Time frequency analysis of sound from a maneuvering rotorcraft

James H. Stephenson\textsuperscript{a,}\textsuperscript{*}, Charles E. Tinney\textsuperscript{a}, Eric Greenwood\textsuperscript{b}, Michael E. Watts\textsuperscript{b}

\textsuperscript{a} Center for Aeromechanics Research, Department of Aerospace Engineering and Engineering Mechanics, The University of Texas, Austin, TX 78712, USA
\textsuperscript{b} NASA Langley Research Center, Hampton, VA 23681, USA

\textbf{Abstract}

The acoustic signatures produced by a full-scale, Bell 430 helicopter during steady-level-flight and transient roll-right maneuvers are analyzed by way of time–frequency analysis. The roll-right maneuvers comprise both a medium and a fast roll rate. Data are acquired using a single ground based microphone that are analyzed by way of the Morlet wavelet transform to extract the spectral properties and sound pressure levels as functions of time. The findings show that during maneuvering operations of the helicopter, both the overall sound pressure level and the blade–vortex interaction sound pressure level are greatest when the roll rate of the vehicle is at its maximum. The reduced inflow in the region of the rotor disk where blade–vortex interaction noise originates is determined to be the cause of the increase in noise. A local decrease in inflow reduces the miss distance of the tip vortex and thereby increases the BVI noise signature. Blade loading and advance ratios are also investigated as possible mechanisms for increased sound production, but are shown to be fairly constant throughout the maneuvers.

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1. Introduction

The role that transient flight maneuvers have in helicopter acoustic emission is of great interest to both military and civilian operations. However, the effects of these maneuvers have only recently been investigated, beginning with the numerical simulations of Brentner and Jones [1], followed by the full-scale experiments by Spiegel et al. [2], Schmitz et al. [3] and Watts et al. [4]. Maneuvers cause transient changes to the blade loading \( (C_T/s) \), rotor inflow \( (\lambda) \), and the advance ratio \( (\mu) \) of the vehicle [5]. These changes manifest themselves acoustically by modifying both the noise intensity and directivity patterns of the vehicle [6]. Very aggressive maneuvers have also been shown in the numerical simulations by Chen et al. [7] to cause vortex bundles to form. Interactions between these vortex bundles and the main rotor could result in “super-blade–vortex interactions” (super-BVI) which have the potential to be more intense than standard BVI.

The sound field of a helicopter is three-dimensional and time-dependent. Several challenges exist if one is to develop an understanding of the acoustic signature (directivity and spectral content) produced by a helicopter undergoing maneuvering
operations (either steady or transient). If one chooses to fix the observer to the helicopter frame, then the difficulties reduce to changes in the source location and intensity due to changes in blade loading, inflow, and advance ratio [3]. Alternatively, if the observer occupies a fixed ground location, the aforementioned difficulties are compounded by additional degrees of freedom brought upon by the change in the position of both the vehicle and its sound source relative to the observer, as well as Doppler effects, ground reflections, and variations in wind patterns and atmospheric conditions. Aside from these complications, the selection of an analysis tool, for characterizing sound intensity and spectral content, is not straightforward. For stationary systems, the undertaking is less ambitious with statistical properties (central moments, probability distributions and spectra) being generated using ensemble averages of long data sets. Because the signal from a transient system is non-stationary, the temporal component must be preserved. This is particularly difficult if the time-scales associated with the important features in the signal reside on the same order of, or are larger than, the time-scale of the transient episode. Hence, a persistent difficulty to developing statistical models of transient phenomena is determining the suitability of the analysis technique [8].

A number of methods have been developed in order to bypass restrictions imposed on transient signals. The short-time Fourier transform (STFT) is one of the more common methods, however there are several short-comings with this approach. Foremost, the STFT imposes a time-scale on the data in the form of the windowing method employed. Furthermore, the Fourier transform (FT) assumes that the signal is steady and periodic, which is certainly not the case during transient maneuvers, or instances where short bursts of energy, like BVI, appear intermittently. One must exercise caution when interpreting results using STFTs on transient data as the FT can artificially increase the energy in the lowest resolvable frequencies. While the overall energy in the signal within a given window will be correct, any band-limited metric will provide erroneous results.

It is therefore preferable to choose a more mathematically appropriate method comprising compactly supported basis functions, as opposed to the harmonic functions used in Fourier analysis. One such method for conducting time–frequency analysis is known as wavelet analysis; whose compactly supported basis functions are called ‘wavelets’ [9,10]. A benefit to using wavelet transforms (WT) is their ability to reproduce distribution functions. That is, stationary signals encompassing short bursts of energy or other localized singularities (like BVI pulses, in the case of helicopter noise) are more accurately resolved. The STFT redistributes singularities across frequency space while simultaneously de-localizing them in time space. Furthermore, both overall energy and band-limited energy should be preserved within any given window of time using wavelet analysis [9].

In this study, the acoustic signals recorded by a stationary observer during several flyovers of a full-scale helicopter are scrutinized by the way of wavelet analysis. Previous efforts by Constantine et al. [11], using discrete wavelet analysis with conjugate qudrature filters, demonstrated the robustness of employing wavelet analysis tools to isolate the BVI noise component from the acoustic signal acquired during steady operations of a helicopter. Here, we employ wavelet analysis to flush out the various sources of noise perceived by a stationary observer in relation to a full-scale helicopter undergoing (1) steady-level-flight and (2) cyclic roll-right maneuvers. A quantitative analysis is first performed to determine the suitability of the chosen wavelet for the data set considered here. The inclusion of multiple wavelets to investigate the appropriateness of each wavelet to helicopter acoustic signals expands on the work of Celi [12].

2. Technical overview

Measurements of a full-scale Bell 430 helicopter undergoing various flight maneuvers were conducted at Eglin AFB during the summer of 2011 (Fig. 1). A full description of this test campaign is provided in Watts et al. [4] with relevant details
being described here. Technical specifications concerning this standard model Bell 430 helicopter are provided in Table 1. This helicopter was outfitted with a Differential Global Positioning System (DGPS), an Inertial Navigation Unit (INU) and a measurement system for recording the tip-path plane (TPP) of the main rotor. The DGPS recorded the aircraft position (± 1.5 m) while providing real-time path guidance to the pilot. The INU provided pitch and roll attitudes (± 0.3°) as well as pitch and roll rates (± 0.01°/s) as functions of time. The DGPS system is sampled at 5 Hz, while the INU system is sampled at 125 Hz; both are synchronized with microphone and weather station data using Coordinated Universal Time (UTC).

Acoustic data was acquired using 31 ground based 1/2 in. B&K type 4189 microphones, shown in Fig. 2, that were operated wirelessly from the control center. Microphones were outfitted with a GPS receiver for accurate positioning relative to the helicopter, and inverted 6.35 mm above a 381 mm round ground board. All 31 channels were sampled simultaneously and uninterrupted at (fs) 25 kHz with 16 bit resolution. Given the enormous amount of available data, only one microphone signal is considered during each flyover test with its location being identified in Fig. 2.

A weather balloon provided atmospheric conditions such as wind speed and direction, temperature, pressure and relative humidity. The balloon profiled atmosphere conditions from 0 m to 91 m during each helicopter flight. Averaged atmospheric properties are displayed in Table 2 for the three flyover conditions studied here. All acoustic pressure time series were transformed from time of observation to time of emission using a time dependent de-Dopplerization algorithm developed by Greenwood and Schmitz [13].

For this study, three different flyover cases are investigated, comprising a steady-level flight (SLF) followed by two roll-right maneuvers. The roll-right maneuvers include two different roll rates, denoted as medium-roll-right (m-RR) and

| Table 1 |
| Bell 430 specifications. |
| Empty weight | 2400 [kg] |
| Maximum gross take-off weight | 4200 [kg] |
| Maximum speed | 73.5 [m/s] |
| Fuel capacity | 711 [L] |
| Main rotor |
| Radius (R) | 6.4 [m] |
| Number of blades | 4 |
| Rotation rate (Ω) | 348.6 [RPM] |
| Blade pass frequency (fMR) | 23.2 [Hz] |
| Tail rotor |
| Radius | 1 [m] |
| Number of blades | 2 |
| Rotation rate | 1880.7 [RPM] |
| Blade pass frequency (fTR) | 62.7 [Hz] |

Please cite this article as: J.H. Stephenson, et al., Time frequency analysis of sound from a maneuvering rotorcraft, Journal of Sound and Vibration (2014), http://dx.doi.org/10.1016/j.jsv.2014.05.018
fast-roll-right (f-RR). These maneuvers are particularly important as the vehicle is rolling towards the advancing side of the rotor disk, which is the area known for creating acoustically significant BVI. All relevant flight parameters are shown in Table 2. For the maneuvers discussed here, the tip-path plane orientation never deflected more than $1\degree$ to $2\degree$, relative to the fuselage. Assuming that no winds are present and the vehicle remains at a level altitude, the tip-path plane orientation is directly proportional to the tip-path plane angle of attack ($\alpha_{TPP}$).

2.1. Coordinate transformation

Prior to analysis, Euler angle transformations were performed to correct for changes in the helicopter position (source) relative to the microphone (observer). The standard horizon-fixed relative microphone position ($\vec{X} = (x, y, z)$) is determined solely through the position and velocity of the helicopter. Here, $x$ and $y$ point towards the nose ($180\degree$ azimuth) and retreating ($270\degree$ azimuth) sides of the helicopter, respectively, with $z$ along the rotor axis ($90\degree$ elevation). This horizon-fixed frame naturally neglects the effects of both pitch and roll. Yaw motion is neglected as it does not influence the aerodynamics of the main rotor system. In order to account for pitch and roll attitude, a two step coordinate transformation is performed as follows:

$$
\Pi_\alpha = \begin{bmatrix}
\cos(\alpha) & 0 & -\sin(\alpha) \\
0 & 1 & 0 \\
\sin(\alpha) & 0 & \cos(\alpha)
\end{bmatrix},
\Pi_\phi = \begin{bmatrix}
1 & 0 & 0 \\
0 & \cos(\phi) & \sin(\phi) \\
0 & -\sin(\phi) & \cos(\phi)
\end{bmatrix},
$$

(1)

using $\alpha$ and $\phi$ to denote pitch and roll, respectively. The full transformation then becomes

$$
\vec{X} = (\Pi_\alpha \Pi_\phi) \hat{X},
$$

(2)

where $\vec{X} = (x', y, z')$ represents the coordinate axis of the tip-path plane after applying both pitch and roll maneuvers. These Euler angle transformations are illustrated in Fig. 3 with the negative $y$-axis being shown for clarity. Pitch angle is a clockwise rotation about the positive $y$-axis and is followed by a roll transformation comprising counterclockwise rotations about the $x'$ direction.

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**Table 2**

Test conditions.

<table>
<thead>
<tr>
<th>Atmospheric properties</th>
<th>SLF</th>
<th>m-RR</th>
<th>f-RR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind speed [m/s]</td>
<td>1.3</td>
<td>0.57</td>
<td>0.77</td>
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<tr>
<td>Temperature [°C]</td>
<td>23.6</td>
<td>24.3</td>
<td>24.7</td>
</tr>
<tr>
<td>Pressure [kPa]</td>
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<td>101.4</td>
<td>101.4</td>
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<tr>
<td>Rel. Hum. [%]</td>
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<td>93.6</td>
<td>89.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flight parameters</th>
<th>SLF</th>
<th>m-RR</th>
<th>f-RR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground speed [m/s]</td>
<td>40.8</td>
<td>40.8</td>
<td>41.3</td>
</tr>
<tr>
<td>Median height [m]</td>
<td>50.0</td>
<td>36.2</td>
<td>40.5</td>
</tr>
<tr>
<td>Gross weight [kN]</td>
<td>38.7</td>
<td>38.4</td>
<td>38.7</td>
</tr>
</tbody>
</table>

*a Values based on readings averaged between 7.6 m and 45.7 m. \pm determined from max. and min. readings.

*b Fuel load readings are accurate to within 0.2 kN.

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A plan view of all three flight patterns is shown in Fig. 2. Each flight path is shown with a 10-s path of interest (PI) window centered around the microphone of interest. The origin $(x, y) = (0, 0)$ is located at the microphone of interest. The resultant microphone positions relative to the vehicle, after Eulerian transformations, are shown in Fig. 4a and b using a Lambert projection. Azimuthal angles ($\Psi$) increase in the direction of rotor rotation with the initiation point (at 0°) being located along the tail of the helicopter, and increasing counter-clockwise. Elevation ($\xi$) on the Lambert projection is shown with 0° identifying the plane of the rotor, and –90° being located directly underneath the vehicle. Markers identifying 1-s intervals are also provided in both figures and align with the pilot inputs illustrated in Fig. 5a. Roll and pitch attitudes for SLF were held nominally at 0° (r3 = 0°). The roll rate ($\phi$) for both the m-RR and f-RR flight patterns are provided in Fig. 5b. The m-RR case shows a slower entrance into the roll, but has a similar maximum roll rate to the f-RR case. Pitch rates ($\alpha$) were negligible for these maneuvers.

For the steady-level-flight pattern, the microphone track in the Lambert projection shows only very small perturbations due to a slight starboard roll. For the roll-right maneuvers, the microphone track is pushed deep into the port (retreating) side of the Lambert projection. This remains true during the majority of the PI.

It is known that the hover tip-Mach number, advance ratio, blade loading, and total inflow are necessary parameters for describing the aerodynamic flow-field of a helicopter [14]. Given the relationship between aerodynamics and acoustics, each of these parameters is expected to be relevant to this study. Changes to sound intensity or spectral patterns experienced by the stationary observer are not expected to depend on the hover tip-Mach number, given the specified rotation rate
provided in Table 1. Variations in the advance ratio (ratio of true airspeed to blade tip-speed), however, are expected to occur during maneuvering operations of the vehicle as the wind speed changes relative to the inertial velocity of the rotor. Likewise, blade loading, a measure of the average thrust on all blades, will primarily affect the acoustic signature of the helicopter by modulating the strength of the shed tip-vortices. BVI is directly proportional to the circulation strength of the vortex, which in turn, is directly proportional to thrust. Therefore, if BVI is present, then an increase in blade loading will strengthen the BVI sound pressure level (BVISPL) for the same inflow and advance ratios. This is captured, to first order, as

$$\Delta_{\text{BVISPL}} = 20 \log_{10} \left( \frac{C_{T_2}}{C_{T_1}} \right),$$

where subscripts indicate blade loading conditions at two different instances in time. The thrust experienced by a maneuvering helicopter is governed by the inertial accelerations due to the maneuver.

The last parameter investigated is the total inflow, which, to first order, is a superposition of both the uniform inflow and the additional inflow caused by rigid body rotation of the vehicle: $\lambda_{\text{tot}} = \lambda + \lambda_{\text{man}}$. Uniform inflow $\lambda$ is determined as

$$\lambda = \mu \tan(\text{TPP}) + \frac{C_T}{2\sqrt{\lambda^2 + \mu^2}},$$

and is a measure of the flow perpendicular to the rotor. The total inflow plays a very important role, as it modifies the miss distance between a vortex and the oncoming blade. Positive inflow indicates that the rotor is pushing air beneath the vehicle. Negative total inflow can occur in descent conditions, when fluid is moving up, through the rotor. In general, when the wake is below the rotor (positive inflow), increasing inflow increases the miss distance which lowers the BVI noise amplitude. For maneuvering flight, a correction is inserted to account for the pitch and roll rates of the vehicle, which can be approximated in the following manner:

$$\lambda_{\text{man}} = \frac{\delta R}{\partial R} \cos(\psi) - \frac{\delta R}{\partial R} \sin(\psi).$$

where $r_b$ is the non-dimensional position along the rotor’s radius ($r_b \in [0, 1]$).

Blade–vortex interaction sound pressure levels, extracted from steady descent noise hemispheres of the Bell 430 vehicle, that propagate in the $\psi = 180^\circ$ and $\xi = -30^\circ$ direction are displayed in Fig. 6. BVISPL is a band-limited pressure integration, with the band limits, chosen from previous work [4], to be between 5/14 and 60/14. BVISPL should represent the relative noise contribution of blade–vortex interactions to the overall signal. The BVISPL levels in Fig. 6 are interpolated from noise hemispheres generated by flight data through the Rotorcraft Noise Model [15]. Noise hemispheres are normalized to a fixed distance (30.5 m) from the rotor hub, with advance ratios and thrust coefficients held constant. The tip–path plane angle of attack was varied by changing the flight path angle of the vehicle, which resulted in a variation of the inflow ($\lambda$). Fig. 6 shows that decreasing inflow results in a corresponding increase in the BVISPL metric. This holds until an inflow of approximately 0.003 is reached, at which point, further decreasing inflow decreases BVISPL. The decrease in BVISPL with decreasing inflow trend is due to the wake now being located above the rotor, and so decreasing inflow increases the miss distance of the vortices. For this experiment, inflow never falls below 0.006, and so the trend of decreasing inflow resulting in an increase in BVISPL is expected.

3. Time–frequency analysis

Time–frequency analysis is used here to extract the spectral content of the acoustic signals as a function of time. The method employs basis functions that are non-zero over a finite time interval thus making them compactly supported. An inherent concern with any time–frequency analysis is the trade-off between frequency and temporal resolution. The greater the resolution in one space, the less resolution in the other. In this study, we choose to employ wavelet transforms as the tool for conducting time–frequency analysis; the interested reader is referred to the work of others for an in-depth discussion on this technique [9,16–18].

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Wavelet transforms temporally convolve an \textit{a priori} known function (the ‘mother’ wavelet) with a signal \( p(t) \), in order to reveal the spectral content in time. In doing so, the spectral characteristics of localized bursts are preserved, which is necessary, given the transient nature of the acoustic signatures produced by maneuvering operations of this helicopter. The convolution comprises various scales \((l)\) that decompose the signal into time-scale space and is determined as

\[
\tilde{p}(l, t) = \int p(t') \psi^{(l)}(t' - t) \, dt,
\]

where \( \psi \) is the analyzing wavelet and \( \tilde{p}(l, t) \) are the wavelet coefficients. Complex valued wavelets yield complex valued wavelet coefficients, which preserve both amplitude and phase information. For \( \psi \) to be considered a wavelet, it must satisfy the admissibility criterion \( (C_\psi < \infty) \), which is defined as follows:

\[
C_\psi = \int_1 \frac{||\hat{\psi}(f)||^2}{|f|} \, df < \infty.
\]

This ensures that artificial energy has not been created during the convolution process. According to Farge [9], this criterion weakly implies that the average of the wavelet must be zero and so \( \hat{\psi}(0) = 0 \). The scale-normalized energy density \( E(l, t) \) is determined as

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

and is known as the Wavelet Power Spectrum (WPS). For the wavelets investigated here, a simple transformation from scale to frequency is performed, such that \( E(l, t) \rightarrow E(f, t) \). The WPS is directly analogous to the power spectral density obtained through the Fourier transform [19], and so calculation of sound pressure levels, as functions of time, can be determined in an equivalent manner. The admissibility factor \( (C_\psi) \) is included in Eq. (8), so that the total energy can be recovered using the following expression:

\[
\|E\| = \int \frac{1}{T} \int E(f, t) \, dt \, df.
\]

Two analyzing wavelet shapes are considered here, that is, the Morlet wavelet and the Derivative of Gaussian wavelet, which are now described.

3.1. Morlet wavelet

One of the more common wavelets is the Morlet wavelet \( (\hat{\psi}_M) \), the shape of which is shown in Fig. 7a (left). When compared to other wavelets, the Morlet wavelet offers better frequency resolution over temporal resolution and is constructed by modulating a sinusoidal plane wave by the way of a Gaussian. Applications of the Morlet wavelet to transient signals range from atmospheric modeling [10] to shock-wave boundary layer interactions [8]. The frequency domain representation of the Morlet wavelet is shown in Fig. 7a (right), and is defined as

\[
\hat{\psi}_M(lo, wo) = \sqrt{2\pi f_s} \frac{\text{Heaviside step function}}{N^o} e^{-\frac{(lo - wo)^2}{2}}.
\]

Here, \( N \) is the number of samples in the data set and \( H(\omega) \) is the Heaviside step function. \( wo \) is a non-dimensional frequency which can be chosen to optimize frequency or time resolution. A higher value of \( wo \) typically yields better frequency resolution, but too high of a value quickly leads to instabilities.

3.2. Derivative of Gaussian wavelet

An alternative to the Morlet wavelet is the Derivative of Gaussian (DOG) wavelet. Depending on the derivative, the DOG can be tailored to achieve better frequency or temporal resolution. However, unlike the Morlet wavelet, the DOG wavelet has the disadvantage of being purely real (for even derivatives) or purely imaginary (for odd derivatives). It is common practice that only even derivatives be used and so any phase information (that is otherwise preserved in the Morlet wavelet) is lost. The Fourier transform of the \( n \)-th DOG wavelet is expressed as follows:

\[
\hat{\psi}_D(lo, n) = \sqrt{2\pi f_s} \frac{f^n}{\sqrt{T(n + 1/2)}} e^{-\frac{(lo - wo)^2}{2}}, \quad n \in \mathbb{N},
\]

where \( \mathbb{N} \) represents natural numbers. The second-DOG is commonly referred to as the Mexican Hat, or more appropriately, the Maar wavelet; it is known to have poor frequency resolution relative to the Morlet wavelet [20]. It is possible to employ higher order DOG wavelets in order to better resolve the higher frequency content. Therefore, the correct order \( (n) \) of the DOG wavelet, and \( wo \) for the Morlet wavelet, is non-trivial and must be determined to ensure that the signal is being properly represented. In the following, an analysis is conducted to identify whether the Morlet or DOG wavelet is more appropriate, and what analysis parameter \( (n, wo) \) is more suitable for analyzing helicopter acoustic data.

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3.3. Shannon entropy cost function

A method for appraising the effectiveness of a wavelet for a given signal can be accomplished using Shannon’s entropy cost function [21]. This quantitative technique reduces dependence on the expertise of the individual researcher. Shannon’s cost function is expressed in normalized form as follows:

$$C(\eta) = \frac{1}{\log(IJ)} \sum_i \sum_j \frac{E(f_j, t_i)}{\|E\|} \log \left( \frac{E(f_j, t_i)}{\|E\|} \right).$$

(12)

A variation of this approach was introduced by Coifman and Wickerhauser [22]. The cost function is bounded between zero and one, which makes it particularly useful for comparing the appropriateness of various wavelets. If all energy is concentrated into a single scale at a single point in time, then $C(\eta)$ is identically zero. Likewise, if the system’s energy is evenly distributed across all scales and time, then $C(\eta) = 1$. And so, the wavelet that represents the signal in the fewest scales and the least number of time steps can be found by the minima of $C(\eta)$, and is deemed to be the ‘best’ wavelet.

For the Morlet and DOG wavelets, the analysis parameter ($\eta$) encompasses variations in the number of oscillations and the order of the derivative, respectively. The results from this cost analysis are shown in Fig. 8 using several data sets (three SLF, four m-RR and four f-RR maneuvers). The findings clearly demonstrate that the Morlet wavelet is preferred over the DOG wavelet for the data being studied here and that $\omega_p$ between 6 and 7 oscillations in the Morlet wavelet yields the smallest cost.

In the following, the Morlet wavelet alone, with $\omega_p = 6$, is used to extract the spectral content of the stationary microphone signals acquired during steady and roll-right maneuvers of a full-scale helicopter. The resolved band of frequencies range between 8.7 Hz < $f < 5808$ Hz using a base-2 logarithmic progression of 76 scales to ensure a uniform grid on a logarithmic scale. While the acoustic data is resolved out to $f_s = 12$ kHz, preliminary results revealed very few recognizable features above 1000 Hz. Overall sound pressure levels (OASPLs) and BVISPL are calculated at a given instant in time by integrating energy density, Eq. (8), over the appropriate frequency range. One must be cautious when interpreting BVISPL, as higher main rotor harmonics, tail rotor harmonics, as well as combinations of the two, heavily contaminate the specified frequency range.

In Fig. 9, a comparison is made between the WT and the STFT for two different window sizes in time; the acoustic pressure signals are shown below each subfigure while the WPS have been averaged across each window to provide a more direct comparison to the power spectral densities provided by the STFT. The first window (Fig. 9a) encompasses a 200-ms integration window and is chosen specifically as it represents the aural integration time of a human ear for low frequency sounds [23]. Given the rotation speed of the main rotor, this comprises one complete revolution of the rotor, and so four
bursts, each corresponding to a blade passage and BVI event, are captured and displayed. Even with this window size, the STFT over-predicts the energy of the first few rotor harmonics by a full order of magnitude when compared to the WPS. This is attributed to a redistribution of energy from the unresolved portions of the spectra. Likewise, higher frequencies are under predicted by the STFT as the impulsive nature of the high frequency BVI components is smeared by the averaging process.

For the smaller time window illustrated in Fig. 9b, only one blade passage is retained. It is shown here that smaller windows are more appropriate for the higher frequency components as their energies are more realistically estimated using STFT when compared to the WT. This, however, leads to an even larger over-prediction in the lower frequencies with the STFT. In summary, Fig. 9 provides a good demonstration that the spectra obtained from a WT of a transient phenomena is not dependent upon the size of the window chosen. The spectra obtained from the STFT, however, is heavily modified by the choice of window size.

4. Wavelet power spectra

Wavelet power spectra are shown in Fig. 10 corresponding to SLF, m-RR and f-RR maneuvers, respectively, and during the same 10-second path of interest (PI) depicted in Fig. 2. Each PI corresponds to the approach, flyover, and departure of the helicopter relative to the stationary microphone observer. Each maneuver has its PI partitioned into the first and last 5-s of the maneuver. These contours are rich with information; interpreting them is equally challenging. Therefore, several windows (1 through 7) are identified and will be the focus of subsequent discussion. Likewise, three columns have been added to the left side of all WPS figures. From left to right, these columns identify the frequency at which the main rotor

Fig. 8. Shannon entropy cost function applied to multiple SLFs and roll right maneuvers of various rates.

Fig. 9. Estimates of power spectral density from the m-RR maneuver microphone signal computed using the STFT and a window averaged wavelet transform performed over (a) 200-ms and (b) 5-ms window. Acoustic pressure time histories are shown below.
Fig. 10. Wavelet power spectra of the transformed signal during (a) SLF, (b) m-RR, and (c) f-RR maneuvers. Contour levels shown at $[54, 61, 64, 71, 74, 81, 84] \text{dB re } 20 \mu \text{Pa} \sqrt{\text{Hz}}$. Horizontal bars on the left side of each figure indicate (from left to right), main rotor harmonics, tail rotor harmonics, and possible sums of main-tail rotor harmonics.
harmonics, tail rotor harmonics, and summed combinations of the two occur. These columns are added only to identify where the harmonic components lie in frequency space, and do not imply amplitude.

In Fig. 10b and c the m-RR and f-RR maneuvers manifest steady growth, saturation and decay in signal intensity. Interestingly, the SLF maneuver exhibits a rapid drop, followed by an immediate recovery, in pressure levels along the first rotor harmonic (Fig. 10a), as the vehicle passes over the microphone and begins departure ($\approx 5\text{-s}$ to $\approx 6\text{-s}$). This is better illustrated in Fig. 11a, and is attributed to the transition from thickness dominated noise to loading dominated noise, as directivity changes. This demonstrates the complexities that become compounded by the additional degrees of freedom brought upon by the moving vehicle (and the directivities of its various sources of noise) relative to the stationary observer, even during steady-level-flight.

A slice extracted from each WPS, from Fig. 10, along the main rotor fundamental frequency is shown in Fig. 11a. This gives a relative comparison in signal intensity between each of the three flight conditions. The dip in energy seen at 6-s for SLF main rotor fundamental might lead one to suspect a lower OASPL at this instant in time. However, this is not the case, as seen in Fig. 11b, where the OASPL is greatest for SLF. This peak in OASPL is anticipated as the vehicle is closest to the microphone at this instant. The OASPL does not decrease despite the dip in the first harmonic, due to a subsequent increase in energy of higher frequencies, which is supported by the BVISPL information shown in Fig. 11c.

Interestingly, the f-RR and m-RR maneuvers have peak OASPLs around the 2.5-s and 3-s marks, respectively, which correspond with their times of maximum roll rate, as seen in Fig. 5b. It is important to note for both of these instants in time, the vehicle location relative to the microphone is very similar, and examination of Fig. 4b shows that the microphone position is approximately 180° azimuth and $-25$° elevation for both maneuvers. This directivity is associated with the $\alpha'$ oblique-BVI identified by Schmitz and Sim [24], and is similar to the directivity chosen in Fig. 6.

In an effort to reduce the amount of information manifest in Fig. 10, we will turn our attention now to the various windows (windows 1 through 7) which identify segments of the signal that will be further scrutinized. Within each window, an average OASPL and BVISPL is calculated to further elucidate the flow physics. The windows are purposefully selected to coincide with various points of interest that are described as follows:

- window-1 (SLF): Acoustic signature of an approaching helicopter during steady-level-flight.
- window-2 (SLF): Acoustic signature directly below a helicopter undergoing steady-level-flight.
- window-3 (SLF): Acoustic signature produced in the aft regions of the helicopter as it is departing the observer location, during steady-level-flight.
- window-4 (m-RR): Acoustic signature produced at the time of maximum roll rate and forward of the helicopter during a medium-roll-right maneuver.
- window-5 (m-RR): Closest position of the microphone relative to the helicopter undergoing a medium-roll-right maneuver.
- window-6 (f-RR): Acoustic signature produced at the instant of maximum roll rate and forward of the helicopter during a fast-roll-right maneuver. This should correspond with window 4 during the m-RR maneuver.
- window-7 (f-RR): Closest position of the microphone relative to the helicopter undergoing a fast-roll-right maneuver. This should correspond to the same instant in time as window 5 during the m-RR maneuver.
The discussion will progress backwards in time, with the helicopter departing the area (window 3), followed by the closest position of the vehicle relative to the microphone (windows 2, 5, and 7). It will conclude with the windows (1, 4, and 6) corresponding to the approaching vehicle for SLF and the maximum roll rates in the case of the maneuvering flight paths. Along with each window is an accompanying table that includes the relevant sound levels, aerodynamic parameters, and distance from the vehicle to microphone (Dv). The inflow given is calculated at 80 percent radius (r8 = 0.8) at an azimuth of 70°. This location is in the vicinity where ‘α’-type BVI occurs. ‘α’-type BVI is known to radiate in the direction of the microphone at the time of maximum roll rate [24]. Azimuthal and elevation directivities are also provided for the beginning and ending time step (subscript ‘beg’ and ‘end’, respectively) of each window.

Fig. 12 shows the WPS and relevant aerodynamic and acoustic parameters for a SLF departing the area. Several important features can be seen in the WPS (Fig. 12a). The first of these is the steady signal seen at 23 Hz, associated with the main rotor blade pass frequency, which can be easily identified in the acoustic pressure time history as the periodic, negative pressure spikes. The full pressure signature associated with a blade passage includes the rise in pressure after the negative spike, and the slow decay until the next blade passage. A subtle second harmonic of the main rotor can be seen at 46 Hz, followed by the signature associated with the tail rotor blade pass frequency at 63 Hz. The signature produced by the tail rotor is intermittent in strength and corresponds to the negative pressure signature already associated with the main blade pass frequency. The main rotor and tail rotor blade passages do not necessarily occur at the same time, but the third harmonic of the main rotor is close in frequency to the main tail rotor harmonic and so their signals overlap each other. This can be seen by the fact that the amplitude and size of each WPS pulse is determined by the strength of the negative pressure spike, but the second harmonic of the main blade pass frequency remains unaffected. Some higher harmonic content is also visible, although it is weak in magnitude.

The sound levels associated with the SLF in departing flight (Fig. 12b) are shown to be low, and is expected for the distance and direction that the vehicle is moving. The blade loading, and advance ratios of the vehicle are both typical values for the Bell 430 vehicle, and the inflow is expected to be enough to convect the tip–vortices away from the blades to prevent BVI. BVI is not seen in the pressure signature due to the location of the microphone relative to the vehicle. In level flight, any BVI that may be seen should predominantly radiate forward of the vehicle, and slightly to the retreating side [24].

When the vehicle is closest to the microphone, Fig. 13, the WPS contains a far richer distribution of harmonics. This figure demonstrates the importance of having employed time–frequency analysis as the WPS for each maneuver shows significant temporal variation. Starting with the SLF condition (Fig. 13a), several differences are immediately obvious when compared with the departing signature (Fig. 12a). First, the signal is rich with higher harmonic information. The main blade pass frequency is stronger than before, but the second main rotor harmonic is present only sporadically. The fundamental tail rotor and third main rotor harmonic are also stronger, and the coupling between the frequencies can be seen by their pulsating strength. Early on in the window, two particularly strong higher harmonic signatures can be seen. These signatures are each associated with a BVI event, which appears subtle in the acoustic time history at the first two main rotor blade passages. There are similar structures seen in the wavelet power spectra that are also linked to blade vortex interactions, although these are much weaker than the first two, and not very distinguishable in the acoustic time history.

Fig. 13b shows the signature produced by the vehicle undergoing m-RR maneuver and at different directivities and distances to the microphone observer as in the SLF case. A very different harmonic energy distribution is manifest in the m-RR maneuver when compared to the SLF. Foremost, the main rotor harmonic is stronger than that seen by the SLF condition. The second main rotor harmonic is also present, but the fundamental tail and third main rotor harmonic do not show clear coupling. The fundamental tail and third main rotor harmonics are more consistent in magnitude, however. Also, there appears to be a significant amount of energy present between 211 and 1000 Hz, a range typically associated with BVI noise, although no BVI appears present in the pressure time histories.
The f-RR maneuver signature (Fig. 13c) is clearly different than either of the previous two maneuvers. Here, the main rotor signature is weaker than before, and the tail and third main rotor harmonic are very intermittent. The second main rotor harmonic is similar to that seen by the m-RR condition, but the higher harmonics are significantly subdued when compared to the other maneuvers. The acoustic parameters are shown in Table 3, where it can be seen that the m-RR OASPL is larger than either of the two maneuvers. This is predominantly attributed to the strong presence of the first main rotor harmonic. Table 3 shows a lower OASPL and BVISPL for the f-RR maneuver, when compared to the other maneuvers at this time. If one isolates the attenuation due to spherical spreading, this would result in a decrease in OASPL for both m-RR and f-RR maneuvers by 1.7 dB and 0.3 dB, respectively.

The BVISPL for the m-RR and SLF maneuvers are very close in magnitude, and this is due to the presence of the higher frequency information in both signals, likely caused by other noise sources (engine, etc.). The fact that BVI is only noticeable in the first two main rotor blade passages of the SLF maneuver (Fig. 13a) is a subtle warning that a high BVISPL measure does not ensure that BVI is strongly present. The advance ratio and blade loading for each of the maneuvers is comparable, and the blade loading would contribute up to a 1.5 dB increase in OASPL for the f-RR case, compared to the SLF case, if the

Table 3

<table>
<thead>
<tr>
<th>Window</th>
<th>2 (SLF)</th>
<th>5 (m-RR)</th>
<th>7 (f-RR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OASPL</td>
<td>95.1</td>
<td>96.1</td>
<td>93.1</td>
</tr>
<tr>
<td>BVISPL</td>
<td>92.0</td>
<td>92.1</td>
<td>89.8</td>
</tr>
<tr>
<td>$C_T/\rho$</td>
<td>0.0685</td>
<td>0.0788</td>
<td>0.0812</td>
</tr>
<tr>
<td>$\mu$</td>
<td>0.185</td>
<td>0.181</td>
<td>0.170</td>
</tr>
<tr>
<td>$\lambda_{tot}$</td>
<td>0.0126</td>
<td>0.0159</td>
<td>0.0195</td>
</tr>
<tr>
<td>$(\Psi, \xi)_{beg}$</td>
<td>(165°, −76°)</td>
<td>(250°, −31°)</td>
<td>(270°, −30°)</td>
</tr>
<tr>
<td>$(\Psi, \xi)_{end}$</td>
<td>(20°, −81°)</td>
<td>(282°, −30°)</td>
<td>(298°, −29°)</td>
</tr>
<tr>
<td>$D_{des}$</td>
<td>54</td>
<td>44</td>
<td>52</td>
</tr>
</tbody>
</table>

![Fig. 13. WPS contours, shown in dB (re 20 μPa/√Hz), corresponding to windows (a) 2, (b) 5, and (c) 7 with harmonics depicted in the left columns. The acoustic pressure signal is located under each WPS.](image-url)
directivities were the same. The inflow for the SLF case suggests that BVI is possible (see Fig. 6), and indeed it was seen. Meanwhile, the inflows of the m-RR and f-RR are larger thereby reducing the likelihood of BVI. As was true with the departing case, the microphone position relative to the vehicle and its heading are not ideal for one to determine the presence of BVI, and so the lack of BVI seen in the m-RR and f-RR cases does not constitute proof that it is not present. Fig. 14 provides the most interesting insight into the transient maneuvering acoustics. At this point in time, the vehicle has reached its maximum roll rate for both m-RR and f-RR maneuvers. Further, the microphone is in a very similar directivity for all three maneuvers, and that directivity coincides with an expected BVI direction. The blade loadings, given in Table 4, are all comparable, and would only contribute to a 0.2 dB deviation between the SLF and f-RR maneuvers. The advance ratios are also very similar, but the inflows are significantly different. From the inflow, and Fig. 6, a hypothesis can be made that little to no BVI will be seen in the SLF condition, while the m-RR condition should experience strong BVI, with the f-RR experiencing BVI to a lesser extent. The BVISPL metric further suggests this, and indeed, when the WPS are inspected, this proves to be true. Corrections for spherical spreading result in a decrease in OASPL of 2.0 dB for the m-RR maneuver, and an increase of 1.4 dB for the f-RR case. Spherical spreading accounts for much of the discrepancy between the medium- and fast-roll-right maneuvers.

![Fig. 14. WPS contours, shown in dB (re 20 μPa/√Hz), corresponding to windows (a) 1, (b) 4, and (c) 6 with harmonics depicted in the left columns. The acoustic pressure signal is located under each WPS.](image1)

Table 4
Relevant acoustic and aerodynamic parameters for each maneuver in Fig. 14, with SPLs listed in decibels (ref: 20 μPa).

<table>
<thead>
<tr>
<th>Window</th>
<th>1 (SLF)</th>
<th>4 (m-RR)</th>
<th>6 (f-RR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OASPL</td>
<td>91.4</td>
<td>99.1</td>
<td>95.4</td>
</tr>
<tr>
<td>BVISPL</td>
<td>89.8</td>
<td>97.6</td>
<td>94.1</td>
</tr>
<tr>
<td>$C_t/\pi$</td>
<td>0.0693</td>
<td>0.0689</td>
<td>0.0677</td>
</tr>
<tr>
<td>$\mu$</td>
<td>0.186</td>
<td>0.181</td>
<td>0.173</td>
</tr>
<tr>
<td>$\lambda_{tot}$</td>
<td>0.0167</td>
<td>0.0067</td>
<td>0.0097</td>
</tr>
<tr>
<td>$(\Psi, \delta_{beg})$</td>
<td>(175°, -26°)</td>
<td>(188°, -25°)</td>
<td>(180°, -18°)</td>
</tr>
<tr>
<td>$(\Psi, \delta_{end})$</td>
<td>(173°, -31°)</td>
<td>(196°, -29°)</td>
<td>(183°, -22°)</td>
</tr>
<tr>
<td>$D_v [m]$</td>
<td>109</td>
<td>87</td>
<td>128</td>
</tr>
</tbody>
</table>

Please cite this article as: J.H. Stephenson, et al., Time frequency analysis of sound from a maneuvering rotorcraft, Journal of Sound and Vibration (2014), http://dx.doi.org/10.1016/j.jsv.2014.05.018
The SLF maneuver on approach is shown in Fig. 14a. The fundamental main rotor harmonic is clearly present across the signal, with the second harmonic steadily present as well. The third main rotor harmonic and first tail rotor harmonic are not very strong, but that is to be expected from this direction. What is most striking is the sharp but low-energy, periodic fluctuations in the higher harmonics between 400 and 1000 Hz. These coincide with the main rotor blade passage, and relate to the BVI signal. BVI can be seen in the sharp positive-negative fluctuations in the pressure time history. These are easily seen in the m-RR case, shown in Fig. 14(b), where the BVI pulses are several times greater than the pulses associated with the blade passage of the main rotor.

The main rotor harmonic is significantly strengthened, in the m-RR case (Fig. 14b). However, the blade loading is not significantly increased due to the maneuver. The relative direction and distance of the microphone to the vehicle is similar, and so the strengthening of the main rotor harmonic is not solely caused by these effects. Instead, it is postulated that the main rotor harmonic signature is enhanced due to the strong BVI presence. This is supported by observing that the main rotor harmonic in the f-RR case is also higher than that in the SLF maneuver, and the f-RR is also experiencing strong BVI. It is notable to see that BVI spikes clearly extend down to 116 Hz, in the WPS, on occasion, which relates to the 5th main rotor harmonic. This observation gives some credence to the BVISPL metric, but further research should be done to determine, non-arbitrarily, in what frequency range BVI is the strongest, and how to account for its effect on the lower harmonics.

Much of what has been discussed about the m-RR case is equally true for the f-RR maneuver. However, the BVI experienced here appears somewhat less in magnitude, than that seen in the m-RR maneuver. After accounting for spherical spreading, BVISPL is 0.5 dB lower for the f-RR compared with the m-RR maneuver. This is in line with the data presented in Fig. 6, for this directivity, where the inflows are near the maximum BVISPL point, and so relatively large changes in inflow result in only small changes in the BVISPL metric.

One visible signature of note is the manifestation of the split tip-path plane that can be seen in both the m-RR and f-RR case. The Bell 430 helicopter has a split tip-path plane which means that one opposing pair of blades sits at a different height, about one blade thickness (0.1 chord), than the other set of blades. The effect of this splitting can be seen in the alternating strength of the BVI pulses. Most notably in the m-RR case, but also in the f-RR maneuver, one very strong BVI pulse is followed by a second, slightly weaker pulse. This is because the miss distance is changing due to the differing blade heights, which further illustrates just how important the miss distance, and thereby inflow, is to the BVI sound signature. The effect of this sub-harmonic did appear in the WPS, although at a lower energy level than shown.

5. Conclusions

The continuous wavelet transform has been discussed and multiple mother wavelets have been quantitatively evaluated to determine the best wavelet for maneuvering helicopter noise. Of the wavelet specifications tested, the Morlet wavelet with a non-dimensional frequency ($\omega_\psi$) between 6 and 7 consistently provided the best representation of the signal for the conditions studied. A coordinate transformation to account for pitch and roll of the helicopter was also presented, so the relative direction of the microphone to the helicopter could be established.

It was shown that both medium and fast rate roll right maneuvers caused an increase in the OASPL and BVISPL, as seen elsewhere [1,3,7]. The increase in the pressure signature associated with BVI was seen as the primary driver of the increase in OASPL. It was shown that the inflow parameter was the significant driver of BVI, as the blade loading and advance ratios were similar throughout the different maneuvers. It was also postulated that BVI can significantly affect the acoustic signature related to the main rotor lower harmonic noise.

A significant drawback from this experimental approach is that it is difficult to use signatures registered at a fixed observer location to distinguish between acoustic effects due to changes in relative directivity and changes due to transient aerodynamic phenomena. A densely populated array of microphones fixed to the helicopter during various maneuver operations would alleviate this difficulty. A similar approach was undertaken by Schmitz et al. [3] but was limited to only a few microphone channels fixed to the vehicle.

Acknowledgments

The flight test data was acquired during a joint test program between NASA Langley Research Center, Bell Helicopter Textron and the US Army Aeroflightdynamics Directorate. JHS would also like to thank the DoD for funding provided through the SMART Fellowship program.

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Please cite this article as: J.H. Stephenson, et al., Time frequency analysis of sound from a maneuvering rotorcraft, Journal of Sound and Vibration (2014), http://dx.doi.org/10.1016/j.jsv.2014.05.018


