DEVELOPMENT OF A SOURCE SEPARATION PROCESS FOR
MULTIROTOR AEROACOUSTIC ANALYSIS

A Thesis in
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by
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Abstract

With increasing interest in electric Vertical Takeoff and Landing (eVTOL) aircraft for Urban Air Mobility (UAM), many companies are making strides in the design, manufacturing, certification, and operation of these aircraft. Their use depends heavily on community perception and acceptance of these aircraft, with noise generation limited to acceptable levels. These aircraft use Distributed Electric Propulsion (DEP) with multiple rotors to provide the required thrust and power. Thus, their resultant aeroacoustic footprint is more complex than with helicopters.

To understand the noise-generating mechanisms of these aircraft: this thesis develops a Source Separation Process (SSP) to separate the noise component produced by each rotor from ground-based flyover acoustic measurements. The SSP is a two-step process that combines time-domain De-Dopplerization with the Vold-Kalman (V-K) order tracking filter. This process can extract rotor components, even when the noise sources continuously change with time, including impulsive noise such as that caused by Blade-Vortex Interaction (BVI). Another advantage of this approach over traditional methods, such as harmonic averaging, is that it preserves the phase and amplitude relationship of acoustic signals throughout the extraction process.

The SSP was applied to multiple data sets to validate and highlight the capabilities and limitations. First, the V-K filter of the SSP is applied to wind tunnel data to understand the noise of the top and bottom rotors in coaxial configuration while operating at nearly identical RPM. Second, the de-Dopplerization of the SSP is applied to acoustic flyover measurements of an sUAS octocopter to understand multirotor noise radiation patterns. Third, the complete SSP was applied to acoustic flight test of Bell 430 helicopter to understand the separated noise source variation with time in maneuvering flight.

For the separated coaxial rotor data, the bottom rotor has higher levels of loading noise radiating out of the plane due to its operation being in the wake of the top rotor. For the de-Dopplerized octocopter data, the broadband noise is dominant underneath the aircraft whereas the tonal noise is dominant toward the in-plane of the aircraft and the noise is most variable in-plane near the horizon of the aircraft. For the de-Dopplerized and separated flight test data, each separated component has different pulse shapes and directivity trends, the source separation for multiple operating conditions was consistent with the aeroacoustic theory.
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List of Symbols

\( a_0 \)  Speed of sound, \( m/s \)

\( t \)  Observer time, \( s \)

\( r \)  Distance, \( m \)

\( \tau \)  Emission time, \( s \)

\( p \)  Acoustic pressure, \( Pa \)

\( A(t) \)  Complex pressure amplitude, \( Pa \)

\( P(t) \)  Complex phasor

\( \omega \)  Rotor shaft speed, \( RPM \)

\( y(t) \)  Total signal, \( Pa \)

\( x(t) \)  Deterministic or harmonic signal, \( Pa \)

\( \nu \)  Stochastic or broadband signal, \( Pa \)

\( k \)  Harmonic order number

\( q \)  V-K filter order

\( bw \)  Bandwidth, \( Hz \)

\( M \)  Mach Number

\( \psi \)  Azimuth angle, \( degrees \)

\( \phi \)  Elevation angle, \( degrees \)

\( \Box^2 \)  Wave operator, \( \Box^2 = \frac{1}{c^2} \frac{\partial^2}{\partial t^2} - \nabla^2 \)
\( H(f) \)  Heaviside function, \( H(f) = 0 \) for \( f < 0 \) and \( H(f) = 1 \) for \( f > 0 \)

\( \delta_{ij} \)  Kronecker delta, \( \delta_{ij} = 1 \) for \( i = j \), otherwise \( \delta_{ij} = 0 \)

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

\( \dot{M}_r \)  \( \dot{M}_i \hat{r}_i \)

\( dS \)  Element of the rotor blade surface

\( \rho_0 \)  Density of air, \( kg/m^3 \)

\( T_{ij} \)  Lighthill stress tensor

\( c \)  Speed of sound, \( m/s \)
First, I would like to sincerely thank my advisor, Dr. Eric Greenwood, for providing me with valuable guidance and support. I would also extend my gratitude to my readers, Dr. Eric Johnson, Dr. Simon Miller, and Dr. Amy Pritchett for taking the time to review my thesis.

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Dedication

To my family.
Chapter 1 | Introduction

1.1 Motivation

There is vast renewed interest in electric Vertical Take-off and Landing (eVTOL) aircraft (such as Urban Air Mobility (UAM) and Advanced Air Mobility (AAM)) due to the potential to provide transportation in urban and highly dense residential areas [1]. The proposed operations of the eVTOL aircraft will fly over communities where their noise can be a major limiting factor. As it currently stands, helicopters have low community acceptance due to the perceived annoyance due to noise, despite their relatively low frequency of operations [2]. Consequently, the proposed high-frequency use of eVTOLs demands that these aircraft operate as quietly as possible. This raises the need for aeroacoustically efficient designs to reduce noise emissions without a large trade-off in performance and handling qualities.

Distributed Electric Propulsion (DEP) would eliminate the noise generated by the engine/motor on the conventional rotorcraft; however, rotor noise is the major contributing factor to the overall acoustic footprint. The noise sources of rotorcraft have been studied for a broad range of operating conditions, and the dynamic nature of some of the noise sources in complex cases is yet to be fully understood. In a conventional helicopter, the tail rotor operates in the wake of the main rotor, resulting in complicated aerodynamics and aeroacoustics generated by the tail rotor. With eVTOL aircraft, this becomes a bigger problem due to the presence of multiple rotors and/or wing combinations operating in close proximity to each other. The aerodynamics of these aircraft is itself a complex problem and can be very hard to accurately model, even when using high-fidelity Computational Fluid Dynamics
(CFD) simulations. These eVTOL aircraft have noise generation mechanisms that are complex, therefore, the aeroacoustics of the eVTOL are difficult to understand. Therefore, the aeroacoustic footprints resulting from these aerodynamic interactions could be much more complex than conventional rotor noise.

Figure 1.1: Electric Vertical Take-off and Landing (eVTOL) aircraft configurations [3]

To understand the acoustic characteristics of UAM aircraft means to understand the rotor noise of these aircraft. Many of the configurations of these proposed aircraft, shown in Figure 1.1, use multiple rotors to provide the thrust needed for vertical take-off. As these rotors reach a steady state for operating conditions as simple as level flight, they use advanced algorithms that manipulate RPM and/or blade pitch angle to provide stability and control. This causes the aeroacoustic state of these aircraft to continuously vary with time. Since the lifting rotors of the aircraft are identical in design, they operate at roughly the same RPM. The rotors are usually not phase synchronized which creates sporadic and continuously varying interference patterns in the generated noise. As a result, coherent addition of this noise may occur and result in lobes of noise in different directions. RPM control further complicates the directivity; as changes in RPM due to control inputs may cause the lobes of noise to dynamically change and propagate in different directions. Consequently, the noise of UAM aircraft as a whole can be highly variable. To overcome this, looking at
individual noise sources and their variation over time may provide better insight into the noise generation mechanisms of the aircraft.

To summarize, the underpinnings of eVTOL aeroacoustics are essential to the development of acoustically aware control strategies and to increase public acceptance of their operation. Therefore, it is essential to understand the noise behavior/characteristics on a rotor-to-rotor basis and to separate the contributions of the individual noise sources. To achieve this, advanced acoustic analysis techniques and strategies must be developed.

1.2 Literature Review

The aerodynamically-generated noise (aeroacoustic) sources of rotorcraft constantly change with time and produce distinctive noise signatures for various operating conditions. These distinctive noise signatures are due to the dominance of different noise sources at different directionality angles. The characterization of these different noise sources is a challenge, especially when the changes are time- and space-dependent due to the directionality.

The noise sources of rotorcraft can be mainly divided into thickness noise, lower harmonic loading noise, high-speed impulsive (HSI) noise, blade-vortex interaction (BVI) noise, and broadband noise [4]. Figure 1.2 (reproduced from Reference [5]) highlights the noise sources for rotorcraft.

Thickness noise is caused by the displacement of the air around the blade when the rotor blade passes through the fluid. The amplitude of the thickness noise is most dominant in the lower harmonics and tends to get smaller as it approaches higher harmonics. It radiates in-plane towards the front of the rotor and is most recognizable in the time-domain with its distinctive negative peaks. As the rotor speed increases, the tip Mach number increases, and the displacement of air by the rotor blade increases. Therefore, there is a correlation between the tip Mach number and the intensity of thickness noise. Also, as the tip Mach number increases, there is an increase in Doppler (or convective) amplification of the sources which increases the intensity. At high forward flight speeds, the tip Mach number can approach 1.0. This arises in a stronger noise source commonly known as High Speed Impulsive (HSI) noise. HSI noise occurs due to the shocks in the flow field caused by the transonic tip
Mach numbers. The directivity of HSI noise is similar to thickness noise but can be observed at locations that are not strictly in the plane of the rotor.

Loading noise occurs from the aerodynamic forces exerted by the rotor blades on the fluid due to the motion of the rotor blade geometry. The amplitude of loading noise is usually larger than other noise sources and it radiates primarily in directions out of the plane of the rotor. Some thickness noise still radiates in the plane of the rotor, e.g., due to drag on the rotor blades. However, since lift is much greater than drag for a well-designed rotor, the loading noise is typically higher out of the plane. The impulsive form of loading noise is Blade-Vortex Interaction (BVI) noise. It occurs when a blade passes through the tip vortices trailed by the preceding blades. Trailed vortices are generated by the spanwise variation in loads/circulation. Therefore, the impulsive nature of the BVI noise originates from the impulsive changes in the aerodynamic forces on the blade as it interacts with the vortices. The directionality of the advancing side BVI noise is out-of-plane and towards the front of the rotor. For retreating side BVI, the noise radiates downward towards the aft of the rotor.

Broadband noise is caused by a number of random sources due to the turbulent nature of the flow around rotor blades. The directionality of broadband noise is the same as the loading noise, i.e., primarily out of the plane. It radiates in all directions.
but becomes dominant at the aft of the rotor due to the absence of strong harmonic noise sources.

Theoretically, the noise generated by these physical mechanisms can be represented by the terms in the Ffowcs Williams and Hawkings (FW-H) [6] Equation 1.1. The FW-H equation is an inhomogeneous wave equation obtained by rearranging the terms of the continuity equation and the Navier-Stokes equation. The left-hand side of the equation is in the form of an acoustic wave equation which describes the propagation of the acoustic waves. The right-hand side of the equation consists of the monopole, dipole, and quadrupole source terms which can represent the physical noise generation sources described above.

\[ \Box^2 p'(\vec{x}, t) = \frac{\partial}{\partial t} \left[ \rho_0 v_n \delta(f) \right] - \frac{\partial}{\partial x_i} \left[ P_{ij} \hat{n}_j \delta(f) \right] + \frac{\partial^2}{\partial x_i \partial x_j} \left[ T_{ij} H(f) \right] \] (1.1)

In the wave equation on the left-hand side, \( \Box^2 \) represents the wave operator and \( p'(\vec{x}, t) \) represents the acoustic pressure. On the right-hand side, the three source terms from left to right are the monopole (thickness noise), dipole (loading noise), and quadrupole (HSI) terms. The monopole term is dependent on the geometry and the displacement of the blade geometry. The dipole term is dependent on the change in the aerodynamic forces and the motions of blade geometry; this is physically equivalent to loading noise (steady and unsteady). The quadrupole term is dependent on the flow field around the blade geometry and becomes important at transonic and supersonic speeds. Physical sources for quadrupole noise term include high speed impulsive noise due to shocks in the advancing side of the rotor. It is usually neglected in the noise computation for rotorcraft due to the high computational cost and low relevance to overall noise levels. Broadband noise can be modeled using either dipole terms or quadrupole terms but is most often computed outside of the FW-H equation using empirical methods.

Farassat provided a solution (Formulation 1) to the FW-H equation by using Green’s function to evaluate the integrals, more details can be found in References [7,8]. Farassat’s Formulation 1 and Formulation 1A neglect the quadrupole noise term from the FW-H equation, but formulation 1A computes the integral form solution to thickness and loading noise terms. It moves the derivatives inside of the integrals, which can make it more suitable for numerical computations. Therefore, formulation
1A is used to make computational predictions of the thickness and loading noise of rotorcraft. Equations 1.2 and 1.3 represent the loading and thickness noise terms and are used in the PSU-WOPWOP [9] noise prediction code that is developed in-house and used for noise predictions at Penn State.

\[
4\pi p'_T(\vec{x}, t) = \int_{f=0} \left[ \frac{\rho_0 (\dot{v}_n + v_n)}{r (1 - M_r)^2} \right]_{ret} dS + \\
\int_{f=0} \left[ \frac{\rho_0 v_n (r M_r + c (M_r - M^2))}{r^2 (1 - M)^3} \right]_{ret} dS
\]

\[
4\pi p'_L(\vec{x}, t) = \frac{1}{c} \int_{f=0} \left[ \frac{\dot{L}_r}{r (1 - M_r)^2} \right]_{ret} dS + \\
\int_{f=0} \left[ \frac{L_r - L_M}{r^2 (1 - M_r)^2} \right]_{ret} dS + \\
\frac{1}{c} \int_{f=0} \left[ L_r \frac{r M_r + c (M_r - M^2)}{r^2 (1 - M_r)^3} \right]_{ret} dS
\] (1.2)

The terms \( p'_T \) and \( p'_L \) on the left-hand side of Equations 1.2 and 1.3 represent the acoustic pressure changes associated with the thickness and loading noise, respectively. These equations are retarded-time equations because the integrands are evaluated at the time when the noise was emitted, known as ‘emission time, \( \tau \)’. To obtain the time when the noise reaches the observer, known as ‘retarded time, \( t \)’ the equation \( t = \tau + r/c \) is used. Note that the denominator of Equations 1.2 and 1.3 includes the \((1 - M_r)\) term; this term is often referred to as Doppler amplification factor. This is caused due to the motion of the source with respect to the medium (air) and it changes the frequency and the amplitude of the acoustic waves as measured by the observer. This leads to the Doppler effect in the measured signals at the observer. The effects and the correction are discussed in greater depth in Section 1.2.1.

All these noise sources appear in normal flight operating conditions, with varying importance. Among the impulsive noise sources, HSI and BVI noise is often the most annoying sources to humans because they are impulsive and tend to dominate the noise metrics when they occur in an operating condition. BVI noise occurs in descending flight conditions and non-steady state operating conditions and tends to cause a significant increase in sound pressure levels.
Experiments are performed in indoor and outdoor settings to further the understanding of the physical noise-generating mechanisms. Indoor experiments, usually performed in wind tunnels and anechoic chambers, allow the design concepts to be tested prior to the development of a full-scale aircraft. These experiments are often performed to understand the acoustics under a controlled environment and with carefully crafted test plans to isolate and investigate different noise-generating mechanisms [10]. The measurements in the wind tunnel tend to be stationary, i.e., the observer and the source are fixed spatially and temporally. Indoor testing can be advantageous in investigating an individual noise-generating phenomenon that would otherwise not be captured in outdoor testing. However, in forward flight regimes, wind tunnel noise tends to increase the background noise, and obtaining a good signal can be challenging albeit at the expense of other noise sources by applying signal processing techniques. Also, due to recirculation effects, recreating accurate equivalent rotor measurements of tonal and broadband noise can be quite challenging [11]. A better way to take acoustic measurements is to perform flight tests with an aircraft in an outdoor setting.

With the knowledge of the computational models and indoor measurements, outdoor flight test plans are prepared to investigate the noise mechanisms under real-life aircraft operating conditions. In some cases, subscale models can be tested to understand how the aeroacoustics differs from computational models and indoor measurements. There are also highly unpredictable and uncontrollable parameters such as weather conditions that dictate the timeline of outdoor testing, potentially causing havoc in the development and certification of the aircraft. However, the noise sources of these aircraft must be understood in a real-life operating environment. Therefore, acoustic flight tests are performed on full-scale aircraft to characterize the noise for different operating conditions.

The acoustic measurements from a flight test can be broadly grouped into these three categories: (1) A leading aircraft fitted with one or more microphones and always flying at a constant distance with respect to the test aircraft [12], Figure 1.3.1, (2) A test aircraft fitted with one or more microphones to record acoustic signals [13], Figure 1.3.2, and (3) A test aircraft flying over a ground-based microphone array [14], Figure 1.3.3.
1.3.1: Non-stationary aircraft and observer

1.3.2: Stationary aircraft and observer

1.3.3: Non-stationary aircraft and stationary observer

Figure 1.3: Three prominent types of acoustic flight test methodologies [12–14]
In the first case, the position and velocity synchronization between the test aircraft and the leading aircraft was performed manually. During this test, maintaining the relative positions of the source and leading aircraft had to be performed by the pilots visually [12]. This could lead to errors in the position due to the challenging task of manually maintaining a constant distance between aircraft without accurate onboard GPS. In either case, the signal-to-noise ratio can be poor due to the noise emitted by the leading aircraft, because the microphones are mounted on the lead aircraft. The directivity information is also limited because the microphones are spatially fixed with respect to the source.

In the second case, the microphones are fixed to the aircraft and can be used to take measurements at fixed positions and distances from the noise source regardless of the motion of the aircraft. However, this could result in the microphones being in the near-field of the aircraft and not capturing the noise sources that are usually dominant in the far-field of the rotor. Both the first and second types of flight tests ensure that the recorded acoustic measurements are stationary, but at the expense of complicated flight test procedures.

In the third case, the ground-based microphones record the acoustic signals, but the ground-fixed observer leads to non-stationarity in the measured signals. If the equivalent stationary signals can be reconstructed with high resolution, then performing these flight tests can provide information about a wide range of noise sources with a good signal-to-noise ratio. During these flight tests, as the moving aircraft approaches and passes a stationary observer, the levels increase and then decrease as heard by the observer thus introducing non-stationarity in the observed signal. Since this is a common type of measurement technique in acoustic flight tests, a reliable way to reconstruct the non-stationary signals into a “stationary” observer that is fixed in distance and position is crucial. The non-stationarity in the signals causes modulation in the frequency and amplitude of the signal [15]. Time-domain techniques can be used to analyze non-stationary signals, but there are serious limitations in the frequency-domain to apply Fourier analysis techniques. This is because the frequency-domain techniques produce poor results for non-stationary signals. To successfully apply the acoustic analysis techniques to ground-based acoustic flight test measurements, a method to account for the non-stationarity must be implemented. This thesis will develop a method that will be applicable to all flight test methodologies.
1.2.1 De-Dopplerization

De-Dopplerization is a procedure to remove the Doppler effect (frequency shift) caused by the change in the position of the aircraft in the acoustic signals measured on the ground. It transforms the ground-based non-stationary acoustic signals to comparable stationary signals moving with the aircraft frame of reference.

As the aircraft flies, the acoustic waves that are emitted by the aircraft propagate in all directions through the air and are measured as acoustic pressures at ground-based observer locations. The measured signals need to be adjusted for the non-stationarity introduced by the motion of the aircraft. Mathematically, the acoustic pressure of a compact point source moving along a path with respect to the observer can be given by Equation 1.4, the derivation is provided by Greenwood and Schmitz [16]. The Doppler amplification factor, \(|1 - M_r|\) is seen in the denominator of Equation 1.4, as it was similarly observed in the denominator of Farassat’s Formulation 1A for the thickness and loading noise from Equations 1.2 and 1.3 from Section 1.2. The roots of Equation 1.4 must be computed to solve for the emission time, \(\tau\).

\[
p'(\vec{x}, t) = \frac{Q(\tau^*)}{4\pi |\vec{x} - \vec{x}_s(\tau^*)| |1 - M_r|} \frac{1}{|1 - M_r|} \tag{1.4}
\]

Solving for the subsonic quadratic root of Equation 1.4 gives Equation 1.5 for the emission time, \(\tau\). Equation 1.5 of emission time, when substituted back into Equation 1.4, gives the equivalent acoustic pressure that is observed at location \(x_1\) for a source moving at a constant speed, \(U\) in the \(x_1\) direction. This equation can be used to demonstrate the Doppler frequency shift that is observed in measured acoustic signals of a moving aircraft. The same effect is seen in the computationally predicted noise because the underlying phenomenon is also seen in the FW-H equation and its retarded-time equation (Farassat Formulation 1A).

\[
\tau^* = t - \frac{M (x_1 - Ut)}{a_0 (1 - M^2)} - \frac{\sqrt{(x_1 - Ut)^2 + (1 - M^2) (x_2^2 + x_3^2)}}{a_0 (1 - M^2)} \tag{1.5}
\]

To understand this non-stationarity of the signals in a physical sense, the following explanation helps. As the aircraft flies over an observer location, the constant change in the position of the aircraft with respect to the observer causes the distance between the source and the observer to change in a corresponding manner. This results in irregularly
spaced reception times for the observer due to the irregular propagation times of the emitted signals. This is illustrated in Figure 1.4 (reproduced from Reference [17]) where the non-stationarity is seen in different time instances as an aircraft performs a flyover with an observer on the ground. The purpose of de-Dopplerization is to correct this.

![Figure 1.4: Graphic depicting the non-stationarity of the measured ground-based acoustic signals of flyover aircraft noise [17]](image)

The problem of de-Dopplerization has been of interest in the measurements of signals for rotor and jet noise applications. Verhas [18] first explored a time-domain de-Dopplerization approach to restore non-stationary signals from a moving source in order to enable the application of frequency-domain Fourier analysis techniques. However, due to the very low resolution in the position data of the aircraft, knowledge of aircraft trajectory was limited, thus leading to inaccuracies in the de-Dopplerized data. To overcome this, Mueller and Preisser [19] performed the de-Dopplerization in the frequency domain. Mueller and Preisser shifted the frequency scale to adjust for the change in the position of the aircraft and the observer. This does not take into account the changing frequencies of tones within the time windows; therefore, the frequencies within time windows remain constant in the signal throughout the
analysis. Essentially, the Doppler frequency shift is not corrected within the time window [17], leading to spectral smearing. “Spectral smearing” occurs in the frequency domain because, within the time window, the position of the aircraft is assumed to be constant with respect to the observer [20]. This assumption does not hold true while integrating for the spectra, because the source and the observer are not fixed in position for the duration of the time window, therefore causing the smearing of tones. This results in the blurring of the tones in the frequency domain, leading to a low signal-to-noise ratio, and causing distortion in the higher harmonic tones [17]. These tones are especially important for eVTOL aircraft noise due to their higher operational blade passage frequency (BPF) than helicopters [21]. To overcome this drawback, Howell et al. [17] applied de-Dopplerization in the time-domain to aircraft flyover acoustic measurements and demonstrated the increase in the resolution of tones of the de-Dopplerized signals.

Kelly and Wilson [20] also performed the de-Dopplerization in the time-domain in an attempt to understand the narrow band spectra from aircraft flyover acoustic measurements. The de-Dopplerized pressure-time history was produced by linear interpolation between the measured pressure-time history. The results showed that the de-Dopplerized tones were at the correct frequencies for the XV-15 aircraft data. This approach by Kelly and Wilson [20] used the Mach number of the aircraft instead of the Mach number of the noise source to account for convective amplification. This incorrectly assumes that the noise is generated at the aircraft Mach number and results in improper convective amplification correction. Greenwood and Schmitz [22] present another time-domain de-Dopplerization approach that preserves the periodicity of the noise sources in an attempt to use harmonic averaging to separate the helicopter main and tail rotor components as discussed in the next section.

1.2.2 Source Separation

The aerodynamic noise of rotorcraft is dominated by the harmonic tones at multiples of the blade passing frequency (BPF) of the rotor [23]. The blade passing frequency of this harmonic noise is dependent on the rotational rate of the rotor, and the number of rotor blades; this can be inferred from measurements. Therefore, the separation of the harmonic noise of rotors is needed to gain insight into the noise sources of individual rotors. There are multiple approaches to separate the harmonic noise of
helicopters, but in some operating conditions their capabilities tend to be limited by the fluctuating rotational rate of the rotors [15] and the dynamically changing noise sources within short periods of time [24,25]. These fluctuations are common in acoustic measurements of conventional rotorcraft during maneuvers, multirotor UAS, and eVTOL aircraft. The fluctuations are required in multirotor aircraft due to the variable RPM for aircraft control, so the conventional source separation approaches of rotorcraft are not appropriate for multirotor aircraft analysis.

Rotor harmonic averaging has often been applied to wind tunnel measurements of rotor noise to reduce the variability of the data and isolate the harmonic noise of the signal [26]. This method works by dividing the measured pressure time-history signal into windows associated with each complete rotation of the rotor shaft. These windows can then be ensemble averaged in either the time or frequency domain, to extract the signal component that is purely harmonic with the shaft order. This technique requires that the rotor be acoustically stationary, i.e., the position of the source and observer is fixed and that the amplitude and phase of the source are not varying over time.

A similar problem was faced by Boxwell et al. [27–29] where the averaging technique failed to capture the phase shift of the impulsive noise due to a 3 ft inaccuracy in the position tracking data of the aircraft. Due to this, a method to identify the periodicity in the acoustic impulses was used as a reference to average the signals [30]. Since the thickness noise is highly periodic, an improvement in the signal-to-noise ratio was obtained by averaging the signal at the periodicity of the thickness noise. BVI noise impulses were identified using the negative peak of the thickness noise as a reference point, and then averaged using a conventional technique to get the averaged BVI impulse. Boxwell et al. [30] also found that the fluctuations in the amplitude and phase of the tonal noise, for instance, due to the effect of turbulence on the rotor wake, are not extracted by the harmonic averaging process.

The separation of the tonal noise and the broadband noise can be done through a signal averaging process to reduce the variability of the tonal components in the signal. This can be done by averaging the signal at fixed time intervals throughout the measurement. This increases the resolution of the tonal noise in the signal while suppressing the broadband noise. Using this principle, early attempts at combining de-Dopplerization with synchronous averaging techniques to separate rotor noise were
investigated by Babkin [15]. The resolution of the rotor speed measurement caused the synchronously averaged signals over a blade passage period to approach zero, regardless of the averaged block size. Babkin suggested that this inaccuracy is due to the non-integral main rotor periods between each rotor speed measurement. Therefore, to perform accurate synchronous averaging, a rotor speed measurement that can capture the variations within the main rotor period is ideal.

Similar averaging techniques have been applied to separate the main rotor and the tail rotor noise components from wind tunnel [31] and in-flight [13] noise measurements where the rotor RPM was measured accurately. This was possible since the main rotor and the tail rotor speeds are non-integer multiples of each other. Yin et al. [31] processed extensive aeroacoustic measurements from a scaled helicopter model in the German-Dutch (DNW) wind tunnel to assess the importance of the tail rotor noise with a harmonic averaging process. To obtain the tail rotor noise component, the measured acoustic pressure-time history was averaged at the tail rotor blade passage periods, where it was the dominant noise source.

Figure 1.5: Plot of the main rotor and tail rotor pulses along with the averaged pulse for one rotation [13]
Sargent et al. [13] applied a harmonic averaging procedure to the acoustic measurements performed with boom microphones mounted on a Bell 206B helicopter in order to understand the tail rotor noise characteristics, test setup is shown in Figure 1.3.2 (b). The averaging approach was effective in separating the tail rotor harmonic noise when the signal was averaged at the tail rotor blade passage periods. The tail rotor harmonic noise from the averaging process was in good agreement with the loading and thickness noise levels predicted using acoustic theory [13]. Figure 1.5 shows the pressure-time histories of the main rotor and the tail rotor pulses within a blade passage period and the averaged main and tail rotor pulse. The averaged pulses need to be synchronized in phase, without this, the variations within the blade passage period would be averaged out as demonstrated in Figure 1.6.

Santa Maria [32] explored the idea of separating the main and tail rotor harmonic noise using a two-dimensional Fourier transform. This method was applied to two flight data sets: (1) with a tail rotor and (2) without a tail rotor. The tones of the tail rotor were unexpectedly lower in some cases of the separated spectra, which were assumed to be due to the MR-TR interaction tones but could not be confirmed as the interaction noise could not be separated. Santa Maria [32] separated the main and tail rotor noise in the frequency domain to reveal the amplitude information. As with most frequency domain methods, this requires additional analysis to reveal the phase relationship. Performing the separation in the time-domain overcomes this
problem and, preserving the phase and amplitude relationship provides an additional advantage.

Given the success of the simple and reliable harmonic averaging method in separating the tail rotor noise, Greenwood and Schmitz [22] developed a new averaging approach to separate both the main rotor and the tail rotor harmonic noise of helicopters from ground-based measurements, for test setup similar to Figure 1.3.3. Greenwood and Schmitz [22] inferred the rotor speed from the measured acoustic signal and were able to separate the main and tail rotor noise components accurately. However, the phase variations of the BVI noise caused the impulses to get averaged out of the signal, as seen in Figure 1.6.1. BVI could be retained through a phase correction process, seen in Figure 1.6.2, but with some energy loss or distortion of other noise sources. Amplitude variations were still averaged out, leading to an incomplete extraction of the tonal noise, more importantly, this technique cannot be applied to unsteady operating conditions. To overcome this correction at the expense of energy loss from impulsive noise, Stephenson et al. [24] developed a wavelet-based method to extract impulsive noise.

Figure 1.7: A Morlet wavelet used to extract BVI noise is shown in time- and frequency-domains with amplitude and phase information [24]

Stephenson et al. [24] looked at impulsive noise such as from BVI through a time-frequency analysis method called “wavelet transform”. This approach uses wavelets as the basis functions as opposed to the harmonic functions used in Fourier transform [33]. The advantage of the wavelet transform over the Fourier transform is that the short bursts of energy like in BVI noise are resolved more accurately. With
a priori information about the frequency and amplitude of the impulsive events, a ‘mother’ wavelet shown in Figure 1.7 is formed and then convolved with the acoustic signal in the time-domain.

Figure 1.8: Comparison of extracted BVI pulse with wavelet transform in the frequency-domain with the original signal [24]

The extracted BVI noise is presented in the time- and frequency- domains in Figure 1.8. In the top plot of Figure 1.8, the frequency spectra of extracted BVI noise are shown in black and the measured signal is shown in grey. In the bottom plot of Figure 1.8, the time history of the extracted BVI noise is shown. From the results, Stephenson et al., [24] showed that the extraction of BVI noise with the wavelet transform method is effective and applicable to transient maneuvers of rotorcraft.

Olsman [25] addressed the issue of separating the rotor noise using a modified Fourier transform with time-variant Fourier coefficients. In order to extract the time history of the harmonic noise, Hermite B-splines were used to approximate the time-variant coefficients of the Fourier transform, enabling the capture of the non-periodic components during non-steady-state operating conditions. The original main rotor signal and the extracted main rotor signal are seen in Figure 1.9. It was
also demonstrated that the non-periodic and non-stationary signals can be extracted accurately by the modified Fourier technique.

However, due to the complexity of the Hermite spline knots required to accurately model the unsteady changes, the impulsive BVI noise was not extracted. Instead, before applying the modified Fourier transform, BVI noise was extracted using a wavelet-based nonlinear filter developed by Stephenson et al. [24]. However, this two-step process can become cumbersome because the BVI extraction method requires an \textit{a priori} estimation of the frequency and amplitude of BVI impulses. Additionally, the application of this method to measurements with low signal-to-noise ratios could cause inaccurate results because of the combination of two complementary procedures that need to be carefully tuned to accurately extract the noise. Additionally, the modified Fourier transform may run into issues with solution convergence when applied to quasi-periodic harmonics that are observed in multirotor aircraft noise [25].

An alternative to harmonic averaging, wavelet extraction, and the modified Fourier transform is the Vold-Kalman (V-K) order tracking filter [34]. Stephens and Vold [34] used the V-K filter to process the acoustic data of Counter-Rotating Open Rotor (CROR) from the NASA Glenn wind tunnel. They showed that the technique is robust for separating the harmonic and the broadband noise where conventional averaging methods have limitations. To understand the noise of the CROR in approach and take-off conditions, Stephens and Vold used the V-K filter to track the loudest forward and aft rotor tones and extract the narrowband random noise. An advantage of this
V-K filter approach over the conventional techniques is that the phase and amplitude relationship of the harmonic noise is preserved throughout the process. Additionally, unlike other conventional methods, the V-K filter approach may be used to separate the noise of rotors that are operating at nearly identical but varying rotor speeds. As such, this approach has the potential to separate the noise of multirotor UAS and UAM aircraft.

Wang et al. [35] looked at separating the aerodynamic (tonal and broadband) noise from computational predictions and measurements of a scaled helicopter model in a wind tunnel using the Vold-Kalman (V-K) filter method. Wang et al. use a cascade filtering process where the tonal and broadband components are extracted using the process that combines the V-K filter approach and a cyclic wiener filter. This process also takes into account the broadband noise modulation about the shaft order, and extracts it during the cyclic wiener filtering process. MR-TR interaction noise was not considered, and therefore the effectiveness of the cascade filtering process on acoustic flight test measurements, where the interaction tones are observed, cannot be determined. The wind tunnel data was measured with constant main rotor and tail rotor RPM values and using a trapezoidal array design. The modulated broadband noise component extracted by the cyclic wiener filter was second-order cyclostationary noise; however, the residual noise may still contain some unsteady loading broadband noise.
noise. Moreover, the cyclic wiener filter is yet to be applied to acoustic flight test measurements, where the broadband noise tends to be much more complex in nature.

An alternate way to separate the noise sources of the multirotor UAS and UAM aircraft could be to combine the wavelet transform and modified Fourier transform, but there is limited applicability of the approach to acoustic measurements of rotors operating at quasi-steady i.e., nearly coherent speed. But an easier approach could be to fine-tune the parameters of the V-K filter; this will be explained in detail in Chapter 4. However, this method has yet to be applied to ground-based measurements of aircraft noise. This thesis will develop a source separation process based on the V-K filter and will be applied to flight test data in Chapters 3 & 4.

1.2.3 Aircraft Noise Directionality Measurements

A source separation process highlights the contributions of each individual rotor to the overall noise of the aircraft. There is a distinct directivity pattern observed for each source, this provides information about the noise radiation patterns of different aircraft. However, for multirotor aircraft, these radiation patterns could be quite complex and highly variable due to the higher relative importance of each rotor. From previous research, helicopter noise radiation patterns are highly dependent on the aircraft type and the operating condition, but are dominated by main rotor directivity in most operating conditions. However, in recent times, using the conventional source separation methods for steady flight cases, tail rotor noise has been shown to be dominant at some directivity angles for helicopter noise [13]. It is important to understand the noise radiation patterns for all rotors on an aircraft, especially for multirotor aircraft. Also, finding a way to separate the individual rotor noise could help reduce variability induced by “beating” between nearly coherent noise sources.

Therefore, for a multirotor aircraft, the radiation pattern of each rotor is important to predict/understand the directivity pattern of the complete aircraft in order to reduce it.

The directionality of aircraft noise can be presented in a representation that is often referred to as an acoustic hemisphere, shown in Figure 1.11. The hemispheres are a good way to visualize noise radiation patterns because they present information about the magnitude and the directivity of noise normalized to a fixed propagation distance. This is a good tool to characterize noise sources and experimentally compare
the directivity to prior knowledge about the directivity of noise sources to aeroacoustic theory.

![Figure 1.11: A sample Lambert conformal projection of noise directivity for helicopter forward flight case](image)

Federal Aviation Administration (FAA) uses the Integrated Noise Model (INM) [36] that is based on the SAE-AIR-1845 noise measurement standards with a single microphone measurement. For helicopters, FAA uses the FAR Part 36 Appendix H with three microphone measurements, due to their more prominent directivity patterns over fixed-wing aircraft. Even with the newer versions of INM, the flight conditions and the angles are limited and produce coarse data which constrain the ability to accurately characterize the directivity of rotorcraft [37]. This approach does not include some prominent noise sources such as HSI and BVI that do not necessarily occur in the limited set of operating conditions [12, 38] tested under FAR Part 36 Appendix H.

Rotorcraft Noise Model (RNM) overcomes these problems by using a linear array of ground-based microphones perpendicular to the flight path of the aircraft [39], as shown in Figure 1.12. The ground-based measurements are depropagated onto a hemispherical surface around the aircraft. The depropagated acoustic measurements are then adjusted
for spherical spreading and atmospheric absorption with a propagation model. RNM measures data for a wide range of directivity angles covered by the microphone array over the course of a flyover, these measurements can then be interpolated onto finer points on a hemisphere. The Acoustic Repropagation Tool (ART) measurement approach within the RNM provided a more accurate way of characterizing rotorcraft noise than INM for steady state flight conditions. It was later extended for non-steady state flight conditions in the Advanced Acoustic Model (AAM), a newer form of RNM [21].

Yin and Buchholz [40] developed a tool “HEMISPHERE” to characterize the rotorcraft noise radiation pattern. This approach was then later extended by Reference [41] with the HELicoper Environmental Noise Analysis (HELENA) model to include more accurate noise predictions for rotorcraft. Additional improvements were made to the propagation model to accurately account for variables such as wind gradients, the Doppler effect, ground reflections, etc. A more recent European helicopter noise model is the Noise of Rotorcraft Assessed by a Hemisphere-approach (NORAH) [42]. These models have the capability to predict noise for helicopters for most operating conditions accurately. These tools enable the industry to design aeroacoustically
efficient aircraft to reduce the operational noise footprint of helicopters. Therefore, a source separation process needs to project the directivity and magnitude information of the multirotor eVTOL noise onto a hemisphere.

To summarize the main points from the literature review; a novel source separation procedure needs to be developed for the analysis of multirotor eVTOL UAS and UAM noise. To enable the application to flight test measurements, the process needs to have de-Dopplerization capability, to accurately reconstruct measured signals and depropagate them into stationary measurements. This needs to be performed in the time domain to eliminate tone smearing. Preservation of impulsive noise is necessary and must not be averaged out like in the harmonic averaging approach.

1.3 Objectives

There is a need for a robust tool to analyze maneuvering noise and separate impulsive noise components of multirotor experimental data from both indoor and outdoor tests. Therefore, the objectives of this thesis are to develop a source separation process that can:

1. Separate harmonic noise of individual rotors simultaneously for multirotor aircraft while the flight condition is changing and therefore the noise sources are changing continuously, as in maneuvers;

2. Preserve the phase and amplitude relationship of signals to perform acoustic post-processing techniques in both the time- and frequency- domains;

3. De-Dopplerize acoustic measurements to be able to process data from outdoor aircraft flight tests; and

4. Depropagate sound pressure levels to evaluate the directivity of separated individual rotor and aircraft noise components.
In this thesis, a new approach to characterize the aeroacoustics of the multirotor eVTOL aircraft is proposed. This approach will de-Dopplerize ground-based acoustic measurements and separate the individual rotor noise components with the capability to extract time-varying impulsive noise. Performing this source separation in the specified time-domain will enable the application of a wide range of post-processing techniques both in time- and frequency- domains. Also, the need to characterize the acoustic directivity of these novel aircraft demands the projection of the processed data onto an acoustic hemisphere to understand the noise radiation patterns.

To address this, this thesis develops a noise Source Separation Process (SSP) based on the Vold-Kalman (V-K) order tracking method. This approach attempts to overcome the limitations of the previous source separation methods outlined in Section 1.2.

The source separation process is comprised of two main steps. First, the measured acoustic signals are transformed into a stationary reference frame moving with the aircraft frame of reference using a time-domain de-Dopplerization procedure. Second, the de-Dopplerized data are processed using the V-K filter to separate the individual rotor harmonic and broadband (i.e., non-rotor-harmonic) components. Finally, the separated components are presented in a noise hemisphere with magnitude and directivity information. The description for each step of the source separation process is provided in this chapter. The capabilities of the approach satisfy all of the thesis objectives outlined in Section 1.3.
2.1 De-Dopplerization

The source separation process needs to be applied to acoustic measurements collected with ground-based observers. Therefore, de-Dopplerization is necessary to make the acoustic measurements stationary with respect to the source.

A time-domain de-Dopplerization procedure was chosen over a frequency-domain approach to avoid “spectral smearing” of the tones. The time-domain process requires accurate position tracking data to calculate the propagation time delay from the aircraft to the location of each observer. The position data of the aircraft usually does not have as high a sampling rate as the acoustic data; for the helicopter and multirotor UAS flight test data used in this thesis, a 1-10 Hz sampling rate of position data was found to be sufficient. The observer times at the microphone locations can be related back to the times of emission corresponding to the aircraft position data. Using this information, the measured acoustic signals can be resampled with respect to the emission time by interpolating [15] the acoustic pressure amplitude. This process is equivalent to transforming the acoustic signals from a ground-based observer to an observer moving with the aircraft and removing the Doppler frequency shift from the signal. The de-Dopplerization method implemented in the source separation process is adapted from Greenwood and Schmitz [22] but uses a higher-order interpolation [43] to limit the high-frequency distortion. A detailed description of the method is provided in this section along with some preliminary tests with wind tunnel measurements to highlight its limitations and capabilities.

The pressure amplitude of the measured acoustic signal changes as the sound waves propagate from the source to the observer. In the case of a moving source, as with a flying aircraft, the source moves with a velocity along the flight path, and this motion modifies the measured pressure amplitudes (spherical spreading) along with adding non-stationarity to the signals. The de-Dopplerization procedure intended to remove the non-stationarity and correct for spherical spreading is described in the rest of the section. Figure 2.1 (reproduced from Reference [22]) represents the de-Dopplerization procedure to transform the signals to a moving observer fixed in the frame of reference of the rotorcraft.

For the rotorcraft, the noise is assumed to originate from a compact source and the emission angles are calculated based on the observer locations. Using the GPS tracking
Figure 2.1: De-Dopplerization cartoon to demonstrate the transformation of ground-based acoustic measurements to measurements at virtual microphones moving in the aircraft frame of reference [22]

data, the position-time histories of the aircraft with respect to observers are calculated in the same coordinate frame as the observer. Since the aircraft tracking data is usually sampled at a much smaller rate than the acoustic data, it must be up-sampled to match the time intervals of the measured acoustic data. This up-sampling of the tracking data does not introduce any inconsistencies in the process because the aircraft motion can be accurately captured by the lower sampling rate. Aircraft position sampling rates were as low as 1 Hz for aircraft forward flight operating conditions of the data used in this thesis.

As mentioned in Chapter 1, the strength of compact point source \( Q(\tau) \) from Equation 1.4 is amplified by the motion of the source with respect to the observer. The relationship between the observer time and the emission time caused by the motion of the aircraft is given in Equation 2.1.

\[
t_o = t - \frac{r(\tau) - r_o}{a_0} \tag{2.1}
\]

where \( r(\tau) \) is the position of the aircraft at the time of emission, \( \tau \), \( t_o \), and \( r_0 \) are the time and distance offsets of the de-Dopplerized observer location with respect
to the aircraft noise source. The variation in the time delay between the emission time and observer time over the course of a flyover causes the Doppler frequency shift in the measured signals. This shift is corrected by calculating the time delay using Equation 2.1 and interpolating the acoustic measurements to equivalent measured signals observed without the time delay.

The signals at the ground-based microphones will be measured at regular intervals with a constant sampling rate. Due to the motion of the aircraft, the propagation times will fluctuate, therefore leading to irregular measurements of the de-Dopplerized signals. Howell et al. [17] discovered, and Glegg [44] confirmed, that a simple linear interpolation produces accurate signals for most purposes. A higher-order interpolation, adapted from Rizzi et al. [43], is used in this thesis to interpolate the signals in order to reduce the high-frequency distortion that is audible when auralizing the de-Dopplerized signals.

Since the propagation distance at the time of emission, \( r(\tau) \), is known, the signal amplitudes can also be normalized to the virtual microphone location at the same time by correcting for spherical spreading. The signal amplitudes are then transformed to account for the spherical spreading using the Equation 2.2

\[
p_o(t_0) = p(\tau) \frac{r(\tau)}{r_0}
\]  

(2.2)

In the source separation process, the spherical spreading can be corrected for virtual observers at any fixed distance from the source. The de-Dopplerization in this thesis was performed assuming straight ray propagation and the acoustic signals were not corrected for atmospheric absorption. Both these assumptions are reasonable for the short propagation distances. For the results presented in Chapters 3 and 4 of the thesis, depropagation ranges span from 15 ft for the multirotor Tarot X8 to 100 ft for the Bell 430 helicopter. The following section explores the effects of interpolation on the spectral content of the measured signals.

### 2.1.1 Interpolation Effects

There is some precedent in the literature regarding the frequency spectra roll-off caused by the interpolation of acoustic signals [44]. For that reason, after the implementation of the de-Dopplerization procedure, an investigation was performed to see the effect
of the interpolation of acoustic pressures on the frequency spectra and the computed
noise metrics. Interpolation of the pressure-time histories to a normalized distance
with fixed observers, but with a constant distance offset, has in some cases led to a
roll-off of the acoustic spectrum at higher frequencies. An investigation of fixed source
and observer data was used to understand the extent of these interpolation effects.

Figure 2.2: Coaxial Acoustic Test Stand (CATS) setup with the top and bottom rotor
stands and the linear microphone array perpendicular to the coaxial rotors in the
Anechoic Wind Tunnel at Penn State

The data used for this investigation were obtained using the Coaxial Acoustic Test
Stand (CATS) in the Anechoic Chamber at Penn State [45], shown in Figure 2.2. A
linear microphone array with Bruel & Kjaer (B&K) 1/2” microphones was positioned
vertically perpendicular to the plane of the mounted coaxial rotors for the acoustic
data collection. Since the distance between the rotor hub and all the microphones was
not the same, a higher order (cubic Hermite spline) interpolation method was used to
reconstruct the acoustic signals to virtual microphones at a fixed distance from the
rotors. The reference distance was that of microphone #05, which is in the plane of the rotors. This allows the construction of an acoustic semicircle with noise levels at elevation angles ranging from −32 degrees to 23 degrees with respect to the rotor tip path plane at a fixed azimuth angle. For the data used in this section, the azimuth is 180 degrees, i.e., directly in front of the rotor.

A coaxial rotor setup with separated rotors operating at a speed of 5000 RPM served as the sample test case. The measured acoustic data were normalized to the virtual microphone locations; all of the virtual microphone locations were the same distance away from the rotor. Acoustic pressure measurements were interpolated using a spline interpolation to a virtual observer microphone at the fixed normalized distance away from the rotor hub. The de-Dopplerization, in this case, was not to remove non-stationarity in the signals but to recreate the acoustic pressures as they would be measured at a closer distance from the microphone.

Fourier transform of the acoustic pressure-time histories was performed to reveal the frequency content and the resultant spectra are presented. Figure 2.3 is the spectrum of the acoustic pressure measured at microphone #03 without interpolation. The spectra are representative of standard acoustic spectra, with the tonal noise harmonics dominating until frequencies of up to 1500 Hz. For content at frequencies greater than 1500 Hz, the noise is representative of the broadband noise spectra with some high-frequency peaks and possible motor tones.

After the interpolation of the acoustic data of the same microphone in the time-domain, the Fourier transform was performed with identical parameters and the resulting spectra were plotted, shown in Figure 2.4. There is a significant roll-off seen in the interpolated data after a frequency of about 10,000 Hz. The tonal noise is not significantly affected by interpolation, whereas the broadband noise at higher frequencies is mischaracterized due to the interpolation procedure.

This effect is noticeable and preliminary attempts to quantify this roll-off are plotted in Figure 2.5. A random signal was generated with simulated white noise and the same interpolation procedure was performed for a constant propagation time offset. There was a correlation between the propagation time offset and sampling time. As seen in Figure 2.5, the slope of the rolled-off spectra is the highest when the ratio of the sampling time and the propagation time is furthest from an integer. Also, the roll-off initiation point remains constant for different ratios. Although not shown here, the
Figure 2.3: Spectra of measured rotor noise with the CATS setup in the anechoic wind tunnel

Figure 2.4: Spectra of interpolated rotor noise normalized to a fixed observer distance with the CATS setup in the anechoic wind tunnel
distortion is not influenced by the use of different interpolation schemes (linear, spline, etc.); identical interpolation effects were seen no matter the interpolation method used.

![Spectra for Different ts/toffset Values](image)

Figure 2.5: Correlation of broadband noise roll-off caused by different ratios of sampling time and propagation time [Note: “True” spectra are behind spectra for \( t_s/t_{offset} = 1 \)]

The interpolation step in the de-Dopplerization process could interfere with the accuracy of the computed noise metrics. The directivity of broadband data with a fixed distance interpolation was very different than what was expected from aeroacoustic theory and noise predictions.

The capabilities and limitations of the de-Dopplerization procedure have been established in this section. Now, the second step of the source separation process, i.e., the V-K filtering, the approach will be described along with the relevant testing procedures.
2.2 Vold-Kalman Filter

The Vold-Kalman (V-K) filter is based on the principle of Wold decomposition, where the signal is assumed to be made up of two different components, one deterministic and one stochastic. The deterministic components of a signal can be modeled with a mathematical expression and usually occur periodically in the signal; therefore, the amplitude can be approximated from the frequency of rotation. Stochastic components of a signal are truly random in nature, without the possibility of approximating the amplitude. In rotor-generated noise, deterministic sources are the loading and the thickness noise and stochastic sources are the broadband noise.

Vold developed this smoothing filter based on the Kalman filtering technique [46] to approximate the unknown amplitudes of harmonics at known frequencies from a signal convoluted with harmonic and broadband noise. The V-K filter uses the rotational rates of the multiple rotors and centers the instantaneous bands around it to essentially extract the harmonics that occur in these narrow bands. As the rotational rate of the rotors is necessary to apply the V-K filter, the accuracy of the filter heavily depends on the accuracy of the measurements of the rotational speed of the rotor.

The source separation process uses the third-generation implementation of the multi-shaft V-K filter. The main advantage of the multi-shaft implementation is that it can extract the interaction tones more accurately than the single-shaft filter and can also extract multiple rotor components simultaneously [34]. This is advantageous for the cases with crossing rotor speeds because, during the crossover when the rotor speeds of rotors are the same, the multi-shaft implementation divides the noise equally between the rotors. In a single-shaft implementation, at the crossover, all the noise of crossing rotors with exactly the same speed would be extracted for each rotor. This would cause the extracted components to have higher energy than that was generated by the rotor at the crossover time instances. An overview of the theoretical foundations of the multi-shaft V-K filter adapted from Stephens and Vold [34] is as follows.

Based on the Wold decomposition, the deterministic part $x(t)$ of the signal $y(t)$ is composed of the harmonic components and the stochastic part $v(t)$ is assumed to be mostly broadband noise. Equation 2.3 is the representation of this where the signal is
written as a convolution of the harmonic noise and the broadband noise.

\[ y(t) = x(t) + \nu(t) \] (2.3)

Therefore, the harmonic noise components can be characterized as the deterministic component \( x(t) \) which produces harmonics at known frequencies with unknown amplitudes. Using the rotational speed measurement, a phasor, \( P(t) \), is constructed for the rotor Blade Passing Frequencies (BPF) and its integer multiples. These are the harmonics that will be extracted from the signal using measured (or inferred) time-varying the rotational speed of the rotor, \( \omega(t) \). So, a phasor contains phase information for all the harmonics (BPF and its integer multiples) which the V-K filter needs to extract from the signal \( y(t) \).

\[ P_h = \exp(2\pi ik\omega(t)t) \] (2.4)

Equation 2.5, \( x(t) \) groups together all the known harmonic components of the signal occurring at frequencies. It represents the deterministic noise, \( x(t) \) as a convolution between the phasor, \( P(t) \) and the unknown amplitudes, \( A(t) \) of the harmonics

\[ x(t) = \sum_{k \in K} A(t) \ast P(t) \] (2.5)

There are two major components in the formulation of the system of equations in the filter: the structural equation and the data equation. Equation 2.6 is the structural equation of the filter, where \( q \) is the order of the filter. This structural equation forces the amplitudes of the extracted signal to be smooth. This equation is critical in the convergence of the solution of the filter and the accuracy of the extracted pressure envelopes.

\[ \nabla^q A(t) = \epsilon(t) \] (2.6)

The term \( \nabla^q \) from Equation 2.6 expands out with the coefficients from Pascal’s triangle. The expanded form is given by Equation 2.7 below for filter orders 1, 2, and 3. Usually, a filter order of 2 is used for the application of the filter in this thesis, as a higher filter order usually needs many more computations, this causes a significant
increase in the computation time [47].

\[ \nabla A(t) = A(t + 1) - A(t) \]
\[ \nabla^2 A(t) = A(t + 2) - 2A(t + 1) + A(t) \]
\[ \nabla^3 A(t) = A(t + 3) - 3A(t + 2) + 3A(t + 1) - A(t) \] (2.7)

Equation 2.8 is the data equation of the filter. It ensures that the extracted signal is closely related to the measured tachometer RPM through the complex phasor, \( P(t) \), where \( P(t) = \exp(2\pi ik\omega(t)t) \). The data equation and structural equation are shown in Equations 2.6 and 2.8 form the system of equations for the solution of the filter.

\[ \nu(t) + \sum_{k \in K} A(t)P(t) = y(t) \] (2.8)

To solve for the complex envelope \( A(t) \) using Equations 2.6 and 2.8, a weighting factor \( r(t) \) is chosen based on the bandwidth to minimize the stochastic terms i.e., such that \( \epsilon(t) \) and \( \nu(t) \) are negligible (\( \cong 0 \)). Then Equations 2.6 and 2.8 can be simplified further to eliminate the stochastic terms; the simplified Equations 2.9 and 2.10 only account for the harmonic noise that is produced at frequencies \( \omega(t) \), defined by the phasor, \( P(t) \).

\[ r(t)\nabla^q A(t) \cong 0 \] (2.9)
\[ \sum_{k \in K} A(t)P(t) \cong y(t) \] (2.10)

where the weighting factor \( r(t) \) is calculated using the bandwidth, \( bw \) with the expression in Equation 2.11

\[ r(t) = \sqrt{\frac{\sqrt{2} - 1}{(2(1 - \cos(2\pi bw)))^q}} \] (2.11)

Equations 2.9 and 2.10 are used to form a “sparse” linear system of equations (Equation 2.12) to solve for the complex envelope \( A(t) \).

\[
\begin{bmatrix}
R \nabla \\
Y
\end{bmatrix} A = 
\begin{bmatrix}
0 \\
Y
\end{bmatrix}
\] (2.12)
where $R$ is a diagonal matrix of the weighting factors $r(t)$, $\nabla$ is the matrix of coefficients from Pascal’s triangle expansion, $P$ is the matrix of the phasor $P(t)$, $A$ is a column vector of the complex envelope of pressure amplitudes, and $Y$ is the vector of signal $y(t)$.

The linear system of equations in Equation 2.12 can be solved as a linear least squares problem, typically using well-known algorithms, such as the Cholesky decomposition, a PCG algorithm, or an LU decomposition. In this thesis, the Cholesky decomposition was used to solve the system in order to minimize the number of numerical operations. By contrast, Stephens and Vold [34] use a QR decomposition for sharper bandwidths at the expense of computational time. In this QR decomposition, a unitary matrix $Q$ is chosen to reduce the left-hand side of Equation 2.12 to an upper triangular matrix. This requires more than twice the number of arithmetic operations than the Cholesky decomposition but enables the V-K filter extraction with very narrow bandwidths.

The complex envelope consists of the pressure amplitudes of all the extracted orders, i.e., extracting the signal while preserving the phase and amplitude relationship of the orders. The extracted signals do not have phase bias because this is not a real-time filter. The VK filter implemented in this thesis was tuned to have a variable bandwidth proportional to the extracted rotor BPF and its multiples. Having a variable bandwidth ensures the accuracy of the extracted rotor components within the bands. The following section will test the accuracy and performance VK filter with noise predictions from VSP2WOPWOP [48] framework developed in-house at Penn State.

### 2.2.1 Test with Predicted Noise

After the Vold-Kalman (V-K) filter was implemented, a series of synthetic noise signals were used to test the effectiveness of the extracted signals. This is to test the V-K filter because the data was for noise predicted with a stationary source and observer. The acoustic predictions are for a tricopter configuration operating at a fairly constant and crossing rotor speed (overlapping sinusoidal RPM signals) without much variation. This is because the capability to predict noise for crossing rotor speeds was not implemented in the PSU-WOPWOP model [9]. The noise predictions for this section were performed using the VSP2WOPWOP.
The predicted acoustic pressure is given as the original signal and the residual signal, this was obtained by subtracting the extracted signal from the original signal. These original and residual signals are plotted in Figure 2.6. This noise prediction is for a tricopter case with the rotor speeds being constant at 2230, 2250, and 2270 RPM. Only the thickness and loading noise was computed with the PSU-WOPWOP and the observer was 15 m away from the noise source. The residual signal is quite minimal and the extracted original signal accurately extracts all the harmonic energy in the signal. Since a clean extraction was seen, this signal was corrupted to get bad signal-to-noise ratios and an investigation was performed on filter accuracy.

Figure 2.6: Plot of original and residual (broadband) signals after the extraction of the harmonic component using the V-K filter

Figure 2.7 presents two examples where the original signal is corrupted with two different signal-to-noise ratios (SNR). This analysis is performed for the same observer location as the time-history plot in Figure 2.6. The extraction was performed and the residual signal is plotted to compare with the original signal for SNR of 20 dB and 0 dB.
At the observer location, components of all three rotors were extracted from a “clean” signal, i.e., the signal did not have any broadband component and just contained the harmonic thickness and loading noise of all three rotors. Then, the overall clean signal was corrupted with white noise of varying SNRs. The extraction was performed again with these corrupted signals to see the performance of the technique in the presence of significant broadband noise sources. Figure 2.8 presents a plot of normalized error in dB as a function of the signal-to-noise ratio of the signal.

As seen in Figure 2.8, the error is very low even for signals with adverse SNR. This demonstrates the capability of the extraction of rotor noise at poor or even adverse (<0 dB) SNRs. The SNR of all the data used in this thesis is between 10 to 15 dB. In the experimental data, the characteristics of broadband noise may change but due to the 15 dB difference between the SNR of the measured noise and the SNR at which
filter performance starts to degrade. Therefore, this procedure will be applicable to almost all experimental datasets.

### 2.3 Acoustic Hemisphere Generation

In Chapter 1, it was shown that a noise hemisphere is used to interpret the directivity and magnitude information in a straightforward way. The acoustic hemispheres can be of many varieties with different projection types such as a stereographic projection, a Mercator projection, etc. The Lambert azimuthal equal area projection is used for the noise hemispheres presented in this thesis. In the noise hemispheres, it is possible to highlight individual noise sources by calculating various integrated noise metrics like Overall Sound Pressure Level (OASPL), Blade-Vortex Interaction Sound Pressure Level (BVISPL [6th to 40th BPF] [22]), A-weighted Sound Pressure Level
(SPL, dBA), etc. A mid-frequency metric was used in this thesis for Bell 430 acoustic flight test data, description and reasoning are given in detail in Chapter 4. For much of the thesis, hemispheres were used to characterize the noise from flight test data. The acoustic hemispheres made from flight test data can accurately characterize only the far-field noise sources because the noise measurements are from ground-based microphones.

Figure 2.9: Nomenclature of the acoustic hemispheres presented in the thesis with aircraft orientation

The nomenclature of projecting the acoustic measurement data onto a two-dimensional hemispherical surface follows a Lambert projection technique. In the projection, the azimuth angle ranges from 0 degrees to 360 degrees, going from the right side to the left side of the aircraft and the elevation angle ranges from 0 degrees to −90 degrees, going from the in-plane of the aircraft pointing to the horizon to directly
under the aircraft. Figure 2.9 represents the coordinate system and the convention used to build the acoustic noise hemispheres.

Using this convention, the trigonometric equations are derived for the azimuthal and elevational angular positions of the observer in the aircraft frame of reference. Azimuth and elevation angles are calculated at the times of emission using the aircraft position-time history and the positions of the ground-based observers. The position data of the aircraft is usually collected using an onboard GPS and/or directly taken from the flight controller.

![Figure 2.10: Measured emission angles of microphone tracks on an acoustic hemisphere along with aircraft orientation](image)

To demonstrate this hemisphere generation, a sample flyover case was used from the Tarot X8 acoustic flight test; this data set is described in greater detail in Chapter 3. For the Tarot X8 data, the accuracy of the position and the sampling rate was about 3 ft and 1 Hz. For the data used in the thesis, this accuracy proved to be sufficient. But at much faster speeds, may need a more accurate recording of the state
data. Once the emission angles (azimuth and elevation) are calculated, the acoustic data are divided into time windows and the respective noise metrics are calculated. Then, the azimuth and elevation angles sampled at aircraft position measurements were interpolated using a spline interpolation to azimuth and elevation angles that correspond to the time windows of noise metrics. At this point, a hemisphere can be sparsely populated, as shown in Figure 2.10.

![Interpolated emission angles of microphone tracks on an acoustic hemisphere along with aircraft orientation](image)

Figure 2.11: Interpolated emission angles of microphone tracks on an acoustic hemisphere along with aircraft orientation

With noise levels at these angles, the acoustic hemisphere does not present much information about the directivity of the noise. The points between the measured emission angles are populated using a 2-D interpolation method. This thesis uses Shepard’s Inverse Distance Weighting (IDW) [49] method to perform this interpolation. The IDW method distributed weights for measured data depending on the geodesic distance away from the unmeasured interpolant location. This method works well with irregularly spaced data, i.e., unequal emission angles on a hemisphere. With the
interpolated emission angles, a densely populated acoustic hemisphere can be created. This densely populated hemisphere is presented in Figure 2.11.

Shepard’s method imposes a cutoff radius so that only data points within a certain radius of the interpolant are used in the interpolation. In this thesis, two values of radius were used; 40 degrees for Tarot X8 data and 30 degrees for Bell 430 data. Note that all the noise spheres in this thesis are processed using the raw separated data without any smoothing applied to the interpolated noise levels, so as to highlight any variations in time and directionality of the noise sources.

The acoustic measurements are collected with multiple microphones in array layouts that provide the capability to characterize noise at different observer locations with respect to the source, i.e., at multiple directivity angles. Acoustic hemispheres can capture variability in measurements with specifically designed microphone arrays where two similar linear arrays can be used to measure noise at similar directivity angles and compare the differences. This microphone array layout is used for the Tarot X8 acoustic flight test, more information is given in Chapter 3. The spherical representation of weighted noise metrics, as well as band-limited metrics, provide greater insight into the directivity of isolated noise sources, as will be discussed in Chapters 3 & 4.

2.4 Source Separation Process Overview

This section summarizes the Source Separation Process (SSP). The SSP with each of its steps; De-Dopplerization, Vold-Kalman (V-K) filter, and Acoustic hemisphere generation is outlined in the flowchart presented in Figure 2.12.
Figure 2.12: Flowchart of the system architecture of the Source Separation Process
Chapter 3  Acoustic Analysis with Components of the Source Separation Process

The goal of this chapter is to demonstrate the applicability of the individual components of the Source Separation Process (SSP) and to highlight its capabilities and robustness. This chapter also highlights the utility of each of the individual components of the SSP for a range of aeroacoustic analysis applications.

In this chapter, the application of components of the Source Separation Process (SSP) is presented in the following way:

1. Vold-Kalman (V-K) filtering technique is applied to anechoic wind tunnel acoustic measurements from a coaxial rotor

2. De-Dopplerization and acoustic hemisphere generation steps are applied to acoustic flyover measurements of the Tarot X8 multirotor aircraft

3.1 Dragonfly Coaxial Rotor Wind Tunnel Test

As stated in Chapter 1, in multirotor UAVs, the change in rotor speed is expected and needed for the control of the aircraft, therefore the V-K filter approach is useful for tackling the problem of separating rotor noise sources of these aircraft. To demonstrate this capability, noise measurements of a counter-rotating coaxial rotor system in the anechoic wind tunnel were analyzed using just the V-K filter portion of the SSP.
The measurement data were part of a testing campaign performed for the preliminary design of the NASA Dragonfly mission [50]. This aircraft is a Quad X8 configuration with coaxial rotors, the project was in collaboration with researchers from the Department of Aerospace Engineering at Penn State University and the Applied Physics Lab at Johns Hopkins University. The initial coaxial rotor design was tested in the Penn State anechoic wind tunnel to characterize the aerodynamic performance; acoustic measurements were also collected during the test campaign.

The following sections will detail the experimental setup, the initial results of the harmonic noise extraction, and the subsequent acoustic findings for the coaxial rotor setup.

### 3.1.1 Experimental Setup

Wind tunnel testing was performed for the preliminary subscale phase 1 Dragonfly rotor design to characterize the performance and acoustics. The experimental setup included a test stand that held the motors in a coaxial configuration. A combination of 1/2” and 1/4” Bruel & Kjaer (B&K) microphones mounted on a curved linear microphone array were used to collect acoustic measurements. Two 1/4” microphones were used for frequency response comparison and the rest of the microphones in the array were 1/2” microphones. A small acoustic phased array was also used to measure the noise of the rotor system, but this data was not used in this thesis. The microphone array along with the rotor test stand is shown in Figure 3.1.

The microphone array was configured to measure acoustic data at 10-degree intervals from −90 degrees to 90 degrees. Figure 3.2 shows the microphone layout for the curved array which could be moved around the vertical axis to collect measurements at more than one elevation angle. In the array, microphones M2' and M11 were 1/4” diameter microphones, and they were used for comparison. These microphones were omitted from the polar plots used to examine directivity in Section 3.1.3. This was done to reduce variability and to ensure all measurements were taken with identical 1/2” diameter microphones.

The rotor stand included a tachometer along with other instrumentation for performance measurements. The tachometer measured the rotor RPM with high resolution at 131 kHz. The acoustic data was also sampled at 131 kHz, this way the
Figure 3.1: Experimental setup of Dragonfly coaxial rotor on a test stand in the Penn State anechoic wind tunnel in forward flight configuration

acoustic signals were synchronized with the measurement of the RPM for both rotors to apply the source separation.

3.1.2 Harmonic Noise Extraction

Harmonic noise extraction was performed with the V-K filtering approach and the original measurement, the extracted rotor components, and the broadband component are plotted for analysis. The broadband component is sometimes alternatively referred to as the residual component throughout this thesis; they are used interchangeably. These results were used to establish a good harmonic noise and broadband noise separation, and are presented in the spectrograms shown in Figures 3.4–3.7. A spectrogram provides a good way to look at the time-frequency content of a signal
Figure 3.2: Microphone array layout of Dragonfly coaxial rotor on a test stand in the Penn State anechoic wind tunnel in forward flight configuration

and to see how the power in the signal fluctuates in the time and frequency domains. A spectrogram takes a time history of a signal and separates it into consecutive time windows based on the bandwidth of the frequency bins. Then, it performs a Fourier analysis of these time intervals to reveal the frequency content. Finally, all the consecutive time intervals are assembled back together to reveal the time-frequency content of the signal.

The approach was applied to a test case with rotors operating in edgewise forward flight with a speed of 26 ft/s. A 60-second snippet with rotors operating close to 3500 RPM is presented in this section to see the extraction of the rotor harmonic and broadband noise using the V-K filter. Figure 3.3 shows the plot of the RPM measurement of both rotors. The rotor speed is not exactly maintained at 3500 RPM after the ramp up but it is quite close to it, this quasi-steady nature of the rotor speed is exploited by the V-K filter to extract the harmonic noise.
The measured acoustic signal was initially passed through a high-pass filter to remove the shaft order energy. This ensures that the acoustic energy from the shaft order tone does not affect computed metrics like the OASPL and makes sure that the residual signal is truly a broadband signal. The V-K filter extraction was performed using a proportional bandwidth of 5 percent of the corresponding multiple of the rotor BPF with a maximum ceiling of 25 Hz. A bandwidth of 2 Hz is used to compute the spectrum using the Short Time Fourier Transform (STFT). Hann windowing was used for the STFT computation with a 50 percent sample overlap.

Once the harmonic noise of both the rotors was extracted from the measurement, the broadband (residual) signal is calculated by subtracting the extracted harmonic components from the original signal. Spectrograms of the original signal, the broadband signal, extracted rotor 1 component, and extracted rotor 2 component are presented below in Figures 3.4, 3.5, 3.6, and 3.7 respectively. Figure 3.4 shows the spectrogram of the original signal and Figure 3.5 shows the spectrogram of the residual signal. The harmonics of the rotors are observed at the blade passing frequencies (BPFs) of the
rotors and their integer harmonics in the spectrogram in Figure 3.4. The rotor speed was roughly around 3500 RPM, so the BPF is around 115 Hz, which should have BPF harmonics at 230 Hz, 445 Hz, and so on. The BPF harmonics at these frequencies are indeed observed in the spectrogram, i.e., horizontal lines occur at these frequencies.

Figure 3.4: Spectrogram of original signal for edgewise forward flight case of acoustic measurement in the anechoic wind tunnel

The harmonic energy of the original signal appears to become broader as the frequency increases, this is due to the difference in rotor RPM of the rotors. At lower harmonics, the difference between rotor 1 and rotor 2 BPFs is small but for higher harmonics, the difference increases, i.e. a BPF difference of 2 Hz becomes a 20 Hz difference for the 10th BPF harmonic. This is tackled by the V-K filter by the implementation of the variable bandwidth proportional to rotor BPF. There is a clear difference between the harmonic content of the spectrograms of the original signal and the residual signal i.e., the BPF harmonics are not seen in the residual spectrogram. The spectrograms of the extracted components are shown in Figures 3.6 and 3.7. And therefore, the residual signal is dominated by energy from the broadband signal.

The residual signal contains a harmonic at 770 Hz, this could be a motor tone because it does not correspond to a BPF harmonic of either of the rotors. There are some weak harmonics in the residual signal that occur exactly between the extracted
Figure 3.5: Spectrogram of residual signal for edgewise forward flight case of acoustic measurement in the anechoic wind tunnel

Figure 3.6: Spectrogram of extracted rotor 1 signal for edgewise forward flight case of acoustic measurement in the anechoic wind tunnel
Figure 3.7: Spectrogram of extracted rotor 2 signal for edgewise forward flight case of acoustic measurement in the anechoic wind tunnel

rotor 1 and rotor 2 components, these are the 4/rev harmonics. These harmonics occur due to the interactions that happen when the 2-bladed rotors cross each other where each blade from the top and bottom rotor is at a 90 degree angle. This acts as a single 4-bladed rotor and produces harmonics with low energy that occurs at twice the BPF of the rotors. These components can be extracted for further examination but for this case only the rotor 1 and rotor 2 harmonics were extracted, leaving them in the residual signal.

The harmonic noise extraction of the rotors is clear in the spectrograms from Figures 3.6 and 3.7. During the first 10 s of the run-up, rotor 1 reaches the desired 3500 RPM more slowly than rotor 2, as seen in blue in Figure 3.3. The same behavior is seen, especially in the higher harmonics of rotor 1 from the spectrogram plot in Figure 3.7. Also, at higher harmonics, rotor 2 seems to have higher energy than rotor 1. This may be due to the unsteady loading caused by the wake of rotor 1 on rotor 2. In the next section, the frequency-domain spectra of rotor 1 and rotor 2 are presented to see a clean extraction of tones.
Since a baseline extraction of individual rotor noise was established for the anechoic wind tunnel data, further investigation was performed for the directivity of the extracted rotor noise and the broadband noise in the following subsection.

### 3.1.3 Investigation of Separated Components

Figure 3.8 is a plot of power spectral density (PSD) spectra for the extracted rotor 1 and rotor 2 components along with the original and residual signal. The separated components are examined at a greater depth after the extraction of the harmonic noise and the broadband noise for individual rotors was performed. One of the main advantages of the developed SSP is that the non-stationary and non-periodic components can be extracted accurately. This was established by applying the V-K regime to the rotor speed ramp-up cases.

The spectra are calculated at a time of 20 s from the case presented in Section 3.1.2, to establish harmonic noise extraction. The components of rotor 1 and rotor 2 are close to each other in the frequency-domain, this is seen in the original signal spectra. The V-K filter extracts the rotor components accurately from the original signal, this is evident from Figure 3.8 as the magnitude and frequency of the extracted rotor 1 and rotor 2 signals correspond to the harmonic peaks from the original signal. This indicates a clean extraction of rotor harmonic components in the frequency-domain. With the confirmation of accurate extraction of the harmonic components in both the time- and frequency- domains, the directivity of the experimental data is investigated for the original, the extracted rotors’ harmonic, and the broadband components.

First, a polar plot with the OASPL of separated components is presented with the directivity and magnitude information. This polar plot is comparable to a similar representation of an acoustic hemisphere where a sparse amount of azimuth angles between −90 degrees to 90 degrees and for one elevation angle. To reiterate, the polar directivity plots in this section are for a 26 ft/s edgewise forward flight case with the microphone array at an elevation angle of −45 degrees.

As in Section 3.1.2, the signal was passed through a high-pass filter to remove the shaft order energy. The sound pressure levels are the mean OASPL, in dB for each microphone location. As before, the rotor 1 and rotor 2 noise was extracted from the original using the V-K filter. The residual signal is the original signal minus the first 10 extracted BPF harmonics of rotor 1 and rotor 2. Figure 3.9 is the directivity plot.
Figure 3.8: Spectra of original, residual, and extracted rotor signals for edgewise forward flight case at time 30 s

of the OASPL in dB that was measured using the 1/2” diameter microphones. The directivity of the residual signal is similar to the expected broadband noise directivity from the aeroacoustic theory. The broadband noise is expected to radiate with the same magnitude in all directions, this is seen in the polar plot. The original signal directivity pattern is similar to that of broadband signal, this could mean that the directivity of coaxial noise is influenced by the directivity of broadband noise in this case.

Figure 3.10 is the polar plot of the extracted BPF harmonics of rotor 1 and rotor 2. The top rotor is rotor 1 and the bottom rotor is rotor 2. This means during the forward flight regime for this experimental setup, rotor 2 is operating in the wake of rotor 1. The directivity is similar for both the rotors but the noise levels of rotor 2 are higher than rotor 1 near the advancing side (−90 degrees to 0 degrees). For the
original signal in Figure 3.9, the directivity is symmetric about the advancing and retreating side i.e., –90 degrees to 90 degrees. This pattern from the original signal is observed in rotor 1 much closer than in rotor 2.

The higher noise levels of rotor 2 in the advancing and the retreating side of the rotor can be attributed to its operation being in the wake of rotor 1, and therefore, rotor 2 experiences greater unsteady loading due to aerodynamic interactions. This causes an increase in the loading noise generated by rotor 2, and since loading noise directivity is towards out-of-plane of the rotor; rotor 2 has more noise radiating out of the plane than rotor 1. Note that the noise of rotor 1 and rotor 2 is the same in the plane in-front of the rotor, this is because thickness noise propagates in this direction. Due to the same blade geometry of rotor 1 and rotor 2, the thickness noise does not change even though rotor 2 is in the wake of rotor 1.
As mentioned in Section 1.2, due to recirculation effects in anechoic chambers, the noise of rotors can be higher out of the plane of the rotor. It could be argued that this may explain the minor discrepancies in the noise levels out-of-plane for rotor 1 and rotor 2. However, the experiment was designed so that recirculation effects are an unlikely candidate for the observed differences.

### 3.2 Tarot X8 Octocopter Flight Test

This acoustic flight test campaign was part of the ASCENT Project 077 [51] and was conducted at Mid-State Regional Airport (KPSB) in Philipsburg, PA. The goals of the project are to develop measurement and data processing techniques to reduce variability in UAS and UAM aircraft noise to inform the Federal Aviation Administration (FAA)
in the development of certification standards for these aircraft. Tarot X8 Octocopter was chosen for its resemblance to the category of drones proposed for package delivery operations by companies like Amazon Prime Air [52]. Researchers from the Applied Research Lab (ARL) at Penn State provided and piloted the aircraft for acoustic flight tests.

An analysis of the same measurements performed by Konzel and Greenwood [53] found that the noise variability for the same altitude and speed was found to be as high as 6 dB in measurements collected during different test days. Relevant information needed to understand the results is presented here. For detailed information about the acoustic flight test please refer to References 53, 54.

The following sections will outline details of the flight test setup and perform acoustic analysis on the measured data. First, the de-Dopplerization step of the source separation process was applied, and then, the acoustic measurements were depropagated to generate acoustic hemispheres.

### 3.2.1 Flight Test Setup

Tarot X8 used 15” propellers and its take-off weight was 12.9 lbs, aircraft shown in Figure 3.11. The specifications of the aircraft are listed in Table 3.1 (Reproduced from Reference [54]). The test matrix that was developed for this test setup reflected the operational regimes that a package delivery UAS aircraft would perform. One of the main focuses of the flight test was the characterization of flyover acoustics.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empty weight</td>
<td>9.59</td>
<td>lbs</td>
</tr>
<tr>
<td>Motor</td>
<td>420</td>
<td>kV</td>
</tr>
<tr>
<td>Wheelbase</td>
<td>41.25</td>
<td>in</td>
</tr>
<tr>
<td>Propeller diameter</td>
<td>15</td>
<td>in</td>
</tr>
<tr>
<td>Battery</td>
<td>2x5000</td>
<td>mAh</td>
</tr>
</tbody>
</table>

Table 3.1: Relevant parameters of Tarot X8 octocopter [54]

The aircraft was controlled by the Pixhawk autopilot which has an in-built GPS and IMU (Inertial Measurement Unit) for state data measurements [55], these data were used to synchronize the acoustic data and generate acoustic hemispheres in the following sections. Test points were created ahead of the flight and the mission
was uploaded onto software similar to QGroundControl \[56\], which flew the aircraft autonomously along the specified waypoints. Autopilot was preferred over manual piloting to eliminate the small perturbances that may otherwise occur and could introduce variability in the acoustic signals. An off-the-shelf Bad Elf GPS \[57\] was attached to the Tarot X8 for another measurement of position data, and to compare the flight path with the onboard GPS data. The files from the autopilot were processed and saved in ‘ulog’ file format.

The microphone array layout was spread across an area of 500 ft x 200 ft and consisted of two linear microphone arrays (M1-M5 and M6-M10) spanning 500 ft each, stacked perpendicularly to the flight path with an offset of 200 ft. There were two microphones (M11 & M12) equidistant between the parallel linear arrays to the right side of the flight path between the M5 and M10. The array layout, along with the operator station, landing zone (LZ), and a sample flyover flight path is shown in Figure 3.12.

Acoustic measurements were taken with the Bruel & Kjaer (B&K) Data Acquisition (DAQ) system using 1/2” diameter microphones. After the on-field measurements,
Figure 2.9. 14 Channel Microphone Array Used in Tarot X8 Acoustic Flight Testing Campaign.

are non-uniformly spaced on the ground so as to measure noise at equally spaced sideline angles when the vehicle is at an altitude of 250 ft and 250 ft ahead of the array center (i.e., at a 45° elevation angle). Similarly, microphones M6 to M10 form an additional linear array, similar to M1 through M5, at a different position along the flight path. The combination of two linear arrays can be used to assess the variability in noise at different instances in time for the same flight over the array, with the observer locations remaining constant. This configuration also allows noise data to be collected across a range of azimuth angles for takeoff, landing, and hover operations.

Figure 3.12: Microphone layout of the Mid-State flight test visualized on Google Earth along with a sample flight path of a flyover

the measured acoustic pressure time histories were saved in ‘hdf5’ file format. The timestamps of the state data saved in the ‘ulog’ files were used to synchronize with the acoustic data from ‘hdf5’ files and correlate the acoustic radiation patterns with the state position data. The aircraft flew at altitudes of 50 ft, 100 ft, and 250 ft for hover and flyover conditions, and at speeds of 10 mph, 20 mph, and 27 mph for the flyover conditions.

3.2.2 De-Dopplerization

The autopilot of the UAS aircraft recorded the state data at a frequency of 10 Hz, including the position and velocity data in the NED (north-east-down) coordinate system. The time stamps of the recorded data were synchronized with Coordinated Universal Time (UTC). Since the B&K data acquisition (DAQ) system also used GPS
time to synchronize the acoustic data with UTC time, the time stamps for both the state and acoustic data were normalized using a reference time for each test point.

To ensure that the GPS time from the B&K system was the same as the GPS UTC time from Pixhawk autopilot, a time hack was conducted with the DAQ system. First, the trajectories measured using the Bad Elf Surveyor [57] were plotted against the Pixhawk position data to confirm that both sets of GPS data were on the same UTC time. Second, the acoustic DAQ system was setup with a single microphone. At a certain UTC time measured using the Bad Elf Surveyor, an impulsive sound was created in-front of the microphone. Then a pressure-time history plot of the recorded acoustic signal revealed that the sound was measured at the same time as the UTC reference time from Pixhawk autopilot. This established that the measured acoustic data and the aircraft state data were on the same reference UTC time. The validation of the timestamps for all the measurements was needed to ensure accurate de-Dopplerization and depropagation of the measurements for acoustic hemisphere generation.

3.2.3 Directivity Investigation

After de-Dopplerization of the acoustic measurements, emission angles were calculated using the procedure mentioned in Section 2.3. A sample projection of emission angles projected onto a hemisphere was presented in Figure 2.10. Interpolating for the points at regular intervals within the hemisphere, a complete hemisphere is populated to present the sound pressure levels.

Two different integrated metrics were calculated to present the directivity information of the Tarot X8 data: A-weighted Sound Pressure Level (SPL), dBA, was used alongside the unweighted Overall Sound Pressure Level (OASPL), dB. The A-weighted SPL integrates the sound pressure to reflect the noise levels as perceived by the human ear. Even though human hearing ranges from 20 Hz to 20 kHz, it is most sensitive to sounds produced at frequencies between 500 Hz and 6 kHz. A-weighted levels account for this and apply weighting to the frequency bands of acoustic energy to reflect the sensitivity of the human ear. As UAS noise perception is a huge contributor to community acceptance of these aircraft [2], A-weighted levels were used to assess the noise that would be most perceptible to people.
The following sections will establish directivity patterns with OASPL noise hemispheres and A-weighted SPL hemispheres. The dependence of directivity on the variability of noise in and between runs will also be investigated with noise hemispheres for repeated flight conditions. Noise hemispheres were produced for flyover measurements of Tarot X8 aircraft with a sphere radius of 15 ft. The integrated levels for the noise hemispheres were calculated with time windows of length equal to 0.1 s. At the expense of some details in magnitude information, the upper and lower SPL limits for all the hemispheres were kept constant. This would simplify the comparison of acoustic hemispheres between different conditions.

3.2.3.1 Variation with Altitude

Figure 3.13 is the acoustic hemisphere with the OASPL metric for a flyover at 50 ft altitude with 10 mph speed. Figure 3.14 is the acoustic hemisphere for the same flyover at a 50 ft altitude with 10 mph speed, but with A-weighted SPL.

At a first glance, the noise hemispheres have similar noise “hotspots” under the aircraft but the noise levels of the OASPL hemisphere are higher in directions nearer to the plane of the horizon. Since the noise levels directly under the aircraft are identical between OASPL and A-weighted hemispheres, the dominant noise sources radiating toward these observer locations are producing noise between 500 Hz and 6 kHz. The OASPL hemisphere has a greater harmonic component than the broadband component at elevation angles between 0 degrees to −30 degrees, as will be explained later. In the OASPL hemisphere from Figure 3.13, there are “lobes” of acoustic energy in the plane of the horizon towards forward and aft directions at azimuth angles of 30, 150, 180, 210, and 330 degrees. The analysis of this data set by Konzel and Greenwood in [53] revealed that tonal noise is dominant at observer locations far from the aircraft. This would be equivalent to a location near the horizon of the acoustic hemisphere, therefore the lobes could be due to the interference of the rotor tonal noise. To eliminate the variability of lower harmonic noise, the A-weighted noise metric is calculated and presented. This highlights the variability of the measured multirotor noise with the unweighted OASPL metric.

To understand the role of tonal and broadband noise in front of the aircraft and below the aircraft in the “hotspot” region, a composite plot is presented in Figure 3.15 with the OASPL metric for a 100 ft flyover at the same speed of 10 mph.
Figure 3.13: Acoustic hemisphere for level flight flyover condition at 50 ft and 10 mph in unweighted OASPL, dB

In the composite plot, on the right side is the OASPL metric acoustic hemisphere, on the top left is the acoustic Power Spectral Density (PSD) spectrum at azimuth 180 degrees and −15 degrees, and on the bottom left is the acoustic PSD spectrum at azimuth 0 degrees and elevation −85 degrees. The acoustic spectra on the top left, corresponding to the front of the aircraft has tonal peaks of harmonic noise, and then the acoustic spectra rolls-off to lower magnitude broadband noise. The acoustic spectra on the bottom left, corresponding to underneath the aircraft have similar tonal noise magnitude but have a higher broadband component until 4000 Hz and then rolls-off to negligible levels of broadband noise at higher frequencies.

The spectra in-front of the aircraft are dominated by the tonal component, whereas the spectra under the aircraft are dominated by the broadband component. As observed from the composite plot in Figure 3.15, the noise is more variable in-front of the aircraft than under the aircraft. To summarize this, it is safe to conclude that the tonal noise for multirotor UAS aircraft is more variable than the broadband noise.
The noise characteristics of the broadband noise and the observed bursts near the in-plane of the aircraft change at higher altitudes, i.e., between flyovers at 50 ft and 100 ft as observed in Figure 3.15. As with the 50 ft flyover case, the acoustic hemisphere with the A-weighted metric for a flyover at 100 ft and 10 mph is presented in Figure 3.16.

The OASPL hemisphere from the composite plot in Figure 3.15 contains higher levels of noise at directivity angles near the in-plane of the rotor, and, the levels beneath the aircraft are similar to the 50 ft case. The A-weighted noise hemisphere reveals that the directivity and magnitude information for the 100 ft case is similar to the 50 ft case. A similar radiation pattern is expected because the noise characteristics would not be expected to change between different altitudes for a flyover case. This is because the dominant noise sources for the aircraft do not change for small changes in altitude, however, the propagation effects could cause some of the increases and decreases in noise levels observed in-plane of the aircraft.
Figure 3.15: Composite plot of level flight flyover condition at 100 ft and 10 mph in unweighted OASPL, dB along with PSD spectra at locations forward and underneath the aircraft
In the next section, the directionality and its variation with speed are presented and discussed. Only A-weighted acoustic hemispheres were used in the next section due to the variability in the OASPL due to the quasi-coherent addition of the rotor tones.

### 3.2.3.2 Variation with Speed

Next, the variation between cases at different speeds will be evaluated. As explained previously, A-weighted hemispheres were used in this section to reduce run-to-run variations while examining the change in noise with speed. To assess the variability, A-weighted noise hemispheres for an altitude of 50 ft and speed of 20 mph are presented in Figures 3.17 and 3.18.

From the differences in Figures 3.17 and 3.18, the peak levels vary as much as 5 dB for the same flight condition. These measurements were taken on the same day within
a time span of 2 hours, there were multiple gusts during the test. These gusts were as strong as 6 kts and caused major differences in the measured levels. It seems that this measured multirotor noise is very sensitive to ambient conditions. The aircraft commanded a control input to correct the flight path perturbations caused by these gusts. This commanded control could be a smaller contributor to the variability seen between the noise hemispheres.

Comparing the noise hemisphere for a 10 mph flyover in Figures 3.14 and 3.16 to a 20 mph flyover in Figures 3.17 and 3.18 the direction of the peak noise levels moves slightly towards the forward of the aircraft with increasing speed. This is expected from the convective amplification of the rotor noise. For the 10 mph case, the “hotspot” was directly under the aircraft at an elevation of −90 degrees. For the 20 mph case, the “hotspot” was slightly in-front of the aircraft at an elevation of −80 degrees. For both the noise hemispheres, the peak levels are within the variability limits expected from the measurements [53]. Moreover, directivity and magnitude changes are the
same as expected from the knowledge of multirotor noise between hemispheres for different speeds.

To look at the variability of the noise levels in the acoustic hemispheres of 50 ft and 20 mph flyover cases, the variance of unweighted OASPL is presented in Figure 3.19. After Shepard’s IDW interpolation method was applied, the variance of the noise levels in dB was calculated for emission angles at intervals of 2 degrees. A total of 7 upwind runs, all taken on the same day were used to calculate this variance.

Most variability of 4 dB is seen near the aft of the aircraft at an azimuth of 15 degrees and an elevation of −30 degrees. High levels of variability are also seen near the horizon in “lobes” at azimuth angles of 30, 240, 335, and 355 degrees respectively. Note that the variability of noise located at the peak level “hotspot” location at around an azimuth of 170 degrees and an elevation of −80 degrees in Figures 3.17 and 3.18 is lower than the variability of other locations in Figure 3.19.
Figure 3.19: Acoustic hemisphere for level flight flyover condition noise variance at 50 ft and 20 mph in unweighted OASPL, dB [7 upwind cases]

The propagation effects may introduce variability that is artificial and affect some metrics such as the OASPL, as evidenced by the results. In all the cases, the noise hemispheres have a slight bias towards the right side of the aircraft, this could be due to the flight traveling about 10 ft to the right of the flight path for the evaluated cases in this section.
The Source Separation Process (SSP) developed and tested in Chapter 2 and verified in Chapter 3 is applied to perform acoustic analysis of helicopter flyover measurements. This flight test measured all the required data needed to apply the complete SSP.

A large portion of the results and analysis performed in this chapter is similar to and built upon the work presented in Vertical Flight Society Forum 78 by Rachaprolu and Greenwood [58]. This chapter presents the results of the source separation process applied to several operating conditions. The desired capabilities outlined as thesis objectives in Section 1.3 are mostly fulfilled by the applicability of the SSP to this helicopter flight test data set. The objective of applying the SSP to acoustic flight test data with rotors operating at nearly the same RPM is not applicable to this data set because the main rotor and tail rotor blade passing frequencies are much further apart than for blade passing frequencies in multirotor aircraft.

### 4.1 Flight Test Setup

Extensive acoustic data were collected during the 2011 flight test of a Bell 430 Helicopter with coordinated efforts from the U.S. Army, Bell Helicopters, and NASA, picture of the helicopter is shown in Figure 4.1. The test details and results are documented in the NASA technical report [14] in great detail; however, some relevant details needed to understand the results are presented in this chapter. All of the acoustic, state
data, and aircraft instrumentation measurements were time synchronized to the same reference time to enable these data to be correlated to one another.

Figure 4.1: Picture of Bell 430 helicopter during hover condition [14]

The acoustic data were acquired using multiple ground-based microphone array layouts for both steady state and maneuvering flight conditions. These array layouts consisted of a linear 27 microphone array for steady state source noise and a distributed 31 microphone array for non-steady state maneuver noise. These array layouts are shown in Figure 4.2; steady state array layout at the top in Figure 4.2.1 and non-steady state array layout at the bottom in Figure 4.2.2.

Among the instrumentation was a main rotor shaft encoder which allowed an accurate measurement of the main rotor rotational speed (RPM). The gear ratio was used to infer the tail rotor RPM from the main rotor RPM measurement, and these RPM readings were used to obtain the blade passage frequencies for both rotors. Using the onboard differential GPS (DGPS) tracking data, the propagation times were calculated, and the acoustic measurements were de-Dopplerized to transform them into a stationary reference frame, as described in Chapter 2. Then the V-K filter was used to extract the first 20 harmonics of the main rotor and the first 10 harmonics of the tail rotor.
4.2 Parameter Tuning

Tuning of several parameters for the V-K filter was performed to obtain more accurate results from the SSP. Since the weighting factor for the structural equation was formulated based on the bandwidth of the filter [47], the convergence of the solution
depends on the choice of bandwidth. Also, the accuracy of signal extraction is dependent on the bandwidth. If the bandwidth is too narrow, the filter does not extract all the energy, performing an incomplete extraction. If the bandwidth is too wide, the filter overextracts the noise, i.e., the filter tries to find periodicity in broadband noise. A plot showing the effect of filter bandwidth on the extracted signal is presented in Figure 4.3 for a sample microphone measurement from a level flight condition. This case was chosen to demonstrate the bandwidth tuning because it is from an acoustic flight test, which encapsulates all the steps of the SSP. For the Dragonfly blade acoustic measurements from the anechoic wind tunnel in Chapter 3, a fixed bandwidth proportional to the rotor BPF was used, but this flight test needed some more tuning of the parameters.

![Figure 4.3: Plot of the original and residual pressure-time histories for bandwidth tuning of the Vold-Kalman filter](image)

The original signal is the de-Dopplerized acoustic pressure time history of the signal and the residual signal is the component that is leftover after extracting the main and tail rotor components. The filter was applied with a filter order of 2 and only the bandwidth is varied between the top plot and the bottom plot in Figure 4.3. In the top plot, the bandwidth is set to a constant 30 Hz for all orders and signals,
and the residual signal has some amplitude modulation, possibly due to incomplete extraction of lower harmonics. In the bottom plot, the bandwidth is proportional and is set to 10% of BPF with the ceiling set to a maximum of 25 Hz, the residual signal is smaller, and there is no visible amplitude modulation resulting in an effective extraction.

In the helicopter flight test data used in this chapter, the main rotor and tail rotor BPFs are generally far apart, therefore the Cholesky decomposition is used with no loss of solution accuracy in the extracted pressure envelopes.

4.3 Steady State Cases

The Source Separation Process (SSP) was first applied to steady state cases to examine the performance with acoustic flyover measurements. During the steady state cases, the acoustic state of the aircraft is straightforward and the noise sources do not change quickly with time. The extracted measurements of the main rotor and the tail rotor are used to produce acoustic hemispheres to investigate the directivity of the rotors.

The steady state cases examined in this section are:

1. Level flight
2. Approach/Descent flight

4.3.1 Level Flight Condition

The level flight condition was with 80 kts indicated airspeed along the flight path displayed in Figure 4.2.1, with the steady state microphone array layout. The extracted pressure-time histories of the main and the tail rotors are presented along with the original and the residual signals. The residual signal is obtained by subtracting the time-domain extracted signals from the original acoustic measurement. These signals are shown for several main rotor blade passages in Figure 4.4. For clarity, the extracted tail rotor signal is omitted from the top plots, and the extracted main rotor signal from the lower plots, although both the main and the tail rotor orders are simultaneously extracted.
There is a clear distinction in the shape of the extracted pulses, which are representative of the main and the tail rotor noise of this helicopter. Looking across the larger time scale, small variations in the amplitude and the shape of the main and the tail rotor pulses can be clearly observed. The residual component primarily contains broadband noise, and the amplitude is significantly lower compared to the extracted main rotor and tail rotor signals.

Figure 4.5 shows the corresponding power spectrum of the extracted signals. A clean separation of the main and tail rotor tones is achieved, even when the harmonics are close to each other. The residual signal does not contribute significantly to the Sound Pressure Level (SPL), and the magnitude is more than 10 dB below the tones across the frequency range of the extraction.

The extracted data from all the microphones were used to populate a noise hemisphere to visualize the directivity of the individual components. As mentioned in Chapter 2, the de-Dopplerized acoustic signals were normalized to a 100 ft radius, forming a hemisphere of data around the rotor. The extracted main rotor noise...
hemisphere is presented in Figure 4.6. Higher main rotor noise levels are seen both towards the advancing side of the rotor and directly in-front of the aircraft.

The extracted pulses shown in Figure 4.7 correspond to the noise “hotspot” near an elevation angle of 140 degrees in Figure 4.6. The extracted main rotor noise signal features a large amplitude acoustic waveform characteristic of the lower harmonic loading noise, with some additional low amplitude higher harmonic content occurring at multiples of the main rotor blade passing period.

Figure 4.8 shows the extracted noise hemisphere of the tail rotor. Here, the noise of the tail rotor reaches a maximum level directly ahead of the helicopter, at an azimuth angle of 180 degrees. Examining the spectral data shown in Figure 4.5, the noise levels of the extracted tail rotor harmonics are 15-20 dB greater than the residual component at all the blade passage frequencies.

In the next section, a descent condition with higher levels of impulsive noise than the level flight condition will be analyzed.
Figure 4.6: Acoustic hemisphere of the separated main rotor for an 80 kts level flight condition

Figure 4.7: Extracted time domain pulses of separated signals for an 80 kts level flight condition at an azimuth of 140 degrees and an elevation of −30 degrees
4.3.2 Approach/Descent Condition

A descent flight condition is analyzed to evaluate the ability of the SSP to extract BVI noise. The selected descent condition has an indicated airspeed of 80 kts and a flight path angle of $-6$ degrees relative to the horizon. Figure 4.9 shows the extracted main rotor noise levels plotted on a hemisphere, following the same process as described for the level flight condition. A strong noise “hotspot” can be observed radiating ahead of the aircraft for this flight condition in the main rotor acoustic hemisphere.

The tail rotor noise hemisphere for the approach condition is shown in Figure 4.10. The directivity of the extracted tail rotor noise is similar to the directivity of the tail rotor from the level flight condition seen previously in Figure 4.8. This is expected because much of the increase in the noise during approach is associated with the main rotor BVI, and so the noise of the tail rotor is not expected to vary much from the level flight condition at the same airspeed.

Figure 4.11 shows the extracted signals for this case at an azimuth of 170 degrees and an elevation of $-50$ degrees. This location was selected on the acoustic hemisphere because it passes through the noise “hotspot” that contains higher noise levels caused
Figure 4.9: Acoustic hemisphere of the separated main rotor for a $-6$ degrees approach/descent flight condition

Figure 4.10: Acoustic hemisphere of the separated tail rotor for a $-6$ degrees approach/descent flight condition
by impulsive BVI events in this flight condition. There is a clear difference in the shape of the main rotor pulses as compared to the level flight condition in Figure 4.4. The descending flight condition has strong impulsive spikes in amplitude at the blade passage frequency of the main rotor, these peaks are characteristic of the BVI noise. Since the amplitude of the main rotor noise is much greater than that of the tail rotor for this flight condition and in the radiating direction, therefore at these peaks, small quantities of energy are misinterpreted and extracted as the tail rotor components.

The tail rotor pulse is seen in the bottom plot of Figure 4.11 features pulses that occur at the tail rotor blade passing period, and are similar in shape to those observed in the level flight condition, shown previously in Figure 4.4.

Figure 4.11: Extracted time domain pulses of separated signals for a −6 degrees approach/descent flight condition at an azimuth of 170 degrees and an elevation of −50 degrees

The spectra of the extracted main and tail rotors are presented in the top and bottom plots of Figure 4.12 respectively. The tonal peaks of the main rotor correspond well in magnitude and in frequency to the peaks from the original signal that occurs at the first 20 harmonics of the main rotor. While the energy of the extracted harmonic components agrees well in the frequency-domain, the extracted signal appears to have
smoothed out the peak-to-peak amplitude of the BVI impulses in the time-domain, as shown in Figure 4.11. Additional tuning of the filter, including the extraction of higher main rotor harmonics, may be required to fully resolve these impulsive peaks.

Figure 4.12: Extracted frequency spectra of separated signals for a $-6$ degrees approach/descent flight condition at an azimuth of 170 degrees and an elevation of $-50$ degrees

The residual signal consists of the broadband component with a slightly higher amplitude than the level flight condition, this is possibly due to the impulsive noise at higher harmonics and leftover harmonic energy from the extraction. It is also possible that the increased amplitude of modulated broadband noise is associated with Blade-Wake Interaction (BWI). In either case, it is clear from Figure 4.12 that any bleed-through to the broadband component does not significantly change the magnitude of tonal peaks at multiples of the BPF of either of the extracted rotor components.

The composite plot shown in Figure 4.13 presents the extracted components at several emission angles “traced” by a microphone under the helicopter during the flyover. This highlights the advantages of the SSP where an effective extraction is performed with continually changing noise sources along the flight path on an acoustic hemisphere. In Figure 4.13, the pressure-time history envelope of the original signal is
Figure 4.13: Acoustic pressure envelope and mid-frequency SPL-time history for the extracted signals along a microphone track with the extracted signals on a hemisphere for an approach/descent flight condition
plotted in the top left plot and an SPL envelope for the same time scale is plotted in the bottom left plot with the integrated SPLs at the mid-frequency range (between the 4th and the 20th main rotor shaft orders) of the separated signals (main rotor, tail rotor, and residual) in order to emphasize the BVI noise of the main rotor. The microphone trace is plotted on a hemisphere in the center. Three pressure-time history plots of extracted signals are plotted for times of 34–34.2 s, 44–44.2 s, and 50–50.2 s along the microphone trace. These are distinctive points on the hemisphere, each of which is characterized by a different composition of noise sources. Note that the vertical axis varies between each of the three pressure-time history plots, this is due to the large variation in the amplitudes associated with the three selected emission angles.

The first signal shown begins at 34 s, corresponding to a location on the hemisphere with an azimuth of 180 degrees and an elevation of −15 degrees. Thickness noise, both that of the main rotor and the tail rotor, dominates this region because thickness noise radiates most strongly in the plane of the rotors in the direction of travel. The second signal begins at 44s, this is at an azimuth of 180 degrees and an elevation of −45 degrees. Here, the observer is out of the plane of the main rotor and the loading noise is dominant. The pulse shapes of the main rotor show strong BVI impulses with a negative peak, indicative of retreating side BVI. The tail rotor component retains the negative peaks associated with the thickness noise at the blade passing period of the tail rotor noise. The third signal begins at 50 s, on the hemisphere, this is at an azimuth of 360 degrees and an elevation of −7 degrees. In this direction, the broadband noise is relatively more significant, since the extracted main and tail rotor noise levels are much lower in directions below and behind the helicopter than ahead of it.

4.4 Maneuver Cases

Maneuvers are examined in this section to investigate the applicability of the method to non-steady state conditions. Since the aircraft and its radiated noise are not stationary throughout a maneuver, it is not possible to construct a meaningful acoustic hemisphere from the measurement data. Instead, the variation in measured noise with time and direction is shown using composite plots throughout this section. The nomenclature of
the plots is the same as the composite plot of the approach condition from the previous section. A microphone is selected and the noise characteristics of the helicopter through the maneuver are analyzed as it was measured at this observer microphone location.

Three transient maneuvers are discussed in this section:

1. Cyclic pitch-up maneuver
2. Cyclic roll-right maneuver
3. Cyclic roll-left maneuver

These conditions all have the presence of BVI noise but with varying relevance. The application of the SSP also reveals how the process could be better used on acoustic flight test data. The presented SPL plots are integrated over a mid-frequency range from 90 Hz to 470 Hz, which is between the 4th harmonic and the 20th harmonic of the main rotor, and were targeted to isolate the BVI noise levels from the extracted signals.

### 4.4.1 Pitch-up Maneuver

The first transient maneuver analyzed in this chapter is a cyclic pitch-up condition initiated at an indicated airspeed of 60 kts. The path traced by the selected microphone underneath the aircraft along the flight path is shown on a hemispherical surface in the center of the composite plot in Figure 4.14. The top left plot contains the envelope of the pressure-time history of the original signal. The corresponding SPL-time history is shown for the same time scale in the bottom left plot for the extracted main rotor, tail rotor, and residual components.

Throughout the maneuver, the mid-frequency main rotor SPL is higher than the tail rotor SPL. The tonal components of both rotors are significantly higher than the residual component. However, the variation in time is significantly different for all three components. The SPL of the tonal component is much greater ahead of the aircraft than toward the rear of the aircraft. The tail rotor SPL stays relatively constant for most of the maneuver, decreasing only after the aircraft has completed the maneuver and has passed over the microphone. In contrast, the main rotor SPL increases by approximately 10 dB during the maneuver. The residual signal SPL peak
Figure 4.14: Acoustic pressure envelope and mid-frequency SPL-time history for the extracted signals along a microphone track with the extracted signals on a hemisphere for a cyclic pitch-up maneuver flight condition
occurs after the peaks of both the extracted tonal components and is biased towards the rear of the aircraft.

The extracted signal of the main rotor is presented along with extracted tail rotor at three different time instants to highlight the different noise sources that occur during a maneuver. The first time window is from 74–74.2 s near an azimuth of 180 degrees and an elevation between 0 degrees to −30 degrees. The extracted main rotor signal shows the prominent negative acoustic peaks associated with thickness noise, although there are also positive impulses associated with the BVI noise at this stage of flight. The second signal shown is from 94–94.2 s which is located at an azimuth of 180 degrees and an elevation of −45 degrees. The pulse shape of the extracted noise in this direction is characteristic of strong BVI noise, with two BVI impulses occurring during each rotor blade passage. The amplitude of the signal is higher than the first time window, and there is a corresponding rise in the main rotor levels in the SPL-time history shown in the bottom left plot. Note, once again that the pressure-time history scale has been changed to better resolve the details of the pulses. The third signal is from 99–99.2 s and is located at an azimuth of 350 degrees and an elevation of −45 degrees. The extracted main rotor noise has shown characteristic thickness noise pulses in the aft direction of the aircraft.

The tail rotor noise is relatively constant throughout the maneuver. Examining the waveforms shows the characteristic negative peaks associated with the tail rotor thickness noise, which are not expected to vary much with changes in the rotor operating condition. Additionally, the microphone remains in the plane of the tail rotor throughout the maneuver, explaining the relative lack of variation in the extracted tail rotor component.

4.4.2 Roll-right Maneuver

A cyclic roll-right maneuver initiated at a forward flight speed of 80 kts is examined in this section. The composite plot for this flight condition is presented in Figure 4.15.

In the SPL-time history plot at the bottom left, the mid-frequency SPL of the main and tail rotors is significantly higher than the residual signal. The peaks occur around the same time for all the signals, in contrast to the pattern seen in the pitch-up maneuver. Like in the previous case, the tail rotor noise remains fairly constant throughout the run and decreases as the aircraft passes the observer. Likewise, the
Figure 4.15: Acoustic pressure envelope and mid-frequency SPL-time history for the extracted signals along a microphone track with the extracted signals on a hemisphere for a cyclic roll-right maneuver flight condition
broadband noise is low throughout the run until the aircraft passes the observer location, and then it becomes more dominant towards the aft of the aircraft.

Three time instances were picked to observe the noise change throughout the maneuver. The first time window is from 84–84.2 s and is at a location with an azimuth of 180 degrees and an elevation of −20 degrees. The extracted main rotor has prominent negative peaks from the thickness noise and some lower magnitude impulsive peaks associated with the BVI noise. The second time window is from 90.4–90.6 s and is at an azimuth of 180 and an elevation of −35 degrees. Here, the extracted main rotor signal has stronger peaks representative of the impulsive BVI noise and the magnitude changes are rapid, even from one blade passage period to another. The impulsive noise peak at 90.45 s is ∼30 Pa, but it rapidly increases for the next pulse at 90.49 s to ∼50 Pa; the V-K filter is able to capture these impulsive variations unlike many of the source separation approaches reviewed in Chapter 1. The third time window is from 94.3–94.5 s and is at an azimuth of 325 degrees and an elevation of −30 degrees. The main rotor noise lowers in overall magnitude and the pulses that resemble the retreating side BVI are observed towards the aft of the aircraft.

The extracted tail rotor noise component remains constant throughout the maneuver and the noise level is more than 10 dB lower than the extracted main rotor component. This behavior is expected from the tail rotor and the noise is expected to be similar to the cyclic pitch-up maneuver condition. Even though the observer is not strictly in the plane of the tail rotor, the variations in the noise levels are minimal.

4.4.3 Roll-left Maneuver

Lastly, a cyclic roll-left maneuver initiated from a level forward flight condition with a speed of 80 knots is analyzed using the SSP. The composite plot of the same selected microphone as the roll-right condition is presented in Figure 4.16. The SPL is pattern similar to the pitch-up maneuver where the main rotor dominates throughout the run and is more than 10 dB higher than the tail rotor component. Broadband noise is much lower than the main and tail rotor components until the aft of the aircraft, where the broadband noise is more dominant but still much lower than the rotor noise.

The noise of the extracted main and tail rotors in the three selected time windows is similar to the noise from the roll-right maneuver condition. Both the first and
Figure 4.16: Acoustic pressure envelope and mid-frequency SPL-time history for the extracted signals along a microphone track with the extracted signals on a hemisphere for a cyclic roll-left maneuver flight condition
second time windows are at a similar range of azimuth and elevation angles as the roll-right maneuver. The first time window is from 81–81.2 s and is at an azimuth of 180 degrees and an elevation of –15 degrees. The extracted main rotor component is similar to the roll-right condition and is composed of the thickness noise and some low impulsive noise sources. The second time window is from 87.8–88 s and is at an azimuth of 180 degrees and an elevation of –32 degrees. The main rotor component is mainly composed of impulsive noise and is lower than the roll-right maneuver. BVI noise is known to be more prominent for transient rolls toward the advancing side of the main rotor than for rolls toward the retreating side of the main rotor. The third time window is from 94–94.2 s and is at an azimuth of 40 degrees and an elevation of –30 degrees. As witnessed in the previous maneuvers, the main rotor component is composed of thickness noise. Also, the peak of the impulsive noise in the SPL plot is not as sharp as the roll-right maneuver and has a smaller magnitude change.

To compare, the noise characteristics are not identical for cyclic roll-right and cyclic roll-left maneuver cases. There are noticeable differences in the BVI noise, this is because, for the roll-left maneuver, the BVI noise is less prevalent. There are also higher levels of broadband noise towards the aft of the aircraft for the roll-right and roll-left maneuvers than for the pitch-up maneuver. This could be due to the fact that the tail rotor remains strictly in the plane of the observer in pitch-up maneuver but deviates out of the plane for roll-right and roll-left maneuver conditions.
Chapter 5  |  Conclusions and Future Work

This chapter concludes the thesis with a summary of the findings and the main conclusions are drawn from the results and discussion. Future work to extend the source separation approach to apply it to flyover measurements of multirotor UAS and UAM aircraft is also discussed in this chapter.

5.1 Summary

This thesis developed a source separation approach based on the Vold-Kalman (V-K) filtering technique. The source separation process was developed systematically and tested with various individual components along with the application of the complete process to aircraft flyover measurements. First, based on the literature review, the gaps in the research were highlighted to derive the objectives of the thesis in Section 1.3. Second, a source separation process was developed in the following way to satisfy all the objectives of this thesis.

To review, the objectives of this thesis as stated in Chapter 1 are to develop a source separation process that can:

1. Separate harmonic noise of individual rotors simultaneously for multirotor aircraft while the flight condition is changing and therefore the noise sources are changing continuously, as in maneuvers;

2. Preserve the phase and amplitude relationship of signals to perform acoustic post-processing techniques in both the time- and frequency- domains;
3. De-Dopplerize acoustic measurements to be able to process data from outdoor aircraft flight tests; and

4. Depropagate sound pressure levels to evaluate the directivity of separated individual rotor and aircraft noise components.

A time-domain de-Dopplerization was chosen to fulfill Objective 3 which is to enable the processing of data from outdoor ground-based aircraft flyover measurements from acoustic flight tests. The Vold-Kalman (V-K) order tracking filter was chosen for its capability to extract harmonic noise from multiple rotors simultaneously in the time-domain. It preserves the phase and amplitude relationship of the separated noise and enables post-processing in both the time- and frequency- domains. This satisfies Objectives 1 and 2. Developing acoustic hemispheres from ground-based measurements enables the directivity investigation of aircraft aeroacoustic footprint and in turn fulfills Objective 4. Therefore, all the objectives outlined in Section 1.3 were satisfied with the developed Source Separation Process (SSP).

With the SSP, multiple datasets were analyzed to understand the noise characteristics of various aircraft and to validate the process:

1. The V-K filtering approach was applied to extract harmonic noise from Dragonfly coaxial rotor acoustic measurements in the anechoic wind tunnel

2. Acoustic measurements of Tarot X8 Octocopter were de-Dopplerized and depropagated onto acoustic hemispheres to understand the directivity and magnitude of multirotor UAS noise emissions

3. The complete SSP was applied to Bell 430 helicopter acoustic flight test measurements of steady state and maneuvering flight cases; both to generate acoustic hemispheres of the different components for steady state flight cases and to investigate the variation of noise generated by different components in maneuvering flight.

This state-of-the-art capability for source separation will enable the noise of multirotor aircraft to be separated into individual rotor components. This will be a large contribution to understanding the noise characteristics of the eVTOL UAS and UAM aircraft.
5.2 Conclusions

The following conclusions were made from the application of the Source Separation Process (SSP) to various data sets in Chapters 3 & 4 of this thesis.

With the V-K filter, rotor harmonic noise from the wind tunnel acoustic measurements was extracted for coaxial rotors operating at close and crossing RPM. It was found that the noise of both the top and bottom rotors is similar in the plane of the rotors. Out of the plane of the rotors, the noise level of the bottom rotor was found to be higher than the top rotor, possibly due to it being in the wake of the top rotor.

With de-Dopplerization, the noise levels of Tarot X8 multirotor UAS were depropagated onto acoustic hemispheres with directivity information. It was found that the peak noise level “hotspot” was underneath the aircraft and most of the variability in noise was detected towards the forward and aft directions of the aircraft. Further spectral comparisons of time windows on a noise hemisphere revealed that the tonal noise is dominant in the directions with the most variability. A comparison of the directivity between altitudes and speeds revealed the “hotspot” moved forward at higher speeds while the directivity pattern remained the same for different altitudes.

With the complete SSP applied to Bell 430 helicopter acoustic flyover measurements, several conclusions were made with the application to steady state and transient maneuver cases. Thickness noise was most significant ahead of the helicopter, and the loading noise was highest out of the plane of the helicopter for a level flight case. The SSP was shown to accurately account for all acoustic energy between the extracted and residual components. The extraction was effective in separating the BVI noise for a descent/approach case. But there was some “bleed through” of the main rotor impulsive noise into the tail rotor signal, since the BVI pulses occupy a similar frequency range but are 8-10 times larger in amplitude. Then, analysis of three cyclic maneuver cases with transient variations in noise, demonstrated that the process can effectively extract time-varying noise, including impulsive noise sources like BVI. In all cases, a clean extraction of main and tail rotor signals was achieved and the extracted noise was consistent with the harmonics from the original signal.

Applications and contributions to the state-of-the-art rotor source separation developed in this thesis are:
The extraction is performed in the time-domain, therefore it can be applied to accurately extract time-varying noise sources. This enables the extraction of rotor noise for operating conditions such as maneuvers, which was a limiting factor of previous methods. The acoustic state of eVTOL UAS and UAM aircraft was shown to be continuously changing. The SSP possesses the ability to overcome this impediment, enabling accurate source separation of eVTOL noise. Analysis of helicopter noise during maneuvers provided insight into the time variation of noise generated by individual components during transient maneuvers. This makes the SSP a powerful tool to understand the noise of rotorcraft, including conventional helicopters and multirotor eVTOL aircraft.

The separation of noise sources is accurate for rotors operating at close and crossing rotational speed, and is conservative, accounting for all the acoustic energy. This is needed for eVTOL aircraft acoustic analysis to separate the noise of multiple rotors operating at almost the same RPM. It was confirmed that the variability of noise is much higher for multirotor aircraft than for conventional rotorcraft. The SSP demonstrated an effective separation of multirotor aircraft noise in indoor experiments and may provide the best way forward to understand the acoustic characteristics of eVTOL multirotor aircraft on a rotor-to-rotor basis.

The process was applied to de-Dopplerize and depropagate the extracted signals onto a hemisphere to present the directivity and magnitude information. This was used to visualize the directivity of a conventional helicopter and a multirotor UAS. Analysis of the directivity data for the multirotor UAS revealed that the highest levels are variability occur in the out-of-plane directions, and are primarily associated with the tonal noise components.

5.3 Future Work

With the helicopter noise measurements, due to the large difference in magnitude, some main rotor noise bled through to the tail rotor component. Future research should investigate whether this “bleed through” can be eliminated by careful tuning
of the source separation process and/or combining the wavelet BVI extraction [24] with the SSP.

Future work is needed to apply the SSP to separate the noise of all the individual rotors on a multirotor aircraft from a single acoustic measurement. This would require accurate measurements of the rotor speed, ideally with high resolution, which can be performed using encoded motors.

To separate the individual rotor noise sources from acoustic measurements of eVTOL UAS and UAM aircraft, the current state-of-the-art approach is the Source Separation Process (SSP) that is developed in this thesis. A more accurate mathematical solution might be developed that could apply sharper bandwidths to more accurately track rotors operating at very close speeds (within 1 RPM) without loss in resolution extraction of acoustic energy.

This technique might be applied to correlate the aircraft state data and the extracted noise generated by individual rotors. This data could then be used to understand and reduce the variability in multirotor aircraft noise measurements. This could also be used to characterize the noise of the aircraft at times when the near-coherence of multirotor aircraft rotors operating at similar RPM causes acoustic interference in the radiated tonal noise.
References


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