HELICOPTER NOISE MODELING WITH VARYING FIDELITY

PREDICTION SYSTEMS

A Thesis in
Aerospace Engineering
by
Lauren Weist

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The thesis of Lauren Weist was reviewed and approved by the following:

Kenneth S. Brentner  
Professor of Aerospace Engineering  
Thesis Advisor

Eric Greenwood  
Assistant Professor of Aerospace Engineering

Joseph Horn  
Professor of Aerospace Engineering

Amy R. Pritchett  
Professor of Aerospace Engineering  
Department Head of Aerospace Engineering
Abstract

Rotorcraft are a versatile and important class of vehicles within the aerospace industry, but they experience a highly varied aerodynamic environment that causes unique acoustic conditions. These acoustics are highly tonal, and are often found to cause community annoyance. Due to this, providing acoustic considerations for rotorcraft is a necessary area of research within the industry.

To aid in these considerations, this thesis addresses noise via modeling through two noise prediction systems (NPS). To account for rotorcraft acoustics in the design stage, a low fidelity NPS, the NDARC NPS, was used. For acoustic considerations of existing helicopters, the high fidelity Penn State NPS is used.

The low fidelity system, the NDARC NPS, is described first. As acoustic consideration in the design stage is not often conducted, development of a rapid tool to give to a designer is paramount. The NDARC NPS was created to fill this desire, and has been further developed as a part of this thesis. The NDARC NPS was fully exercised to identify issues and improve the system. Improvements to the blade-vortex interaction model, comprised of the Beddoes wake model and Vatistas implementation of the Biot-Savart law were completed. Improvements were made to the user interface, the complete suite of example cases was improved and expanded, and the User’s Manual was completed.

The mid-fidelity system, known as the Penn State NPS, is used to aid in providing guidance on noise abatement procedures for existing vehicles to aid in the reduction of community annoyance. In this work, the Penn State NPS was used to conduct several studies on the effects of real flight variations on noise. First, a study of longitudinal and vertical accelerations through the lens of flight path angle were conducted for the Sikorsky S-76D helicopter to understand how flight path angle and flight path angle rate changes can effect noise. Then, a study of helicopter configuration and the impact of weight and number of blades on noise was conducted. Four vehicles, the Sikorsky S-76D, the Bell 205, the Bell 407, and the Bell 206 were all analyzed in descent to understand how vehicle configuration influences noise.
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$\Box^2$ wave operator, $\Box^2 = \frac{1}{c^2} \frac{\partial^2}{\partial t^2} - \nabla^2$

c sound speed in quiescent medium

$C_T$ coefficient of thrust

$D_f$ flat plate drag ($\frac{1}{2} \rho V f$)

d$\mathbf{f}_z$ differential force in the z direction

$f = 0$ function that describes the source surface, e.g., a rotor blade

$g$ retarded time function, $g = \tau - t + r/c$

$H(f)$ Heaviside function, $H(f) = 0$ for $f < 0$ and $H(f) = 1$ for $f > 0$

$l_r$ component of local force that acts on the fluid in the radial direction, $l_r = \hat{r}_i P_{ij} \hat{n}_j$

$m$ vehicle mass

$\mathbf{M}$ local Mach number vector of source with respect to a frame fixed to the undisturbed medium, with components $M_i$

$M_r$ Mach number of source in radiation direction, $M_i \hat{r}_i$

$\hat{n}$ unit outward normal vector to surface, with components $\hat{n}_i$

$P_{ij}$ compressive stress tensor

$p'$ acoustic pressure, $p - p_0$, in undisturbed medium

$p_0$ atmospheric pressure

$r$ blade radial station or distance from source to observer

$R$ rotor radius

$r_c$ vortex core size

$r_v$ non-dimensional radial location of vortex element

$r_r$ non-dimensional wake contraction radius

$dS$ element of the rotor blade surface

$T$ main rotor thrust

$t$ observer time

$T_{ij}$ Lighthill stress tensor, $p u_i u_j + P_{ij} - c^2 \rho' \delta_{ij}$

$u_i$ component of local fluid velocity

$U_n$ Normal component of fluid velocity

$V$ helicopter velocity

$v_\theta$ induced velocity due to a vortex

$W$ helicopter weight
Cartesian reference frame with longitudinal, lateral, and vertical components

\( \vec{x} \) observer position vector, with components \( x_i \)

\( \vec{y} \) observer position vector, with components \( y_i \)

\( \vec{z} \) observer position vector, with components \( z_i \)

**Greek letters**
- \( \alpha_{TPP} \): tip path plane angle
- \( \gamma \): flight path angle (FPA)
- \( \dot{\gamma} \): time rate change of flight path angle
- \( \gamma_v \): nondimensional vortex strength
- \( \gamma_{eff} \): effective flight path angle
- \( \delta(f) \): Dirac delta function
- \( \delta_{ij} \): Kronecker delta, \( \delta_{ij} = 1 \) for \( i = j \), otherwise \( \delta_{ij} = 0 \)
- \( \theta \): angle between the normal direction \( \hat{n} \) and the radiation direction, \( \hat{r} \)
- \( \lambda_i \): induced inflow ratio
- \( \lambda_0 \): mean induced inflow
- \( \lambda_1 \): wake contraction inflow ratio
- \( \mu_x \): advance ratio in the longitudinal direction
- \( \mu_z \): advance ratio in the vertical direction
- \( \rho_0 \): density of quiescent medium
- \( \phi \): wake age angle
- \( \chi \): wake skew angle
- \( \psi \): azimuth angle
- \( \Omega \): rotor angular velocity

**Acronyms**
- BPM: Brooks, Pope, and Marcolini model for broadband noise
- BVI: Blade-Vortex-Interaction
- BVISPL: BVI Sound Pressure Level
- CHARM: Comprehensive Hierarchical Aeromechanics Rotorcraft Model
- COB: Change of Base (i.e., coordinate transformation)
- CVC: Constant Vorticity Contours
- eVTOL: electric Vertical Take-Off and Landing
- FAA: Federal Aviation Administration
- HAI: Helicopter Association International
- NASA: National Aeronautics and Space Administration
- NDARC: NASA Design and Analysis of Rotorcraft
- NED: North-East-Down (reference frame used in HeloSim)
- NPS: Noise Prediction System
- OASPL: Overall Sound Pressure Level
- UAM: Urban Air Mobility
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Chapter 1
Introduction

1.1 Introduction to rotorcraft

With multitudes of civil and military applications, helicopters encompass a specific use space in the aviation field. Their ability to move both vertically and horizontally independently makes them a versatile tool that have many benefits over traditional aircraft. As helicopters don’t require large runways, they are ideal vehicles for locations where space is limited. Some of the main uses of helicopters include short distance transport, search and rescue, and military applications. Rotorcraft are often used for transportation within in urban areas for both emergency and business activities. For example, hospitals often use helicopters to transport patients between urban facilities. Currently, there is also a movement for the use of modern electric rotorcraft for passenger travel.

A consequence of these and other applications is that as rotorcraft become more common in urban areas, community push back has become stronger. Many communities have identified rotorcraft as a source of annoyance, and as rotorcraft use has become more frequent in locations with high populations, considerations must be taken to mitigate community annoyance [1].
1.2 Helicopter noise

Frequently, the annoyance caused by helicopters is associated with the sound they produce. Helicopters are unique in that they experience a large number of different aerodynamic conditions that each produce noise. The loud and sometimes impulsive noise caused by the rotors is easy to identify in an urban environment, and is a source of annoyance and community push back against helicopters [1]. Unlike vehicles like cars and airplanes, which produce a more steady noise, helicopter noise can be highly tonal and varies as a function of blade passage frequency, which is annoying to the human ear [2]. Thus, the field of helicopter acoustics aims to understand and reduce the noise a helicopter produces or otherwise mask its noise in order to reduce community impact.

There are two paths to reduce rotorcraft noise explored in this thesis. One path is to reduce rotorcraft noise in the design stage by making noise a design parameter. By prioritizing noise during design, it is possible to make design decisions before production to make quieter, more acceptable designs. Currently, there are several urban air mobility (UAM) companies who cite creating low-noise vehicles as an important part of their goals, such as the Joby Aviation electric tilt-propeller [3]. The other path is to reduce the noise of current vehicles by training pilots to fly with noise in mind. There are several projects that make this their aim. One such program, the Helicopter Association International’s (HAI) *Fly Neighborly*, aims to reduce community annoyance via pilot acceptance of and practicing guidelines to quieter flying [4]. The *Fly Neighborly Guide* suggests noise abatement procedures that can be used by pilots in modern helicopters to improve community acceptance.

Partially in response to the *Fly Neighborly Guide*, the Federal Aviation Administration (FAA) started Project 38 through their Aviation Sustainability Center (ASCENT, a.k.a the Center of Excellence for Alternative Jet Fuels and Environment [5]). Project 38,
“Rotorcraft Noise Abatement Procedures Development”, aims to understand and provide noise abatement procedures for a variety of helicopter classes. In order to provide guidelines for noise abatement procedures, understanding the noise of various vehicles in various flight conditions is needed.

1.3 Helicopter noise prediction

To accomplish the goal of understanding and reducing rotor noise, the use of noise prediction systems are required. These systems are designed to use computational modeling and analysis tools to create computer representations of rotorcraft, which are used to predict noise profiles.

There are several benefits to using a noise prediction tool instead of directly measuring noise. One such benefit is that noise can be predicted for novel vehicle designs to better understand the impact of design on noise before such a vehicle is built. Another benefit is that noise prediction systems are capable of mitigating the work and cost required to quantify rotorcraft noise. Acquiring acoustic data from a test aircraft requires expensive equipment, a test crew to conduct the tests, a location to fly the vehicle, the vehicle itself, and a pilot to fly it, all which incur significant cost and time. The cost of performing a flight test can be compared to a noise prediction tool, which can be completed by one person in a matter of hours to days. A noise prediction tool also allows for analysis of the rotorcraft with more detail than possible with flight test data. For example, noise sources (main rotor, tail rotor, etc.) can be analyzed separately, and different noise source theory can be used to gain a deeper knowledge on the physical mechanism of the radiated sound.

Noise prediction tools are coupled with other analytical tools to create noise prediction systems. These systems can predict flight trajectory, rotorcraft states, and design feasibility. Three such tools used in this thesis are flight simulations, comprehensive analysis tools, and conceptual design tools, which are described here.
A conceptual design tool is typically one of the first tools used in rotorcraft design. These tools create a computer model of a vehicle to allow a designer to make more informed decisions on the configuration of a rotorcraft. The ability to optimize a vehicle is a hallmark of conceptual design tools, as the ability to design a vehicle with the minimization or maximization of a certain parameter via design sweeps is a desirable capability for designers. Conceptual design tools such as these typically use rapid, lower fidelity predictions that provide a representation of a given rotorcraft with acceptable levels of accuracy.

Flight simulation software uses a computer modeled aircraft design to predict a desired trajectory, computing relative state data for analysis. Flight simulation is used to obtain flight dynamics for a vehicle, which can then be used in further calculations, such as noise predictions. Flight simulation can either use linear or nonlinear equations of motion to calculate a state space model of the desired vehicle configuration. These state space models are often more simplified than what can be obtained with CFD or a comprehensive analysis code, but can provide a more rapid prediction. Flight simulation software is used to determine dynamics of a flight trajectory, which are then used in a higher fidelity model, such as CFD, to obtain higher resolution and more accurate information. Therefore, the benefit of flight simulation is its modularity, speed, and ability to predict complicated flight maneuver dynamics of an entire vehicle.

A comprehensive analysis code is used to produce mid-fidelity information on a given flight vehicle. Comprehensive analysis is often moderately computationally expensive, but provides performance, aerodynamic and structural loads, blade dynamics, and trim on a given configuration [6]. Comprehensive analysis codes are used to produce a complete understanding of the aerodynamic environment and performance for a vehicle in a given flight condition but with more detail than in flight simulation. Often, the goal of utilizing comprehensive analysis codes is to produce mid-fidelity airloads and provide
understanding about how the vehicle flies for both design and analysis purposes [7].

This thesis specifically looks at two noise prediction systems. One system, the NDARC NPS, combines a conceptual design tool (the NASA Design and Analysis of Rotorcraft or NDARC [8]) with an acoustic prediction tool (PSU-WOPWOP [9]) and was used for a system verification and refinement study. The second system, the Penn State NPS, couples a flight simulation (PSUHeloSim [10]), a comprehensive analysis tool (the Comprehensive Hierarchical Aeromechanics Rotorcraft Model or CHARM [11]), and an acoustic prediction tool (PSU-WOPWOP) and was used to study the effects that control perturbations and vehicle weight class have on noise. These specific systems, and the associated software within them, are described in detail in later chapters.

1.4 Current effort

This thesis aims to investigate noise reduction tools through a two-pronged approach, separated by tool fidelity. Both efforts use a noise prediction system to predict helicopter noise, but the goals of each system vary based on the needs of the tool and the research desired.

The first part of this thesis uses a coupling between a conceptual design tool and a noise prediction code. This system is designed to provide noise considerations for rotorcraft during the design stage. The work in this thesis aims to further refine the model and prepare the system for an initial release. The effort for this work included verifying the system as a novice user, improving the loading noise model in the coupling tool, and creating a users manual, example cases, and training materials.

The second part of this thesis uses coupled flight simulation, comprehensive analysis, and noise prediction tools. The goals of this work were to aid in providing noise abatement procedures of existing helicopters. By modeling helicopters in a flight simulation, studies of noise can be conducted for existing vehicles without flight tests. The initial study
with this tool focused on the impact of flight control variation on noise during descent cases for a Sikorsky S-76D helicopter. The effects of short-term vertical and longitudinal acceleration on noise were analyzed for their impact on noise. The second study consisted of a comparison of low-noise approaches for four different helicopters to analyze the impact of helicopter configuration on rotor noise. Both vehicle weight and number of main-rotor blades were parameters. The focus of this research was to use the noise prediction system and flight test data to analyze commanded helicopter flight and explain trends caused by varying vehicle accelerations and vehicle configuration.
Chapter 2  
Helicopter acoustics theory

In this chapter, helicopter acoustic theory is introduced. The governing equations for this work are presented and described. Additionally, the source equations used to develop the governing equations are presented.

Helicopter acoustic prediction began with several key researchers. By the 1950s, several models for airplane propeller noise had been developed, namely by Gutin [12] and later Garrick and Watkins [13]. Gutin developed equations from aerodynamic principles for lower harmonic noise prediction of a propeller in still air a large distance from an observer. Garrick and Watkins expanded this work to model subsonic, steady flight for an arbitrary observer for a propeller in forward flight. A static propeller is analogous to a helicopter rotor in hover, while a propeller in forward flight is effectively the same as a helicopter rotor in vertical climb or descent. These and other propeller models were only applicable to steady flight conditions for airplane propellers, and so a new model would have to be developed for helicopters in edgewise flight (forward flight), as propeller models could only be applied to helicopters in axial flight (hover, vertical climb, and vertical descent). Helicopter forward flight introduced unsteady loading that had not yet been modeled, and so additional work was required to fully model helicopter acoustics.

Some of the first noise prediction methods for rotorcraft noise specifically was done by Lowson [14] and Wright [15]. Lowson developed his model for a point acoustic stress
in arbitrary motion, which could then be integrated across a surface to produce a model for helicopter noise. Wright built from the model developed by Gutin, and modeled helicopters as a rotating sinusoidal pressure pattern. These models were limited by the computer power available at the time, and largely neglected thickness noise, but represented the first successful explorations of rotor noise, which would then be expanded upon in future years. All these models considered all sources as one entity, and often neglected to consider thickness noise [16].

2.1 Noise source modeling

The methodology of noise modeling used in this thesis is based on a model created for acoustic radiation in 1952 by Sir James Lighthill. The two major developments released by Lighthill are entitled “On Sound Generated Aerodynamically I. General theory” [17] and “On sound generated aerodynamically II. Turbulence as a source of sound” [18]. Lighthill provided a methodology for calculating sound propagating through a stationary fluid from a distribution of fictitious sources representing real acoustic sources. This method, called the Lighthill Acoustic Analogy, used the conservation of mass and momentum to create an inhomogeneous wave equation. Lighthill’s worked modeled turbulence noise from a distribution of quadrupole terms integrated over a volume.

Lighthill used the idea that noise could be modeled as a distribution of different point sources, which could then be integrated. These point sources summed together to model the radiated sound. Point sources can be classified as one of three different categories: monopole, dipole, and quadrupole. The monopole source is the most simple of the three and can be modeled in classic acoustics as a sphere that is expanding and contracting in space. For the monopole modeling method to apply, the source sphere must be significantly smaller than the distance the sound must radiate and the source motion must be significantly lower than the speed of sound. The dipole is comprised of
two monopoles side-by-side fluctuating in opposite phase, modeled as two closely placed spheres in space. Finally, the quadrupole is made up of two opposite phase dipoles within a sphere.

Curle extended Lighthill’s theory to also model immovable objects in the flow [19]. Curle added a dipole term to Lighthill’s analogy that accounted for the force acting on the flow due to the object. Thus, by combining Lighthill’s quadrupole term and Curle’s dipole term, a wave equation that accounts for both turbulence and the force exerted by the source could be modeled.

The work of Curle and Lighthill was later extended by Ffowcs Williams and Hawkings (FW-H) in 1969 by adapting Lighthill’s equation to model surfaces in arbitrary motion and include monopole noise generation [20]. The Ffowcs Williams and Hawkings method used generalized function theory, which allows variables to be defined throughout unbounded space. The extension of the variables to generalized functions allows the variables to be defined both in the fluid and inside the surface.

The FW-H formulation rearranges the Navier-Stokes equations into a inhomogenous wave equation that contains a monopole and dipole source distribution on the surface and a quadrupole source distribution in the volume around the body. The FW-H formulation is shown in Eqn. 2.1

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

(2.1)

where \(T_{ij}\) is the Lighthill’s Stress tensor, shown in Eqn. 2.2

\[
T_{ij} = \rho u_i u_j + P_{ij} - c^2(p - \rho_0) \delta_{ij}
\]

(2.2)

and \(H(f)\) is the Heaviside function, which is defined as one when \(f\) is positive and zero when \(f\) is negative. Additionally, \(\delta(f)\) is the Dirac delta function, which is zero
everywhere except when \( f \) is equal to zero, where it is undefined except when integrated. \( f \) is a location variable that is 0 on the surface, greater than 0 outside the surface, and less than 0 inside the surface. Finally, \( \Box \) is the wave operator and is defined by Eqn. 2.3.

\[
\Box = \frac{1}{c^2} \frac{\partial^2}{\partial t^2} - \nabla^2
\]  

(2.3)

The formulation presented here is based on the form in Ref. [21], which varies slightly with the formulation presented by Ffowcs Williams and Hawkings.

### 2.2 Extension of noise modeling to rotors

The formulation derived by Ffowcs Williams and Hawkings was then applied to rotors by Farassat [22]. Additionally, Farassat created an integral form of the FW-H equation that can then be more easily computed. Farassat uses the Green’s function for unbounded space to create a formulation that could use integration in the time domain to achieve acoustic results. This formulation neglects the quadrupole term in the FW-H equation, as this term represents turbulence, which is considered a poor propagator of noise by Farassat. Farassat’s approach allows Eqn. 2.1 to be reduced to an integral formulation. Thus, Farassat’s first formulation, Formulation 1 for retarded time, becomes Eqn. 2.4.

\[
4\pi p'(x, t) = \frac{1}{c} \frac{\partial}{\partial t} \int_{f=0} \left[ \rho_0 c \nu_n + \frac{l_r}{r|1 - M_r|} \right]_{ret} dS - \int_{f=0} \left[ \frac{l_r}{r^2|1 - M_r|} \right]_{ret} dS
\]  

(2.4)

where \( l_i = \Delta P_{ij} \hat{n}_j \) is the force acting on the blade and the subscript \( ret \) implies that the integrand is evaluated at the retarded time.

This formulation can then be improved for both speed and accuracy by analytically taking the time derivative inside the first integral. This also allows the formulation to be separated into two pressure terms, one that governs thickness noise and one that
governs loading noise. These two formulas can then be added together to obtain a general pressure term, shown in Eqn. 2.5.

\[ p'(x, t) = p_T(x, t) + p_L(x, t) \]  \hspace{1cm} (2.5)

where \( p_T \) is the thickness noise term defined by Eqn. 2.6 and \( p_L \) is the loading noise term defined by Eqn. 2.7. The final combined result is called Farassat’s Formulation 1A.

\[ 4\pi p_T'(x, t) = \int_{f=0} \left[ \frac{\rho_0 (\hat{v}_n + \hat{v}_r)}{r |1 - M_r|^2} \right]_{ret} dS + \int_{f=0} \left[ \frac{\rho_0 v_n (r \hat{M} r + c M_r - c M^2)}{r^2 |1 - M_r|^3} \right]_{ret} dS \]  \hspace{1cm} (2.6)

\[ 4\pi p_L'(x, t) = \frac{1}{c} \int_{f=0} \left[ \frac{\hat{r} r}{r |1 - M_r|^2} \right]_{ret} dS + \int_{f=0} \left[ \frac{l_r - l_M}{r^2 |1 - M_r|^3} \right]_{ret} dS \]  
\[ + \frac{1}{c} \int_{f=0} \left[ \frac{l_r (r \hat{M} r + c M_r - c M^2)}{r^2 |1 - M_r|^3} \right]_{ret} dS \]  \hspace{1cm} (2.7)

where the subscripts \( n \) and \( r \) designate a dot product with the unit normal vector, \( \hat{n} \), the unit radiation vector \( \hat{r} \), respectively. The specific form of equations 2.6 and 2.6 and their derivation can be found in Ref. 21.

\section*{2.3 Component noise analysis}

As both the FW-H equation and Farassat’s Formulation 1A can be divided into different terms that can then be added together, it is logical to divide those sources into individual categories that can be described individually. Rotor noise sources can be classified as two types: deterministic and non-deterministic noise. Deterministic noise can be subdivided into three categories: thickness noise, loading noise, and high-speed-impulsive noise. Non-deterministic noise, contains all noise sources not described by deterministic sources, and requires nondeterministic loading to be predicted by Farassat’s Formulation 1A.
The directivity of these sources is shown graphically in Fig. 2.1. Each noise source has a different directivity associated with it; therefore, understanding each component individually is important for creating a complete understanding of rotorcraft noise.

![Figure 2.1. Rotor noise directivity. From Ref. 21](image)

### 2.3.1 Thickness noise

The noise source associated with the first term in the FW-H equation (Eqn. 2.1) is thickness noise, which is the monopole term. Thickness noise is caused by pressure fluctuations due to the motion of the blade passing through a medium and displacing fluid. As the name suggests, thickness noise is primarily influenced by the thickness of the blade, though more generally it is affected by the geometry of the blade as a whole.

This source is most influential in the plane of the rotor. As the observer (a term used for what is receiving the noise, person or microphone) moves further out of plane of the
rotor, thickness noise reduces. This is due to the thickness noise from different locations on the blade are cancelled out, causing a reduction in thickness noise out-of-plane of the rotor. It is also influenced by Doppler amplification, which causes noise to be stronger downstream of the rotor, and weaker upstream [23].

### 2.3.2 Loading noise

The second term in the FW-H equation (Eqn. 2.1) is governed by the forces on the blade. The second term is often referred to as ‘loading noise,’ which is due to the force on the fluid due to the presence of the blade. The loading source can be modeled as a distribution of dipoles over the blade, and is at a maximum directly below the rotor. The loading noise source is constantly changing as it is governed by the acceleration of the force on the blade, which is constantly changing as the blade moves around the rotor disk.

Loading noise can also be further separated into different sources by the aerodynamic condition that is causing the noise. One major loading noise component is blade-vortex interaction [24]. Blade-vortex-interaction (BVI) noise occurs when the shed tip vortex of one blade impacts another blade on the rotor. BVI creates a high magnitude loading fluctuation on the blade, which creates a loud impulsive sound. BVI noise is most frequent in slow descent, when the wake produced by the rotor is most likely to interact with the rotor blades. The strength of the BVI is determined by three factors: vortex circulation strength, distance of the vortex core from the blade, and the angle between the blade and the vortex [25]. The closer the blade is to the vortex core, the larger strength the BVI will be. Additionally, the more parallel the blade and vortex are to each other, the stronger the BVI. The lowest magnitude BVI would be attributed to a perpendicular BVI pulse, as the blade and the vortex interact over a longer period of time; hence, less impulsively.
2.3.3 High-speed-impulsive noise

The final pertinent deterministic noise source is high-speed-impulsive noise (HSI). HSI noise is caused by high speed flight and is created when the blade of a rotor begins to experience local shock formation such as compressibility. Rotor blade tip speed is a function of both forward flight speed and rotational speed, the rotor blade can therefore experience transonic effects even though the helicopter forward speed does not approach transonic speeds.

The HSI term is specifically difficult to model, as it requires accurate time-varying off-surface data to be captured well for the FW-H equation, as HSI noise is governed through the quadrupole term in the FW-H equation. Different formulations of the FW-H equation have been able to model it more accurately, and the field of computational fluid dynamics (CFD) has also found success in predicting and modeling HSI noise [26, 27].

2.3.4 Non-deterministic noise

The final category of rotor noise types contains noise sources that cannot be modeled as simply by the FW-H equation. There are several types of non-deterministic noise, but the only one used in this thesis is ‘broadband’ noise. Broadband noise is caused by the interactions between turbulent flow with the fuselage or blades of the vehicle. This noise category mainly encompasses noise sources caused by various forms of turbulence. Some methods of broadband noise are: inflow turbulence noise, turbulent-boundary-layer trailing edge noise, laminar-boundary-layer-vortex-shedding noise, boundary layer noise, separation-stall noise, and vortex noise (as seen in Fig. 2.2).

For this thesis, only inflow turbulence, boundary layer noise, and vortex noise are accounted for in the model used. Inflow turbulence noise is caused by the ingestion of turbulence into the rotor disk, boundary layer noise is caused by interactions between the turbulent boundary layer and the blade, and vortex noise is caused by the formation
of vortices by the tips of the blades. As turbulence modeling is statistical in nature, modeling this noise source is quite difficult. Non-deterministic semi-empirical or fully empirical models have found good success as a combination of blade parameters and statistical values [28, 29].

The research in this thesis uses the Pegg empirical model for broadband noise [29]. The Pegg model uses empirical scaling factors to compute peak broadband noise frequencies using thrust and rotor tip speed. Specifically, the Pegg model requires tip speed, blade area, shaft tilt, and lift coefficient to produce predictions. Then, the one third-octave peak frequency is calculated using the geometry of the blade and the lift of the blade to produce the sound pressure level for broadband noise. The Pegg broadband noise

![Diagram of rotor self noise sources](image)

**Figure 2.2.** Rotor self noise sources. From Ref. 28.
prediction method, while empirical in nature, is capable of predicting broadband noise with acceptable accuracy. The Pegg model calculates three possible broadband sources: inflow turbulence, boundary layer noise, and vortex noise.
Chapter 3  
Noise prediction systems

In this chapter the two noise prediction systems used in this thesis are introduced. Both systems use PSU-WOPWOP, a noise prediction code created at The Pennsylvania State University. PSU-WOPWOP is introduced and described, then the two noise prediction systems are described.

3.1 PSU-WOPWOP

PSU-WOPWOP is an acoustic prediction code that uses Farassat’s formulation 1A as the method for acoustic calculation [9,30–33]. PSU-WOPWOP is capable of predicting noise for a number of rotorcraft configurations and observers. The code is capable of predicting thickness, loading, and broadband noise for one or multiple rotors, and has a variety of output capabilities to allow a user to analyze rotorcraft noise and noise sources. It was introduced in 2003 by G. A. Brès et al. at Penn State [9].

There are three types of files read into PSU-WOPWOP to create the aircraft and observers: a namelist file, change of base (COB) files, and patch files. The namelist file is the file where all inputs and commands are specified. The namelist file is a simple text file in the FORTRAN namelist file format that contains the atmosphere definitions, observer and aircraft descriptions, and the flags for computation and output options.
The namelist file also references all COB and patch files. A change of base allows a user to define translations, rotations, or axis changes for a given object. These objects are either specified within the namelist or read in with a patch file. The patch file is a file that defines the blade geometry, which can be translated and rotated via the COB commands. Figure 3.1 shows how these input types can be used to build a rotorcraft, a complete description of this methodology can be found in Ref. 33.

![Figure 3.1. PSU-WOPWOP aircraft definition layout. From Ref. 33.](image)

The code reads in the blade motion and loading as well as the geometry of the desired vehicle. The user can then specify the desired observer locations, vehicle movement, and other atmospheric conditions. PSU-WOPWOP calculates the acoustic pressure at the observer locations, and then produces data in the forms specified by the user, performing any desired post-processing calculations.

Additionally, PSU-WOPWOP contains two broadband noise models, the Pegg model
and the Brooks, Pope, and Marcolini (BPM) model [28]. The BPM model is semi-empirical model, and the Pegg model is fully empirical. Both models provide estimated broadband noise predictions. Either model can be used to predict broadband noise, and the selected model will be incorporated into the acoustic results. All the work in this thesis makes use of the Pegg model.

PSU-WOPWOP is capable of producing a number of outputs. A few examples include acoustic pressure time history, overall sound pressure level (OASPL), perceived noise level (PNL), audio files, spectrum data, and sigma surfaces. Sigma surfaces are a PSU-WOPWOP capability for visualizing data and debugging. Several different scalar and vector values can be plotted as a function of time over the surface of any selected rotor. For example, the loading of a blade can be plotted over one blade passage for the z loading variable, which allows for visualization of loading changes over the rotor disk. These files can then be used to analyze the noise produced by the rotorcraft.

3.2 NDARC/PSU-WOPWOP noise prediction system

The first noise prediction system described in this thesis is called the ‘NDARC NPS’ and is a tool that couples the NASA Design and Analysis of Rotorcraft (NDARC) and PSU-WOPWOP with a coupling tool called WOPIt. The NDARC NPS system aims to create a tool useful to the design space of rotorcraft. The NDARC NPS aims to provide rapid and accurate noise predictions early in the design process. The software used in the system are described in detail here, and the changes to the system are described in Chapter 4.

3.2.1 NDARC

NDARC is a tool coded in Fortran and designed at NASA by Wayne Johnson to support the conceptual design of various rotorcraft [8]. The NDARC code is able to aid a
rotorcraft designer and analyze various configurations of rotors, wings, fuselages, tails, and propulsion systems. NDARC performs two distinct operations: the design step and the analysis step. The design step allows a user to read in a desired configuration and perform various sizing and optimization tasks. The goal of the design step is to have a user test multiple variables to create the optimal vehicle for a given goal. The analysis step then takes the vehicle configuration created in the design step and conducts various calculations to give a full understanding of the capabilities and costs of the configuration.

NDARC uses an iterative process in which a desired parameter is sized (optimized) for a variety of flight conditions and then all other variables are verified to be within a desired limit. Sizing can be done for a variety of parameters or desired conditions to gain an understanding of what the desired aircraft may be. The iteration process and code layout for NDARC is shown in Fig. 3.2. Examples of goals that may be desired in a design sweep are minimum weight, maximum distance, or maximum speed.

To create an NDARC case, a complete description of the base vehicle is required. The base vehicle is created in a ‘list’ FORTRAN namelist input file. Inside the list file, variables for all required vehicle parameters are input. As NDARC is sizing a whole vehicle, it needs a large variety of inputs. Some inputs include: the rotors, fuselage, engines, propulsion systems, payloads, and weight distributions.

Once the ‘list’ file is created, the user must then create a ‘run’ file. The run file is where the user specifies what tasks NDARC is to complete. The run file lists all the sizing tasks that NDARC is to run, as well as any flight parameters for performance sweeps. Once a given sizing task is complete, NDARC can then be used to conduct a basic analysis of the vehicle. Different ‘Off-Design’ mission tasks can be used to see the performance of the vehicle in various flight conditions, and component performance maps can be generated to produce a total understanding of a given configuration to inform the selection of a final configuration. Within one run, a user can run a range of sizing,
off-design, and performance missions all at once.

Once the run is complete, NDARC creates two files. An ‘.out’ file provides all the steps NDARC went through during running to allow a user to find any stopping points or errors. A ‘.soln’ file contains all the final solutions from the run. This solution file can then be parsed and information on the rotorcraft can be extracted. The solution file is designed to provide a user all parameters needed to continue their design in one complete file.

Due to the nature of the design stage, where desired parameters can be changing
rapidly and iteration is required, having a tool that can run quickly is important. NDARC uses low-resolution calculations and empirical models for fast execution. While such low-fidelity models are useful for the sizing of a rotorcraft, higher fidelity models are required for a noise prediction system. With regards to the NDARC NPS, NDARC does not provide blade loading with sufficient temporal and spatial resolution for noise prediction with PSU-WOPWOP. An intermediate tool is therefore needed to take the mission and relevant rotorcraft data from NDARC and create airloads that satisfy the computational requirements of PSU-WOPWOP. This work is completed by WOPIt, which is described in the next section.

### 3.2.2 WOPIt

WOPIt was created to couple NDARC and PSU-WOPWOP, because NDARC does not provide blade loading with sufficient temporal and spatial resolution for noise prediction. Therefore, recalculation of the blade loading is required for use with PSU-WOPWOP. WOPIt also reads in the outputs from NDARC to produce the namelists and required data files for PSU-WOPWOP. The WOPIt code was originally developed by Kalki Sharma in 2016 [34], enhanced by Thomas Jaworski in 2018 [35], and further developed in this thesis. The general design of WOPIt is described here, with a more in-depth explanation of the work added in Chapter 4.

As a first step, WOPIt processes the NDARC output files. As NDARC does not produce files in a form desirable for PSU-WOPWOP, WOPIt takes the information provided by NDARC and alters it. WOPIt uses a blade element theory (BET) model to calculate blade loading, and matches the trimmed forces and moments to those predicted by NDARC. Then, WOPIt creates blade geometries using dual compact thickness and compact loading models, which are simplifications that create faster predictions than using whole blade models [36]. WOPIt also has a BVI module based on the Beddoes
wake model [37] and Vatistas implementation of the Biot-Savart law [38]. Finally, an
ad-hoc HSI noise model can be used after an initial run of PSU-WOPWOP to account
for transonic effects on noise.

Once those calculations are complete, WOPIt then also creates the file directory
structure necessary for PSU-WOPWOP runs. As WOPIt can process multiple runs
at once, it builds the file directory tree for PSU-WOPWOP to populate, creates the
PSU-WOPWOP namelists, and then executes PSU-WOPWOP.

3.2.3 NDARC noise prediction system

As the design of the system intended to make execution as straightforward as possible,
the entire system is run using one bash script (Linux). This allows for multiple design
cases to be run all at once without any additional work by the user. The code reads in
NDARC inputs and NDARC NPS inputs, runs NDARC, extracts the outputs, puts them
through WOPIt, extracts those outputs, runs PSU-WOPWOP, and then places those
results in the final folders. The workflow of the NDARC NPS is depicted in the flowchart
in Fig. 3.3. The methodology of having a single script execute the system reduces the
chances for mistakes to be made, and in this thesis work multiple safeguards were put in
place to stop the system if erroneous data is found.

Figure 3.3. NDARC NPS workflow schematic.
The NDARC NPS also has the added benefit of having several flags to produce plots not normally generated by NDARC or PSU-WOPWOP. As WOPIt conducts calculations of wake, induced velocity, blade loading, inflow, blade flapping, and momentum, the capability to output plots of all these variables was created. All are accessed via a flag in the namelist and use Plot3D format.

Specific PSU-WOPWOP input files are used for the NDARC NPS system. The Pegg model was used to predict broadband noise. Dual compact thickness files were used to predict thickness noise and compact loading files were used to predict loading noise. Besides these specific requirements, any options that PSU-WOPWOP uses for noise prediction and data processing are available within the NDARC NPS.

Coupling NDARC, WOPIt, and PSU-WOPWOP together creates a low-fidelity system for rapid noise prediction in the design stage. All approaches and models used in the NDARC NPS were selected to emphasize rapid calculation while still maintaining accuracy. The next noise prediction system, the Penn State NPS, contains higher fidelity, albeit more computationally expensive, models. Thus the Penn State NPS occupies a different part of the prediction code space than the NDARC NPS.

### 3.3 PSUHeloSim/PSU-WOPWOP noise prediction system

The second noise prediction system used in this work is the Penn State NPS. The Penn State NPS has key differences from the NDARC NPS, but still uses PSU-WOPWOP as the acoustic prediction code. The Penn State NPS also uses HeloSim, which is a flight simulation code written in MATLAB; and CHARM, a comprehensive analysis tool developed by Continuum Dynamics, Inc [6]. The coupling of HeloSim and CHARM is referred to as PSUHeloSim, and contains a slightly modified version of the base HeloSim
flight simulation code. These three tools coupled together creates high-fidelity acoustic predictions that follow trajectories created to simulate actual flight. The three tools used in the system are described in this section, with the work conducted for this thesis described in Chapter 5.

3.3.1 HeloSim

HeloSim is a basic helicopter flight simulation tool created at PSU to generate flight dynamics for various vehicles [39]. Initially, this system used GENHEL-PSU, a modification of the NASA/Army GENHEL flight dynamics model. GENHEL-PSU also interfaced with the CHARM comprehensive analysis code, but was eventually phased out for the HeloSim model as HeloSim is a flight simulation model capable of predicting more complicated flight conditions.

The HeloSim flight simulation uses a 21-state nonlinear model that combines nonlinear fuselage motion, second order rotor flapping dynamics, and a Pitt-Peters inflow model. As the rotor model is post-processed via CHARM, having this lower fidelity system allows for rapid calculation of rotor states that is then later improved via coupling with CHARM. A diagram of HeloSim and how it operates is shown in Fig. 3.4.

The main benefit of using HeloSim is that it uses a nonlinear dynamic inversion control law. A nonlinear dynamic inversion control law is a high performing control model is able to accurately follow desired trajectories in non-standard flight regimes. This method of control is described in detail in Ref. 41. Additionally, to improve the simulation’s ability to match real-world conditions, the ability to follow flight test trajectories was added [42]. The flight test trajectory following method reads in trajectory data from the desired flight test data (in this case the 2017 and 2019 joint NASA/FAA/Army flight tests [43,44]), and matches the position, velocity, acceleration, and heading of the selected flight test trajectory in the flight simulation. As shown by Zachos, the flight
simulation model was able to accurately follow the flight test data for several helicopters flown in the 2019 flight test [42]. This thesis improved the models of the 2017 helicopter and one 2019 helicopter, as explained in Chapter 5.

### 3.3.2 CHARM

CHARM, or the Comprehensive Hierarchical Aeromechanics Rotorcraft Model, is a comprehensive analysis tool developed by Continuum Dynamics, Inc. that models the complete aerodynamics and dynamics of rotorcraft [6, 11, 45]. This tool is used to create a total understanding of a rotorcraft flight state, and generally produces high-fidelity aerodynamic and blade motion results.
HeloSim is coupled with CHARM to produce high resolution airloads that can be used for analysis or as an input to PSU-WOPWOP. The system of the two coupled codes is referred to as PSUHeloSim. CHARM uses a Constant Vorticity Contour (CVC) full-span free-vortex wake method, with a vortex lattice lifting surface blade model [46]. A CVC model creates a vortex sheet that trails from each blade, which eliminates the span-wise and azimuthal separation that marks non-sheet methods. This produces a highly accurate wake prediction for each blade. This is coupled with the vortex lattice lifting surface blade model, which provides high-accuracy models of tip effects and blade-vortex interactions, as the loading on the blade is modeled across the whole surface instead of a single lifting line, unlike what is used in the NDARC NPS.

There are two ways that CHARM can be used when coupled in the PSUHeloSim system. The first method is called the ‘one-way’ or ‘open loop’ method, where HeloSim is run independently and then post processing is computed in CHARM using the outputs from HeloSim. In the second method, the ‘two-way’ or ‘closed loop’ method, PSUHeloSim uses CHARM to calculate the forces and moments used by HeloSim and creates a closed loop system that is able to produce highly accurate airloads [47]. Either method produces airloads able to be processed by PSU-WOPWOP, and so the speed and accuracy of the desired results must be weighed before either method is selected. For the work in this thesis, the closed loop method is always used.

3.3.3 PSU-WOPWOP (Penn State NPS specific)

As with the NDARC NPS, specific methodologies were employed with the use of PSU-WOPWOP. Dual compact thickness files were once again used, but PSUHeloSim uses quasi-periodic multi-time thickness files to predict thickness noise. Additionally, full blade panel loading models were selected to make use of the full capability of CHARM in the PSU-WOPWOP predictions. Additionally, as CHARM outputs new loading values
every half second, a specific moving average windowing function must be used with one-eighth-octave filters. This improves the signal being processed by PSU-WOPWOP, and helps remove erroneous data and numerical errors. The Penn State NPS also has the option of either using the Pegg or BPM broadband model, for this work the Pegg model was used. In addition, all PSU-WOPWOP data processing options were available for use with this system.

3.3.4 Penn State NPS

Combining HeloSim, CHARM, and PSU-WOPWOP creates the Penn State NPS. The system operates by initially running a simplified version of HeloSim to gain control inputs, then running PSUHeloSim, which couples both CHARM and HeloSim. In PSUHeloSim, CHARM is used to produce force and moment values and HeloSim is used to command vehicle trajectories. PSUHeloSim then generates inputs and namelists for PSU-WOPWOP, which is used to create noise predictions. Figure 3.5 shows a diagram of this system and how it operates. This system was first introduced in Ref. 40 and has been developed by several students since then.
Figure 3.5. PSUHeloSim Code layout. From Ref. 48.
Chapter 4
Conceptual design noise prediction system

The NDARC NPS is a conceptual design noise prediction system, as introduced in Chapter 3. The goals of this system is to provide support for noise analysis during the conceptual design of rotorcraft. When revising this system, an emphasis was put on the ability to get solutions rapidly to enable an iterative design process. With this in mind, lower fidelity models were selected to minimize analysis time.

4.1 Initial system design

The work in this thesis builds upon work completed by two previous students. Initial design of the system was completed in 2016 by Kalki Sharma [34]. This work consisted of the creation of the system and the initial coding of the bridge code, WOPIt. Changes were then made by Thomas Jaworski in 2020 in an effort to expand the tool and increase robustness [35]. The system, as it existed before this work, is described here.

The first step to create this system was to develop the coupling code, WOPIt. WOPIt was designed to take information from NDARC, modify and enhance it, and then supply the inputs for PSU-WOPWOP to predict the noise. The goal of the NDARC NPS was
to create a rapid tool; therefore, several simplifications were used, namely the use of a
dual compact thickness assumption to predict thickness noise and a compact loading
model for loading noise. These choices were compatible with the assumptions used in
the design process.

The dual compact thickness model was developed by Tianxiao Yang [36] and models
the thickness noise produced by the rotor as two spanwise lines, one ahead of the
maximum thickness and the other behind the maximum thickness of the blade. and
one on the aft. Yang’s method is inspired by Isom’s thickness noise formulation [49].
The location of the lines is determined by the geometry of the blade, but Yang found
that placing the lines at 13% chord and 87% chord worked well for a large number of
airfoils [36]. The magnitude of the loading vectors along the lines is determined by
integrating the pressure distributions around the front and rear of the blade, with each
corresponding to the nearest line. This magnitude is then represented as force vectors,
which together produce the thickness noise of the blade. This model was found to match
with full-blade models quite well, and it requires significantly less computation time.

The compact loading model in WOPIt is a blade element theory (BET) model that
calculates the forces and moments, including unsteady loading, at each radial station
in the rotor disk. For BET to be used, inflow, blade flapping, blade pitching, blade
rotation, and blade geometry are required. These blade motion parameters are then used
to calculate inflow at the quarter chord position, representing the loading produced by
each airfoil section. This model was created following Leishman’s implementation, which
can be found in Ref. 50, as it was readily accessible and widely used. One drawback to
the base BET model is that it does not account for loading fluctuations caused by BVI.
As an approximation, BVI loading was added separately to the BET loading calculation
using the Beddoes wake model and Vatistas implementation of the Biot-Savart law.

The NDARC NPS also has the capability of predicting high speed impulsive (HSI)
noise. HSI noise is predicted using an ad-hoc model that post-processes noise to account for the shearing caused by approaching transonic Mach numbers. This is a semi-empirical model based on CFD data from Ref. 51.

Finally, the NDARC NPS is capable of broadband noise predictions via the Pegg broadband model. WOPit calculates the blade area, thrust force, and blade tip velocity and provides these values to PSU-WOPWOP, which then predicts the broadband noise produced by the rotors.

At the end of Jaworski’s work [35], there were still several issues in the system that needed to be addressed before release. First, the system required verification that cases in the documentation were consistent with what the system predicted at the end of Jaworski’s work. Verification was also required to catch any bugs or errors in the system before release. Secondly, there was a known issue with the BVI implementation, which required addressing. Finally, before release, a full suite of training materials including manuals, example cases, and example results were required. These issues were addressed as a part of this thesis, and are discussed in the next section.

4.2 Verification of results

The goals of a system verification is to ensure that results are consistent with the documentation results and identify any issues before release. Since, prior to this publication, the system was not released publicly; therefore, it was important to create documentation and training materials with a ‘novice user’ in mind. To complete this verification, the system was provided, along with training materials that had been created by Sharma. Additionally, as a resource and a point of comparison, Jaworski’s thesis was provided. To emulate the plots created in Jaworski’s thesis, four vehicles were created and analyzed. These vehicles were a helicopter, tandem helicopter, coaxial helicopter, and hexacopter.

To reflect the most common aircraft designs, in-depth verification was mainly com-
pleted for the helicopter and tandem helicopter, with fewer cases considered for the coaxial helicopter and the hexacopter. Thirty cases were provided in Jaworski’s thesis, and twenty-five were replicated. To highlight the verification and issue identification process, the helicopter results from the unedited system are presented here with a discussion of the found issues.

It is important to note that when the system was initially developed, issues had been noted with the BVI module. Because of this, the initial verification was conducted with BVI in mind, although any further issues were also identified for the system update.

4.2.1 Helicopter and case description

The first vehicle analyzed in this work is the NDARC example helicopter, which is provided with the NDARC distribution [52]. Since the verification was for the NDARC NPS system and not NDARC, it was important to use an NDARC case that had been thoroughly vetted. Specifications of the main rotor and tail rotor parameters are contained in Table 4.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main rotor number of blades</td>
<td>4</td>
</tr>
<tr>
<td>Main rotor radius</td>
<td>7.62 m</td>
</tr>
<tr>
<td>Main rotor chord</td>
<td>0.58 m</td>
</tr>
<tr>
<td>Main rotor thickness to chord ratio</td>
<td>0.09</td>
</tr>
<tr>
<td>Main rotor rotation speed</td>
<td>28 rad/s</td>
</tr>
</tbody>
</table>

| Tail rotor number of blades            | 4           |
| Tail rotor radius                      | 1.55 m      |
| Tail rotor chord                       | 0.23 m      |
| Tail rotor thickness to chord ratio    | 0.09        |
| Tail rotor rotation speed              | 116 rad/s   |

Table 4.1. NDARC example helicopter specifications from Ref. 52.

Additionally, two cases were analyzed in depth for each study. They will be referred to as ‘segment 5’ and ‘segment 6’ to remain consistent with the NDARC naming convention. Segment 5 is described in Table 4.2 and segment 6 is described in Table 4.3. These two segments were selected as the have the same forward flight and advance ratio, but
different descent rates and angles. Segment 5 is a case that had been identified in Jaworski’s thesis as being a BVI case, whereas segment 6 did not have high BVI. Using two similar cases that had different BVI conditions would allow for comparison when changing the BVI module during the system update.

<table>
<thead>
<tr>
<th>Forward flight velocity (m/s)</th>
<th>25.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advance ratio</td>
<td>0.119</td>
</tr>
<tr>
<td>Vertical velocity (m/s, + climb)</td>
<td>−2.69</td>
</tr>
<tr>
<td>Descent angle (degrees)</td>
<td>5.99</td>
</tr>
</tbody>
</table>

Table 4.2. Flight segment 5 parameters.

<table>
<thead>
<tr>
<th>Forward flight velocity (m/s)</th>
<th>25.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advance ratio</td>
<td>0.119</td>
</tr>
<tr>
<td>Vertical velocity (m/s, + climb)</td>
<td>−0.51</td>
</tr>
<tr>
<td>Descent angle (degrees)</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Table 4.3. Flight segment 6 parameters.

4.2.2 WOPIt verification

To first identify if the vehicle is flying correctly and if the wake is moving through time correctly, helicopter wake plots were produced. The NDARC NPS utilizes a BET loading model and a prescribed wake model to provide low-fidelity but high resolution loading calculations for noise prediction purposes. Wake plots are created by the NDARC NPS to aid in vehicle visualization. In this specific case, the purpose of these wake plots was to identify if the wake modeling was correct. The wake should be skewing away from the vehicle and contracting slightly as it convects in time.

Figure 4.1 depicts the main rotor wake for both segments 5 and 6. Wake modeling is done via a modified Beddoes prescribed wake model [37]. The Beddoes model is a low-fidelity model that tracks the wake shed by the tip of the blade as the blade moves through the air. This model considers critical locations for wake distortion, and then approximates the rest. The base Beddoes wake model is combined with the Vatistas
implementation of the Biot-Savart law [38] and the Landgrebe wake contraction model [53] to provide wake tracking and blade-vortex interaction data. The specific implementation followed was that of Greenwood [54]. The two cases plotted have similar forward velocities and advance ratios, with the only difference being descent rate and angle. Segment 5 contains a $-2.69$ meters per second vertical velocity and a 5.99 degree descent angle, compared to segment 6, which has a vertical velocity of $-0.51$ meters per second with a
1.1 degree descent angle. Based on these flight conditions, the wake in segment 5 should be closer to the rotor disk, which is reflected in the plots.

This initial step gave some information that the wake may have been moving in time correctly, as the wake skew between the two seemed to follow the trend of steep and shallow descent correctly. But, the vertical displacement of the wake may be too extreme, as the vehicle is mainly moving in forward flight. Another geometry consideration for the wake is that of the wake contraction. As the wake convects away from the rotor, it has a tendency to reduce in radius, called wake contraction. For the model used in WOPIt, Landgrebe’s wake contraction correction was used. The wake contraction correction is a term added to the prescribed wake model that accounts for wake contraction as the wake moves away from the vehicle. The rate of contraction is controlled by a constant specified in the WOPIt code, and can be changed to reduce or increase the rate of contraction. The correction term in Fig. 4.1 is slightly more extreme than that expected, so the correction term required refinement.

The next verification step was to examine the induced loading. The wake is first processed by the Beddoes wake model, and is then given a strength to induce changes on blade loading via the Vatistas implementation of the Biot-Savart law [38]. This model gives a strength value to each vortex, and if a blade-vortex interaction occurs, it induces a velocity on the rotor disk. This induced velocity is then accounted for in the thrust produced by the blade, causing a change in loading and therefore loading noise. Figure 4.2 shows the induced velocity and z loading for the main rotor during both segment 5 and segment 6. The induced velocity and z loading disk plots highlight a few issues that required correction in the system. The major issue is the jagged lines along the predicted tip vortex path shown in Fig. 4.2. The jaggedness of the lines are numerical in nature and are inducing non-realistic noise in the prediction. Additionally, blade loading is typically maximum at the blade tips and minimum inboard, but the initial disk plots
depict a maximum at the front of the rotor and a minimum at the back, which was identified as possibly being incorrect.

**Segment 5**

![Segment 5 graphs](image)

**Segment 6**

![Segment 6 graphs](image)

**Figure 4.2.** NDARC NPS unedited system main rotor induced velocity (left) and vertical loading (right) for segment 5 and segment 6.

The final step in the verification process was to analyze the noise prediction results to see the impact these loading issues had on predicted noise. As blade loading only has an impact on loading noise, that was the component selected for analysis. To even further
honed in on the impact of loading, a band pass filter of 125 Hz to 715 Hz was used. This type of filter is frequently referred to as blade vortex interaction sound pressure level (BVISPL), and in this work the frequency range selected spans the 6th through the 40th harmonics.

A hemisphere of observers were used to provide an understanding of the noise directivity below the rotor. In order to better see the information presented in this three dimensional hemisphere, a 2D projection was used. This projection evenly spaces the azimuthal resolution on the $x$ axis and the elevation resolution on the $y$ axis, as shown in Fig. 4.3. This projection, as with many projection methods, distorts the areas of the results, but allows for the analysis of all hemisphere locations without manipulation of the sphere.

Figure 4.4 depicts BVISPL projections for helicopter segments 5 and 6 for a hemisphere of 30 azimuthal observers by 8 elevation observers. All observers are a distance of 10 rotor radii from the center of the main rotor. This plot contains a few spots of maximum noise besides the main hot spot on the advancing side of the rotor, spread across the retreating side of the rotor. While not immediately wrong, it is likely caused by the jagged loading lines, and is likely numerical in nature. Additionally, when compared to the results for segment 6, there is a roughly 10 dB difference in noise between the two when comparing the maximum noise location around 90 degrees azimuth and $-45$ degrees elevation.

With these observed issues in the system, it was decided that the BVI module had to be debugged to fix the problems. The next section goes over the details of the models used in the system, and the results that the changes in the system produced.
Figure 4.3. 3D hemisphere to a 2D projection as used in this work.
4.3 System update

Several changes have been made to the NDARC NPS to prepare it for release. The blade-vortex-interaction model was re-written to fix numerous issues with the implementation. The NDARC NPS system was updated to a more recent version of NDARC and PSU-
WOPWOP, and restructured for future updates. Base resolutions were changed to improve predictions. Several additional minor bug fixes were also implemented that are not discussed in this thesis.

### 4.3.1 Blade-vortex interaction module

The first model that was repaired was a modified Beddoes wake model. This model combines an inflow model with a wake tracking model to predict the location of the shed tip vortices produced by the blade. The modified Beddoes wake model also calculates the induced inflow of these shed tip vortices. This model essentially models the vortex as a line, and ignores viscosity effects.

Equations 4.1 through 4.5 describe the complete calculation for the induced inflow across the rotor disk. \( \chi, \lambda_i, \) and \( \lambda_0 \) must be solved iteratively as the three equations are functions of each other. Iterative solving is done via the Newton-Raphson method, and values of \( C_T \) are pulled from the NDARC output. Additionally, the implementation of the wake model used accounts for wake contraction in the inflow equation, governed by Eqn. 4.4. Each equation is detailed in the following paragraphs.

\[
\lambda_i = \lambda_0[A\chi(\cos(\psi) + |r_v\sin(\psi)|^2) + 2B\mu_z\sin(\psi) + C] \tag{4.1}
\]

\[
\lambda_0 = \frac{C_T}{2\sqrt{(\mu_z + \lambda_i)^2 + \mu_x}} \tag{4.2}
\]

\[
\chi = \tan^{-1}\left(\frac{\mu_x}{\mu_z + \lambda_0}\right) \tag{4.3}
\]

\[
r_v = r_r[D + (1 + D)e^{-\lambda_1\phi}] \tag{4.4}
\]
The induced inflow over the rotor disk is described by Eqn. 4.1. Equation 4.1 is a slightly modified version of Beddoes’s method that uses constants to allow for refinement of the inflow distribution. A represents the longitudinal component of the prescribed linear distribution of inflow, B represents the lateral component, and C represents the mean component. These constant scaling factors allow for a more exact matching of inflow, and different values were tested to give the most accurate result. With respect to this work, the values of $A = 0.5$, $B = 1$, and $C = 1.1$ were used. The implementation used and the values for $A$, $B$, and $C$ were selected to match the implementation of Ref. 54. This model tracks the wake using two angular values, $\psi$ and $\phi$. $\psi$ is the azimuthal station where the inflow is being calculated and $\phi$ is the wake age, found by subtracting the azimuthal vortex location ($\psi_v$) from the azimuthal blade location ($\psi_b$).

The induced inflow equation also requires a mean inflow calculation, shown in Eqn. 4.2. The mean inflow is the average inflow across the rotor disk and is calculated via momentum theory. The mean inflow accounts for the base loading across the rotor disk due to thrust. This is then used to scale the induced loading used in Beddoes’s wake model. Both equations are solved iteratively together with the wake skew equation.

The final equation required for the Beddoes’s implementation is the wake skew angle calculation, $\chi$. As wake progression roughly maintains the shape of the rotor disk, a rough cylinder is formed as the vortices convects. The wake skew is the angle between the center of this wake cylinder and the rotor disk, and changes for different descent angles and descent rates. Wake skew angle gives a mean prediction of what angle the wake is from the rotor disk, measured from the rotor plane to the center of the vortex cylinder.

Before the location of each shed tip wake can be calculated, there is one final parameter.

$$\lambda_1 = 0.145 + 27C_T$$ (4.5)
that must be taken into account, and that is wake contraction. As a wake moves away from a rotor, the wake has the tendency to shrink or contract. Landgrebe created a semi-empirical method that calculates the radius of the shed tip vortex geometry in hover as it moves away from the rotor [53]. This implementation is found to hold well for forward flight conditions as well, and is used in Eqns. 4.4 and 4.5. Different values of $D$ and $r_r$ can be used to refine this contraction parameter. For this work, a $r_r$ of 0.98 was used (a value of one would refer to no contraction), and a value of $D = 0.8$ was selected to remain consistent with the Greenwood’s implementation.

As the inflow and wake has been calculated, the geometry of the shed tip vortices was then predicted for each azimuthal step around the rotor. The $x$ and $y$ geometry of the wake was slightly altered by wake contraction, but were otherwise unaltered by the inflow across the rotor, as seen in Eqn. 4.6 and Eqn. 4.7.

$$x = r_v \cos(\psi_v) + \mu_x \phi$$

$$y = r_v \sin(\psi_v)$$

The $z$ location of the wake is the most altered by inflow, and contains the entire induced inflow term in it’s calculation. The $Z$ location is recalculated for each step of the wake. This specific equation only holds for wake tracking over the rotor disk and below the rotor. Any wake element above the rotor is not considered in this implementation.

$$z = \mu_z \phi - \lambda_0 [A \chi(\cos(\psi) + |r_v \sin(\psi)|^3) + 2B \mu_x \sin(\psi) + C] \phi$$

When implemented in WOPIt, the new wakes for segment 5 and segment 6 were produced, as shown in Fig. 4.5. These wakes contract less than those in Fig. 4.1, as a different value of $r_r$ was selected. Additionally, there is much more wake interaction that
would cause BVI in these wakes than the previous version. As segment 5 is a maximum BVI case, and segment 6 also has weak BVI, it seems logical that both would show wake interactions in the side profiles. But, it does appear that the advance ratio between Fig. 4.1 and Fig. 4.5 may be different. Although an effort was made not to alter flight condition during implementation changes, the advance ratio between the two runs should be verified to ensure the accuracy of the wake changes. Additionally, validation with other known wake tools must be completed, but general improvement has been found.

Once the wake model was completed, changes to the velocity induced on the blade as it moves around the rotor disk were made to account for the viscous vortices shed by the blade tips. As previously mentioned, viscous vortex calculation was done via Vatistas implementation of the Biot-Savart law [38]. Equation 4.9 is the governing equation of the induced velocity due to a viscous vortex. This induced velocity is added to the inflow velocity on the blade to account for vortices in both the blade induced velocity and $z$ loading.

\[ v_\theta = \frac{\gamma \nu r}{2\pi (r^2 + r^2) \frac{1}{\pi}} \]  \hspace{1cm} (4.9)

\[ \gamma_v = \frac{-dfz}{\rho\Omega R} \]  \hspace{1cm} (4.10)

Vatistas implementation combined with the Beddoes wake model creates the perpendicular velocity and $z$ loading seen in Fig. 4.6. The first noticeable difference between these disk plots (Fig. 4.6) and those of the previous implementation (Fig. 4.2) is that the new $z$ loading plots do not contain the numerical issue present in the previous implementation of the system. As suspected, the choppy loading lines present in the previous version were caused by implementation errors in the code, and by rewriting that section, the errors were removed. The noise predictions of the NDARC NPS will no longer have an influence from these numerical issues.
The next notable change between Fig. 4.6 and Fig. 4.2 is that segment 5 now contains more vortex passages. In the previous implementation, segments 5 and 6 had a similar amount of vortex passages, whereas now there are significantly more passages in segment 5, implying more possible BVI events. Additionally, repairing the inflow and induced loading model caused the blade loading to be more balance fore and aft, with loading maximums at the blade tip. One final difference between the two implementations is that
the new implementation (Fig. 4.6) contains more tip vortex passages on the advancing side of the rotor disk, centered around $\psi = 90^\circ$ and depicted in red. The previous implementation (Fig. 4.2) contained a nearly symmetric loading disk.

The next required step for this system would be a validation of these implementations with CFD or a comprehensive analysis code to verify the wake shape and BVI location.
A full validation would lend credibility to loading and BVI module used in the present implementation. The final step in the analysis of the re-implementation was to analyze the noise hemispheres produced by segments 5 and 6.

Figure 4.7 depicts a 2-D projection of a hemisphere of loading noise for a grid of 30 azimuthal by 8 elevation observers with a band pass filter from 125 Hz to 715 Hz. As expected, the maximum BVISPL is on the advancing side below the rotor, where BVI noise has the most impact. The spikes in noise around 300 degrees azimuth are no longer present. It is interesting to note that the changes to the system increased the differences in noise between segment 5 and segment 6, where the maximum noise from segment 5 is around 82 dB, and the maximum in noise in segment 6 is about 50 dB. This increased difference shows how large an impact BVI can have on noise prediction.

4.3.2 Other updates

An additional change made was to upgrade the system to work with both NDARC v1.15 and PSU-WOPWOP v3.4.4. As WOPIt reads in information from NDARC and creates the inputs for PSU-WOPWOP, changing those codes requires changes within WOPIt as well. Namely, the formatting and information of the NDARC .out file and the formatting of the PSU-WOPWOP input namelist and COB files were changed. While configuring this within the code, restructuring of the code was also completed. Initially, reading in NDARC information and creating PSU-WOPWOP inputs was spread about the code. In order to ‘future proof’ the code, these data structures were grouped into one Fortran module. This allows for easy changes to the system for future NDARC updates. Additionally, the system was changed from being a Windows tool to being a Linux tool. This was done to make the code accessible to Linux users, which includes several of the U.S. Government labs that may use the system.

The second additional change was altering the resolutions of various variables to
Figure 4.7. BVISPL hemisphere projections for segment 5 and segment 6. Includes system changes.

ensure a smooth output. This was done in conjunction with the re-implementation of the BVI model, as the azimuthal resolution between each calculation of both the blade and wake had an impact on BVI modeling. The system now uses fifty radial stations along the blade, computes a wake line for every one degree of rotation, and computes
wake interactions for every one degree of blade movement. This resolution was selected to match Ref. 54, and was found to give the best results without noticeably increasing computational time.

4.4 Documentation and user interface

The final task of this work was to create a full distributable package for the NDARC NPS and to make changes to the system with a user in mind. This package included a complete build of the system, a suite of completed example cases, and a users manual. Additionally, changes in the user interface were made to improve the experience of a system user. A system distribution had not been created since Sharma in 2016, and the documentation and examples required changes to include the updates to the system since then.

The first step when creating a distribution of the system to was to improve the user interface. This work began from the viewpoint of a ‘novice user’ and this mindset was continued when developing the user interface. One challenge when a new user begins to use the system is understanding when and how a case has failed. To provide this information, run segmentation was added to separate the different run segments of the system and stop the run if the outputs of a previous segment failed to be created. Additionally, various error messages were added within WOPIt to give the user a better understanding of their cases and where the error might have occurred.

Figure 4.8 shows the output of an example run of the system. Although the exact length of the output of each code changes depending on the debug flags set by the user, the structure of the output will remain the same. The first three lines of Fig. 4.8 show the clearing of the directory tree, as the system requires a clear directory in which to build the predictions. Then, lines 4-6 are where any command line outputs from NDARC will appear. Lines 7-20 are the command line outputs from WOPIt, lines 22-59 the
outputs from PSU-WOPWOP, and lines 60-61 the command line outputs from ShearIt. This clear separation of codes enables a user to follow the debug outputs of each code and clearly find where any errors are encountered.

Figure 4.8. NDARC NPS system run output.

The next step in creating the system distribution was to create a full suite of training materials. As the system has had many changes and has been upgraded for both NDARC and PSU-WOPWOP, recreating the example cases and adding a few additional cases was
necessary. The users manual walks a user through twenty different uses of the NDARC NPS, and it was necessary to update those cases before making changes to the users manual.

As this suite of examples is designed for a user that has never used NDARC, PSU-WOPWOP, or the NDARC NPS, the first eleven example cases walk a user through introductory cases. The first eleven cases are as follows:

- Case 1: Walks a user through building the path directory for a NDARC NPS run and execute an NDARC NPS run
- Case 2a: How to change the NDARC case being executed
- Case 2b: How to specify which NDARC sections to run within an NDARC run
- Case 3: Rotor selection and how to enumerate different rotors
- Case 4: How to analyze specific rotor components
- Case 5: Different noise source options and how to flag them
- Case 6: Running a case for a single observer specified by an Cartesian location
- Case 7: Using a rectangular observer grid
- Case 8: Using a spherical observer grid
- Case 9: Attaching an observer to the vehicle in motion
- Case 10: Running the noise prediction for a specific time period (either as a function of blade period or seconds)
- Case 11: How to segment an analysis period for averaging over increments
While these cases are very simple, they give a new user a comprehensive understanding on how to build a desired case before moving to more useful runs. The next 9 cases go through more complicated cases and the outputs they produce. The cases are as follows:

- Case 12: Producing an acoustic pressure time history over one rotor period for a single observer attached to the aircraft

- Case 13: Creating a sound pressure level spectrum for the same observer as case 12

- Case 14: Using the segmentation from case 11 to produce an overall sound pressure level (OASPL) plot

- Case 15: How to create an OASPL plot for a flyover where the observer is in a fixed position and the vehicle 'flies over' it

- Case 16: Using the same observer as case 15, creating an effective perceived noise level and perceived noise level plot

- Case 17: Making a hemisphere of observers attached to the vehicle and processing the OASPL at each location to create an OASPL hemisphere plot - this is then plotted onto a 2d projection over azimuth and elevation

- Case 18: using ShearIt to processes HSI noise into an acoustic pressure time history plot

- Case 19: Analyzing a BVI case for a single observer - includes creating an acoustic pressure time history plot, a $z$ loading disk plot, an induced perpendicular velocity plot, and a blade and wake plot

- Case 20: How to attach a reflective wall to emulate flight test measurements and compare with Bell 430 flight test data for an OASPL plot
All of the example cases were then documented in the User’s Manual (Appendix A) to give a new user a complete demonstration of the system as it operates. Each case contains the inputs, the namelist variables, and if applicable, the plots they should produce.

The User’s Manual also contains other pertinent information for a user of the system. First, the manual reviews the steps for compiling the source code of WOPIt. While a new user will not always be sent the source code, the instructions for building were included for completeness and to assist the next developer of the system. The next instructional steps explain how to build the code directory structure for the NDARC NPS, as having the directory structure built correctly is necessary for running the code. The User’s Manual explains the lines of the bash script used to execute the code, as this needs to be changed to be consistent with the user’s operating system. This manual is then packaged with all example cases, the code itself (without NDARC), and some instructional documents to help a new user navigate the system for the first time. The User’s Manual in its entirety is included in Appendix A.
Chapter 5  
Flight simulation coupled noise prediction system

In this chapter, the studies conducted using the Penn State NPS are described. The goals of the research are introduced and the previous work that has been conducted is reviewed. Then, a study of the differences between the noise of a flight test following trajectory and a steady commanded case was conducted for longitudinal accelerating descent cases. Finally, a study on the effect of vehicle weight class on noise was conducted for four helicopters: the Bell 407, the Sikorsky S-76D, the Bell 205, and the Bell 206. This study was conducted following flight test trajectories of a low noise approach flight condition. Both these studies were conducted with the goal of understanding noise abatement procedures in helicopters and the effectiveness of low-noise maneuvers.

5.1 Research objectives and previous work

Understanding and reducing helicopter noise is necessary for the increased acceptance of helicopter use in urban areas. The *Fly Neighborly Guide* aims to provide guidance on the development of noise abatement trajectories and to encourage the use of low-noise maneuvers to reduce community annoyance [4]. In order to provide the necessary data
to help with the development of such maneuvers, the Aviation Sustainability Center (ASCENT), created research programs to analyze flight test data and use prediction systems to better understand helicopter noise.

Much of the methodology for understanding rotor noise comes from acoustic flight testing, which can be costly and time consuming. As such, there is a desire for a purely computational tool to predict realistic helicopter noise. To fill this desire, the Penn State NPS was developed. The system is able to use flight simulation to predict noise from helicopter models, compare the predictions with measurements of existing vehicles, and thus increase the understanding of the noise produced by these vehicles.

A previous study, conducted by Botre, introduced time-dependant capabilities to the system so maneuvers could be “flown” [48]. Then, a checkout of the system was done for various flight conditions including level flight, descents, turn, and various combinations of the three. Noise predictions for the Bell 407, Airbus AS350, Robinson R66, Bell 206L, and Robinson R44 were completed and compared with flight test data from the 2017 NASA/FAA/Army flight test of light weight vehicles [43]. Some conclusions on the noise produced by these vehicles were drawn.

A second study conducted for this objective was completed by Zachos [42]. This work improved the ability of the Penn State NPS to follow trajectories recorded by flight test data. Flight test trajectories allow for the inclusion of non-standard responses in the flight simulation. Unexpected stimuli such as gusts, weather, and vehicle responses make it challenging for a pilot to fly a perfect flight trajectory every time, and these responses may induce changes in noise not predicted by a standard flight simulation. Additionally, models for medium weight helicopters were developed, namely the Sikorsky S-76D and the Bell 205, in particular. The noise predictions for these vehicles were validated against the 2019 NASA/FAA/Army flight test data for various maneuvers [44]. Finally, Zachos conducted a comparison between the Sikorsky S-76D and Bell 407 was conducted to
begin an analysis of the impact of vehicle weight class on noise. A similar study was conducted between the Bell 205 and the Bell 206, but only for level flight.

As there are many different parameters and studies that can still be conducted for a variety of vehicles; hence this work is ongoing. Two major studies were conducted as a part of this thesis to improve the understanding of helicopter noise. The first study examined short longitudinal and vertical accelerations and analyzed the impact these movements have on noise. This analysis of accelerations was done in conjunction with several parametric studies, which conducted acceleration sweeps to understand the influence of small acceleration changes on noise. These parametric sweeps and their conclusions can be found in Ref. 55. The second study examined the differences in noise for approach for four different vehicles: the Bell 407, Sikorsky S-76D, Bell 205, and Bell 206. The Sikorsky S-76D and Bell 205 are medium weight class vehicles, while the Bell 407 and Bell 206 are light weight class vehicles. By comparing noise predictions of these four vehicles during a low-noise approach, conclusions may be drawn about the impact vehicle weight class can have on noise.

5.2 Impact of longitudinal and lateral accelerations on noise

A major source of noise for any given helicopter is loading noise, caused by the accelerating loading force due to the blades as they provide lift and thrust. This loading force can be influenced by any given number of conditions, with vehicle acceleration being one such mechanism that can affect noise. Research conducted by Gopalan [56] and Pascioni et al. [57] found that flight path angle (FPA) correlated with BVI noise. Gopalan conducted his study using a simulation system and Pascioni analyzed flight test data from the 2019 NASA/FAA/Army flight test.
Gopalan found that inducing a longitudinal acceleration over a rotor caused an effective change in flight path angle. The effective flight path angle ($\gamma_{eff}$) combines flight path angle and acceleration in one variable, shown in Eqn. 5.1.

$$\gamma_{eff} = \gamma + \frac{\dot{V}}{g}$$

(5.1)

The rotor state is influenced by longitudinal acceleration through Eqn. 5.2. Gopalan used the $x$ force equation to create his equation for $\gamma_{eff}$. As the thrust on the rotor is influenced by the drag, flight path angle, and longitudinal acceleration on the vehicle, introducing a longitudinal acceleration will induce a change in thrust proportional to a change in flight path angle (if weight and thrust are assumed equal).

$$-T\alpha_{TPP} = D_f + W\gamma + m\dot{V}$$

(5.2)

The final influence on thrust that must be considered is the flight path angle rate of change ($\dot{\gamma}$), which can be induced by a vertical acceleration. Originally derived by Schmitz [58], Eqn. 5.3 gives a relation between thrust and $\dot{\gamma}$. As $\dot{\gamma}$ and vertical acceleration can be equated, this creates a change in thrust due to vertical acceleration.

$$T = W + mV\dot{\gamma}$$

(5.3)

As the helicopter requires more thrust, an increase in loading is required, which leads to a change in loading noise. While BVI has already been identified as major contributor to loading noise that is affected by acceleration, the other influences of acceleration on noise, such as changes to $x$ force and $z$ force, should be explored.
5.2.1 Flight test prediction variations due to acceleration

Flight simulations typically follow a nominal trajectory; however, during a flight test there are several other inputs that may influence the trajectory, including pilot induced deviations, atmospheric turbulence and gusts, etc. The unplanned changes to the flight trajectories will likely lead to changes in FPA ($\gamma$) and FPA rate ($\dot{\gamma}$) which in turn have been shown to affect the noise radiated by the aircraft. In this work, a comparison between flight test trajectory data from the 2019 NASA/FAA/Army flight tests are compared with steady flight simulations to assess the differences experienced by the main rotor and the changes in aircraft noise for a Sikorsky S-76D helicopter.

The Penn State flight simulation and noise prediction system has the capability to follow flight test trajectories. Trajectory following is done by commanding inputs every 0.6 seconds that follow the trajectory data from a flight test. Then, ten seconds are added to the beginning and five seconds to the end of the flight to allow for stabilization of the model. This method has been found to match well with flight test data [42]. Processing flight test information in this manner allows for component-wise analysis of noise sources while maintaining the variation found in the flight test.

The Sikorsky S-76D helicopter flown in the 2019 joint NASA/FAA/Army flight test was modeled in PSUHeloSim, as described in detail in Appendix D. The model was commanded to match a 70 knots, 6 degree descent case in PSUHeloSim. A small section of the flight path (25-30 seconds) was selected for analysis as the time range captures when the vehicle transitions from forward flight to descent, and experiences several different accelerations. Variation was contained between 0° and $-3^\circ$ for the flight path angles (though effective FPA was outside this range) and FPA rates ranged from $\pm 1$ deg/s.

The flight test simulation prediction was then compared to a “baseline” case ($-6^\circ$ descent with $\dot{\gamma} = 0$ deg/s). Unlike the flight test simulation prediction, this case contains
no accelerations; hence a constant flight trajectory is used to compare with the flight test simulation prediction. This comparison was begun by contrasting the flight path angles between the two cases. The effective flight path angle ($\gamma_{\text{eff}}$) for the selected time span is shown in Fig. 5.1. As expected, the baseline flight case (shown as an orange dashed line) contains both a constant effective flight path angle and a zero flight path angle time rate of change. The baseline model experienced no longitudinal acceleration to induce an effective flight path angle offset. The baseline case was compared with the flight test trajectory following prediction values (shown in blue). The actual and effective flight path angle varied due to the accelerations experienced by the vehicle. These adjustments depict induced variation experienced during flight testing. Over the selected span of time, the flight test following prediction experienced both a positive, negative, and a near zero time rate of change of effective flight path angle. Additionally, the prediction captured the variation in the flight path angle caused by longitudinal acceleration changes.

To understand the effects these flight path angle changes have on the prediction noise, a comparison of the forces and moments on the main rotor was analyzed. Figure 5.2 depicts the magnitude of the average force differences of the main rotor from the baseline across the three time periods. For all three time segments, there is no significant difference in the $x$ and $y$ forces on the main rotor compared to the baseline. The $z$ force (thrust) on the rotor, which varies by as much as 550 lbs from the baseline case, is potentially significant according to the parametric studies conducted previously. The thrust changes, caused by the flight path angle changes throughout the time span, provides insight regarding what changes in noise are expected.

The load distributions along a rotor blade for one revolution are shown in Fig. 5.3. The first time segment (at 25 seconds, with the lowest change in vertical thrust) shows rapid blade loading fluctuations at $\psi = 45^\circ$ and $\psi = 315^\circ$. These fluctuations suggest that BVI is present during this test case. The fluctuations are more pronounced compared
Figure 5.1. Effective flight path angle between baseline and flight test prediction. Three selected time spans highlighted. 70 knots, $-6^\circ$ FPA.

to the baseline case. The overall magnitude of the loads along this blade are slightly lower than the baseline case. The parametric studies (conducted in the first portion of Ref. 55) indicated this would result in lower loading noise, though the existence of higher BVI at this time step may alter this conclusion.

The blade loads for the second time step changed the most from the baseline, according to the total magnitude shown in Fig. 5.2. This time section has significantly less BVI
than the baseline case and shows a slight increase in loads along the blade tip but an overall loading reduction across the span. The reduction in BVI is expected to reduce the blade loading noise. However, the slight change in blade loads at the tip is expected to provide an increase in loading noise for this time segment according to the parametric studies [55]. It was predicted that these two loading noise changes would cancel each other out when the total loading noise was calculated, resulting in a similar total noise prediction between the baseline and the second time step, as shown later in this section.

The final time segment (29s) also experienced a 300 lbs change in vertical rotor force. This change in force manifests as a decrease in loads at the blade tip (compared to the baseline case) and more rapid fluctuations in blade loads at $\psi = 45^\circ$ and $\psi = 315^\circ$. According to the parametric studies, the increased negative magnitude of the blade loads at the rotor tips should result in an increase in loading noise [55]. The presence of BVI in this case will also likely cause a larger magnitude noise change.

As shown previously, a negative FPA rate creates a negative addition to thrust (as
Figure 5.3. Vertical component of blade loads predicted by CHARM for specified time steps and baseline comparison case. S-76D 70 knots, $-6^\circ$ FPA, three selected time periods seen in Eqn. 5.3). The lower FPA rates present in time segment 1 and 3 lead to a decrease in thrust magnitude. The higher FPA rate in time segment 2 increases the magnitude of the main rotor thrust, bringing the overall loading distribution closer to zero magnitude. However, for these flight test conditions, there is also a steady FPA change caused by longitudinal acceleration (Eqn. 5.2). According to the longitudinal acceleration parametric studies, a negative change in FPA leads to a small positive
addition to thrust [55]. The larger FPA experienced in time segment 1 causes a reduction in thrust magnitude. Time segments 2 and 3 predicted smaller FPA; therefore, there is a smaller reduction in thrust.

To analyze the affect these changes in thrust have on noise, a hemisphere of noise predictions was created for each time segment. The hemisphere contains observers located 10 main rotor radii away from the main rotor hub that move with the vehicle. The hemisphere was then projected onto a 2D plane via a stereographic projection, which is completed by placing each observer at equally spaced azimuth and elevation locations. OASPL values calculated with a 0.5 second window, were selected for this study to show the noise produced by the helicopter main rotor and tail rotor at a snapshot in time. These noise predictions were then separated into each noise component (thickness, loading, Pegg-Broadband, and total noise) for analysis, as shown in Fig. 5.4. There is very little change in thickness and Pegg-broadband noise across the three time segments. Furthermore, neither thickness nor broadband noise contribute significantly to the total OASPL. This is consistent with the conclusions from the parametric studies conducted in Ref. 55.

Loading noise is the only noise component to change over each of these time steps. Difference hemispheres for this study were created by subtracting the predicted OASPL dB levels for the baseline case from the OASPL predictions for the three times in the flight test prediction (see Fig. 5.5). A positive OASPL difference value (red) represents an increase in noise from the baseline, and a negative difference value (blue) represents a decrease in noise. As the baseline hemisphere in Fig. 5.4 reflects a steady flight condition, the noise does not change over time. The baseline hemisphere contains noise maximums (shown in dark red) directly below the rotor on the advancing side and minimums (shown in dark blue) in-plane on the retreating side of the rotor.

As predicted by the changes in thrust shown in Fig. 5.2, the third time segment has
Figure 5.4. Stereographic projection of OASPL hemispheres for flight test prediction. Loading, thickness, Pegg-broadband, and total OASPL. S-76D helicopter, 70 knots, $-6^\circ$ FPA. Hemisphere radius of 10 MR radii with 18 azimuthal stations and 9 elevation stations.
Figure 5.5. Stereographic projection of loading OASPL hemispheres. Baseline, flight test prediction, and difference. S-76D helicopter, 70 knots, $-6^\circ$ FPA. Hemisphere radius of 10 MR radii with 18 azimuthal stations and 9 elevation stations.
the largest increase in noise of all three time segments (6 dB). The first time segment, where thrust was also increased, shows an increase in noise in several locations. The noise increase for the first time segment is smaller in magnitude than the third time segment. The second time segment shows an overall decrease in noise, corresponding with the largest decrease in thrust. This is the most significant change in noise, with a decrease of up to 8 dB being predicted. At this segment, both FPA and FPA rate contribute to the loading noise reduction.

These trends all suggest that during flight, changes to aircraft state occur (around the nominal or desired state), and these changes have an effect on noise. Unlike a steady condition, changes in both longitudinal and vertical acceleration influence the thrust on a rotor via effective flight path angle and flight path angle time rate of change. These changes can lead to either an increase or decrease in noise, depending on if the introduced flight path angle change causes a positive or negative change in thrust. Additionally, a relatively small change in thrust (only a few hundred lbs, which is roughly 1%-5% of the weight of the helicopter) can induce a significant change in loading noise (8 db in this study). Further studies should be conducted to better understand how much these introductions of acceleration can alter the noise on a rotor for a multitude of flight conditions.

5.3 Helicopter configuration approach maneuvers

Another study conducted using the Penn State NPS was an analysis of the impact of helicopter configuration on noise. For this study, four vehicles were selected. Two medium weight class vehicles (the four-bladed Sikorsky S-76D and the two-bladed Bell 205) and two light weight class vehicles (the four-bladed Bell 407 and the two-bladed Bell 206L3) were chosen. These vehicles were selected as they were validated for the Penn State NPS (see Ref. 42 and Ref. 48), and because flight test data is available from the 2017 and
5.3.1 Case selection

The goal of this study was to compare models that mimic actual flight patterns for the four vehicles, thus cases were selected that aimed to fly the same trajectory. Due to the nature of flight test trajectories, it was not always possible to fly the exact desired condition because of deviation in the helicopter controls, wind gusts, etc. The case that was selected was nominally a 110 ft/sec, −9 degree descent case. Five second spans of near consistent parameters were prioritized if possible, but some variation was allowed.

Each of the four vehicles was first processed through the HeloSim MATLAB script, then ran in the PSUHeloSim system (coupling with CHARM). Then, the necessary parameters were passed through to PSU-WOPWOP for acoustic processing. Each vehicle must be modeled in HeloSim in order to compare flight test data to simulation prediction. Modeling is completed by reading in vehicle parameters to the HeloSim MATLAB script, and then commanding the vehicle to fly the prescribed trajectory from flight test data. Several changes were made to the HeloSim and CHARM helicopter models to improve predictions, explained in Appendix D.

The characteristics used for the four vehicles used in this study are described in Table 5.1. These values were selected from resources available publicly and may not be exactly those of the flight vehicle, but match the vehicle as it was run in the Penn State NPS.

The parameter given the highest priority when selecting cases was vehicle velocity. The parameters that were held constant for all cases were velocity and flight path angle. As these parameters would drastically influence the noise produced by the rotor disk, they were held as constant as possible to minimize their impact on noise. For this study, an x velocity near 110 ft/sec, a y velocity near 0 ft/sec, a z velocity near −17 ft/sec, and a flight path angle near −9 deg was selected. This case was chosen as there were several
Table 5.1. Vehicle parameters as used in the Penn State NPS.

<table>
<thead>
<tr>
<th></th>
<th>Sikorsky S-76D</th>
<th>Bell 407</th>
<th>Bell 205</th>
<th>Bell 206</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (lbs)</td>
<td>10,687</td>
<td>3,600</td>
<td>7,460</td>
<td>3,300</td>
</tr>
<tr>
<td>MR # of blades</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>MR radius (ft)</td>
<td>22</td>
<td>17.5</td>
<td>24</td>
<td>16.67</td>
</tr>
<tr>
<td>MR thickness to chord ratio</td>
<td>9%</td>
<td>12%</td>
<td>12%</td>
<td>12%</td>
</tr>
<tr>
<td>MR chord length (ft)</td>
<td>1.29</td>
<td>0.90</td>
<td>1.75</td>
<td>1.00</td>
</tr>
<tr>
<td>MR rotation speed (rad/sec)</td>
<td>32.83</td>
<td>43.25</td>
<td>33.93</td>
<td>41.26</td>
</tr>
<tr>
<td>MR tip speed (ft/sec)</td>
<td>722</td>
<td>757</td>
<td>814</td>
<td>688</td>
</tr>
<tr>
<td>TR # of blades</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>TR radius (ft)</td>
<td>4</td>
<td>2.71</td>
<td>4.25</td>
<td>2.7</td>
</tr>
<tr>
<td>TR thickness to chord ratio</td>
<td>12%</td>
<td>12%</td>
<td>12%</td>
<td>12%</td>
</tr>
<tr>
<td>TR chord length (ft)</td>
<td>0.721</td>
<td>0.5</td>
<td>0.7</td>
<td>0.4</td>
</tr>
<tr>
<td>TR rotation speed (rad/sec)</td>
<td>261.8</td>
<td>261.8</td>
<td>174.04</td>
<td>261.8</td>
</tr>
</tbody>
</table>

flight test runs that contained these flight conditions for each vehicle.

Main rotor forces and moments were also analyzed. These were used as a verification method of the models used. Specifically, as $z$ force is roughly meant to be on the order of the weight of a vehicle, it was used to verify the forces on the rotor.

The positions and velocities of the four vehicles for each time span are shown in Fig. 5.6. Plots are shown in the North-East-Down (NED) reference frame, and are shown for a five second time span. Flight test data trajectories have been transformed from the flight test reference frame to the HeloSim NED reference frame. Positions are shown in ft, and velocities in ft/sec. Most have smooth velocity trajectories, with exception of the Bell 205, which has some slight variation in the $z$ velocity direction. Averaged values are then calculated for these five second spans, and presented with each vehicle description.

Next, the forces and moments on the main rotor were processed. These are shown in Fig. 5.7. All four vehicles are shown for a selected five second span that contained the best match to the desired parameters, as shown in Fig. 5.6. With exception of the Bell 205, all forces and moments are shown for the same $y$ axis ranges. Forces are calculated in lbs and moments are calculated in ft-lbs. As the Bell 205 force and moment predictions contain some errors, a different span had to be used to show the values produced by
Figure 5.6. Position and velocity in NED frame for four analyzed helicopters. Each time segment is 5 seconds.
PSU-HeloSim. The Bell 205 model prediction resulted in very high peak-to-peak values for the $x$ and $y$ moments experienced by the vehicle. These large peak to peak values are leading to an expected over-prediction of moment magnitude, which will be discussed in the vehicle description.

The velocities, forces, moments, and flight path angles for the four vehicles were then analyzed for both proximity to desired values and validity. This was done by examining the trajectories in Fig. 5.6 and Fig. 5.7. Additionally, values were averaged over their 5 second times spans to give a numerical value that is easy to compare between vehicles. These averages and discussions of results are presented below.

The first vehicle processed through the Penn State NPS was the Sikorsky S-76D. This is a four-bladed, 10,687 lbs vehicle, and the selected time segment was between 50 and 55 seconds. PSUHeloSim calculated the trajectories based on flight test run 177212 from Ref. 44, a nominally 60 knot, $-9$ deg FPA descent case. Average values for this time segment are listed in Table 5.2. This case represented the lowest flight path angle at $-8.5$ deg, but matched well in velocity for $x$, $y$, and $z$, and was therefore allowed to be the lower limit of the flight path angle range. Forces and moments also fell within the expected values for this vehicle, with $z$ force being on the order of the weight of the vehicle.

<table>
<thead>
<tr>
<th>Position (ft)</th>
<th>Velocity (ft/s)</th>
<th>Force (lbs)</th>
<th>Moment (ft-lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x$</td>
<td>$-479.01$</td>
<td>$dx$ 114.72</td>
<td>$Fx$ 855.99</td>
</tr>
<tr>
<td>$y$</td>
<td>$-25.23$</td>
<td>$dy$ 2.38</td>
<td>$Fy$ 117.63</td>
</tr>
<tr>
<td>$z$</td>
<td>250.19</td>
<td>$dz$ $-17.33$</td>
<td>$Fz$ $-9514.66$</td>
</tr>
</tbody>
</table>

Table 5.2. Average positions, velocities, forces and moments for the S-76D PSUHeloSim prediction over $t = 50$-55 seconds.

The second vehicle processed was the Bell 407. This vehicle, like the S-76D, has a four-bladed main rotor, but is in the light vehicle class at 3,600 lbs. The trajectory for this vehicle was processed to match flight test run 284197, conducted in Amedee field with a nominal trajectory of 60 knots with a $-9$ deg flight path angle [43]. The velocities
Figure 5.7. Main rotor forces and moments for four analyzed helicopters. Each time segment is 5 seconds. (*Bell 205 vehicle using different $y$ ranges to depict forces and moments.)
for this run were close to the desired values, and the flight path angle of $-9.46$ deg also fell close to the desired value. Averaged position, velocity, force, and moment values for the time segment, $t = 75$-80 seconds, are presented in Table 5.3.

<table>
<thead>
<tr>
<th>Position (ft)</th>
<th>Velocity (ft/s)</th>
<th>Force (lbs)</th>
<th>Moment (ft-lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x$</td>
<td>2736.28</td>
<td>104.54</td>
<td>$-513.39$</td>
</tr>
<tr>
<td>$y$</td>
<td>83.47</td>
<td>$-3.20$</td>
<td>$Fy$</td>
</tr>
<tr>
<td>$z$</td>
<td>449.5</td>
<td>$-17.41$</td>
<td>$Fz$</td>
</tr>
</tbody>
</table>

Table 5.3. Average positions, velocities, forces and moments for the Bell 407 PSUHeloSim prediction over $t = 75$-80 seconds.

The third vehicle, the Bell 205, is a 7,460 lbs vehicle in the medium weight class with two main rotor blades. Trajectories were processed to match $t = 50$-55 in flight test run 168144, collected in the 2019 flight test [44]. Nominal values for run 168144 were 60 knots forward flight with a $-9$ deg FPA. The velocities of the PSUHeloSim prediction fell close to the range selected, and the flight path angle of $-8.59$ deg was shallower than desired, but acceptable. Position, velocity, force, and moment averages are shown in Table 5.4.

<table>
<thead>
<tr>
<th>Position (ft)</th>
<th>Velocity (ft/s)</th>
<th>Force (lbs)</th>
<th>Moment (ft-lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x$</td>
<td>-1304.03</td>
<td>116.84</td>
<td>$-551.95$</td>
</tr>
<tr>
<td>$y$</td>
<td>10.24</td>
<td>$-0.09$</td>
<td>$Fy$</td>
</tr>
<tr>
<td>$z$</td>
<td>354.58</td>
<td>$-18.72$</td>
<td>$Fz$</td>
</tr>
</tbody>
</table>

Table 5.4. Average positions, velocities, forces and moments for the Bell 205 PSUHeloSim prediction over $t = 75$-80 seconds.

The final vehicle analyzed was the Bell 206. This vehicle has a two-bladed main rotor and weighs 3,300 lbs. Averaged values over the selected time span of 75-80 seconds are presented in Table 5.5. This time span is from run 277127 of the 2017 flight test and is nominally a 60 knot forward flight with a $-9$ deg FPA [43]. This vehicle contains the highest flight path angle of all the ranges at $-9.86$ deg, but the velocities fall close to the desired value.

Once the vehicles were modeled in HeloSim and processed through the PSUHeloSim system, blade loading information was passed to PSU-WOPWOP for noise calculations.
Position (ft) | Velocity (ft/s) | Force (lbs) | Moment (ft-lbs)
--- | --- | --- | ---
$x$ | $-1086.75$ | $dx$ | $105.23$ | $Fx$ | $-513.39$ | $Mx(L)$ | $401.15$
$y$ | $29.92$ | $dy$ | $-0.88$ | $Fy$ | $81.38$ | $My(M)$ | $-93.11$
$z$ | $204.34$ | $dz$ | $-18.29$ | $Fz$ | $-3423.91$ | $Mz(N)$ | $-245.93$

Table 5.5. Average positions, velocities, forces and moments for the Bell 206 PSUHeloSim prediction over $t = 75-80$ seconds.

Acoustic results from these predictions are presented in the next section.

5.3.2 Noise analysis

The first step in an acoustic analysis of the results produced by the Penn State NPS is to examine the loading results produced by CHARM and visualized by a PSU-WOPWOP sigma surface [33]. As all four helicopters are flying a similar flight trajectory, but have different designs and weights, the presence of BVI is one way that the noise may differ between the vehicles. While the presence of BVI will also be able to be seen in acoustic pressure time history plots, examination of the loading profiles gives a more expansive understanding of the loading environment being experienced by each rotor. Figure 5.8 shows the loading of one blade of each rotor over one rotor period within the selected time span for each vehicle.

The loading disks for the S-76D, Bell 206, and Bell 205 exhibit loading changes that may be attributed to BVI. Blade-vortex passages can be seen as fluctuation in loading across the rotor disk. These passages may not directly cause BVI events, but are possible locations of BVI events, as the vortices are passing close to the rotor disk but do not necessarily cause interactions significant enough for noise. Both the S-76D and Bell 206 exhibit these fluctuations clearly, with the Bell 205 containing fluctuations to a lesser extent. The Bell 407 does not show these fluctuations, and therefore is not likely to contain BVI for this flight condition.

Once the blade loading analysis was complete, single observer acoustic pressure time histories were produced. Three observer positions were selected: one directly in front of
the rotor, one 45 degrees below the front of the rotor, and one directly below the rotor. Each of these observer positions are ten rotor radii from the center of gravity of the vehicle. These three observer locations enable analysis of thickness, loading, and BVI noise. Thickness noise is a maximum in the plane and ahead of the rotor, while loading noise is a maximum 45 degrees below the rotor. Additionally, BVI can be identified as sharp pulses in loading noise, especially 45 degrees below the rotor. The observer directly below the rotor is expected to show almost no thickness noise, but some loading noise.

For each vehicle, thickness and loading acoustic pressure time history plots were produced for the three selected observer locations. The first vehicle processed was the Sikorsky S-76D, shown in Fig. 5.9. As seen in the loading disk plots (Fig. 5.8), this
flight condition exhibits BVI noise, which can be seen roughly every 0.1 second in the loading noise plot. These high magnitude pulses are much higher than the background loading noise, which do not surpass $\pm 2$ Pa, while the BVI peaks become as large as $-11$ Pa peak-to-peak. This shows just how much noise BVI can cause. The BVI condition experienced by the S-76D is expected to be the largest of the four vehicles, based on the blade loading plots of Fig. 5.8.

The thickness noise acoustic pressure time history for the S-76D is periodic in nature, as is expected, and near zero below the observer. This numerical noise can be seen as very slight bumps in the otherwise smooth thickness noise pulses. These bumps are not periodic in nature, and appears even when the tail rotor is not processed for its acoustic contributions, so they cannot be attributed to tail rotor noise. This leads to the conclusion that these bumps are due to numerical calculation errors, and are not a physical contributor to noise.

Next, the Bell 407 was processed for acoustic pressure time histories, shown in Fig. 5.10. Unlike the S-76D, the Bell 407 does not exhibit BVI, and thus the loading noise does not contain the sharp loading spikes associated with BVI noise. This decreases the loading noise, and this vehicle exhibited the lowest loading noise magnitude of all four vehicles. The thickness noise was once again periodic in nature and maximum in plane of the rotor and nearly zero thickness noise directly below the rotor. Also, this vehicle contains numerical errors in the thickness noise plot, which causes the non-periodic bumps in the thickness noise prediction. Finally, the loading noise does not follow the expected trend at 45 degrees below the rotor, where the maximum noise level is expected. For this condition, the maximum level is below the rotor. But, the loading noise is less periodic than the 45 degree case, with more frequent peaks. This increase in noise may be attributed to the main rotor noise being combined with tail rotor noise, causing there to be more loading noise as the observer is located further toward the rear of the vehicle.
Figure 5.9. Sikorsky S-76D acoustic pressure time history loading and thickness noise for an observer in front of, 45 degrees below, and 90 degrees below. Observer distance of 10 rotor radii.
Figure 5.10. Bell 407 acoustic pressure time history loading and thickness noise for an observer in front of, 45 degrees below, and 90 degrees below. Observer distance of 10 rotor radii.
The third acoustic pressure time history prediction was for the Bell 205, shown in Fig. 5.11. The Bell 205 contains very high thickness noise compared to the other vehicles, but as the main rotor blades have a twelve percent thickness to chord ratio and a 1.75 ft chord, they are the thickest and largest blades of the four vehicles, which is a strong factor in thickness noise predictions. Additionally, as seen in Table 5.1, the Bell 205 has a tip speed of 814 ft/sec, the highest of any of the four vehicles. The numerical anomalies in between each peak of thickness noise is the most visible for the Bell 205 and not physical in nature. The loading noise of the Bell 205 does exhibit very slight BVI as is to be expected from Fig. 5.8, but the BVI is much lower in magnitude than that of the S-76D and, therefore, has a smaller effect on noise.

The Bell 206 acoustic pressure time history results are shown in Fig. 5.12. The loading noise acoustic pressure time history does show small BVI noise, as predicted by the loading disk plots in Fig. 5.8. The loading noise below the rotor is similar in magnitude than that of both in front and 45 degrees in front and below the rotor. The noise below the rotor contains more contributions from TR noise than that in front of the vehicle, where the loading noise pulses are much smoother and have a higher magnitude for longer. BVI noise can also be seen for the Bell 206, shown by the sharp loading noise lines at $-45$ degrees and at $-90$ degrees. The Bell 206 has very low magnitude thickness noise, but the thickness noise follows the expected trend of maximum in front of the rotor and minimum below. The thickness noise also exhibits the numerical anomaly between peaks, which has been seen in all of the vehicles.

To conclude the acoustic pressure time history study, the acoustic pressure time histories of all four vehicles for an observer 45 degrees in front and below the rotor are plotted in the same figure in Fig. 5.13. All four vehicles are plotted over the same pressure range for thickness and loading noise to allow for magnitude and shape comparison between vehicles.
Figure 5.11. Bell 205 acoustic pressure time history loading and thickness noise for an observer in front of, 45 degrees below, and 90 degrees below. Observer distance of 10 rotor radii.
Figure 5.12. Bell 206 acoustic pressure time history loading and thickness noise for an observer in front of, 45 degrees below, and 90 degrees below. Observer distance of 10 rotor radii.
When comparing loading noise between the four vehicles, the S-76D contains the highest loading noise due to BVI. This is followed by the Bell 205 and Bell 206, which have much lower BVI at this flight condition, but higher average loading noise. Finally, the vehicle with the lowest loading noise is the Bell 407. If BVI is not considered, the Bell 205 and Bell 206 have the highest loading noise. These two vehicles have two-bladed main rotors; therefore, they have higher individual blade loading than the four-bladed vehicles. Additionally, the Bell 205 has the highest tip speed at 814 ft/sec, which is a significant factor in it being the loudest vehicle. The Bell 206, though, has a tip speed of 688 ft/sec, which is the lowest tip speed of all four vehicles, although it has higher loading noise than the four-bladed vehicles. The Bell 407 has a four-bladed main rotor with a tip speed of 757 ft/sec, the second highest tip speed. The Bell 407 is a light weight class vehicle, and exhibits no BVI at this flight condition. Therefore, it is not surprising it has the lowest loading noise for this flight condition, even with the second highest tip speed.

Thickness noise of the four vehicles, as shown in Fig. 5.13, displays some general trends that can be observed. First, all four vehicles contain the numerical anomalies of small spikes in between peaks, which is due to the calculations and is not physical in nature. Next, the four-bladed vehicles have a shorter period in between peaks, because there are four blade passages per period, while the two-bladed vehicles only have two blade passages per period. The vehicles with the two largest blades, the S-76D (9% thickness to chord ratio (t/c)), 1.29 ft chord, 22 ft radius, and 722 ft/sec tip speed) and the Bell 205 (12% t/c, 1.75 ft chord, 24 ft radius, and 814 ft/sec tip speed) have the highest magnitude thickness noise, with the Bell 205 having the largest thickness noise of all four vehicles. The two smaller vehicles have the smallest thickness noise, with the Bell 206 being the smallest of the four. The Bell 407 contains a blade with a 12% t/c, a 0.9 ft chord, a 17.5 ft radius, and a 757 ft/sec tip speed. The Bell 206 blade has a with a
Figure 5.13. S-76D, Bell 407, Bell 205, and Bell 206 acoustic pressure time history loading and thickness noise for an observer 45 degrees in front and below the rotor. Observer distance of 10 rotor radii.
12% t/c, a 1 ft chord, a 16.7 ft radius, and a 688 ft/sec tip speed.

Now that single observer trends have been analyzed, OASPL values for a hemisphere of observers are explored. The use of a hemisphere enables visualization of the directivity and relative magnitude of noise over a variety of observers. Additionally, A-weighted SPL hemispheres were produced to verify the presence of BVI. A-weighting emphasizes frequencies that are most detectable to the human ear, and BVI noise is in that frequency range. Hemispheres are presented via a Stereographic projection. Each hemisphere contains a grid of 20 azimuthal and 10 elevation locations. Each observer is 10 rotor radii from the aircraft c.g. and the hemisphere is below the vehicle. The front of the rotor is associated with \( \psi = 180^\circ \) and directly below the rotor is associated with the center of the stereographic projection.

Hemispheres are grouped by noise type to easily compare between different vehicles. OASPL ranges are selected to be consistent among all the vehicles for each noise type. Each noise source is be analyzed individually, then the total impact of these sources is analyzed via total OASPL.

The first source to analyze is thickness noise, as depicted in Fig. 5.14. As OASPL ranges are fixed for each of the four vehicles, the the Bell 407 values are too low in magnitude to show much thickness noise. As this vehicle has the smallest chord length and secon smallest radius, the fact that thickness noise is low is not surprising. But, it was expected to be closer in magnitude to the Bell 206, especially because the Bell 407 has the second highest tip speed, while the Bell 206 has the lowest tip speed. Of the four vehicles, the Bell 205 contains the highest thickness noise, reaching about 100 dB of noise directly in front of the vehicle, as is to be expected of the vehicle with the largest blade radius, largest chord length, and highest tip speed. The S-76D has the second highest thickness noise OASPL, about 90 dB in front of the vehicle. The Bell 206 is around 85 dB in front of the vehicle, and the Bell 407 is 73 dB in front of the vehicle. All four
vehicles contain thickness noise maximums in front of the vehicle, which is to be expected. Both the S-76D and Bell 205 contain some noise in a line from 0 degrees azimuth to 180 degrees azimuth. This noise can be attributed to the tail rotor contributing noise to the vehicle, as the maximum tail rotor thickness noise would be along the 0 deg azimuth line. The S-76D has more pronounced tail rotor noise, as it has a 4-bladed, 4 ft radius tail rotor, compared to the Bell 205’s tail rotor, which has a 2-bladed, 4.25 ft radius.

Figure 5.14. Stereographic projection of thickness OASPL hemispheres. Hemisphere radius of 10 MR radii with 20 azimuthal stations and 10 elevation stations.

It is interesting to note that the Bell 205 is lighter than the S-76D, but as has
physically larger blades, leading to higher magnitude thickness noise. As the Bell 205 has main rotor blades with a chord of 1.75 ft and a thickness of 0.21 ft, compared to the main rotor blades of the S-76D, which has a chord of 1.29 ft and a thickness of 0.12 ft, it is logical that the Bell 205 has the highest thickness noise. This is followed by the Bell 206, which has a main rotor blade thickness of 0.12 ft and a chord length of 1 ft. Since the S-76D has two more blades than the Bell 206 with a larger blade area, it is logical that the S-76D has the higher thickness noise between the two helicopters. Finally, the Bell 407 has a 0.11 ft thick blade with a 1.75 ft chord, and has the lowest noise of all four vehicles.

Next, broadband noise is considered. Acoustic hemispheres for the four vehicles are shown in Fig. 5.15. This analysis revealed that the Bell 206 model contains the highest broadband noise of all the vehicles, having no point on the hemisphere quieter than 85 dB, and a maximum of 92 dB. The Bell 205 has a slightly lower maximum broadband OASPL than the Bell 206, with roughly 80 dB in plane of the rotor. The S-76D has slightly lower broadband noise than the Bell 205, and the Bell 407 has the lowest broadband noise of all four rotors, having a maximum of only 85 dB directly below the vehicle.

The Pegg model was used to predict broadband noise; hence, there are only three model sources of broadband noise: inflow turbulence, boundary layer noise, and vortex noise, although the Pegg model does not allow for differentiation between the three sources. The major contributions to the Pegg model are tip speed, blade area, shaft tilt, and lift coefficient. Therefore, it is expected that the vehicles with the highest tip speed, largest weight, and largest blades will have the most broadband noise. This, then, explains why the Bell 205 and S-76D have high broadband noise, as those vehicles have the fastest tip speeds, highest weights, and largest blade area, with the Bell 205 having higher values than the S-76D in all these categories except for weight. The only vehicle that does not have results that follow this trend is the Bell 206, which has the highest
Figure 5.15. Stereographic projection of Pegg-broadband OASPL hemispheres. Hemisphere radius of 10 MR radii with 20 azimuthal stations and 10 elevation stations.

broadband noise of any of the vehicles. It is possible that this high prediction is due to a scaling problem with the Pegg model in PSU-WOPWOP (see Ref. 42). It may be that the Bell 206 broadband noise prediction is too high and needs to be adjusted.

Figure 5.16 depicts the loading noise hemispheres for the four helicopters. The loading noise hemispheres show that the helicopters with the most loading noise are the Bell 205 and S-76D, followed by the Bell 206. The Bell 407 has much lower loading noise than the other three, with a maximum of 93 dB below the aircraft. The Bell 206, notably, has a
higher minimum noise than the other three, with the minimum noise produced being 90 dB. The Bell 205 and S-76D have a maximum loading noise of 100 dB. Maximums are either below the rotor, for the S-76D and Bell 407, or in front of and slightly below the rotor tip path plane (TPP), for the Bell 205 and Bell 206. These differences in directivity may be due to a number of factors, namely presence of BVI, blade geometry, and even tail rotor contributions.

Figure 5.16. Stereographic projection of loading OASPL hemispheres. Hemisphere radius of 10 MR radii with 20 azimuthal stations and 10 elevation stations.

The next step in understanding the loading noise of these vehicles is to look for BVI
noise. A BVI study must be done before general conclusions can be drawn for the loading noise trends, as BVI noise, when present, is a large contributor to loading noise.

To identify high frequency noise for the four vehicles, A-weighted loading OASPL hemispheres were produced, shown in Fig. 5.17. Noise in the A-weighted spectrum are most commonly attributed to BVI and tail rotor noise. As the z loading disks in Fig. 5.8 suggest, the S-76D, Bell 205, and Bell 206 contained the possibility for BVI, with the S-76D containing the most vortex fluctuations. The Bell 407 also contains some slight high frequency noise, but not as high magnitude as the other two. With regards to noise contributions to loading, the S-76D is the only vehicle where the BVI noise is expected to make a large contribution to the loading noise of the vehicle at this flight condition. As the noise maximum for the S-76D also lies along the 0 deg azimuth line, it is also likely that some of this noise is tail rotor noise. Additionally, there will be slight BVI contributions to the loading noise for the Bell 205 and Bell 206, especially in front of the rotor, where the A-weighted loading OASPL values reach a maximum of about 82 dB.

When looking at the unweighted OASPL hemispheres for loading through the lens of high frequency content, the contribution of BVI or tail rotor noise to the hemisphere can be seen. With exception of the maximum noise spike around ninety degrees azimuth on the Bell 205, the maximum noise on the loading hemispheres comes from high frequency content. The contributions of BVI and tail rotor noise are likely why the S-76D and Bell 205 have similar amounts of high loading noise, although it was expected that the Bell 205 would have had more loading noise. The Bell 205 and S-76D are expected to have higher loading noise due to their weight requiring a higher blade loading. As the Bell 205 and Bell 206 are two-bladed vehicles, it is expected that they would have higher noise levels than their four-bladed counterparts. This is because each blade must support a larger portion of the rotor thrust as compared to a four-bladed vehicle, and therefore each blade would have a higher loading. Because of this, the loading noise for the Bell
Figure 5.17. Stereographic projection of A-weighted loading OASPL hemispheres. S-76D, Bell 407, Bell 205, and Bell 206. Hemisphere radius of 10 MR radii with 20 azimuthal stations and 10 elevation stations.

205 and Bell 206 would be higher, on average, than the S-76D and Bell 407. But, as the S-76D has high BVI noise, it is closer in magnitude to the Bell 205 than would be expected if loading noise was only looked at through the distributions of weight on the blades.

The three noise components can then be combined to get visualizations of total OASPL, shown in Fig. 5.18. As seen with previous hemispheres, the Bell 205 contains
the maximum noise, 104 dB directly ahead of the helicopter. This is followed by the S-76D, which has a maximum directly below the vehicle only slightly lower in magnitude than the Bell 205. Following the trends of the previous hemispheres, the Bell 206 has the highest noise minimum at 91 dB behind the helicopter, but a lower maximum than both the Bell 205 and S-76D. The Bell 407 contains both the lowest minimum noise, 80 dB in the plane of the main rotor, and the lowest maximum noise at 94 dB below the main rotor. As OASPL is the combined values from all the components, those trends are the combined effects of all the components.

When comparing the maximum and minimum noise shapes produced over the four total hemispheres to the three component hemisphere plots (loading noise in Fig. 5.16, thickness noise in Fig. 5.14, and broadband noise in Fig. 5.15), loading noise seems to contribute the most noise. Loading noise is roughly 10 dB higher than the other two components, and therefore has a higher noise contribution than either thickness or broadband. This implies that for the $-9$ deg descent case, focusing on reducing loading noise would produce the most immediate noise reduction, although thickness and broadband noise cannot be ignored as contributors.

### 5.3.3 General observations

When analyzing the four vehicles in a $-9$ deg flight path angle, 110 ft/sec forward flight condition, the differences between the four configurations can be seen. Generally, the Bell 205 was consistent in being the loudest vehicle of the four. As a two-bladed medium weight class vehicle, the individual blade loading is higher than the higher weight S-76D. The S-76D has the second highest noise, as it has the largest weight of all four vehicles but has four main rotor blades, so has a lower individual blade loading. But, the S-76D also had a large contribution in noise from BVI, which made it closer in noise magnitude to the Bell 205 than expected. The Bell 206 generates the most consistent noise across
Figure 5.18. Stereographic projection of total OASPL hemispheres. S-76D, Bell 407, Bell 205, and Bell 206. Hemisphere radius of 10 MR radii with 20 azimuthal stations and 10 elevation stations.

Finally, the Bell 407 was the quietest vehicle, as it only differs from the Bell 206 by about 400 lbs, but contains four blades instead of two.

One reason these vehicles have different noise directivities and levels, besides weight and number of blades, is the flight condition. Even though they are nominally flying the same conditions, the different vehicle weights alter the disk loading on each main
rotor, causing different inflow conditions across the rotors. This influences whether the rotor encounters BVI or not. The S-76D had the most BVI noise, with the Bell 205 and Bell 206 also containing BVI, which would cause higher noise levels than any non-BVI condition. But, the BVI amount may change with different flight conditions or descent rates. Additionally, flight tests continue to reveal the challenge in flying a precise trajectory. Although nominally these vehicles were asked to fly the same condition, achieving this in a real world scenario is challenging. Atmospheric perturbations, control variation modes, and vehicle characteristics create a challenging environment for a pilot to produce a consistent, exact trajectory. Deviations from a consistent trajectory can lead to excess loading noise and BVI that is not expected for a given flight condition, and should be considered during noise analysis.

Finally, combined with the loading noise studies conducted in the previous section, it is obvious that loading has a large impact on noise, and can be influenced by both vehicle weight, number of blades, longitudinal acceleration, vertical acceleration, and tip speed. For a -9 deg descent case, loading noise tends to be the largest contributor of noise when compared to thickness and broadband noise. Focusing on loading noise as a means of noise reduction would be an effective way of reducing helicopter noise.
Chapter 6  

Concluding remarks

This chapter summarizes the work of this thesis and the key takeaways from each chapter. The conclusions drawn from the work conducted are then explored. Finally, future work recommendations are detailed.

6.1 Conclusions

This work presented key updates and studies using two different fidelity noise prediction systems. Changes were made to the NDARC NPS to fix known problems with the BVI prediction model. The Beddoes wake model and Vatistas implementation of the Biot-Savart law were reimplemented in WOPIt to improve BVI prediction capabilities. Additional changes included upgrading the system to newer tools, UI improvements, and various bug fixes. A verification of the changes were presented for the NDARC model helicopter.

A second effort was made with the Penn State NPS to study the effects of flight perturbations on noise and to analyze these effects over various weight class vehicles. The first study analyzed short time span changes in acceleration and its affect on noise. The other study looked at overall trends between the S-76D, Bell 205, Bell 206, and Bell 407 helicopters to understand the differences in vehicle weight class and how vehicle
weight affects rotor noise.

6.1.1 NDARC NPS status

Multiple changes have been made to the NDARC NPS system to improve the system and prepare for a full release. A full verification of the previous work with the system was conducted to identify and fix issues. Four NASA NDARC example vehicles were used for this study: a helicopter, tandem helicopter, coaxial helicopter, and a hexacopter, although only the results from the helicopter were presented. The results from the other three vehicles are contained in Appendix A. Each vehicle was flown to match conditions published in Ref. 35 to provide a comparison. Blade loading disk predictions, wake displacements, acoustic pressure time histories, OASPL hemispheres, and BVISPL hemispheres were all analyzed to verify the results.

It was found during the verification that there were several issues with WOPIt that required addressing. Namely, the vortex model used to predict the loading change due to blade-vortex interactions was producing numerical scalloping, which influenced the acoustic results. Additionally, the initial implementation was predicting BVI in conditions where it was not expected. In order to address these issues, the BVI module was reimplemented. The model is comprised of a modified Beddoes wake model and Vatistas implementation of the Biot-Savart law. The Beddoes wake model is a low fidelity model used to track the vortices shed by the tip of a rotor blade. This was combined with Vatistas implementation of the Biot-Savart law, which accounts for vortex viscosity and calculates the velocity induced by a blade-vortex interaction. The exact implementation used follows the methodology proposed by Greenwood [54].

The system was also updated to NDARC 1.15 and PSU-WOPWOP 3.4.4 and restructured to simplify future updates. This was completed with the desire to keep the system up-to-date going forward. Changes to the user interface, such as clarifying variable names,
restructuring the system run file, and improving output structure, were done to make the system as easy for a new user as possible.

The NDARC example helicopter cases used in the initial verification were then reprocessed using the revised system to highlight the changes made. Differences between the two implementations are presented for comparison.

Finally, the complete set of example cases were updated with the new system. These cases are designed to give a new user a walk-through of how to use the system, and are provided in conjunction with a User’s Manual. The User’s Manual walks a new user through each of these example cases. Additional new content was added to the User’s Manual to aid in building the run directory of the NDARC NPS and compiling the code. Several additional example cases that walk a user through using the tip vortex and blade loading plot features of WOPIt were also created and added to the users manual. The example cases and User’s Manual were then packaged together with the improved NDARC NPS for distribution.

6.1.2 Penn State NPS conclusions

The Penn State NPS was used to conduct two separate studies designed to support the FAA’s *Fly Neighborly* Guide in producing flight abatement procedures for existing helicopters. Both studies use the “flight test trajectory following” trajectory model in PSUHeloSim, which uses the data from the 2017 and 2019 FAA/NASA/Army joint flight tests to introduce flight variation into flight simulation.

The first study using the Penn State NPS looked at the influences of vertical and longitudinal accelerations on noise. To accomplish this, five second spans of flight were processed for the Sikorsky S-76D in descending flight to look at changes induced in noise by both longitudinal and vertical accelerations. This study found that vertical accelerations induced a change in flight path angle, called an effective flight path angle,
which altered the thrust of the main rotor. Additionally, it was found that a vertical acceleration induced a change in flight path angle rate of change, which also changed the thrust of the main rotor. Both of these effects were studied for flight test following predictions for three different flight path and effective flight path angle ranges found in a nominal 70 knot, −6 deg flight path angle flight. The flight test trajectory following results were compared to a constant commanded trajectory that followed the nominal case. All three time segments contained variations of both effective flight path angle and effective flight path angle rate of change that influenced the noise of the main rotor, with the largest impact being a 10 dB decrease in the plane of the rotor. Up to a 5 dB increase was found as well, mostly in the rear and below the rotor.

The second study aimed to analyze the differences in noise between helicopters in different weight classes. Flight test trajectories with a nominal 100 ft/sec, −9 degree descent were selected. Four helicopters were chosen, two medium-weight-class helicopters and two light-weight-class helicopters. Within each weight class, one two-bladed helicopter and one four-bladed helicopter were selected to capture both the effect of weight class and the effect of number of blades on noise.

During the weight class study, several alterations were made to the Bell 407, Bell 206, and Bell 205 models to improve the accuracy of the models and hence improve loading predictions. Once this was completed, a full acoustic analysis of the four vehicles was conducted. It was found for this flight condition that the Bell 205 was the loudest vehicle, followed by the Sikorsky S-76D. Between the light-weight-class vehicles, the Bell 206 predicted higher noise than the Bell 407, which was the quietest helicopter of the four. It was found that the S-76D, Bell 205, and Bell 206 contained BVI noise, while the Bell 407 did not. In this study, weight class did not directly correlate to BVI regions, as the helicopters with the most BVI were the S-76D and the Bell 206, a medium-weight, four-bladed vehicle and a light-weight, two-bladed vehicle, respectively.
Additionally, the tip speeds factored into the noise produced by each vehicle. The Bell 205, the loudest medium weight class vehicle, had the highest tip speed. The Bell 407, the quietest helicopter, has the second highest tip speed, but does not contain BVI noise, resulting in less noise than the other vehicles. The helicopter with the third highest tip speed is the S-76D, which is the second loudest vehicle. Finally, the Bell 206 has the lowest tip speed, and is the quietest of the helicopters that contain BVI noise.

This study produced several surprising results that did not follow the expected trends of weight class and number of blades. The Bell 206 was consistently louder than the Bell 407 by a large margin, while the Bell 205 and S-76D were relatively close in noise. The Bell 206 also had the loudest broadband noise of all four vehicles, although it is lower in weight.

Generally, the weight class study concluded that for a descent case, the two bladed vehicles were louder than the four bladed vehicles in the same weight class. This is likely due to the decreased loading per blade in the four-bladed main rotor cases. Additionally, it was found that loading noise was dominant in approach for all vehicles, with loading noise being on average 10 dB louder than either thickness or broadband noise.

Both studies found that the flight test trajectory following commander was able to introduce variations not captured by a flight simulation commander aiming to fly a nominal trajectory. Nominal and constant trajectories are not always achievable, which can induce variations within a singular flight or when comparing multiple flight cases. These changes in trajectory due to external perturbations can induce a perceivable difference in noise during a flight or when comparing helicopters.

### 6.2 Future work

There are several key items that need to be completed with both of these systems. Future work recommendations and justifications are presented for each system individually in
the following subsections.

6.2.1 NDARC NPS

To complete the NDARC NPS system, several tasks must be completed. First, the high-speed-impulsive noise model needs calibration and validation before it can accurately predict high-speed-impulsive noise. As the model is an ad-hoc addition to WOPIt that scales acoustic pressure time history data based on empirical values, comparison with HSI data is required to ensure accurate noise prediction.

Similarly, the BVI module reimplementation requires verification. This work presented the initial changes made to the BVI module and compared the changes to the previous implementation, but comparison with external tools is desired. Comparison with a higher fidelity free-wake model is recommended, as mean wake age should align, and vortex-interaction locations would be similar if the BVI module is correct. This is required to lend credibility to the changes made to the BVI model, and refinement of the implementation may be required if results do not align with external comparisons.

Full validation of the results produced by the NDARC NPS should also be conducted to gain confidence in the tool. This could be done by building an NDARC model for an existing helicopter and comparing the acoustic results to flight test data. The current NDARC NPS has yet to validated via external comparison, and as WOPIt alters the predictions produced by NDARC, validation of the new predictions must be conducted.

Finally, the implementation of an interaction model should be considered. Many novel concept vehicles being explored by rotorcraft designers contain multiple rotors, which all interact aerodynamically. Currently, the NDARC NPS processes each rotor in isolation, which means interactional effects are not captured. Implementation of a rotor-interaction model to capture the aerodynamic effects of nearby rotors in the WOPIt loading model would allow designers to consider noise produced by rotor proximity in
their concept vehicles.

6.2.2 Penn State NPS

There are several changes that could be made to the Penn State NPS to improve the system. The flight simulation used could be upgraded to a more complex simulation that would allow other vehicles besides traditional helicopters, such as DEPSim [59]. HeloSim is only capable of modeling single main rotor tail rotor helicopter configurations. But, the capability to model other vehicle configurations, such as tandem helicopters, coaxial helicopters, or multicopters, would allow the Penn State NPS to be used to provide noise abatement guidance on such configurations. Additionally, the numerical anomaly in the thickness acoustic pressure time history must be identified and resolved to remove any affects this anomaly may be having on the noise prediction.

Further research into the impact that longitudinal and vertical acceleration have on noise should be conducted. As only a short time span was analyzed for a single flight case, the full influence these accelerations can have on noise has not been captured. Expanding this work to a broader range of acceleration rates, airspeeds, and flight path angles would give a wider understanding of the expected thrust changes introduced at these conditions and provide a more comprehensive understanding of how loading noise may change. Expanding this study to more helicopters would also be beneficial to explore whether vehicle weight or configuration influence the amount of thrust that changes with acceleration.

Additionally, when conducting the study on helicopter weight class, several results were surprising, namely with the broadband and thickness predictions of the Bell 206 and Bell 407. While the fact that the result did not follow the initially expected trend does not invalidate them, the study should be reviewed for accuracy. If the results are found to be accurate, further study into both the Bell 206 and Bell 407 should be conducted.
to understand why the Bell 206 produced high broadband noise and thickness noise predictions, and why the Bell 407 noise predictions were much quieter when the two helicopters are within the same weight class.

Finally, further analyses comparing vehicles of different weight classes in different flight conditions should be analyzed to further understand how weight influences rotor noise. Analyzing maneuvers, climb, and hover will give a more complete understanding of how vehicle weight impacts rotor noise, and improve understanding in how quiet flight can be achieved.
References


Appendix A
NDARC NPS User Manual

This appendix contains the current version User’s Manual for the NDARC NPS. This version contains all changes to the system and explains how to use the current system. For a description of the system and the changes made see Chapter 4. Slight changes from the official User’s Manual have been made for the purposes of formatting consistency.
A.1 Assumptions and Warnings

A.1.1 Assumptions

These are the following assumptions made when running the system:

- The system is run using an Ubuntu Linux operating system with the capability to run csh and bash scripts. The system run file (WOPIt.run) is a bash script and the NDARC run file is a csh script.

- The NDARC case file uses English/US Customary units.

- The NDARC solution file is written in the same directory as the NDARC run file.

- The NDARC version being utilized is 1.15, as this version has the output files that the NPS can read.

A.1.2 Warning

This is a preliminary version of the documentation for the new NPS system. Some tools are not completely correct or finalized. The intention of this manual is to begin getting the system in the hands of the users as fast as possible. Please heed all warnings within the manual regarding the state of the system. If something is encountered that seems incorrect or system-breaking, please contact the development team.

A.1.3 Getting Started

The purpose of this manual is to provide a user with a thorough understanding of the system and how to properly use the system. In this chapter the reader is introduced to the purpose and tools of the system and a reader’s guide.

A.1.4 System Purpose

The purpose of the system is to allow a user to predict the noise for the missions and flight conditions of any NDARC case.
A.1.5 Tools

The system is comprised of four tools: NDARC, PSU-WOPWOP, WOPIt, and ShearIt. NDARC functions as the design and analysis tool that supplies data to WOPIt. WOPIt then writes the files necessary for PSU-WOPWOP to perform the noise prediction. ShearIt is a separate module utilized in calculating High-Speed-Interaction (HSI) noise. WOPIt produces the inputs for ShearIt, the first run of PSU-WOPWOP creates preliminary acoustic data, ShearIt does the necessary calculations for HSI noise, and then the new data can be read back into PSU-WOPWOP to create the final noise data set. The tools WOPIt, ShearIt, and PSU-WOPWOP function as separate noise prediction modules for NDARC.

A.1.6 Reader’s Guide

In certain chapters there are portions of text which are blue. The blue text highlights the important portions of the chapters relevant to building a case.

Chapters 3-5 outline how the user file WOPIt.nam can be modified when setting up each case. Each of these methods of modification are followed by segments of text contained within a

\[
\text{box}
\]

The box contains the default values of the variables contained within the file WOPIt.nam. If variables are not specified by the user in the file WOPIt.nam they are then set to the default values specified in the file Dictionary.pdf. In these chapters there are also sample cases which contain text with a

\[
\text{box}
\]

For the sample cases, the variables within the box are the variables the user should modify.

Each sample case builds from chapter to chapter so it is recommended to follow the manual sequentially. In the directory Cases the user builds each sample case. Another directory, Cases_Check, contains all the sample cases already setup and run through the system. So if problems arise when setting up a case, the user can check the case files with those in the folder Cases_Check. The user can also compare the output for the sample cases with those in Cases_Check to ensure that the correct data is being output when the the system is run.

Chapter 3: Compiling the Code

Details how the user can compile the source version of the system (without NDARC), if it has been provided to them. This is not a necessary step, but requires some setup if the users desires to compile the code themselves. NDARC is distributed separately from the noise prediction system described here.
Chapter 4: System Setup
Outlines the directory structure of the system: location of required folders. Outlines
the system run file. The system run file is the bash script which runs the entire
system. Then the steps the user should follow in setting up a case to run for the
system are listed.

Chapter 5: NDARC Case
Outlines how to specify an NDARC case to analyze.

Chapter 6: Rotors and Noise Sources
Specifies how to select the rotors of the helicopter configuration and the noise
sources to analyze.

Chapter 7: Noise Prediction
Outlines how to specify the noise prediction parameters.

Chapter 8: Cases
Outlines cases for various conditions.

Chapter 9: System Capabilites
Lists the acoustic and plot flags present in the system and what they correspond
to.

A.2 Compiling the Code

If the user has been provided the source code and wishes to use it to compile their own
version of the code, this section details the steps for creating a new executable for both
WOPIt and ShearIt. As PSU-WOPWOP has its own instruction set for compilation, it
will not be described here. If the user simply wishes to just use the NPS, then this entire
section can be ignored and the system will still work as desired.

A.2.1 Possible Methods

There are a few different ways to compile the code, some of which will be detailed here.
The method outlined here utilizes Cygwin (on Windows) to use CMake and is compiled
with Intel Fortran, but this can also be done with the GUI of CMake, or in Visual Studio
2019 without Cygwin or CMake at all. The system currently does not compile with
GFortran.

This system can be compiled and used in either Windows or Linux, following slightly
different procedures outline below.
A.2.2 Tools Required - Windows

In order to compile the NPS, a user needs the following tools:

- Cygwin
- the Cygwin CMake library or CMake independently
- the Intel Math Kernel Library
- Intel Fortran (2019 or newer)
- Source Code for NDARC 1.15 (must be obtained from NASA)

A.2.3 Steps - Windows

Step 1: Import NDARC Files

The first thing that needs to be done is to import a few .f90 files from the NDARC source code. This can be done in two ways.

The first way is to point to the NDARC files without moving them. Go to the WOPIt source code and open ndarcModule.f90. At the bottom of this file there are four include statements that point to the NDARC files. Change these paths to where those files are located in the NDARC source code. Currently they point to placeholder files (these will not work), and so the user must point these includes to the real files.

The second way to do this is to simply copy the NDARC files into the WOPIt source code folder, and to replace the placeholder files with real files. If the user decides to follow this method, they must be careful if they share the source code, as NDARC is a restricted program and so sharing these files needs to be in compliance with the restrictions. Once this has been completed, the WOPIt source code is ready to be compiled.

Step 2: Run Intel Fortran

The first step is to start up Intel Fortran(ifort) using ifortvars.bat. This can be done by using the command terminal to change the directory to where ifortvars.bat is located, and call the batch file. Then change the directory back to where Cygwin is located and call:

```
start mintty -i /Cygwin-Terminal.ico -
```

This starts up a Cygwin Terminal, and you should now be able to use Intel Fortran in Cygwin.

Step 3: Go To Source Code

Next, change the directory from the Cygwin folder to the source code folder. This can be done using a command similar to
but the command will change depending on the location of the source code on the
users computer.

**Step 4: Compile WOPIt**

The commands shown below can be used to start up CMake and change its
configuration so that it can be edited.

```
>ccmake .
>c
t
```

Line 1 starts CMake in the current directory, line 2 starts the configuration window,
and line 3 toggles CMake into advanced mode. Now move through the configu-
ration window using the arrow keys, and go to 'CMAKE_BUILD_TYPE', hit enter,
change the type to 'Release' and hit enter. Then go to 'CMAKE_Fortran_COMPILER'
and make it 'ifort' using the same method. Then enter the following commands.

```
c
c
>g
```

This rewrites the cache, reconfigures the compilation, and generates the Make file.
The call of ‘g’ also closes the ccmake window. Now the user can enter

```
>make
```

and this builds the executable, which can then be moved to the NPS directory for
use.

**Step 5: Building Other Executables**

Now the same procedure can be utilized for ShearIt, and a similar method for
PSU-WOPWOP.

---

**A.2.4 Differences With Linux**

Much of the procedure discussed above can be followed in order to compile the system
on Linux. First the user must have a Linux operating system; this guide used Windows
Subsystem for Linux (WSL) and the Ubuntu operating system. The user will still need to
download CMake. Additionally, the user would need to have Intel Fortran, by acquiring
Intel oneAPI.

Once this has been done, the user must initialize Intel Fortran. This can be done by
going to the location of the file 'setvars.sh' and call 'source setvars.sh.' If the user is
using WSL and Ubuntu, this location will be '/opt/Intel/oneapi.' Once this is done,
simply follow step 3 onward for compiling in windows, as it operates the same way.
A.2.5 Warning

Due to the size of the code, the system currently only operates on Linux. But, previous versions of the system can be run on Windows, and so the windows instructions are left in the documentation.

A.2.6 System Setup

The system will only run properly if the folders and their corresponding files are organized correctly. The order of the files and folders is correct the first time the user unzips the system.

To perform the initial setup of the system the user must unzip the file NPS.zip in the desired directory location. The directory path to the NPS folder is considered the root directory path for the system.

A.2.7 Directory Structure

In order for the system to work properly, the folder locations must be the same as shown in the directory tree below. When the user initially unzips the file NPS.zip the folder and file locations are in the correct hierarchy.

1. NPS
   (a) NDARC
      i. engine
      ii. examples
   (b) PSU-WOPWOP
   (c) WOPIt
   (d) Shearit

A.2.8 System Run File

The first file the user must edit is the bash script named WOPIt.run. The default template of the bash script is shown in Fig. A.1.

In order to edit the file the user must open the file WOPIt.run and set the value of the variable root to the root directory path in “quotes”. By default, root="/mnt/c/users/lauren/desktop/rundir_linux". Notice that there is no forward slash (/) after the name of the folder NPS. In this manual, it is assumed the user will be using WSL with Ubuntu on a windows computer. The root could also be specified as it would on Unix or Linux:

root="/home/lauren/Desktop/NPS"

as long as this is the correct path in the running environment. The important code lines in the file WOPIt.run are defined below.
#!/bin/bash
# change the value of "root" to your location of the NPS
root="/mnt/c/users/lauren/desktop/rundir_linux"
runFile='helicopter.run'
runFileDir="$root"/NDARC/examples
WOPItDir="/cygdrive/c/users/lauren/documents/GitHub/NPS/WOPIt SRC"
ShearItDir="$root"/ShearIt
caseFileDir="$root"/Cases/13_SPL
solnFile="$(runFile%.soln"

########################## Check if directory already exists, ask to delete or exit
cd "$caseFileDir"
if test -f "HSIFlag.txt"; then
echo "WOPIt files already exist in this directory, delete them or exit? (type d or e)"
read response
if [ "$response" == "d" ]; then
echo "Deleting WOPIt files"
rm cases.nam HSIFlag.txt parameters.soln #$solnFile
rm -rf ./*
else [ "$response" == "e" ]
echo "Ending run. Please move run directory or remove WOPIt files."
exit 1
fi
fi
########################## Run NDARC
cd "$runFileDir"
if grep -Fq "$OUT_solution=0" $runFile then
    sed -i "s/OUT_solution=0/OUT_solution=1/g" $runFile
printf " ---------------- Begin NDARC ---------------- 
./$runFile
printf " ---------------- End NDARC ---------------- 
"
else [ "$response" == "e" ]
if test -f "cases.nam"; then
    echo "WOPIt ran sucessfully"
else
    echo "WOPIt failed to run. Ending run."
exit 2
fi
fig. A.1. WOPIt.run bash script file.
Line 4: Sets runFile to the NDARC run file the user wishes to analyze.

Line 5: Sets runFileDir to the path location of runFile defined in Line 4.

Line 6: Sets WOPWOPFileDir to the path of the executable PSU-WOPWOP.exe.

Line 7: Sets WOPItDir to the path of the executable WOPIt.exe.

Line 8: Sets ShearItDir to the path of the executable ShearIt.exe.

Line 9: Sets caseFileDir to the path of the working directory.

Line 10: Sets solnFile to the value of runFile but removes the extension and appends .soln to the file name.

Lines 14-27: Checks to see if the code outputs into a directory that already has output files, as this will cause the code to fail.

Line 29: Changes the working directory path to the value of runFileDir.

Lines 30-33: If OUT_solution=0 in runFile then sets OUT_solution=1.

Lines 35: Executes runFile.

Lines 40: Copies solnFile from the working directory to the path caseFileDir.

Lines 41: Changes working directory to caseFileDir.

Lines 42: Executes WOPIt.exe in the working directory and reads in data from the file WOPIt.nam.

Lines 44-49: Ensures that WOPIt completed running without a failure before proceeding.

Lines 55: Executes PSU-WOPWOP.exe in the working directory.

**Sample Case: Root Directory**

**Objective:** Specify the root directory for the system.

**Step 1:** Access the root directory.

**Step 2:** Follow the path ./.Cases/01_root.

**Step 3:** Open WOPIt.run
Step 4: Set the value of `root` to the root directory path in “quotes”. Do not place a slash after the folder name NPS.

Step 5: Open a Cygwin terminal and change the path in the Cygwin terminal to the directory path shown in Step 2.

Step 6: Run the file `WOPIt.run`. The output on the Cygwin terminal should match that shown in Fig. A.3.

One folder (Heli) and four files (Cases.nam, helicopter.soln, HSIFlag.txt and parameters.nam) should have been created in the working directory (Fig. A.2). The

<table>
<thead>
<tr>
<th>Name</th>
<th>Date modified</th>
<th>Type</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heli</td>
<td>11/23/2020 3:13 PM</td>
<td>File folder</td>
<td>2 KB</td>
</tr>
<tr>
<td>cases.nam</td>
<td>11/23/2020 3:38 PM</td>
<td>NAM File</td>
<td></td>
</tr>
<tr>
<td>helicopter.soln</td>
<td>12/12/2019 6:55 PM</td>
<td>SOLN File</td>
<td>1,089 KB</td>
</tr>
<tr>
<td>HSIFlag.txt</td>
<td>11/23/2020 3:37 PM</td>
<td>Text Document</td>
<td>1 KB</td>
</tr>
<tr>
<td>parameters.soln</td>
<td>11/23/2020 3:37 PM</td>
<td>SOLN File</td>
<td>84 KB</td>
</tr>
<tr>
<td>WOPIt.nam</td>
<td>11/23/2020 3:12 PM</td>
<td>NAM File</td>
<td>1 KB</td>
</tr>
</tbody>
</table>

Figure A.2. Working directory after running the system.

names of the folder Heli and file helicopter.soln are dependent on the NDARC case. The folder Heli contains all the files required by the tool PSU-WOPWOP to perform noise prediction. The files are contained in the lowest levels of each directory tree contained within the folder. In Fig. A.4 the folders at the lowest level are distinguished with a vertical black line.

A.2.9 Building a Case

In this section the steps required for running the system are outlined. Though it is not required for the user to follow the steps in this succession, it is considered best practice. The order of the steps are the following:

Step 1: Setup system directory tree.

Step 2: Specify root directory in the system run file.

Step 3: Specify NDARC case to analyze.

Step 4: Specify which rotors to analyze.

Step 5: Specify the noise sources to predict.

Step 6: Specify the observer parameters.
Figure A.3. Cygwin terminal after running first sample case. Only the first mission segment run in PSU-WOPWOP is shown here, but there should be 9 mission segments and 4 flight conditions run in PSU-WOPWOP (i.e., there will be 13 sections of output from PSU-WOPWOP each ending with “Environment Destroyed”).

**Step 7:** Specify the domain of the output files.

**Step 8:** Specify a noise metric.

In the previous sections in this chapter, steps 1 and 2 were explained. In the following chapters steps 4-8 will be explained. If the prior steps were followed correctly, then the user should have the system directory set up correctly and know how to specify the value of the root directory in `WOPIt.run`.

### A.2.10 NDARC Case

When specifying the NDARC case to analyze, the files `WOPIt.run` and `WOPIt.nam` must be edited. The user must first open `WOPIt.run` and change the value of `runFile` to the name of the NDARC run file in “quotes”.

```plaintext
runFile=“helicopter.run”
```
Next the user must open WOPIt.nam and in the namelist &CASEPARAM set the variable solutionFile to the name of the chosen NDARC run file with the extension .soln in “quotes”. The default value for solutionFile is:

```
&CASEPARAM
  solutionFile="helicopter.soln"
/
```

After selecting the NDARC case, the user must specify the missions and flight conditions to analyze. By default all the missions and flight conditions are analyzed.
To pick specific off-design missions and segments the user must open \texttt{WOPIt.nam} and in the namelist \texttt{&CASEPARAM} specify values for \texttt{offMissFlag}, \texttt{nOffMiss}, \texttt{offMiss}, \texttt{nOffMissSeg}, and \texttt{offMissSeg}. The variable \texttt{offMissFlag} specifies if the system analyzes user specified off-design missions. By default \texttt{offMissFlag} is set to \texttt{.false.}, if the user wishes to pick off-design missions then \texttt{offMissFlag=.true.}. \texttt{nOffMiss} is the number of off-design mission segments; \texttt{offMiss} is an array of the off-design missions; \texttt{nOffMissSeg} is the number of mission segments; \texttt{offMissSeg} is an array of the mission segments. If \texttt{offMissFlag=.false.} then the remaining four variables are ignored by the system.

\begin{verbatim}
&CASEPARAM
  offMissFlag=.false.
  nOffMiss=
  offMiss=
  nOffMissSeg=
  OffMissSeg=/
\end{verbatim}

To pick specific sizing missions and segments the user must open \texttt{WOPIt.nam} and in the namelist \texttt{&CASEPARAM} specify values for \texttt{sizeMissFlag}, \texttt{nSizeMiss}, \texttt{sizeMiss}, \texttt{nSizeMissSeg}, and \texttt{sizeMissSeg}. The variable \texttt{sizeMissFlag} specifies if the system analyzes user specified sizing missions. By default \texttt{sizeMissFlag} is set to \texttt{.false.}, if the user wishes to pick sizing missions then \texttt{sizeMissFlag=.true.}. \texttt{nOffMiss} is the number of sizing mission segments; \texttt{sizeMiss} is an array of the sizing missions; \texttt{nSizeMissSeg} is the number of mission segments; \texttt{sizeMissSeg} is an array of the mission segments. If \texttt{sizeMissFlag=.false.} then the remaining four variables are ignored by the system.

\begin{verbatim}
&CASEPARAM
  sizeMissFlag=.false.
  nSizeMiss=
  sizeMiss=
  nSizeMissSeg=
  SizeMissSeg=/
\end{verbatim}

To pick specific performance conditions the user must open \texttt{WOPIt.nam} and in the namelist \texttt{&CASEPARAM} specify values for \texttt{perfCondFlag}, \texttt{nPerfCond}, and \texttt{perfCond}. The variable \texttt{perfCondFlag} specifies if the system analyzes user specified performance conditions. By default \texttt{perfCondFlag} is set to \texttt{.false.}, if the user wishes to pick performance conditions then \texttt{perfCondFlag=.true.}. \texttt{nPerfCond} is the number of performance conditions and \texttt{perfCond} is an array of the performance conditions. If \texttt{perfCondFlag=.false.} then the remaining two variables are ignored by the system.
To pick specific sizing conditions the user must open WOPIt.nam and in the namelist &CASEPARAM specify values for sizeCondFlag, nSizeCond, and sizeCond. The variable sizeCondFlag specifies if the system analyzes user specified performance conditions. By default sizeCondFlag is set to .false., if the user wishes to pick sizing conditions then sizeCondFlag=.true.. nSizeCond is the number of sizing conditions and sizeCond is an array of the sizing conditions. If sizeCondFlag=.false. then the remaining two variables are ignored by the system.

Sample Case: Solution File

Objective: Analyze the helicopter case.

Step 1: Access the root directory.

Step 2: Copy the files WOPIt.run and WOPIt.nam from the folder ./Cases/01_root into the folder ./Cases/02a_solutionFile.

Step 3: In the folder ./Cases/02a_solutionFile, open WOPIt.run

Step 4: Set the value of runFile to “helicopter.run” then close WOPIt.run. (The value should already be “helicopter.run” if you are continuing from the example in the previous chapter.)

Step 5: Open the file WOPIt.nam.

Step 6: Choose the helicopter NDARC case to analyze.

Step 7: Open a Cygwin terminal and change the path in the Cygwin terminal to the directory 02a_solutionFile.
Step 8: Run the file WOPIt.run.

Step 9: In the Cygwin terminal type in the command `du -sh` and ensure that the directory space is 1.8M.

The last step is a check to ensure that the system ran properly. This sample case is identical to Sample Case: Root Directory. The only difference is that in this sample case the value of `solutionFile=“helicopter.soln”`. But, just as in the previous sample case, if the namelist variable was left blank it would default to “helicopter.soln”.

**Sample Case: Mission Segments**

**Objective:** Write out files for the first off-design mission and mission segments three, five, and seven.

Step 1: Access the root directory.

Step 2: Copy the files WOPIt.run and WOPIt.nam from the folder `.Cases/02a_solutionFile` into the folder `.Cases/02b_segment`.

Step 4: Specify that the first mission segment should be analyzed and that no performance conditions should be analyzed. Then specify that mission segments 3, 5, and 7 should be analyzed.

```
&CASEPARAM
    solutionFile=“helicopter.soln”
    offMissFlag=.true.
    nOffMiss=1
    offMiss=1
    nOffMissSeg=3
    offMissSeg=3,5,7
    perfCondFlag=.true.
    nPerfCond=0
/
```

Step 7: Open a Cygwin terminal and change the path in the Cygwin terminal to the directory 02b_segment.

Step 8: Run the file WOPIt.run.

Step 9: In the Cygwin terminal type in the command `du -sh` and ensure that the directory space is 1.3M.

In the folder Heli there should now only be mission segments 3, 5, and 7 in the first off-design mission. Still no acoustic results have been written to any of the folders.
A.3 Rotors and Noise Sources

A.3.1 Rotor

Each NDARC case has an associated rotorcraft configuration, and the configuration has an associated number of rotors. The user specifies the number of rotors and which rotors to analyze. To do this, the user must first open WOPIt.nam. Then in the namelist &NOISE, set the variable nRotor to the number of rotors and the variable rotors to an array of rotors.

```
&NOISE
  nRotor=2
  rotors=1,2
/
```

The number associated with each rotor is determined by NDARC. If, for a helicopter configuration, the main rotor is the first rotor in a NDARC configuration, then the number 1 is also associated with the main rotor for the system.

Sample Case: Number of Rotors

Objective: Analyze the first rotor (main rotor) and the second rotor (tail rotor) of the helicopter configuration.

Step 1: Access the root directory.

Step 2: Copy the files WOPIt.run and WOPIt.nam from the folder ./Cases/02a_solutionFile into the folder ./Cases/03_nRotor.

Step 3: Analyze the main and tail rotors.

```
&NOISE
  nRotor=2
  rotors=1,2
/
```

Step 4: Open a terminal and change the path in the terminal to the directory 03_nRotor.

Step 5: Run the file WOPIt.run.

Step 6: In the Cygwin terminal type in the command du -sh and ensure that the directory space is 1.8M.

The results for this sample case are also identical to the first and second sample cases. This is because the values for nRotor and rotors has been set to the default values.
Sample Case: Rotor Order

Objective: Analyze the second rotor (tail rotor) for the helicopter configuration.

Step 1: Access the root directory.

Step 2: Copy the files WOPIt.run and WOPIt.nam from the folder ./Cases/02a_solutionFile into the folder ./Cases/04_rotors.

Step 3: Analyze only the tail rotor.

```plaintext
&NOISE
  nRotor=1
  rotors=2
/
```

Step 4: Open a terminal and change the path in the terminal to the directory 04_rotors.

Step 5: Run the file WOPIt.run.

Step 6: In the Cygwin terminal type in the command `du -sh` and ensure that the directory space is 1.5M.

In this case, only the tail rotor is analyzed and the main rotor is ignored. To only analyze the main rotor set rotors=1.

A.3.2 Noise Sources

The system allows for noise prediction from 5 sources. They are thickness noise, loading noise, BVI noise, high-speed-impulsive noise, and broadband noise. Each noise source is outlined in the theory manual. To write out the files required for noise prediction of a noise source the user must open WOPIt.nam and in the namelist &NOISE set the variables Thickness, Loading, HSI, Broadband, and BVI to either 1 or 0. The value of 1 specifies for the system to write out the files for noise prediction of that source.

If HSI=1 the user must take additional steps after the first run of the system. As HSI noise is an ad hoc addition to the NPS, it is run separately from the regular WOPIt system. When HSI = 1, WOPIt creates a text file called HSIFlag.txt that lets the system know whether to write out the necessary namelists for HSI noise. Running the NPS with HSI on creates two global namelists, HSI_name.nam and HSIParameters.nam, as well as a HSIParam.nam and name.nam for each individual rotor. How to run the NPS for HSI noise will be explained later in the document.
Sample Case: Thickness and Loading Noise

**Objective:** Write out the thickness and loading noise prediction files of the helicopter main and tail rotors.

**Step 1:** Access the root directory.

**Step 2:** Copy the files `WOPIt.run` and `WOPIt.nam` from the folder `./Cases/03_nRotor` into the folder `./Cases/05_noise`.

**Step 3:** Write out the files for thickness and loading noise prediction.

```plaintext
&NOISE
  Thickness=1
  Loading=0
  HSI=0
  Broadband=0
  BVI=0
/
```

**Step 4:** Open a Cygwin terminal and change the path in the Cygwin terminal to the directory `05_noise`.

**Step 5:** Run the file `WOPIt.run`.

**Step 6:** In the Cygwin terminal type in the command `du -sh` and ensure that the directory space is 13M.

### A.4 Noise Prediction

#### A.4.1 Observer

The noise is computed at user specified node points on a grid. For the remainder of the manual these nodes are referred to as “observers”. The user can specify the observer initial position and the motion. Each section in this chapter outlines how to adjust these properties.

Before specifying the observer properties the user must determine in which manner to compute the observer time, position, and angle variables. To specify the manner in which
time, position, and angles are inputted into the system the user must open WOPIt.nam and in the namelist &OBSERVERPARAM set the variables time, position, and angle to either 1 or 0. For time, 1 specifies that the observer time will be the user input times the time it takes for the first rotor specified in the array rotors to complete a single revolution. For position, 1 specifies that the observer position will be specified in terms of the radius of a blade of the first rotor specified in the array rotors multiplied by the user specified value. For angle, 1 specifies that the user must use degrees instead of radians when using angle values in the namelist. The default values are:

```
&OBSERVERPARAM
   time=1
   position=1
   angle=1
/
```

### A.4.1.1 Position

The observer position can be specified for a single observer, a rectangular observer grid, or a spherical observer grid. The observer is positioned relative to the origin specified by NDARC. The observer coordinate system is designated as +x aft of the aircraft and +y to the right of the aircraft. Single Observer To specify a single observer position relative to the origin the user must open WOPIt.nam and in the namelist &OBSERVERIN give values to the variables xLoc, yLoc, and zLoc. The default values are:

```
&OBSERVERIN
   xLoc=0
   yLoc=0
   zLoc=0
/
```

Rectangular Observer Grid To specify a rectangular observer grid relative to the origin the user must open WOPIt.nam and in the namelist &OBSERVERIN give values to the variables nbx, nby, nbz, xMin, xMax, yMin, yMax, zMin, and zMax. The variables nbx, nby, and nbz determine the number of observers along the x, y, and z-axis, respectively. The variables xMin and xMax specify the initial and final location of the observers along the x-axis. The variables yMin and yMax specify the initial and final location of the observers along the y-axis. The variables zMin and zMax specify the initial and final location of the observers along the z-axis. The default values are:
Spherical Observer Grid To specify a spherical observer grid relative to the origin the user must open WOPIt.nam and in the namelist &OBSERVERIN give values to the variables \texttt{radius}, \texttt{nbTheta}, \texttt{nbPsi}, \texttt{thetaMin}, \texttt{thetaMax}, \texttt{psiMin}, and \texttt{psiMax}. The variable \texttt{radius} is the radial distance of the observers with respect to the origin. The variables \texttt{nbTheta} and \texttt{nbPsi} are the number of observers in the $\Theta$ (azimuth) and $\Psi$ (elevation) direction, respectively. The variables \texttt{thetaMin} and \texttt{thetaMax} defines the range of $\Theta$. The variables \texttt{psiMin} and \texttt{psiMax} defines the range of $\Psi$. The default values are:

\begin{verbatim}
&OBSERVERIN
  nbx=0
  nby=0
  nbz=0
  xMin=0
  xMax=0
  yMin=0
  yMax=0
  zMin=0
  zMax=0
/
\end{verbatim}

\textbf{Sample Case: Single Observer}

**Objective:** Position an observer 10 rotor radii ahead and 10 rotor radii below the main rotor hub of the helicopter.

**Step 1:** Access the root directory.

**Step 2:** Copy the files WOPIt.run and WOPIt.nam from the folder ./Cases/05_noise into the folder ./Cases/06_single.

**Step 3:** In the folder ./Cases/06_single, open WOPIt.nam

**Step 4:** Specify that the observer position is in terms of rotor radii.
Step 5: Position an observer 10 rotor radii in front and below the helicopter.

Step 6: Open a Cygwin terminal and change the path in the Cygwin terminal to the directory 06_single.

Step 7: Run the file WOPIt.run.

Step 8: In the Cygwin terminal enter the command `du -sh` and ensure that the directory size is 13M.

Sample Case: Rectangular Observer Grid

Objective: Position a grid of 5x5 observers 10 rotor radii directly below the main rotor hub of the helicopter. The dimensions of the grid are 5 rotor radii by 5 rotor radii.

Step 1: Access the root directory.

Step 2: Copy the files WOPIt.run and WOPIt.nam from the folder ./Cases/05_noise into the folder ./Cases/07_rectangular.

Step 3: In the folder ./Cases/07_rectangular, open WOPIt.nam

Step 4: Specify that the observer position is in terms of rotor radii.

Step 5: Setup a 5x5 observer grid in the x-y plane and have the grid by 10 rotor radii by 10 rotor radii. Position the grid directly below the helicopter with center of the grid directly below the main rotor hub.
Step 6: Open a Cygwin terminal and change the path in the Cygwin terminal to the directory 07_rectangular.

Step 7: Run the file WOPIt.run.

Step 8: In the Cygwin terminal enter the command `du -sh` and ensure that the directory size is 13M.

(Note: This case will take longer than for the single observer case – about 25 times longer. The noise computation time scales with the number of observers.)

Sample Case: Spherical Observer Grid

Objective: Position a semi-spherical grid of observers, which are 10 rotor radii from the main rotor hub, surrounding the helicopter.

Step 1: Access the root directory.

Step 2: Copy the files WOPIt.run and WOPIt.nam from the folder ./Cases/05_noise into the folder ./Cases/08_sphere.

Step 3: In the folder ./Cases/08_sphere, open WOPIt.nam

Step 4: Specify that the observer position is in terms of rotor radii and the angle values are in degrees.

```
&OBSERVERPARAM
  position=1
  angle=1
/
```

Step 5: Create a 5x5 observer grid where each observer is 10 rotor radii from the main rotor hub. Have the grid sweep from azimuth angles of 135° to 225° and elevation angles of -30° to 30°.
Step 6: Open a Cygwin terminal and change the path in the Cygwin terminal to the directory 08_sphere.

Step 7: Run the file WOPIt.run.

Step 8: In the Cygwin terminal enter the command `du -sh` and ensure that the directory size is 13M.

A.4.1.2 Motion

The observers, by default, remain stationary while the aircraft performs its maneuvers. Attached to the Aircraft In order to fix the observers in the aircraft frame of reference (i.e., the motion of the observers to be the same as the aircraft), the user must open WOPIt.nam and in the namelist &OBSERVERIN set the variable attachedTo = "Aircraft".

Warning: To avoid a current bug in the system that fails to attach the observer to the aircraft, make sure there is a space on either side of the equals sign and the 'A' in 'Aircraft' is capitalized. This is found to be effective in preventing the bug.

Sample Case: Attached Observer

Objective: Set the motion of a single observer to that of the helicopter.

Step 1: Access the root directory.

Step 2: Copy the files WOPIt.run and WOPIt.nam from the folder ./Cases/06_single into the folder ./Cases/09_attached.

Step 3: In the folder ./Cases/09_attached, open WOPIt.nam

Step 4: Attach the observer motion the that of the aircraft.
Step 5: Open a Cygwin terminal and change the path in the Cygwin terminal to the directory 09_attached.

Step 6: Run the file WOPIt.run.

Step 7: In the Cygwin terminal enter the command `du -sh` and ensure that the directory size is 13M.

A.4.2 Domain

The acoustic results can be analyzed in the time and frequency domains.

A.4.2.1 Time

In order to specify the time range the user must open WOPIt.nam and in the namelist &OBSERVERIN specify values for the variables `tMin` and `tMax`.

```
&OBSERVERIN
  tMin=0
  tMax=1
/
```

A.4.2.2 Frequency

To output the acoustic prediction in the frequency domain the user must open WOPIt.nam and in the namelist &ENVIRONMENTIN create the variable `spectrumFlag` and set its value to `.true.`.

```
&ENVIRONMENTIN
  spectrumFlag=.false.
/
```

Segments If desired, frequency analysis can be performed over specific time steps. In order to do this, the user must open WOPIt.nam and in the namelist &OBSERVERIN specify values for `segmentSize` and `segmentStepSize`.

```
&OBSERVERIN
  segmentSize=0.5
  segmentStepSize=0.5
/
```
Windowing In order to apply windowing in the frequency domain the user must open \texttt{WOPIt.nam} and in the namelist \&\texttt{OBSERVERIN} specify a value for the variable \texttt{windowFunction}. Three value options are “Hanning Window”, “Blackman Window”, and “Flat Top Window”.

\begin{verbatim}
&NOISE
    windowFunction=""
/
\end{verbatim}

Frequency Cutoff To specify cutoff frequencies the user must open \texttt{WOPIt.nam} and in the namelist \&\texttt{OBSERVERIN} specify values for the variables \texttt{highPassFrequency} and \texttt{lowPassFrequency}. The variable \texttt{highPassFrequency} cuts off all frequencies lower than the specified value. The variable \texttt{lowPassFrequency} cuts off all frequencies higher than the specified value.

\begin{verbatim}
&OBSERVERIN
    highPassFrequency=8
    lowPassFrequency=11220
/
\end{verbatim}

By default the \texttt{lowPassFrequency} is set to the highest value its corresponding data type can display.

**Sample Case: Time**

**Objective:** Set the time range of acoustic prediction to the time it takes the main rotor blade to complete a single revolution.

**Step 1:** Access the root directory.

**Step 2:** Copy the files \texttt{WOPIt.run} and \texttt{WOPIt.nam} from the folder \texttt{./Cases/06_single} into the folder \texttt{./Cases/10_time}.

**Step 3:** In the folder \texttt{./Cases/10_time}, open \texttt{WOPIt.nam}

**Step 4:** Specify that the input time is in terms of the period of a single blade.

\begin{verbatim}
&OBSERVERPARAM
    position=1
    time=1
/
\end{verbatim}

**Step 5:** Set the time range to a single blade period.
Step 6: Open a terminal and change the path in the terminal to the directory 10_time.

Step 7: Run the file WOPIt.run.

Step 8: In the Cygwin terminal enter the command du -sh and ensure that the directory size is 13M.

Sample Case: Frequency

Objective: Perform acoustic analysis over the time range it takes for a rotor blade to complete a quarter revolution and increment to time range by the same amount.

Step 1: Access the root directory.

Step 2: Copy the files WOPIt.run and WOPIt.nam from the folder ./Cases/10_time into the folder ./Cases/11_frequency.

Step 3: In the folder ./Cases/11_frequency, open WOPIt.nam

Step 4: Perform frequency analysis every quarter blade period and increment the time a quarter blade period.

Step 5: Open a terminal and change the path in the terminal to the directory 11_frequency.

Step 6: Run the file WOPIt.run.

Step 7: In the Cygwin terminal enter the command du -sh and ensure that the directory size is 13M.
A.4.3 Noise Output and Metrics

This section demonstrates how to write out the noise and specify noise metrics.

A.4.3.1 Acoustic Pressure

In order to output the acoustic pressure at each observer location the user must set the variable `acousticPressureFlag=.true.` in the namelist `&ENVIRONMENT`. To specify the file location and name specify values for the variables `pressureFolderName` and `pressureFileName`, respectively.

```
&ENVIRONMENT
   acousticPressureFlag=.false.
   pressureFolderName=""
   pressureFileName="pressure"
/
```

A.4.3.2 Sound Pressure Level

In order to output the sound pressure level at each observer location the user must set the variables `SPLdBFlag=.true.` and `spectrumFlag=.true.` in the namelist `&ENVIRONMENT`. To specify the file location and name specify values for the variables `SPLFolderName` and `SPLFileName`, respectively.

```
&ENVIRONMENT
   SPLdBFlag=.true.
   spectrumFlag=.true.
   SPLFolderName=""
   SPLFileName="SPL"
/
```

A.4.3.3 Overall Sound Pressure Level

In order to output the overall sound pressure level at each observer location the user must set the variable `OASPLdBFlag=.true.` in the namelist `&ENVIRONMENT`. To specify the file location and name specify values for the variables `OASPLFolderName` and `OASPLFileName`, respectively.

```
&ENVIRONMENT
   OASPLdBFlag=.true.
   OASPLFolderName=""
   OASPLFileName="OASPL"
/
```
A.4.3.4 Effective Perceived Noise Level

In order to output the effective perceived noise level at each observer location the user must set the variable EPNLFlag=.true. and PNLTFlag=.true. in the namelist &ENVIRONMENT.

```
&ENVIRONMENTIN
  EPNLFlag=.true.
  PNLTFlag=.true.
/
```

Sample Case: Acoustic Pressure

**Objective:** Compute the acoustic pressure for an observer attached to an aircraft for the case defined in 10_time.

**Step 1:** Access the root directory.

**Step 2:** Copy the files WOPIt.run and WOPIt.nam from the folder ./Cases/10_time into the folder ./Cases/12_pressure.

**Step 3:** In the folder ./Cases/12_pressure, open WOPIt.nam

**Step 4:** Attach the observer motion to that of the aircraft.

```
&OBSERVERIN
  xLoc=-10
  yLoc=0
  zLoc=-10
  tMin=0
  tMax=1
  attachedTo = “Aircraft”
/
```

**Step 5:** Specify that the system should write out the acoustic pressure file.

```
&ENVIRONMENTIN
  acousticPressureFlag=.true.
/
```

**Step 6:** Open a terminal and change the path in the terminal to the directory 12_pressure.

**Step 7:** Run the file WOPIt.run.
Step 8: In the Cygwin terminal enter the command `du -sh` to ensure that the directory size is 15M.

Within the folder Heli are mission segment and flight condition folders. In the lowest levels of each directory tree are the files `pressure.tec`. These files, when opened in Tecplot, display the pressure time history. A Tecplot layout file is located in the folder `./Cases/12_pressure`. Copy the `pressure.lay` file into the directory `./Heli/OffD-Miss/Mission_001/Segement_003`. Then open the file `pressure.lay` with TecPlot and it should be identical to Fig. A.5.

![Acoustic Pressure Time History](image)

**Figure A.5.** Acoustic pressure time history of mission segment 3 of off-design mission 1.
Sample Case: SPL

Objective: Compute SPL for an observer attached to an aircraft in the frequency domain for the case defined in 10_time.

Step 1: Access the root directory.

Step 2: Copy the files WOPIt.run and WOPIt.nam from the folder ./Cases/10_time into the folder ./Cases/13_SPL.

Step 3: In the folder ./Cases/13_SPL, open WOPIt.nam

Step 4: Attach the observer motion to that of the aircraft.

```
&OBSERVERIN
  xLoc=-10
  yLoc=0
  zLoc=-10
  tMin=0
  tMax=1
  attachedTo = “Aircraft”
/
```

Step 5: Specify that the system should write out the SPL file.

```
&ENVIRONMENTIN
  SPLdBFlag=.true.
  spectrumFlag=.true.
/
```

Step 6: Open a terminal and change the path in the terminal to the directory 13_SPL.

Step 7: Run the file WOPIt.run.

Step 8: In the Cygwin terminal enter the command `du -sh` an ensure that the directory size is 14M.

Copy the spl.lay file into the directory ./Heli/OffDMiss/Mission_001/Segment_003. Then open the file spl.lay with TecPlot and it should be identical to Fig. A.6.
Sample Case: OASPL

Objective: Compute OASPL for a stationary observer domain for the case defined in 11_frequency.

Step 1: Access the root directory.

Step 2: Copy the files WOPIt.run and WOPIt.nam from the folder ./Cases/11_frequency into the folder ./Cases/14_OASPL.

Step 3: In the folder ./Cases/14_OASPL, open WOPIt.nam

Step 5: Specify that the system should write out the OASPL file.

Figure A.6. SPL of mission segment 3 of off-design mission 1.
Step 5: Open a terminal and change the path in the terminal to the directory 14_OASPL.

Step 6: Run the file WOPIt.run.

Step 7: In the Cygwin terminal enter the command `du -sh` and ensure that the directory size is 13M.

Copy the `oaspl.lay` file into the directory `./Heli/OffDMiss/Mission_001/Segement_003`. Then open the file `oaspl.lay` with TecPlot and it should be identical to Fig. A.7.

Figure A.7. OASPL of mission segment 3 of off-design mission 1.
A.5 Cases

Each section outlines a different case highlighting the various capabilities of the system. The cases go step-by-step in setting up the run and input files for the user to follow.

A.5.1 OASPL for a Flyover

In this section the user predicts the acoustic results for the main rotor tail rotor helicopter. An observer is positioned 150 meters below and 50 meters ahead of the helicopter.

OASPL is an integration of the noise over a frequency range. Therefore, OASPL is computed as a single value. If the OASPL is to be computed over the entire time range then a single value is outputted. For multiple values of OASPL the time range must be broken up into segments over which frequency analysis is performed.

Step 1: Access the root directory.

Step 2: Copy the files WOPIt.run and WOPIt.nam from the folder ./Cases/11_frequency into the folder ./Cases/15_OASPLFlyover.

Step 3: In the folder ./Cases/15_OASPLFlyover, open WOPIt.nam

Step 4: Specify helicopter.run as the NDARC case and only analyze the third segment of the first off-design mission.

```plaintext
&CASEPARAM
    solutionFile="helicopter.soln"
    offMissFlag=.true.
    nOffMiss=1
    offMiss=1
    nOffMissSeg=1
    offMissSeg=3
    perfCondFlag=.true.
    nPerfCond=0
/
```

Step 5: Compute thickness, loading, and broadband noise for both rotors.

```plaintext
&NOISE
    nRotor=2
    rotors=1,2
    Thickness=1
    Loading=1
    Broadband=1
/
```

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Step 6: User specified values of position and time.

```
&OBSERVERPARAM
  position=0
time=0
/
```

Step 7: Position a single observer 150 meters in front and 50 meters below of the helicopter; compute the noise of a time range of 10 seconds and perform frequency analysis over 0.5 seconds while stepping in time every 0.5 seconds.

```
&OBSERVERIN
  xLoc=-150
  yLoc=0
  zLoc=-50
  tMin=0
  tMax=10
  segmentSize=0.5
  segmentStepSize=0.5
/
```

Step 8: Compute and output the OASPL.

```
&ENVIRONMENTIN
  OASPLdbFlag=.true.
/
```

Step 9: Open a terminal and change the path in the terminal to the directory 15_OASPLFlyover.

Step 10: Run the file WOPIt.run.

In the working directory copy the file oasplFlyover.lay into Segement_003. Then open the file oasplFlyover.lay and it should be identical to Fig. A.8.

Copy the oasplFlyover.lay file into the directory ./Heli/OffDMiss/Mission_001/Segement_003. Then open the file oasplFlyover.lay with TecPlot and it should be identical to Fig. A.8.
A.5.2 EPNL for a Flyover

In this section the user computes the EPNL results for observers below the main rotor tail rotor helicopter.

Step 1: Access the root directory.

Step 2: Copy the files WOPIt.run and WOPIt.nam from the folder ./Cases/11_frequency into the folder ./Cases/16_EPNLFlyover.

Step 3: In the folder ./Cases/16_EPNLFlyover, open WOPIt.nam

Step 4: Specify helicopter.run as the NDARC case and only analyze the third segment of the first off-design mission.
Step 5: Compute thickness, loading, and broadband noise for both rotors.

Step 6: User specified values of position and time.

Step 7: Position a single observer 150 meters in front and 50 meters below of the helicopter; compute the noise of a time range of 10 seconds and perform frequency analysis over 0.5 seconds while stepping in time every 0.5 seconds.

Step 8: Compute and output the EPNL.
Step 9: Open a terminal and change the path in the terminal to the directory 16_EPNLFly-over.

Step 10: Run the file WOPIt.run.

In the folder Segment_003 should be the file spl_EPNL.txt. Open the file in a text editor and the total EPNL should be listed as 105.5075.

A.5.3 OASPL for Frontal Observers

In this section the user compares the OASPL in front of helicopters for three configurations: main rotor tail rotor helicopter, coaxial helicopter, and the tandem helicopter.

Step 1: Access the root directory.

Step 2: Copy the files WOPIt.run and WOPIt.nam from the folder ./Cases/10_time into the folder ./Cases/17_OASPLFrontal.

Step 3: In the folder ./Cases/17_OASPLFrontal, open WOPIt.nam

Step 4: Specify helicopter.run as the NDARC case and only analyze the third segment of the first off-design mission.

Step 5: Compute thickness, loading, and broadband noise for both rotors.
Step 6: Set user specified value time, position in terms of rotor radii, and angles in degrees.

```plaintext
&OBSERVERPARAM
  position=1
  time=0
  angle=1
/
```

Step 7: Create a 5x5 observer grid where each observer is 10 rotor radii from the main rotor hub. Have the grid sweep from azimuth angles of 135° to 225° and elevation angles of −30° to 30°. Perform acoustic prediction for a time range of 1 seconds and attach the observer motion to that of the aircraft.

```plaintext
&OBSERVERIN
  radius=10
  nbTheta=5
  nbPsi=5
  thetaMin=135
  thetaMax=225
  psiMin=-30
  psiMax=30
  tMin=0
  tMax=1
  attachedTo = "Aircraft"
/
```

Step 8: Compute and output the OASPL.

```plaintext
&ENVIRONMENTIN
  OASPLdBFlag=.true.
/
```

Step 9: Open a terminal and change the path in the terminal to the directory 17_OASPLFrontal.

Step 10: Run the file WOPIt.run.

In the working directory copy the file oasplFront.lay into Segement_003. Then open the file oasplFront.lay and it should be identical to Fig. A.9.
A.5.4 Single Observer HSI Noise

This sample case outlines how to compute the HSI contribution to the total noise. This is a noise source which is not computed through PSU-WOPWOP.

If HSI=1 the user must take additional steps after the first run of the system. As HSI noise is an ad hoc addition to the NPS, it is ran separately from the regular WOPIt system. When HSI = 1, WOPIt creates a text file called HSIFlag.txt that lets the system know whether to write out the necessary namelists for HSI noise. Running the NPS with HSI on creates two global namelists, HSI__name.nam and HSIParameters.nam, as well as a HSIParam.nam and name.nam for each individual rotor.

The HSI executable ShearIt.exe can be used after the initial run of WOPIt, and is followed by running PSU-WOPWOP a second time. This creates the plot for the final pressure profile: FINAL_HSI_Pressure.tec.

Figure A.9. OASPL of mission segment 3 of off-design mission 1.
Step 1: Access the root directory.

Step 2: Copy the files `WOPIt.run` and `WOPIt.nam` from the folder `./Cases/06_single` into the folder `./Cases/18_hsi`.

Step 3: In the folder `./Cases/18_hsi`, open `WOPIt.nam`.

Step 4: Specify `helicopter.run` as the NDARC case and only analyze the third segment of the first off-design mission. (Note the change in mission segment to 4, a higher flight speed.)

```plaintext
&CASEPARAM
  solutionFile="helicopter.soln"
  offMissFlag=.true.
  nOffMiss=1
  offMiss=1
  nOffMissSeg=1
  offMissSeg=4
  perfCondFlag=.true.
  nPerfCond=0
/
```

Step 5: Specify noise prediction for the main rotor, and for the noise sources thickness, loading, and HSI.

```plaintext
&OBSERVERIN
  nRotor=1
  rotors=1
  Thickness=1
  Loading=1
  HSI=1
/
```

Step 6: Change the observer position and attach the observer motion to that of the aircraft. (This observer position is nearly in plane of the main rotor, ahead of the helicopter.)

```plaintext
&OBSERVERIN
  xLoc=-10
  yLoc=0
  zLoc=0
  attachedTo = "Aircraft"
/
```
Step 7: Write out the acoustic pressure.

```
&ENVIRONMENTIN
    acousticPressureFlag=.true.
/
```

Step 8: Open a Cygwin terminal and change the path in the Cygwin terminal to the directory 18_HSI.

Step 9: Run the file WOPIt.run.

Step 10: In the Cygwin terminal, type in "../ShearIt/ShearIt.exe". This points the directory to the ShearIt executable and runs ShearIt for the current case.

Step 11: Now in the Cygwin terminal, type "../PSU-WOPWOP/PSU-WOPWOP.exe". This points the directory back to PSU-WOPWOP and executes it. This produces the final data for the sheared HSI noise.

Finally, copy the file sheared.lay into the folder Segment_004 then open the file using Tecplot. The resulting file should be identical to that shown in Fig. A.10
A.5.5 BVI for a Single Observer with Wake Outputs

This sample case outlines how to compute a case for BVI noise and the visualization tools that are possible with the NPS. BVI is most visible in descent with the observer in front of and below the plane of the rotor. In this case we will use the Helicopter NDARC case mission segment 6 of off-design mission 1, as this is a descent case.

Step 1: Access the root directory.

Step 2: Copy the files WOPIt.run and WOPIt.nam from the folder .//Cases/11_frequency into the folder .//Cases/19_bvi.

Step 3: In the folder .//Cases/19_bvi, open WOPIt.nam

Figure A.10. Acoustic pressure accounting for HSI noise of mission segment 3 of off-design mission 1.
Step 4: Specify `helicopter.run` as the NDARC case and only analyze the sixth segment of the first off-design mission.

```
&CASEPARAM
  solutionFile="helicopter.soln"
  offMissFlag=.true.
  nOffMiss=1
  offMiss=1
  nOffMissSeg=1
  offMissSeg=6
  perfCondFlag=.true.
  nPerfCond=0
/
```

Step 5: Specify noise prediction for the main and tail rotor, and for the noise sources thickness, loading, and BVI.

```
&OBSERVERIN
  nRotor=2
  rotors=1,2
  Thickness=1
  Loading=1
  BVI=1
/
```

Step 6: Change the observer position and attach the observer motion to that of the aircraft. (This observer position is 45 degrees out of plane of the main rotor, ahead of the helicopter.)

```
&OBSERVERIN
  xLoc=-10
  yLoc=0
  zLoc=-10
  attachedTo = "Aircraft"
/
```

Step 7: Output both the acoustic pressure and the pertinent sigma flags. Sigma surfaces can be opened in either TecPlot or FieldView, and can be used to visualize the movement of the vehicle and the interaction between the wake and the rotor. This can be used to see when the vortices from the rotor are interacting, and if the vehicle is moving and oriented the way that the user desires.
Step 8: Compute and output the Blade and Wake plots and rotor disk plots. These plots are also useful in visualizing the wake-rotor interactions, and the orientation of the vehicle.

Notice: The globalBnW flag is very useful for vehicle orientation and wake visualization, but it does greatly increase the run time of the code. Be aware of this when running a case.

Step 9: Open a Cygwin terminal and change the path in the Cygwin terminal to the directory 19_BVI.

Step 9: Run the file WOPIt.run.

Finally, copy the files pressure.lay and disk.lay into the folder Segment_005 then open the file using Tecplot. The resulting file should be identical to those shown in Fig. A.11 and Fig. A.12. The file globalBnW.tex is already formatted, and should match Fig. A.13.
A.5.6 Bell 430 Flyover

Setup a stationary observer and attach a reflective wall at the location of the observer. Then have Bell 430 helicopter fly over and compute the OASPL.

Step 1: Access the root directory.

Step 2: Copy the files WOPIt.run and WOPIt.nam from the folder ./Cases/15_OASPLFlyover into the folder ./Cases/20_Bell430.

Step 3: In the folder ./Cases/20_Bell430, open WOPIt.nam

Step 4: Specify Bell430.run in WOPIt.run as the NDARC run file.
Figure A.12. Disk plots of the main rotor for loading in the z direction and $\Delta U_p$ of mission segment 6 of off-design mission 1.

```
runFile=Bell430.run
```

Step 5: Specify **Bell430.run** as the **NDARC** case and only analyze the fifth segment of the first off-design mission.

```
&CASEPARAM
  solutionFile="Bell430.soln"
  offMissFlag=.true.
  nOffMiss=1
  offMiss=1
  nOffMissSeg=1
  offMissSeg=5
  perfCondFlag=.true.
  nPerfCond=0
/
```

Step 6: Compute thickness, loading, BVI, and broadband noise for both rotors.
Figure A.13. Plot of blade and wake location for mission segment 6 of off-design mission 1.

\begin{verbatim}
&NOISE
   nRotor=2
   rotors=1,2
   Thickness=1
   Loading=1
   BVI=1
   Broadband=1
\end{verbatim}

**Step 7:** User specified values of position and time.
Step 8: Position a single observer 609.6 meters in front and 60.96 meters below of the helicopter; compute the noise of a time range of 22.218 seconds and perform frequency analysis over 0.5 seconds while stepping in time every 0.5 seconds. Also set the time steps to 50000.

Step 9: Compute and output the OASPL.

Step 10: Open a terminal and change the path in the terminal to the directory 20_Bell430.

Step 11: Run the file WOPIt.run.

Step 12: Access the directory ./Heli/OffDMiss/Mission_001/Segment_005.

Step 13: Open the file name.nam and specify one wall in the namelist &ENVIRONMENTIN.

Step 14: Insert the namelist &WallIn after the namelist &ENVIRONMENTIN and prior to the namelist &ContainerIn with the variables and values specified in the box below.
&WallIn
    normalVector = 0.0, 0.0, 1.0
    pointOnPlane = -609.6, 0.0, -60.96
/

Step 15: Access the folder 20_Bell430 and open WOPIt.run.

Step 16: Comment out the command which executes WOPIt.exe using # to ensure that WOPIt.exe will not be execute and therefore the file name.nam will not be overwritten.

# "$WOPItDir"/WOPIt.exe < WOPIt.nam

Step 17: Run the file WOPIt.run.

In the working directory copy the files Flyover.lay and Flyover.png into the folder ./Heli/OffDMiss/Mission_001/Segment_005. Then open the file Flyover.lay and the OASPL should be the same as shown in Fig. A.14.
Figure A.14. OASPL results of a Bell 430 flyover of a stationary observer.
Appendix B
Vehicle Verification

As a part of the verification of the NDARC NPS, three additional vehicles were analyzed in addition to the vehicle shown in Chapter 4. These vehicles are a tandem helicopter, a coaxial helicopter, and a ‘hexacopter’, which is a novel six-rotor concept vehicle. Several addition helicopter cases were also run, which are included as well. Each of the results are presented here for completeness. All of these cases were produced during the system verification, which occurred before any changes or repairs were made to the system.

B.1 Helicopter

Vehicle parameters and description for the helicopter can be found in Chapter 4. In addition to the validations conduction in that chapter, OASPL hemispheres were analyzed. Those are shown in this section for completeness. The flight conditions used for this analysis are shown in Table B.1.

<table>
<thead>
<tr>
<th>Segment</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward flight velocity (m/s)</td>
<td>48.5</td>
<td>40.5</td>
<td>25.7</td>
<td>25.7</td>
</tr>
<tr>
<td>Advance ratio</td>
<td>0.225</td>
<td>0.187</td>
<td>0.119</td>
<td>0.119</td>
</tr>
<tr>
<td>Vertical velocity (m/s, + climb)</td>
<td>3.96</td>
<td>0.0</td>
<td>−2.69</td>
<td>−0.51</td>
</tr>
<tr>
<td>Climb angle (degrees)</td>
<td>4.9</td>
<td>0.0</td>
<td>−5.99</td>
<td>−1.1</td>
</tr>
</tbody>
</table>

Table B.1. Flight segment parameters for the NDARC example helicopter.
Figure B.1. Helicopter OASPL projection for an observer 10 RR away. (A) Best rate of climb (48.5 m/s forward flight, 0.225 advance ratio, 3.96 m/s climb, 4.9 deg climb), (B) best endurance (40.5 m/s forward flight, 0.187 advance ratio, level), (C) six degree descent (25.7 m/s forward flight, 0.119 advance ratio, −2.69 m/s descent, −5.99 deg descent), (D) one degree descent (25.7 m/s forward flight, 0.119 advance ratio, −0.51 m/s descent, −1.1 deg descent).

B.2 Tandem helicopter

The second vehicle analyzed in this study was the NDARC reference tandem helicopter. This vehicle is modeled after a CH-47D tandem helicopter. Both rotors are modeled to be the same size. Values were extracted from Ref. 52 and exact rotor specifications for each of the two rotors are contained in Table B.2. The flight conditions used for this analysis are shown in Table B.3.

<table>
<thead>
<tr>
<th>Number of blades</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td>9.144 m</td>
</tr>
<tr>
<td>Chord</td>
<td>0.81 m</td>
</tr>
<tr>
<td>Thickness over chord</td>
<td>0.1</td>
</tr>
<tr>
<td>Rotation speed</td>
<td>23.33 rad/s</td>
</tr>
</tbody>
</table>

Table B.2. NDARC example tandem helicopter specifications from Ref. 52.
Table B.3. Flight segment parameters for the NDARC example tandem helicopter.

<table>
<thead>
<tr>
<th>Segment</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward flight velocity (m/s)</td>
<td>46.7</td>
<td>46.4</td>
<td>25.7</td>
<td>25.7</td>
</tr>
<tr>
<td>Advance ratio</td>
<td>0.216</td>
<td>0.215</td>
<td>0.121</td>
<td>0.121</td>
</tr>
<tr>
<td>Vertical velocity (m/s, + climb)</td>
<td>4.29</td>
<td>0.0</td>
<td>−2.7</td>
<td>−0.51</td>
</tr>
<tr>
<td>Climb angle (degrees)</td>
<td>5.28</td>
<td>0.0</td>
<td>−5.99</td>
<td>−1.1</td>
</tr>
</tbody>
</table>

Figure B.2. Tandem helicopter shed tip wake plots. 25.7 m/s forward flight, 0.121 advance ratio, −2.7 m/s descent, −5.99 deg descent.
**Figure B.3.** Tandem helicopter induced velocity and z loading for the front rotor (left) and rear rotor (right). Interactional effects ignored. 25.7 m/s forward flight, 0.121 advance ratio, −2.7 m/s descent, −5.99 deg descent. 25.7 forward flight, 0.130 advance ratio, −2.69 m/s descent, −5.99 deg descent.
Figure B.4. Tandem helicopter acoustic pressure time history and spectrum loading plots. Observer 10RR away, −26 deg elevation, 223 deg azimuth, 25.7 m/s forward flight, 0.121 advance ratio, −2.7 m/s descent, −5.99 deg descent.
Figure B.5. Tandem helicopter BVISPL for an observer 10RR away. 25.7 m/s forward flight, 0.121 advance ratio, −2.7 m/s descent, −5.99 deg descent.

Figure B.6. Tandem helicopter OASPL projection for an observer 10 RR away. (A) Best rate of climb (46.7 m/s forward flight, 0.216 advance ratio, 4.29 m/s climb, −5.28 deg descent), (B) best endurance (46.4 m/s forward flight, 0.215 advance ratio, level), (C) six degree descent (25.7 m/s forward flight, 0.121 advance ratio, −2.7 m/s descent, −5.99 deg descent), (D) one degree descent (25.7 m/s forward flight, 0.121 advance ratio, −0.51 m/s descent, −1.1 deg descent).
B.3 Coaxial helicopter

Third, a coaxial vehicle was analyzed. This helicopter is modeled after a XH-59 coaxial helicopter. Values were extracted from Ref. 52 and exact rotor specifications for each of the two rotors are contained in Table B.4. The flight conditions used for this analysis are shown in Table B.5.

<table>
<thead>
<tr>
<th>Number of blades</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td>6.10 m</td>
</tr>
<tr>
<td>Chord</td>
<td>0.38 m</td>
</tr>
<tr>
<td>Thickness over chord</td>
<td>0.09</td>
</tr>
<tr>
<td>Rotation speed</td>
<td>32.5 rad/s</td>
</tr>
</tbody>
</table>

**Table B.4.** NDARC example coaxial helicopter specifications from Ref. 52.

<table>
<thead>
<tr>
<th>Segment</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward flight velocity (m/s)</td>
<td>40.6</td>
<td>41.5</td>
<td>25.7</td>
<td>25.7</td>
</tr>
<tr>
<td>Advance ratio</td>
<td>0.204</td>
<td>0.209</td>
<td>0.130</td>
<td>0.130</td>
</tr>
<tr>
<td>Vertical velocity (m/s, + climb)</td>
<td>5.02</td>
<td>0.0</td>
<td>−2.69</td>
<td>−0.51</td>
</tr>
<tr>
<td>Climb angle (degrees)</td>
<td>7.05</td>
<td>0.0</td>
<td>−5.99</td>
<td>−1.1</td>
</tr>
</tbody>
</table>

**Table B.5.** Flight segment parameters for the NDARC example coaxial helicopter.

**Figure B.7.** Shed tip wake for both rotors (left) and the lower rotor (right). 25.7 m/s forward flight, 0.130 advance ratio, −2.69 m/s descent, −5.99 deg descent.
Figure B.8. Coaxial helicopter induced velocity and z loading for the lower rotor (left) and upper rotor (right). Interactional effects ignored. 25.7 m/s forward flight, 0.121 advance ratio, −2.7 m/s descent, −5.99 deg descent.
Figure B.9. Coaxial helicopter BVISPL for an observer 10RR away. 25.7 m/s forward flight, 0.130 advance ratio, −2.69 m/s descent, −5.99 deg descent.

Figure B.10. Coaxial helicopter OASPL projection for an observer 10 RR away. (A) Best rate of climb (40.6 m/s forward flight, 0.204 advance ratio, 5.02 m/s climb, 7.05 deg climb), (B) best endurance (41.5 m/s forward flight, 0.209 advance ratio, level), (C) six degree descent (25.7 m/s forward flight, 0.130 advance ratio, −2.69 m/s descent, −5.99 deg descent), (D) one degree descent (25.7 m/s forward flight, 0.130 advance ratio, −0.51 m/s descent, −1.1 deg descent).
The hexacopter example vehicle is not based on any available rotorcraft, and is instead designed to give an example of a novel UAM concept vehicle. Vehicle parameters were pulled from Ref. 35. All rotors contain the same parameters, and the values for each rotor is contained in Table B.6. The flight conditions used for this analysis are shown in Table B.7.

<table>
<thead>
<tr>
<th>Number of blades</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td>3.05 m</td>
</tr>
<tr>
<td>Chord</td>
<td>0.22 m</td>
</tr>
<tr>
<td>Thickness over chord</td>
<td>0.09</td>
</tr>
<tr>
<td>Rotation speed</td>
<td>70 rad/s</td>
</tr>
</tbody>
</table>

**Table B.6.** NDARC example hexacopter specifications from Ref. 35.

<table>
<thead>
<tr>
<th>Segment</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward flight velocity (m/s)</td>
<td>34.8</td>
<td>44.0</td>
<td>25.7</td>
<td>25.7</td>
</tr>
<tr>
<td>Advance ratio</td>
<td>0.161</td>
<td>0.205</td>
<td>0.121</td>
<td>0.121</td>
</tr>
<tr>
<td>Vertical velocity (m/s, + climb)</td>
<td>2.97</td>
<td>0.0</td>
<td>−2.69</td>
<td>−0.51</td>
</tr>
<tr>
<td>Climb angle (degrees)</td>
<td>4.87</td>
<td>0.0</td>
<td>−5.99</td>
<td>−1.1</td>
</tr>
</tbody>
</table>

**Table B.7.** Flight segment parameters for the hexacopter vehicle design.
Figure B.11. Hexacopter shed tip wake plots. 25.7 m/s forward flight, 0.121 advance ratio, 
−2.69 m/s descent, −5.99 deg descent.
Figure B.12. Hexacopter OASPL projection for an observer 10 RR away. (A) Best rate of climb (34.8 m/s forward flight, 0.161 advance ratio, 2.97 m/s climb, 4.87 deg climb), (B) best endurance (44.0 m/s forward flight, 0.205 advance ratio, level), (C) six degree descent (25.7 m/s forward flight, 0.121 advance ratio, $-2.69$ m/s descent, $-5.99$ deg descent), (D) one degree descent (25.7 m/s forward flight, 0.121 advance ratio, $-0.51$ m/s descent, $-1.1$ deg descent).
Appendix C
PSU-WOPWOP/AAM conversion tool

This appendix exists to document the creation of a tool to convert files from the PSU-WOPWOP Plot3D style files to the Advanced Acoustics Model’s (AAM) netCDF stype files. This appendix exists both to explain the desires of such a conversion tool and to operate as a user’s guide for the code.

A tool to convert from the PSU-WOPWOP output files to the Advanced Acoustics Model (AAM) input files was desired by the Volpe team. AAM is a suite of acoustic prediction codes used to predict rotorcraft noise at the U.S. Department of Transportation’s Volpe Center [60]. The creation of a conversion tool would aid in continued cooperation between Penn State and Volpe and allow for further analysis of PSU-WOPWOP outputs.

The PSU-WOPWOP/AAM conversion code is written in Fortran, and requires two inputs to run. The first is the SEL.x file output by PSU-WOPWOP, and a namelist called AAM_factors.nam, which reads in the additional parameters not included in the SEL file, but required by AAM. The code then reformats these parameters, converts them to the netCDF format, and outputs the .nc file. This can then be read in by AAM and used for calculations.

In order to run the conversion tool, first a user runs PSU-WOPWOP, ensuring the namelist flag “SPLdBFlag” is set to true. Once the PSU-WOPWOP run is completed, the file “SEL.x” should be copied into the directory where the executable “aam_convert.exe” is contained. The user then fills out the “AAM_factors.nam” namelist, shown in Fig. C.1. Once done, the user can execute the conversion code, which will produce a .nc file, which contains the noise data in the format required by AAM.

The flags in Fig. C.1 are defined as follows. These flags provide information required by AAM that cannot be taken from the SEL file.

- ncname: The desired filename for the netCDF file for use with AAM
- phi: The number of azimuthal stations of the SEL file
- dphi: The resolution of azimuthal stations of the SEL file
- theta: The number of elevation stations of the SEL file
- dtheta: The resolution of elevation stations of the SEL file
- Mach: The Mach number of the vehicle being predicted
- fpa: The flight path angle of the vehicle being predicted
- tilt: The nacelle tilt of the vehicle being predicted
- r: The main rotor radius of the vehicle being predicted

```
&FILEINPUT
   ncname = aam_sphere_test.nc
&END

&FLIGHTPARAMS
   phi = 10
   dphi = 1
   theta = 10
   dtheta = 1
   mach = 1
   fpa = 1
   tilt = 1
   r = 1
&END
```

**Figure C.1.** An example “AAM_factors.nam” namelist file for use with the PSU-WOPWOP/AAM conversion tool.

This code is a first attempt at a conversion tool between PSU-WOPWOP and the Advanced Acoustic Model. Testing and verification still needs to be conducted. Additionally, use of this tool requires the netCDF, zlib, and hdf5 libraries present to execute the code. This is due to the requirements of the netCDF format library, which AAM uses for acoustic hemisphere import data.