn and roll-offset of 5° toward the advancing side has resulted in higher broadband noise levels (Note: Pegg’s empirical model was not developed for turn maneuvers and as such could result in overprediction. The Pegg model results might be improved for turns and complicated maneuvers by adjusting scaling parameters.) The loading OASPL is overestimated for the AS350 helicopter and well predicted well for the Bell 407 helicopter.

The fourth validation case is the decelerating, level advancing-side and retreating-side turns. The predicted SEL were within 2–4 dBA of the flight test. Even with the added complexity of the maneuver, the prediction shows better comparison than the level turn. A primary reason is the contribution from the loading noise when compared to broadband noise is higher for this maneuver than for the level turns. The SELdBA is higher during the decelerating turn than during the level and level turn flight procedures. The deceleration of the helicopter results in increasing the flight time and increasing the annoyance caused by the helicopter. The predicted time histories were capable of capturing the overall trend seen during the flight test but missed the levels for microphones located outside the turn due to missing the noise directivity and missing a potential BVI noise event. The loading noise levels are higher on the advancing side of the rotor irrespective of the turn direction. The noise levels and their time histories are very dependent on the flight trajectory. The transient stages during any maneuver; start/stop of deceleration/acceleration, or roll-in and roll-out of turns, increases the loading noise, especially the higher-harmonic loading noise (observed in A–weighted SPL) and in some cases BVI noise than the loading noise generated during the steady part of the maneuver, i.e. constant rate of deceleration or turn at constant roll angle. Another parameter affecting the generation of the higher-harmonic loading is the rate of change of the flight parameters such as the roll angle or velocity. For
a lower rate of change the noise levels are observed to be significantly lower and the quality of the prediction is better. This observation is made by comparing the Bell 407 and AS350 noise levels. The quasi-periodic loading assumption used in the prediction system may be inadequate for high rates of change of the flight parameters.

The last validation case is the descending turns. During this flight procedure the helicopter is performing steady 6° descend followed by descending turn with variation in helicopter speed (though not intended). The BVI noise is a major contributor to the total noise generated during the flight procedure. Similar to decelerating turns, the another factor contributing to the total noise is the transient maneuvers resulting in BVI and higher-harmonic loading noise. The SEL predictions are within 1-2 dBA of the flight test and shows better correlation than the level turns. The time histories shows that the peaks are dominated by the loading noise, similar to the steady descent case. The BVI directivity has shown to play an important role in underprediction (for microphones located outside the turn) or overprediction (microphones located under the flight path) of the noise levels at certain microphone locations. The broadband and loading noise both contribute to the A-weighted SPL.

6.3 Key understanding from the maneuvers for noise abatement procedures development

1. One difference in the SEL generated by the advancing-side turn and retreating-side turn is the contribution of the tail rotor loading noise to the total noise for the sideline observers located inside the turn. The noise level is higher when the helicopter is performing retreating-side turn. The tail rotor thrust requirement increases during the turn maneuver and this increase is higher when the helicopter is performing the retreating-side turn. As such higher tail
rotor loading noise is observed inside the turn of the retreating-side turn flight procedure. The radiation distance and continuous change in the directivity of the noise sources (tilting the helicopter changes the directivity of the main rotor noise away from underneath the flight path while for the tail rotor loading noise the directivity moves towards the ground plane) due to changes in the rotor orientation results in significant contribution from the tail rotor to the total A-weighted loading SPL and is especially important for the Bell 407. Do not ignore the tail rotor when designing a noise abatement procedures.

2. The time histories of the loading noise shows that it dominates peak OASPL (mainly the main rotor) when the helicopter is overhead or closer to the sideline microphones; however, the A-weighted loading SPL peaks, generated by the main rotor, are observed when the helicopter is performing a transient maneuver, roll-in or roll-out of turn. The higher harmonic blade loading noise (and BVI noise may occur) occurs because of the higher time-derivative of blade loads during the maneuver. (Farassat’s Formulation 1A includes $\dot{l}$ for calculating loading noise and this term depends on dot product between the $\dot{l}$ and radiation vector. During a transient maneuver low rates of change of velocity and helicopter attitude is the best approach for reducing the higher-harmonic loading noise.

3. The term $\dot{M}_r$ term in Eqn. 2.4—used for calculating loading noise, plays a significant role during maneuver as the incident velocity is changing and the directivity of the $\dot{M}_r$ moves towards ground as the rotor disk tilts. During maneuvers, terms not important during steady flight procedures affect the noise levels as the rotor orientation changes the directivity of the noise sources.

4. The 6° steady descent flight conditions (the standard descent angle for approach) generated noise levels higher than any other complex maneuvers considered for validation. During a descent procedure the rotor experiences
upwash and when the upwash is enough to push the wake into the rotor, the BVI occurs. However, during a turn the helicopter main rotor tilts and the resulting wake is skewed not only in the $z$–axis but also in the $x – y$ plane. The effective inflow determining the wake skew angle relative to the rotor tip path plane is now a function of the heading velocity (resultant $v_x$ and $v_y$) and rate of descent ($v_z$). So even if the motion in $z$–direction increases the upwash in the $z$–direction, the inflow velocity component in the $x – y$ plane, comprising of the forward speed, pushes the wake away from the rotor and as such the effective BVI miss distance is higher during a $6^\circ$ descending turn than during a steady $6^\circ$ descent maneuver. Further study is required to analyze this hypothesis. *Avoid steady BVI flight conditions and instead adopt deceleration or decelerating descent flight condition to reduce BVI noise.*

5. During turns and near the flight path, the noise levels observed are higher on the advancing-side of the rotor irrespective of the direction of turn. Also, the observers being impacted by the noise are continuously changing–except if they are inside the turn, especially at the center of the turn. *Sensitive noise zone should not be near the flight path and inside the turn. Outside the turn and at sideline distance the noise levels are low.*

6. *The noise source directivity and distance between the helicopter and observer (radiation distance) plays significantly larger role than some noise source generation mechanism, such as the harmonic loading and thickness noise, for developing noise abatement procedures.*
7

Future Work

In this chapter the scope for future development of the noise prediction system, analysis of maneuvering flight procedures, and generation of noise abatement procedures is discussed.

7.1 Noise prediction system development

The validation of the noise prediction system is covered in depth in the dissertation. The system was enhanced whenever it was deemed most important. However, some features that should be included or enhanced were not completed. Recommendations for these improvements are provided in this section.

1. The helicopter models based on engineering judgement could be further improved by cross-comparing the flight test data with the predicted noise levels for a steady flight conditions and then use those newly defined models for developing noise abatement procedures. For example, effective hinge offset of the main rotor and the minimum vortex core size of the trailing vortices and the tip vortex could improve the accuracy of BVI noise prediction by improving the prediction of blade flapping motions, thus changing the BVI miss distance and the strength of the blade tip-vortex.
2. The thickness noise calculation requires the blade geometry information. In the current noise prediction system, the blade was defined as an unstructured time-independent, three-dimensional grid. The coordinate transformations (change of base) used in PSU-WOPWOP accounts for the rotor rotation, changes in the helicopter flight trajectory and attitude but not the blade flapping motions. The flapping motion of the blade should have been updated at each time step in the time-dependent blade surface geometry file, but it was not. This motion might affect the noise levels and directivity observed during a maneuver and could explain some of the discrepancies in the predicted thickness noise for the Bell 407 helicopter (this rotor has high blade-tip speed and without the flapping motion the resultant velocity on the advancing side is higher).

3. The lack of shielding or scattering effect from the fuselage has resulted in overprediction of the thickness noise generated by the tail rotor during approach. For future work, properly accounting for the presence of the fuselage should be done when developing noise abatement procedures.

4. The broadband noise was predicted using Pegg’s empirical formula [37]. The empirical calculation was shown to overpredict the total A-weighted SPL, especially during a maneuvers. The model’s reliance on using steady flight conditions to define the empirical constants and its lack of scalibiltiy for different number of blades suggests it may be advantageous to use a better empirical model. Implementing higher-fidelity models such as the Brooks, Pope, and Marcolini (BPM) [15] for calculating the self-noise generated by the rotors along with other empirical models to calculate the inflow turbulence and blade-wake interaction noise is appropriate for future development.

5. The loading noise calculations use ‘Reconstruction’ in the CHARM rotor module (described in Chapter 3). Although high-fidelity blade loads are
generated with this feature, its use has resulted in numerical error (every 15° of blade azimuth for the main rotor). This numerical error is amplified in tail rotor blade loads and required a reduction in azimuthal discretization (blade loads discretized for every 15° of rotor azimuth, instead of 1°). Future work is required to eliminate this source of numerical error.

6. One of the needs from external agencies involved in low community noise assessment is the use of the noise prediction system to generate noise level hemispheres for a range of steady flight conditions. This database is required for developing noise abatement procedures. Future work to automate the generation of such hemispheres more efficiently into this database would be helpful.

7.2 Analysis of maneuvering flight procedures

The current work focused on using time histories of noise levels and SEL to understand the events occurring during the flight test. The blade loads seen during the maneuver were not used to demonstrate the analyses but were used for understanding the flight procedures. This approach to understand the noise generation mechanism during a maneuvering flight procedures, by studying the time histories of noise levels and identifying the time at which the intense noise was generated and focusing the analysis on those instances by correlating the blade loads and their time derivatives with the noise on hemisphere, was possible due to the use of a comprehensive noise prediction system.

An example of the analysis is shown here for the Bell 407 performing a descending advancing-side turn maneuver. The flight trajectory information is provided in Fig. B.74. The main rotor blade loads are calculated during 6 instances of the flight run (shown in Fig. 7.1); 1) $t = 10$ seconds–steady level flight, 2) $t = 25$ seconds–steady descent flight 3) $t = 30$ seconds–start of roll-in motion, 4) $t = 35$ seconds–maximum
roll angle of approximately $35^\circ$, 5) $t = 43$ seconds–roll-out of turn, and 6) $t = 47$ seconds–steady shallow descent.

Figure 7.1: Rotor blades loads in the lift direction (in N/m) for the Bell 407 performing descending advancing-side turn (rotor azimuth shown on left).

The blade loads in the lift direction ($z$–axis) are shown for the six instances with the $x$–direction being the initial direction of helicopter motion. As the helicopter maneuvers, it is harder to define the helicopter motions ($t = 47$ seconds the direction of flight is approximately in the $–y$ direction). The blade loads show intense fluctuations in the first quadrant for $t = 25$ seconds (high BVI) and this intensity reduces as the helicopter turns and increases during the roll-out maneuver. During the roll-in and maximum roll angle of the turn, the rotor blade has high fluctuations (compared to blade loads at $t = 10$ seconds and $t = 47$ seconds) along the azimuth
and results in higher-harmonic loading noise.

The loading BVISPL for the main rotor (frequency range from 6\textsuperscript{th}–40\textsuperscript{th} blade passage harmonic), over the hemisphere described in Appendix A.1, was calculated for the above blade loads and is shown in Fig. 7.2. Stronger BVI noise is seen during steady descent at $t = 25$ seconds and followed by roll-out of turn at $t = 43$ seconds. Some higher-harmonic loading noise is seen during roll-in motion at $t = 30$ seconds. During the maximum roll angle turn and shallow descent the noise levels are much lower. Examining the connection between blade loads and the associated noise (BVISPL in this case), as shown in this section, helps to explains why a 6° steady descent generated higher noise levels than maneuvering flight procedures.

Figure 7.2: Loading, BVISPL for the Bell 407 performing descending advancing-side turn.

The approach used to analyze the blade loads and the associated noise during maneuvering flight procedures is advantageous to understand the effect of flight conditions such as roll-in/roll-out, descending turns and so forth have on noise levels.
during transient flight conditions. Such understanding is important to develop a
general strategy for generating noise abatement procedures with transient effects.
This approach could be further extended to other aerial vehicles such as eVTOL,
UAM, and UAV aircraft, as not much is known about the noise generated during a
flight procedures of these vehicles. The extension of the noise prediction system,
described in the current work, has an advantage over other available tools as the
steady state assumption is not employed. Furthermore, transient and unsteady
flight conditions can be simulated for the new aircraft and analysed in detail.

7.3 Comprehensive noise abatement procedures development

A comprehensive noise abatement procedures development requires a functional
relation between flight conditions (velocity, flight path angle, rate of descent or climb,
acceleration or deceleration, roll or heading and total flight time) and geometric
flight path (altitude, sideline distance, and directionality).

The HAI’s noise contour is an example of analyzing the noise levels generated at
different flight conditions, without accounting the flight path. HAI’s noise contour
(the rate of descent/climb vs. helicopter speed) is populated with maximum A–
weighted SPL ($L_A$) for avoiding BVI noise [1]. The contour plot was easier to
interpret for pilots and operators and to avoid the BVI flight conditions during
approach. In the current work, an attempt was made to extend the HAI’s noise
contour to include the effect of total exposure time, unsteady flight conditions and
noise source directivity by using sideline observers. The noise abatement contour
is shown in Fig. 7.3. It has same axis as the HAI’s noise contour, i.e., the rate of
descent/climb vs. helicopter speed, but with a new equivalent SEL to account for
the sideline observers and total exposure time. The equivalent SEL integrates the
A–weighted SPL over the entire flight duration for each observer and then the final
contour is populated by summing weighted average equivalent SEL over all the
observer positions (50%) and the maximum equivalent SEL (50%). The contour
shows that the noise levels are higher near the BVI flight condition (around 6°:
flight path angle shown as dotted line and the noise levels as solid lines) and at low
speed due to higher exposure time.

A major limitation of the approach was that the noise abatement contour needs
to be generated for every unsteady flight condition. This failed to provide the same
ease as was available when interpreting HAI’s noise contour. Secondly, the noise
contours shows very small difference in noise levels for the range of flight conditions
(seen especially for unsteady flight conditions). Third; the computation time and
effort required for generating one noise abatement contour is still very high.

Future work should focus on addressing the current limitations of the noise
abatement contours. For the first limitation, computer software to assist the pilot is
a good approach. It is not practical for pilots or operators to understand the large
number of contours for developing strategy to fly low noise flight procedures. The
tool should not only be user friendly, but since the database is previously created,
the computation time will be low and can be used in real-time. For the second
limitation; one of the reasons for low level difference in the contour is the use of
total noise for defining an equivalent SEL contour. Future work should focus on
defining the contour for specific noise sources to clear the effect of flight conditions.
on noise levels. For the third limitation; future work should employ an efficient strategy and automation to not only to generate the noise abatement contours with the understanding gained from analyzing maneuvering flight procedures, but also to calculate the equivalent SEL.

A final element for developing noise abatement procedures is to include the effect of geometric flight path (altitude, sideline distance, and directionality) on noise levels. These two elements need to be combined for developing a comprehensive strategy for generating low noise flight procedures.
References


Appendices provided as a separate file in the same link
Vita
Mrunali Botre

Mrunali Botre was born in Pune, India. She got her Bachelor’s in Mechanical Engineering from Veermata Jijabai Technological Institute (VJTI), Mumbai, India. After obtaining her Bachelor’s degree she did an internship with Mahindra & Mahindra Ltd., Mumbai. After doing almost a year of internship she decided to pursue her Master’s in Mechanical and Aerospace Engineering from Syracuse University and focus on computational fluid dynamics.

Following the Masters’ work, Mrunali Botre started her doctoral studies at The Pennsylvania State University in the Department of Aerospace Engineering. Her doctoral research focused on rotorcraft aerodynamics and aeroacoustics under the guidance of Professor Kenneth Brentner. Currently, she is working full-time at Continuum Dynamics Inc., NJ. Her job includes research in rotorcraft aeroacoustics and aerodynamics.