An extraction method is proposed to investigate blade vortex interaction noise emitted during helicopter transient maneuvering flight. The extraction method allows for the investigation of blade vortex interactions, independent of other sound sources. It is based on filtering the spectral representation of experimentally acquired full-scale helicopter acoustic data. The data is first transformed into time-frequency space through the wavelet transformation, with blade vortex interactions identified and filtered by their high amplitude, high frequency impulsive content. The filtered wavelet coefficients are then inverse transformed to create a pressure signature solely related to blade vortex interactions. Analysis on a synthetic data set is conducted, and it is shown that blade vortex interactions can be accurately extracted so long as the blade vortex interaction peak energy signal is greater or equal to the energy in the main rotor harmonic. A brief analysis shows that the extraction method performs admirably throughout a fast advancing side roll maneuver. Using this method, it was shown that peak blade vortex interaction noise levels are linked directly to the roll rate of the vehicle, and are directed towards the retreating side during the transient portion of the maneuver.

**Motivation**

Understanding helicopter transient maneuvering noise is the next great hurdle to overcome in the world of helicopter acoustics. While there is still much work to be done across the width and breadth of the helicopter acoustics field, insight into transient maneuvering acoustics is still lacking (Ref. 1). The effects of these maneuvers are of special importance to the military as maneuvering is known to impact vehicle acoustics, and therefore vehicle detection. Civilian impacts are also important, as vehicle maneuvers can impact community annoyance levels.

Unfortunately, experimental helicopter acoustics are predominantly relegated to expensive, full-scale flight tests. This results in relatively few experiments, with which numerical results can be validated against. Transient maneuvering acoustics face another challenge, caused by the very nature of its transitory signature. The selection of an appropriate analysis tool for characterizing sound intensity and spectral content of a transient signal is non-trivial. In the case of stationary systems, statistical properties can be generated through ensemble averages over long data sets. Because transient signals are non-stationary, the temporal component of the signal must be preserved, and ensemble averages are no longer possible. Hence, determining the suitability of the analysis technique is a persistent difficulty in the statistical modeling of transient phenomena (Ref. 2).

To date, the noise generated by maneuvering flight has been predominantly focused on steady maneuvers including steady turns and ascent/descents. The effects of transient maneuvers, where a vehicle transitions from one steady maneuver into another, has only recently been investigated. Research into the prediction of acoustics resulting from transient maneuvers was initiated by Brentner and Jones (2000) (Ref. 3) who used numerical simulations to investigate an arrested descent flight condition. Full-scale experiments into transient maneuvers was initiated by Spiegel et al. (2005) (Ref. 4), followed closely by Schmitz et al. (2007) (Ref. 5), and later by Watts et al. (2012) (Ref. 6). Understanding and predicting the acoustic effects of transient maneuvers can be used to reduce community annoyance levels near heliports as well as detection distances for helicopters in flight.

The PSU-WOPWOP code, developed by Brentner et al. (2002) (Ref. 1), was coupled with GENHEL and used by Brentner et al. (2003) (Ref. 7) to investigate a transient roll maneuver. Ref. 7 concluded that acoustic amplitude is affected during a transient roll maneuver. Later, the PSU-WOPWOP code was coupled to a free wake vortex method to investigate several flight conditions by Hennes et al. (2004) (Ref. 8). Comparing to the works of Ref. 7, Ref. 8 suggested that a more accurate free wake model is necessary for predicting acoustics during transient maneuvers. Ref. 8 concluded that the simplified blade loading information provided by GENHEL is insufficient for accurately predicting the blade vortex interactions.

A competing noise computation algorithm was described by Perez and Costes (2004) (Ref. 9), and was based on the European codes HOST - MINT - MENTHE - ARHIS and MANEUVER PARIS. Essentially, Perez and Costes used a newly developed free wake code (MINT) coupled with a FW-
Investigating an advancing side roll maneuver, they saw a 10 dB increase in noise level immediately upon initiation of the roll maneuver. This increase in noise was determined to be caused by an increase in blade vortex interaction noise due to a decrease in miss distance on the advancing side of the rotor.

Advancing side transient roll maneuvers were also numerically investigated by Chen, Brentner, and Shirey (2005) (Ref. 10), although they used the PSU-WOPWOP program chain described in Ref. 8. The aggressive dynamic advancing side roll maneuver investigated, lead to the advancing side vortices bundling together before interacting with the rotor. Greenwood, Schmitz, and Sick-erberger (2012) confirmed the conclusion of Ref. 13 that transient pitch up maneuvers exhibited blade vortex interaction phenomenon. The interaction itself occurs because of a very aggressive roll rate, which reaches a maximum of 40 degrees per second. The roll they investigated was established in a period of approximately one second, and this interaction helped lead to the conclusion that a free wake vortex method, and fully transient analysis, is needed for the investigation of transient maneuvers (Ref. 12).

Currently, only a few flight tests exist that include transient maneuvers (Refs. 4–6, 13). Spiegel, Buchholz, and Pott-Pollenske (2005) (Ref. 4) investigated the noise footprint of two helicopters during transient roll maneuvers and ascent/descent flight patterns. They used a heavily instrumented BO-105 vehicle whose main rotor system was equipped with strain gauges, used for the calculation of blade motion, and on-blade pressure sensors. A differential Global Positioning System was used on both the BO-105 vehicle and the EC135-FHS, and 43 microphones were deployed on the ground to capture the acoustic footprint of the vehicle during maneuvers. Ref. 4 showed that the BO-105 vehicle was louder than the EC135-FHS vehicle, except during steep descents. They also showed that noise directivity patterns were different between advancing side and retreating side roll conditions.

Another experimental investigation using a Bell 206B vehicle with a crop dusting boom attached that was modified to hold microphones for in-flight measurements was conducted by Schmitz et al. (2007) (Ref. 5). The published data from this experiment has focused on steady and accelerating descents where it was shown that accelerating during a descent could reduce the overall sound pressure level. Particular attention was also paid to a steady advancing side roll, where an increase in the noise was seen to be louder, and shifted compared to the steady level flight condition. This increase in noise was attributed to the increase in thrust required by the tail rotor, in order to compensate for the increase in thrust on the main rotor. The origin of the shift in the noise directivity is difficult to determine, as a horizon-fixed coordinate system was used, and so the roll attitude of the vehicle was not accounted for.

A later test by Sickenberger, Gopalan and Schmitz (2011) (Ref. 13) was conducted with a ‘clean’ Bell 206B vehicle and 5 ground based microphones. This flight test focused on several pull-up maneuvers, and employed a rigid wake model to predict blade vortex interaction locations and subsequently the noise contributed to that signal. A time domain method for extracting the blade vortex interaction noise was developed, and a detection algorithm was used to identify changes in detection distances during each maneuver. The described extraction method is based on removing the impulsive nature of the blade vortex interaction noise from the original signal, and then interpolating and smoothing into place a new acoustic signal derived from the harmonic information located temporally around the removed signal. Using this method, Ref. 13 showed that the blade vortex interaction signal contributed up to 16 dB of the blade vortex interaction sound pressure level. The experiment also showed that blade vortex interaction noise for transient pull up maneuvers are predominantly forward and centered on the vehicle. Their technique for identifying blade vortex interactions, however, was not discussed.

The data set from Ref. 5 was also used to help develop a semi-empirical model to predict rotorcraft noise during maneuvering flight (Ref. 14). Greenwood, Schmitz, and Sick-erberger (2012) (Ref. 14) confirmed the conclusion of Ref. 13, that transient pitch up maneuvers exhibited blade vortex interaction noise predominantly forward and centered on the vehicle. However, transient advancing side rolls showed blade vortex interaction noise predominantly forward and to the retreating side of the vehicle. Ref. 14 also developed a prescribed wake model based on Beddoes’ method, that allows for changes in the inflow as a function of time. They used this method to show that the amplitude change in the blade vortex interaction signal was primarily a function of the miss distance of the tip vortex during each maneuver.

In the study presented, a time-frequency analysis of the sound produced by a Bell 430 helicopter during transient flight will be investigated. Data was acquired during a recent test campaign conducted by NASA, in conjunction with Bell Helicopters and the US Army (Ref. 6). The NASA, Bell and US Army experiment investigated both steady and transient flight maneuvers, acquiring a total of 410 data points. Preliminary results by Watts et al. (2012) (Ref. 6) showed a particularly large increase in noise for maneuvers controlled through cyclic inputs alone. This work continues that of Stephenson and Tinney (2013) (Ref. 15), and pursues a technique to identify and extract acoustic signals related to blade vortex interactions that occur during transient maneuvering flight. This will shed light on how transient maneuvers affect the noise footprint of a helicopter, while also providing a way to isolate the effects such maneuvers have on the impulsive blade vortex interaction noise.

**Wavelet Transforms**

Investigating impulsive events such as blade vortex interactions, and transient events such as those present during unsteady maneuvers, is a non-trivial task as standard statistical methods are no longer applicable. Therefore, a methodology capable of handling transient phenomenon is required if one is interested in the spectral properties of the signal.
Time-frequency analysis methods employ basis functions that are non-zero over a finite time interval thus making them compactly supported. This differs from the standard Fourier transform technique, which uses trigonometric basis functions and relies on three basic assumptions. The Fourier transform assumes the signal is steady, periodic, and Lipschitz continuous (Ref. 16). The steady and periodic assumptions are invalidated for transient maneuvers, as well as instances where blade vortex interactions occur. Thus, time-frequency methods must be employed for the analysis of such signals.

The methodology employed here to investigate the spectral content of the acoustic signals as a function of time, continues from the work of Ref. 15, and is called wavelet transforms. The interested reader is referred to the work of others for an in-depth discussion on this technique (Refs. 17–20). Wavelet transforms are only one of many techniques that fall underneath the time-scale analysis category.

Wavelet transforms temporally convolve an a priori known function (the ‘mother’ wavelet \( \psi_M \)) with a signal in order to reveal its time varying spectral content. In doing so, the spectral characteristics of localized bursts are preserved. The convolution comprises various scales \( l \) that decompose the signal into time-scale space, and is determined by Torrence and Compo (1998),

\[
\hat{p}(l,t) = \frac{1}{\sqrt{l}} \int_{-\infty}^{\infty} p(t') \psi_M(t'/l) dt.
\]  

(1)

where \( \hat{p}(l,t) \) are the wavelet coefficients. In general, small scales represent high frequency content in the signal, while large scales represent low frequency content. Wavelets do not, however, need to have a one to one correspondence between scale and frequency (Ref. 18).

There are an infinite number of possible wavelets, and every wavelet must satisfy the admissibility criterion \( C_\psi < \infty \), defined as (Ref. 20)

\[
C_\psi = \int_1 |\hat{\psi}_M(l)|^2 \frac{dl}{l} < \infty.
\]

(2)

According to Farge (1992) (Ref. 18), this criterion weakly implies that the average of the wavelet must be zero and so \( \hat{\psi}_M(0) = 0 \). Every wavelet must also have finite energy, to ensure that artificial energy is not created in the convolution process. Thus, the wavelet must also satisfy the following,

\[
E_\psi = \int_{-\infty}^{\infty} \psi_M(t) \, dt < \infty.
\]

(3)

Complex wavelets have one additional criterion. The Fourier transform of a complex wavelet must be real valued and must vanish for negative frequencies (Ref. 20). Thus, only single-sided spectral characteristics are possible with the wavelet transform.

Similar to the Fourier transform, the wavelet transform has a defined inverse transformation. The inverse wavelet transform is given as,

\[
p(t) = \frac{1}{C_\psi} \int_{-\infty}^{\infty} \sqrt{l} \hat{p}(l,t') \psi_M(l(t') - t) \, dl' \, dt.',
\]

(4)

and can be used to recreate the original signal, or any portion thereof. Perfect reconstruction of the signal is possible when the scale space integral is performed across all decomposed scales. However, wavelet transforms can be used to filter signals by performing the scale space integral across a subset of scales. This technique is typically applied to remove noise from signals by recreating the signal using only the lower frequency (high scale) content (Ref. 20).

In the current study only one mother wavelet, the Morlet wavelet \( \psi_M \), will be used. The shape of the Morlet wavelet is shown in figure 1. The Morlet wavelet is one of the more commonly used wavelets today, and when compared to other wavelets the Morlet wavelet offers a good frequency and temporal resolution. It is constructed by modulating a sinusoidal plane wave by way of a Gaussian function (Ref. 20).

Applications of the Morlet wavelet to transient signals range from atmospheric modeling (Ref. 21) to shock-wave boundary layer interactions (Ref. 2). The frequency domain representation of the Morlet wavelet is shown in figure 1 (right), and is defined by Torrence and Compo (1998) (Ref. 21) as

\[
\psi_M(l/\omega, \omega) = \sqrt{\frac{2\pi}{N}} \frac{f_s}{\pi^{1/4}} H(\omega) e^{-i(\omega - \omega_\psi)^2/2}.
\]

(5)

Here, \( N \) is the number of samples in the data set and \( f_s \) is the sampling rate. \( \omega_\psi \) is a non-dimensional frequency which can be chosen to optimize frequency or time resolution. A higher value of \( \omega_\psi \) results in more oscillations in the time domain. This typically yields better frequency resolution, but too high of a value can quickly lead to instabilities.

Reference 15 applied the Shannon cost analysis to several steady level flight and advancing side roll maneuvers to determine the best wavelet for helicopter acoustics. Employing both derivative of Gaussian wavelets and Morlet wavelets, Ref. 15 showed that the Morlet wavelet with \( \omega_\psi = 6 \) is the ‘best’ wavelet in evaluating helicopter acoustic signals. Hence, the Morlet wavelet with \( \omega_\psi = 6 \) will be used in the current study.

The scale-normalized energy density \( E(l,t) \) is given as

\[
E(l,t) = \frac{1}{C_\psi} \frac{|\hat{p}(l,t)|^2}{l^2}.
\]

(6)

and is known as the wavelet power spectrum (WPS). The admissibility factor \( C_\psi \) is included in equation (6), so that the
total energy can be recovered as follows
\[
\|E\| = \int \left( \frac{1}{T} \int E(t,t)dt \right) dl.
\] (7)

The wavelet power spectrum, in scale space, is directly analogous to the power spectral density, in frequency space, obtained through the Fourier transform. For the wavelet investigated here, a simple transformation from scale to frequency is available and performed, such that \( E(l_j,t_i) \rightarrow E(f_j,t_i) \). Thus, calculation of sound pressure levels can be determined in a fully equivalent manner. Sound pressure levels (SPL) as a function of time can be determined as,
\[
SPL(t) = 10 \log_{10} \left( \frac{\int E(f,t) df}{p_{ref}} \right),
\] (8)
where \( p_{ref} \) is the reference pressure (20 \( \mu \)Pa/\( \sqrt{\text{Hz}} \)).

**Technical overview**

Measurements of a full-scale Bell 430 helicopter undergoing various flight maneuvers were conducted at Eglin Air Force Base during the summer of 2011. A full description of this test campaign is provided in Ref. 6 with relevant details being described herein. The full ten day campaign acquired 410 test points including steady flight, transient and steady maneuvering flight, as well as landing profiles.

The Bell model 430 is a ten seat vehicle with twin Allison 250-C40B turboshift turbine engines. This helicopter was outfitted with a differential Global Positioning System, an inertial navigation unit and a measurement system for recording the tip-path-plane of the main rotor. The Bell 430 helicopter has a 4 bladed main rotor system, whose specifications are found in Table 1. The main rotor system has a split tip-path plane, so one pair of opposing blades sits at a slightly higher elevation than the other pair. When the main rotor system is tracked, this separation distance is maintained.

Acoustic data was acquired using 21 ground based microphones that are operated wirelessly from the control center. 1/2 inch B&K type 4189 free-field microphones are used with their diaphragms inverted 6.35 mm above a 381 mm round ground board. Each microphone has a frequency range from 20 Hz to 20 kHz with a dynamic range from 16.5 dB up to 134 dB. Every wireless acoustic microphone system was outfitted with a differential Global Positioning System receiver for accurate positioning relative to the vehicle. All microphone channels were sampled simultaneously and uninterrupted at \( f_s \) = 25 kHz with 16 bit resolution.

Acoustic pressure time series are transformed from time of observation to time of emission using a time domain de-Dopplerization algorithm developed by Greenwood and Schmitz (2009) (Ref. 22). The de-Dopplerization algorithm uses a linear interpolation scheme to adjust the pressure at time of reception to time of emission by accounting for the distance between the vehicle and microphone, as well as the speed of sound. Pressure amplitudes are subsequently scaled to adjust for spherical spreading losses, so that the microphone pressure signatures are scaled uniformly to 100 meters from the vehicle.

The time dependent de-Dopplerization scheme is based on similar work developed for fixed wing aircraft (Ref. 23). Due to the nature of the time dependent transformation, the de-Dopplerized signal is no longer sampled uniformly. Howell et al. (1986) (Ref. 23) used this process in an investigation of the signal to noise ratio for a Doppler-shifted, band-limited random noise after de-Dopplerization. They showed that when the initial : final sampling rate was 2 : 1, then the signal to noise ratio after de-Dopplerization was 35 dB for linear interpolation and only 18 dB if the signal was resampled using a “nearest neighbor” approach. Thus, a linear interpolation scheme is used to resample the resulting randomly sampled, de-Dopplerized signal at a lower sampling rate. The resulting sampling rate is 12 kHz, instead of the original 25 kHz. While this technique would affect the higher frequency components, the original signal is sufficiently oversampled, and the final linear resampling corrects many of the negative effects. Further, since the acoustics of interest in this study occur below 1 kHz, the resampling process should have very little affect on the resulting analysis. No other post-processing of the pressure signatures are performed.

One transient, fast advancing side roll maneuver will be investigated. Figure 2 provides the ground track of the vehicle maneuver with respect to each of the microphones. The transient maneuver was initiated at approximately 1 second into the 10 second path of interest. Averaged, relevant flight parameters include a ground speed of 41.5 ms\(^{-1}\), median height of 41.5 meters, and gross weight of 38.7 kN. The relevant vehicle parameters for roll attitude (\( \phi \)) and rate of change (\( \dot{\phi} \)) for the maneuver can be found in figure 3. The attitude and rate of change for roll confirm that the maneuver initiated approximately 1 second into the 10 second path of interest. Each dynamic maneuver in the full experiment, was designed to focus on a single pilot input, and so the advancing side roll maneuver has negligible pitch attitude or pitch rates of change (Ref. 15). The peak roll rate achieved for this maneuver never exceeds 18 degrees per second, and the transient

<table>
<thead>
<tr>
<th>Main Rotor</th>
<th>Tail Rotor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Blades</td>
<td>4</td>
</tr>
<tr>
<td>Radius (R)</td>
<td>6.4 [m]</td>
</tr>
<tr>
<td>Chord (c)</td>
<td>0.34 [m]</td>
</tr>
<tr>
<td>Rotation Rate (( \Omega ))</td>
<td>348.6 [RPM]</td>
</tr>
<tr>
<td>Blade Pass Frequency (( f_{MR} ))</td>
<td>23.2 [cycles/s]</td>
</tr>
</tbody>
</table>

Table 1: Bell 430 rotor specifications
Fig. 2: Ground track of the fast advancing side roll maneuver across the microphone array.

The weather balloon provided atmospheric conditions such as wind speed and direction, temperature, pressure and relative humidity. Averaged atmospheric properties are displayed in table 2 for the flyover condition studied. It should be noted that wind speeds are relatively low for this maneuver, and the temperature and relative humidity are fairly high. Despite high humidity levels, no atmospheric adjustments were made to the pressure signatures.

**Table 2: Atmospheric conditions for the maneuver are averaged between 7 m and 46 m.**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Speed</td>
<td>2.9 [m/s]</td>
</tr>
<tr>
<td>Temperature</td>
<td>24.70 [°C]</td>
</tr>
<tr>
<td>Pressure</td>
<td>100.4 [kPa]</td>
</tr>
<tr>
<td>Rel. Hum.</td>
<td>89.2 [%]</td>
</tr>
</tbody>
</table>

**Blade Vortex Interaction Extraction Method**

Noise generated by blade vortex interactions are the predominant source of increased sound pressure levels during transient maneuvers (Refs. 8–10). However, methods to extract the noise signature related to the transient blade vortex interaction phenomenon have proven difficult to develop. Blade vortex interaction extraction methods are desired, as they allow for the direct investigation of the physics that result in changes to blade vortex interaction noise levels.

Difficulties with developing extraction techniques stem from the transient nature of blade vortex interactions. As a helicopter proceeds through its flight path, it can experience a widely varying array of aerodynamic conditions. Any changes in local aerodynamics, say from wind gusts or due to transient maneuvers themselves, will affect the nature of the blade vortex interaction. Changes in advance ratio, inflow ratio, coefficient of thrust, and Mach-trace number can all affect the radiated noise pattern (Refs. 24–26).

Therefore, a blade vortex interaction extraction technique must be able to adapt to changes in amplitude and frequency of the radiated noise. Subsequently, a straight high-pass filter...
is not advised as it would not adapt to changes in frequency. Further, a high pass frequency filter would also extract higher frequency information, not associated with blade vortex interactions.

To date, two methods of note have been proposed to extract blade vortex interaction noise from experimentally acquired data. Davis et al. (1997) (Ref. 27) first used a discrete wavelet transform to identify and extract the blade vortex interaction noise from a relatively clean microphone pressure signature. They resolved the time-frequency representation of the signal into five frequency sub-bands, in which one band was dominated by the blade vortex interactions. This band could then be extracted, and the blade vortex interaction signal reconstructed. The Davis et al. (1997) method worked well for the case where very little higher harmonic information, unrelated to blade vortex interactions, was present in the original sound signature. Further, their method was based on the removal of an entire sub-band of data, making it essentially a pass-band frequency filter.

The second extraction technique was proposed by Sick- enberger et al. (Ref. 13). Their technique identified the blade vortex interaction signature through an undocumented method and removed the entire signal from the time-history. They then used harmonic data from the surrounding, unmodified data to create a signal to fill in the ‘missing’ information. This method is not necessarily a blade vortex interaction extraction method as the method for the identification and ‘cropping’ of blade vortex interactions is not described. Instead, the approach of Ref. 13 is more of a method to treat the residual signature when blade vortex interactions are removed.

The extraction technique developed here, will be an extension of Ref. 27’s technique to continuous wavelet transforms. It will also provide a way to filter out higher harmonic information that is unrelated to blade vortex interactions. An example of the time-frequency representation of a transient maneuvering helicopter acoustic signal using wavelet transforms is provided in figure 5. The wavelet power spectra in figure 5 has frequency on the vertical axis, with time on the horizontal axis. Three columns have been added to the left side of the wavelet power spectra to identify from left to right, the main rotor harmonics \( f_{MR} \), tail rotor harmonics \( f_{TR} \), and summed combinations of the two \( (\alpha f_{MR} + \beta f_{TR}) \). The columns identify only where in frequency space the harmonics lie, and do not imply amplitude of the signal. Underneath the wavelet power spectra is the corresponding pressure signature in the time domain. Several main rotor, tail rotor, and combinations thereof have been further defined by dashed horizontal lines in the wavelet power spectra.

Acoustic features of note, have also been identified in figure 5. These features include the tail rotor noise, a full blade passage, and blade vortex interaction noise. Here, blade vortex interactions are identified primarily by their higher harmonics, as was seen previously in Refs. 15, 27. Further, this is in accordance with the analytical work of Widnall (1971) (Ref. 26) as well as Martin and Hardin (1988) (Ref. 28), who showed that the blade vortex interaction signature exists pre-dominantly in the higher harmonics of the pressure signature.

It can be seen in figure 5 that when blade vortex interactions occur they are of similar peak strength as the main rotor harmonic. This was seen previously in Ref. 15 during an investigation of multiple flight conditions. Therefore, a filtering method can be developed based off of the simultaneous occurrence of higher harmonic content that exceeds some amplitude threshold relative to the main rotor harmonic strength.

Mathematical Description

The method for filtering blade vortex interactions will first be developed and implemented on a sample wavelet power spectrum. Then the method will be employed on a synthetic set of data to determine whether or not the method can accurately recreate blade vortex interactions from only their high amplitude, high frequency components.

The filtering method to remove the high frequency, high amplitude components of the blade vortex interaction noise signal is described as follows.

\[
\tilde{p}(f_t, t_i) = \begin{cases} 
\hat{p}(f_t, t_i) & \text{if } f_t > f_{cut} \\
E(f_t, t_i) > E(f_{MR}, t_i) - A_{cut} \cdot (9) & \text{otherwise}
\end{cases}
\]

Here \( \hat{p}(f_t, t_i) \) are the wavelet coefficients described in equation (1) for the corresponding wavelet scale \( (l_j) \). The frequency cutoff \( (f_{cut}) \) is based on harmonics of the main rotor frequency, while the amplitude cutoff \( A_{cut} \) is relative to the energy in the main rotor harmonic.

The filtering method can easily be tailored to remove any high amplitude signal that falls within a given frequency range, and so has applications beyond the removal of blade vortex interaction noise. A sensitivity analysis has previously been conducted by Stephenson (2014) (Ref. 29), on 21 microphones for three different helicopter maneuvers using two distinct metrics. It was determined that the best tuning parameters for the removal of blade vortex interaction noise during transient maneuvers was \( f_{cut} = 7f_{MR} = 164.2 \text{ Hz}, A_{cut} = -6 \text{ dB} \) (Ref. 29).

A schematic of the proposed extraction technique is now provided in figure 6. The full blade vortex interaction extraction process is shown, complete from transforming the original pressure signature through the use of the wavelet transform, filtering the transformed data via equation (9), and then inverse transforming the filtered data to create the associated pressure signatures.

A sample of the filtering method just described, is now presented from a pressure signature extracted during the fast advancing side roll maneuver. The original wavelet power spectra is shown in figure 7a, where the figure is identical in structure to figure 5. The signal investigated spans just over 1 complete rotor revolution and shows 4 predominant blade vortex interactions as well as several negative pressure spikes associated with the tail rotor thickness noise. The wavelet
power spectra shows a very strong (85 dB) main rotor harmonic, with clear and well defined higher frequency spikes associated with the strong blade vortex interactions.

The filtering method is now applied to figure 7a with the resulting extracted signal shown in figure 7b. The extracted wavelet power spectra is shown with its associated blade vortex interaction pressure signature reconstructed beneath. The recreated pressure signature for the blade vortex interaction shows five distinct events. Some differences are seen between each of the signatures, due to the presence of the tail rotor signature that shifts in time, relative to each blade passage.

The tail rotor also produces energy in the higher frequencies, and so a small portion of the tail rotor signature is also removed in the current implementation of the described filtering process. The presence of the tail rotor signature is noticeable at the end of the first interaction, near 3.01 seconds. The tail rotor signature can be seen to extend the blade vortex interaction extracted spectra into lower frequencies around 200 Hz. The tail rotor signature further manifests itself in a slight negative pressure peak in the reconstructed pressure signature at the end of the first blade vortex interaction. The tail rotor frequency components can also be seen in the second interaction just after 3.04 seconds, but does not appear in the final two complete interactions.

The residual signature without blade vortex interactions is given in figure 7c. When comparing to the original signal in figure 7a, the overall shape of the pressure signature is pre-
served, with only the blade vortex interaction signal removed. There is a small pressure rise at each blade passage that is slightly larger in magnitude than what one intuitively anticipates. This pressure rise is particularly evident in the first and third blade vortex interaction events.

This pressure rise suggests that the full blade vortex interaction signal is not represented entirely by its higher harmonic components, but also exists in some limited lower frequency content as well. This is anticipated, since the blade vortex interactions can occur at every blade passage, so logically some energy associated with these interactions must be in the main blade pass frequency. This was also suggested by Ref. 28. However, investigating the main rotor harmonic signature in either figures 7a or 7c shows that the energy within the first

Fig. 6: Schematic diagram of the full blade vortex interaction extraction process, from original pressure signal through to the final, extracted signals.
hundred hertz does not change during blade vortex interaction events. This prevents the lower harmonics from being removed from the wavelet power spectra by any wavelet based filtering technique, as the energy in the lower harmonics attributed to blade vortex interactions are indistinguishable from the rest of the signal.

**Synthetic Signal Analysis**

Now that the general technique has been developed, let us investigate a couple of signals to further understand the implicit assumptions made in the filtering technique. Determining how the energy of a blade vortex interaction is distributed in spectral space is a non-trivial task. Ref. 13 performed a Fourier transform on a cropped blade vortex interaction, a sample of which is provided in figure 8. Sickenberger’s

![Fig. 7](image1.png)

**Fig. 7:** Blade vortex interaction extraction technique applied to a sample wavelet power spectrum extracted during a transient fast advancing side roll maneuver. The (a) original signal, (b) blade vortex interaction extracted signal, and (c) residual signal are all provided.

![Fig. 8](image2.png)

**Fig. 8:** (a) Extracted blade vortex interaction pressure signature and (b) associated Fourier transform produced in Sickenberger et al. (2011) (Ref. 13).

Fourier transform, shown in figure 8b, shows that the energy of a blade vortex interaction is distributed fairly evenly across all but the mid-frequency range. This is directly contrary to what is seen in the wavelet power spectra of figure 7a where the energy is focused primarily in the higher frequencies. The distribution of energy found by Sickenberger et al. is most likely tainted by the small interrogation window, and therefore large frequency bin size, necessary to investigate a blade vortex interaction pulse in isolation (Refs. 15, 29).

To determine a more realistic energy distribution, a ‘typical’ blade vortex interaction noise signature must be identified. Since the noise signature of a blade vortex interaction is highly dependent on the aerodynamics surrounding each blade vortex interaction, no ‘typical’ signature can truly be
developed. Instead of attempting to develop a ‘typical’ signature, the data can provide one from the situation viewed in figure 9. This signal is extracted from the microphone located at \((X = 10, Y = -20)\), during the fast advancing side roll maneuver.

By time averaging the blade vortex interaction pressure signatures of the four full blade vortex interactions shown in figure 9, a ‘typical’ pressure signature can be determined. This pressure signature is passed through a Gaussian window to ensure zero acoustic pressure at the beginning and ending of the signature, and is shown in figure 10. This ‘typical’ blade vortex interaction is comprised of one primary pair of negative-positive pulses, and occurs over a time span of less than ten milliseconds.

The ‘typical’ blade vortex interaction signature can then be repeated at the main rotor blade passage frequency, to generate a pressure signature that contains only ‘typical’ blade vortex interactions. Performing a wavelet transform on a string of such interactions, results in figure 11. This shows that the majority of the energy contained within a blade vortex interaction is, indeed, located within the higher harmonics.

A Fourier transform of the same data also provides the spectral representation of the signal. Figure 12 shows the Fourier transform of a full 1 second blade vortex interaction signal. The peaks in the spectra occur at each main rotor harmonic, and the energy content is clearly focused in the high frequency region. The full signal is used in the Fourier transform to ensure adequate frequency resolution and window size for correct energy determination. Again, the energy is focused predominantly in the higher frequency content, in contrast to the findings of Ref. 13, but in agreement with Ref. 25.

Using wavelet transforms, the signature related to the main rotor harmonic can also be extracted. Extracting the main rotor harmonic by itself, allows the energy in the harmonic to be scaled independently of the strength of the blade vortex interactions. Figure 13 shows a scaled main rotor harmonic signature superimposed with the ‘typical’ blade vortex interaction signal shown in figure 11. In figure 13, the main rotor energy is scaled to be 3 dB greater than the peak blade vortex interaction energy \((\Delta \text{MRE} = 3 \text{ dB})\).

Recall that the filtering method, given in equation (9), required the simultaneous occurrence of energy above a certain frequency, and a given amplitude that was measured in relation to the main rotor harmonic energy level. Thus, varying the energy level of the main rotor harmonic allows one to investigate how the main rotor harmonic strength affects the resulting extracted blade vortex interaction signal.

Signals representing various main rotor harmonic strengths

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**Fig. 9:** Wavelet power spectra and associated pressure signature, extracted from microphone located at \((X = 10, Y = -20)\).

**Fig. 10:** ‘Typical’ blade vortex interaction pressure signature, extracted and averaged from the data provided in figure 9.

**Fig. 11:** Wavelet power spectra of the ‘typical’ blade vortex interaction pressure signature. Note the contour levels have changed so that the lower harmonic energy of the blade vortex interactions can be seen.

**Fig. 12:** Fourier transform of the full ‘typical’ blade vortex interaction pressure signature.
are shown in figure 14. In each successive figure, the main rotor harmonic has been uniformly scaled to a higher energy value. The extraction technique with cutoffs of \((f_{cut} = 7f_{MR} = 162.4 \text{ Hz}, A_{cut} = 6 \text{ dB})\) is then applied to this artificial data.

The resulting extracted pressure signatures are shown in figure 15 where labels are consistent with figure 14. It can be seen that as the energy in the main rotor harmonic increases, relative to the blade vortex interaction strength, then less and less of the blade vortex interaction is extracted. Finally, when the energy in the main rotor harmonic is 5 dB or greater than the blade vortex interaction energy, little to no signal is extracted. This is expected, as the amplitude cutoff for extracting blade vortex interactions was set at 6 dB below the main rotor harmonic energy level.

The same signals are also filtered by way of the Fourier transform. A Fourier transform was applied to the signals shown in figure 14. Then, energy in frequencies below 7 blade rotor harmonics are set to zero. A sample of this filtering technique is shown in figure 16. The main rotor harmonic is clearly the strongest frequency in the signal, peaking at close to 100 dB. However, the main rotor harmonic has seriously affected the energy in the higher frequencies as well. If this figure is compared to the original blade vortex interaction spectra in figure 12, it is obvious that the higher frequency components have more energy than before.

The presence of higher energy in the higher frequencies, is due to the way the Fourier transform distributes energy into its full harmonic components. Previously, however, it was seen that changing the main rotor harmonic signal did not affect the amplitudes of the higher frequencies, when using the wavelet
The Fourier filtered spectra is then inverse transformed, and only the real component of the resulting pressure signal is retained. The resulting pressure signatures are shown in figure 17, where the lower harmonic energy is still clearly present in the filtered signals. This was expected, as it was noted that the energy from the main rotor harmonic was distributed into the higher frequencies as well. Since this method is simply a high pass filter, the extraction technique removes a portion of the signal, regardless of the energy fluctuations at the main rotor harmonic.

Analyzing the sound pressure level of the resulting extracted pressure signatures, from both the wavelet transform and Fourier transform techniques, provides a means for quantifying the effect that the main rotor energy level has on the extracted signal. The sound pressure level, relative to the original ‘typical’ blade vortex interaction signal, can be calculated as follows,

$$\Delta SPL = 20 \log_{10} \frac{P_{RMS}^{i}}{P_{RMS}^{o}}.$$  \hspace{1cm} (10)

In equation (10) RMS stands for the root-mean-square of the signal $P$, ‘$i$’ represents the $i$th energy level of the main rotor harmonic, and ‘$o$’ is the value for the original, ‘typical’ blade vortex interaction pressure signature.

The main rotor scaling process was performed for relative main rotor energies ranging from 35 dB below the peak blade vortex interaction level, to 7 dB above. It can be seen, in figure 18, that the Fourier transform extraction method requires the main rotor harmonic energy to be significantly below the peak blade vortex interaction level, in order for proper reconstruction of the blade vortex interaction signal. When the main rotor harmonic energy is half the strength of the peak blade vortex interaction energy ($\Delta MRE = 3$ dB), then the reconstructed signal is accurate within 2 dB. However, the employed metric only investigates the fluctuating component of the signal, and does not properly take into account the slow, main rotor harmonic fluctuations that are still clearly visible in the extracted signal. Hence, a visual inspection of figure 17 shows a substantial portion of the lower main rotor noise remains in the extracted signal for $\Delta MRE = 3$ dB.

Further, the accuracy of this technique is true only for the signal investigated, which was steady with identical blade vortex interactions occurring at a fixed time interval. In a transient signal, like those exhibited by a transient maneuvering helicopter, the Fourier transform extraction method is expected to perform quite poorly in capturing and filtering individual blade vortex interactions. This is due to the very small time windows over which blade vortex interactions occur. It was shown previously, in Ref. 15 that the Fourier transform does not provide consistent spectra at such small window sizes, and so the filtering and reconstruction process will be severely affected by the necessary window size.
The wavelet transform extraction technique, however, shows that when blade vortex interactions are as strong as (or more powerful than) the main rotor harmonic, the extracted signal is correct within 1 dB. When the main rotor harmonic energy is more powerful than the energy in the blade vortex interactions, especially 2 dB above the peak value, then the resulting wavelet transform extracted signal is no longer indicative of the `true` blade vortex interaction signal. Further, the extracted signal does not show any presence of the main rotor harmonic energy, as was seen in the Fourier transform case. Preliminary results from Ref. 15, and figure 5, shows that when blade vortex interactions occur their peak energies are, in general, more powerful than the main rotor harmonic energy. Thus, unless otherwise noted, it will be assumed with some confidence that blade vortex interactions identified and extracted through this method represent the ‘true’ blade vortex interaction signal.

**Results**

The blade vortex interaction extraction method is applied to all microphones using the tuning parameters of frequencies above 7 main rotor harmonics ($f_{cut} = 7f_{MR} = 162.4$ Hz), and amplitudes greater than 25% of the energy in the main rotor harmonic ($A_{cut} = -6$ dB). The energy threshold is relative to the main rotor harmonic measured by each individual microphone at every point in time. Contour plots of the blade vortex interaction extracted sound pressure levels, and overall sound pressure levels will be investigated through the use of a Cartesian projection of spherical space.

The projection used here has the in-plane elevation ($\theta = 0^\circ$) at the top of the graph, while below the rotor, indicated by $\theta = -90^\circ$, is at the bottom of the graph. The azimuthal angle increases, starting at $\psi = 0^\circ$ along the tail, counter clockwise with the main rotor rotation. Thus the right half of the vehicle is from $0^\circ$ azimuth, to $180^\circ$; while the left half of the vehicle is from $180^\circ$ azimuth to $360^\circ$. The Cartesian projection then, decreases in azimuth from $360^\circ$ to $0^\circ$, such that the left half of the vehicle appears on the left half of the Cartesian projection, and the right half of the projection is dedicated to sound propagating to the right side of the vehicle. All sound pressure levels presented have been averaged over a quarter second interval, centered on the given time step, which encompasses at least one full rotor revolution.

Information extracted from these contour plots will be used to evaluate the changes in blade vortex interaction noise during the transient advancing side roll maneuver. The characteristic of blade vortex interaction noise is expected to change throughout the transient maneuver, as the maneuver will modify the advance ratio, inflow, and thrust coefficient of the vehicle (Ref. 24). This will lead to the interactions occurring over various spans of the blade, which will affect the noise according to Ref. 25, and will also modify the Mach-trace number of the interaction which will alter the emitted sound (Refs. 26, 30).

The fast advancing side roll maneuver is now analyzed using the blade vortex interaction extraction method. Beginning at 0.5 seconds into the maneuver, the sound pressure level contours for both the overall sound pressure level and blade vortex interaction extracted sound pressure level are shown in figure 19. Note from figure 2, the vehicle is on approach and so all microphones are forward of the vehicle. The individual contour range for overall sound pressure level and blade vortex interaction sound pressure level will be the same for all contour plots. The 15 dB contour range for overall sound pressure level and 30 dB range for blade vortex interaction sound pressure level provides adequate resolution throughout the maneuver. The maximum of 110 dB was kept constant between the overall sound pressure level contours and blade vortex interaction contours to help aid in the comparison of both figures.

Figure 19 shows peak overall sound pressure levels of around 103 dB, directly in front of the vehicle at an elevation of approximately $-20^\circ$. Blade vortex interactions are also noticeable, and peak at 98 dB in the same direction. Blade vortex interactions are not seen in all microphones present, based on the extraction method, and so the contour map does not project a color to those areas. In the future, some microphones will have measurable blade vortex interaction levels below the 80 dB cutoff range, and so they will also not have a projected color.

The blade vortex interactions that are seen in figure 19b, agree with the expected directivity of such interactions, namely that they are forward and below the rotor, as first in-
vestigated by Schmitz et al. (1976) (Ref. 31). Employing an aerodynamic analysis described in Ref. 32, an estimate for the relevant rotor aerodynamics is provided in Table 3. The relevant parameters for blade vortex interactions occurring in this experiment are inflow ($\lambda$), coefficient of thrust ($C_T$), forward advance ratio ($\mu_x$), and roll rate ($\phi$). Each of these parameters contributes in some way to modifying the strength of the vortex, the miss distance of the vortex, or the location of the vortex interaction. The coefficient of thrust is calculated through a 3 degree-of-freedom trim calculation, with inflow found from momentum theory using the following equation,

$$\lambda = \mu_x \tan(\alpha) + \frac{C_T}{2 \sqrt{\mu_x^2 + \lambda^2}} + \mu_z.$$  \hspace{1cm} (11)$$

The overall sound pressure levels seen near the plane of the rotor ($\theta \approx 2^\circ$) are 6 dB in strength below those seen at the peak of their propagation path. Figure 20 compares the pressure signatures associated with the peak microphone to that of the microphone in the top right of figure 19. The microphone with peak overall sound pressure level is shown in figure 20a. This microphone also has the peak blade vortex interaction signature, which has been extracted and shown in said figure. The original pressure signature shows a very strong main rotor lower harmonic noise, as well as clear and powerful instances of blade vortex interactions. The extraction method was able to adequately identify these impulses, without removing higher harmonic content unrelated to blade vortex interactions.

The pressure signature extracted from the in-plane microphone (figure 20b), located at ($\psi = 134^\circ, \theta = -3^\circ$), shows a strong thickness noise signature associated with the helicopter main rotor. The original pressure signature does not contain noticeable blade vortex interactions, and the tail rotor signature is negligible in this direction at this time. There are also no sharp negative pulses associated with high-speed impulsive noise, as anticipated for a modern commercial helicopter. The extracted blade vortex interaction signal seen for this instance is identically equal to zero, as the filter method has no strong harmonic information to extract. Instead, the residual signal matches the original signal exactly, showing that the wavelet transformation method can recreate the original signal with significant aberrations.

The analysis jumps now, to $t = 1.5$ seconds in the maneuver. Figure 21 shows sound pressure levels extracted from

![Fig. 20: Pressure signatures extracted from 0.5 seconds into the fast advancing side roll maneuver.](image1)

![Fig. 21: Contour plots of the (a) overall and (b) blade vortex interaction extracted sound pressure levels extracted 1.5 seconds into the fast advancing side roll maneuver.](image2)
tex interactions. The contour plots shown in figure 21 show that the peak blade vortex interaction sound pressure level is approximately 103 dB, where the overall sound pressure level is only 1 dB greater than that. This is a sizable jump, as previously the blade vortex interaction sound pressure level was 5 dB less than the overall sound pressure level.

Schmitz et al. (2007) (Ref. 5) demonstrated that the tail rotor noise contributed significantly to the increase in overall sound pressure level during steady turning flight. They postulated that the tail rotor noise signature increased due to the increase in thrust needed to maintain steady flight. This resulted in an increase in rotor torque and therefore tail rotor thrust. This is not that case in the current transient maneuver, however, as the thrust has not significantly changed as demonstrated in table 4. Here, the coefficient of thrust is less than 1% greater than it was for the 0.5 second, steady level flight portion of the maneuver. Figure 22 shows the pressure

\[
\begin{align*}
\lambda & = 1.42 \times 10^{-2} \\
C_T & = 4.61 \times 10^{-3} \\
\mu_x & = 0.175 \\
\phi & = 10 \, [\text{°/s}] \\
\end{align*}
\]

Table 4: Calculated aerodynamic properties from 1.5 seconds into the fast advancing side roll maneuver.

The extraction method was again able to identify the blade vortex interaction impulses, but has also extracted some limited energy from the tail rotor signatures as well. This highlights a problem with the filtering technique, where a strong tail rotor presence can lead to the extraction of some tail rotor energy. However, the ability to extract blade vortex interactions in general, is a powerful tool, and an improved filtering technique could eliminate tail rotor noise from the extracted signal.

Table 4 also shows that the roll rate is at 10 [°/s] and the vehicle has increased its inflow, while slowing slightly. The motion of the vehicle, at this time, is easily enough to cause a decrease in the miss distance, and could thus explain why the blade vortex interaction sound pressure level is seen to increase (Ref. 14).

Slightly further into the maneuver, at 2.0 seconds, the overall sound pressure level has increased by another 2 dB, as seen in figure 23. So far, there has been an increase in the overall sound pressure level of 7 dB in the peak direction, when compared to the original steady level signature in figure 19. This increase in sound pressure level is close to the computational work of Ref. 9, who saw a 10 dB increase in noise for an advancing side roll maneuver. Their maneuver, however, comprised multiple pilot inputs and a roll rate of approximately 7 [°/s], so a direct comparison of maneuvers is not possible.

The blade vortex interaction sound pressure level has also increased, and the peak direction has shifted closer to the re-
treating side of the vehicle. This agrees with the flight tests of Ref. 4, who saw peak noise shift to the retreating side of the vehicle during a transient roll to the advancing side. This was contrary to the normally perceived noise pattern, which typically sees a peak on the advancing side of the vehicle during steady rolls towards the advancing side (Ref. 4). This increase in sound pressure level is directly associated with the increase in the roll rate of the vehicle, as seen in table 5. Reference 4

\[ \lambda = 1.43 \times 10^{-2} \]
\[ C_T = 4.69 \times 10^{-3} \]
\[ \mu_x = 0.174 \]
\[ \phi = 15 \ [\degree / s] \]

Table 5: Calculated aerodynamic properties from 2.0 seconds into the fast advancing side roll maneuver.

also noted that the advancing side roll is less sensitive to roll rate than the retreating side transient roll maneuver. So a future investigation into retreating side transient rolls using this analysis technique is warranted.

With the increase in roll rate, the advance ratio has further decreased, and the inflow and thrust coefficient are still increasing. The increase in thrust coefficient, and therefore the strength of the tip vortices is not significant enough to increase the magnitude of the sound pressure levels to the extent that has been seen thus far. Assuming the thrust coefficient is directly proportional to the strength of the blade vortex interaction sound pressure level, then a change in thrust coefficient would result in a change in the blade vortex interaction sound pressure level according to the following approximate equation (Ref. 15),

\[ \text{ABVISPL} = 20 \log_{10} \frac{C_{T_1}}{C_{T_2}} \]  

(12)

Thus, the expected increase in sound pressure level from 1.5 seconds to 2.0 seconds would be on the order of a tenth of a decibel. The 2 dB increase in sound pressure level, therefore, is more likely to be caused by a change in the miss distance of the tip vortices due to the transient rolling maneuver.

Half a second later, at 2.5 seconds into the maneuver, the aerodynamic parameters have changed very little relative to the 2.0 second mark, as seen in table 6. This was not unexpected, as the vehicle is near the maximum roll rate of the fast advancing side roll maneuver. The sound pressure contours, given in figure 24, are also very close in magnitude to what was seen in figure 23. However, the blade vortex interaction sound pressure level contour map is more fully flushed out due to the change in the microphones relative to the vehicle.

Seemingly anomalous blade vortex interactions are present and extend deep beneath the rotor at an azimuth of 218° and elevation of –80°. The pressure signature seen in figure 25 shows that the extraction method, in this direction, has filtered out higher harmonic noise unrelated to blade vortex interactions.

The original pressure signature in figure 25, shows a weaker main rotor lower harmonic noise presence than what was seen in figure 20a. This weaker presence suggests a lower energy in the main rotor harmonic. With this lower energy, the amplitude cutoff allows in noise from higher frequency sources outside of blade vortex interactions. This is why there is significant activity in the extracted blade vortex interaction signal in figure 25. This is a known weakness with the filtering method.

Regardless of the filtering error, the calculated blade vortex interaction sound pressure level shows that this phenomenon is only a partial contributor to the overall signal. The blade vortex interaction sound pressure level for this direction is 9 dB lower than that seen for the peak direction. Thus, being only one-eighth the peak energy, the signal in this direction is easily negligible.

Improving the cutoff amplitude criteria could result in a cleaner blade vortex interaction signal. One such way would be to apply a lower threshold to the main rotor harmonic energy signature. However, the filtering method as described is
Three seconds into the fast advancing side roll maneuver, the peak blade vortex interaction sound pressure level has shifted to nearly in-plane with the rotor and on the retreating side of the vehicle, as shown in figure 26. There are also some blade vortex interactions extracted at the rear of the vehicle, close to 360° azimuth.

Figure 27 shows a comparison between the peak blade vortex interaction signal, and the microphone recording blade vortex interactions at the rear of the vehicle. The microphone recording the noise propagating backwards has identified higher frequency noise unrelated to blade vortex interactions. This was expected, as the magnitude of the sound pressure level was 12 dB less than the peak in the blade vortex interaction signal, and was 9 dB less than the overall sound pressure level at that point.

The peak blade vortex interaction signal, shown in figure 27a, however, shows very strong blade vortex interactions that were extracted quite cleanly. The original signal possesses a high presence of energy in the main rotor harmonic with a strong blade vortex interaction signal, and so the filtering method worked quite well. The tail rotor signature is also quite strong, with higher harmonics clearly present by the sharpness of the thickness noise signature. Despite the sharp presence of the tail rotor suggesting high amplitudes in the tail rotor higher harmonics, the tail rotor signature is not extracted alongside the blade vortex interaction signal. The partial extraction of the tail rotor signature is avoided as the main rotor harmonic is strong enough such that the amplitude cutoff is above the strength of the tail rotor higher harmonics.

However, the increase in the tail rotor signature does contribute to the overall sound pressure level. Further, this increase was expected as the coefficient of thrust has increased 7% over the original thrust at 0.5 seconds, seen in table 3. This is consistent with the findings of Ref. 5, who showed that...
tail rotor noise could be a major contributor to the increase in overall sound pressure level for steady turning flight.

The overall sound pressure levels seen in figure 26 are slightly decreased from what was seen at the 2.5 second mark. This decrease in overall sound pressure level is partially due to the decreasing roll rate of the maneuver, as given in table 7. Having reached the maximum roll rate, the vehicle is

\[
\begin{align*}
\lambda &= 1.37 \times 10^{-2} \\
C_T &= 5.02 \times 10^{-3} \\
\mu_s &= 0.172 \\
\phi &= 13 \degree/s
\end{align*}
\]

Table 7: Calculated aerodynamic properties from 3.0 seconds into the fast advancing side roll maneuver.

approaching its desired roll attitude. The inflow and thrust coefficient, however, are still increasing as the centripetal forces on the vehicle are increasing.

The decreasing roll rate likely results in a slightly larger miss distance than what was experienced at the 2.5 second mark. Although the blade vortex interaction sound pressure level has not altered dramatically, and so none of these changes have resulted in significant acoustic implications. Instead, the decrease in the overall sound pressure level, without a subsequent decrease in the blade vortex interaction sound pressure level, suggests that another mechanism is responsible for the changes. It is postulated that the change in overall sound pressure level is a result of changes in the loading noise mechanism as the vehicle roll rate is decreasing but centripetal forces are increasing the required vehicle thrust.

Skipping ahead to the 4.0 second mark, the sound pressure level contours in figure 28 are close to those seen at the 3.0 second mark. The only significant difference is the lessening of the overall sound pressure level due to the blade vortex interaction signal. The blade vortex interaction sound pressure level is still strongly present, with the same core directivity as seen before. While the directivity pattern appears somewhat different than what was seen in figure 26, this is primarily caused by the interpolation scheme used and not due to a change in the physics of the interaction. The strength of the blade vortex interactions are decreased slightly, compared to the maneuver at 3 seconds. However, the microphones located in the peak direction register very similar magnitudes; the differing contour grids are due to the change in relative microphone positions.

The aerodynamic parameters, provided in table 8, show

\[
\begin{align*}
\lambda &= 1.24 \times 10^{-2} \\
C_T &= 5.38 \times 10^{-3} \\
\mu_s &= 0.171 \\
\phi &= 4 \degree/s
\end{align*}
\]

Table 8: Calculated aerodynamic properties from 4.0 seconds into the fast advancing side roll maneuver.

that at the four second mark, the vehicle roll rate has decreased significantly to only 4 \degree/s. The thrust has increased by 7% compared to the previous time step, while the inflow has reduced by almost 10%. The decrease in advance ratio should have resulted in larger miss distances, but with decreasing inflow ratio these two parameters can partially cancel each other out, resulting in similar blade vortex interaction noise levels.

Seemingly anomalous blade vortex interaction sound pressures are measured on the rear, advancing side of the rotor. The sound pressure levels measured in this area are quite small with a magnitude approximately 6 dB less than that seen in the peak direction. The low blade vortex interaction level compared to the peak direction suggests that blade vortex interactions are not present in the signal or are very weak. The pressure signatures shown in figure 29 confirms that blade vortex interactions are not present. Instead, the filtering method has extracted higher frequency noise due to the low main rotor harmonic energy content.

It is apparent that the primary weakness in the employed filtering technique comes from the amplitude cutoff criteria. The higher harmonics of the tail rotor extend into the frequency range of interest for blade vortex interactions, and so a single frequency cutoff will always intrude on the tail rotor signature. However, the amplitude cutoff fails whenever there are very strong higher tail rotor harmonics, or when the main rotor harmonic energy drops to lower levels. Fortunately, the instances when the extracted signal does not contain blade vortex interactions is easily determined, as the sound pressure
Conclusions

An experimental investigation of the acoustic signature emitted during advancing side transient roll maneuver of a Bell model 430 helicopter was conducted. The current analysis focused on a fast advancing side roll maneuver, utilizing 21 microphones in an attempt to flush out the relevant physics that affected the noise characteristics throughout the transient roll maneuver.

A method for the identification and extraction of blade vortex interactions was developed to assist in this effort. The method that was developed, identifies and isolates high frequency, high amplitude pressure signatures based on physically relevant tuning parameters. The filtering method was based on previous analytical research that showed blade vortex interactions exist predominantly in the higher frequency range of a signal (Refs. 26, 28). This was further confirmed in previous research, where it was shown that blade vortex interactions were quite powerful relative to the overall pressure signal, when they were present (Ref. 15).

The blade vortex interaction extraction method was first implemented on a synthetic pressure signal comprised solely of ‘typical’ blade vortex interactions. It was shown that the extraction method could adequately recreate the pressure signature of a blade vortex interaction from only its high frequency, high amplitude wavelet coefficients. Further, this method was compared to a high frequency filtering of the data using the Fourier transform. It was shown that the Fourier transform was inadequate for extracting the blade vortex interaction data as the main rotor harmonic signal was still present in the extracted pressure signatures.

Using the wavelet transform based, blade vortex interaction extraction technique, it was shown that the overall sound pressure level increased by at least 7 dB in the peak direction during a transient advancing side roll maneuver. Further, it was shown that the blade vortex interaction peak direction shifts during the maneuver to a direction slightly on the retreating side of the vehicle, in agreement with Ref. 4.

Most importantly, however, the blade vortex interaction extraction method was shown to work exceptionally well. The method is easily implementable and has only two physically relevant parameters. The method correctly identified the direction of peak blade vortex interactions and extracted minimal noise unrelated to blade vortex interactions. There was one primary limitation to successful interpretation of the extraction results. However, with judicious use of engineering judgment, this limitation can easily be mitigated.

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