Real Time Helicopter Noise Modeling for Pilot Community Noise Awareness

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ABSTRACT
A method of providing helicopter pilots with real time awareness of the community noise impact of their operations is developed in this paper. Using flight test data, a semiempirical model of the helicopter noise sources is constructed. This model is then applied to generate a database of acoustic spheres describing the external noise radiation characteristics of the helicopter over a wide range of operating conditions. During normal flight operations, inertial measurements of the helicopter’s orientation, acceleration, and velocity are used to estimate the helicopter’s performance state at each instant. This performance state is associated with a sphere from the acoustic database, which is then aligned with the predicted orientation of the helicopter with respect to the ground. A ground noise level contour representing the acoustic impact of the helicopter at that emission time is generated from the selected sphere using straight ray propagation and a line search routine. In this paper, the real time noise model is applied to a simulated AS350 helicopter. The computational cost of the real time noise modeling is assessed. Examples are provided for how the community noise information generated by the model can be displayed and used by pilots for community noise abatement.

1 INTRODUCTION
Helicopters serve a number of useful roles within the community, such as electronic news gathering and aerial photography, inspection and maintenance of power lines, police and emergency medical services, aerial cranes, cropdusting, civil transport, and sightseeing. However, community acceptance of these operations is limited by the resulting noise. For instance, voluntary restrictions on helicopter operations have recently been adopted in the Los Angeles and New York City areas to increase community acceptance.1–3 The acoustic impact of civil helicopter operations will need to be reduced in order to allow for a greater variety and volume of helicopter operations in the future. In the long term, design changes such as reduced tip speeds or the widespread adoption of active and passive rotor noise reduction technologies may result in significant reductions in the noise emitted by future helicopters. However, because the noise radiated by helicopters is extremely sensitive to the helicopter’s operating state, immediate noise reductions can be achieved through the development of low noise flight procedures applicable to the existing civil fleet.

Since 1981, the Helicopter Association International (HAI) has published “Fly Neighborly”4 guidance intended to provide helicopter operators with effective methods to reduce helicopter noise impacts on communities and increase public acceptance of helicopter operations. The “Fly
“Fly Neighborly” guidance includes general techniques for reducing community noise impacts, such as avoiding noise sensitive areas or flying at a higher altitude, as well as advice on developing more specific noise abatement procedures that avoid noisy flight conditions unique to the type of helicopter flown. While community noise levels during quiet (e.g., cruise) flight conditions may be dominated by tail rotor noise sources, the primary cause of the noisiest flight conditions is main rotor Blade-Vortex Interaction (BVI).

BVI occurs when the blades near the rear of the rotor disk pass close by the tip vortices formed previously near the front of the rotor disk, as shown in Fig. 1. The interaction between the tip vortex and the blade causes a rapid fluctuation of the aerodynamic loads on the blades, which results in the radiation of highly impulsive, and therefore annoying, noise. The directivity of BVI noise is a function of the angle between the tip vortex and the azimuth angle of the blade during the interaction, which is determined by the top view geometry of the wake shown in Fig. 1a.

The intensity of BVI noise is a strong function of the vertical distance between the rotor disk and the shed tip vortices. When the helicopter descends along a shallow trajectory, the wake will convect below the rear portion of the rotor disk, as shown in Fig. 1b, resulting in the onset of BVI noise. As the helicopter descends more steeply, Fig. 1c, the wake convects into the rotor disk and the most intense BVI noise occurs. Further increases in the rate of descent, shown in Fig. 1d, cause the wake to convect above the rotor disk, reducing BVI noise from the peak level. The rates of climb and airspeeds where BVI occur are a function of the helicopter’s weight, drag, and rotor geometry, and therefore, vary between different types of helicopters.

The operational conditions determined to cause BVI noise are displayed in the “Fly Neighborly” guidance using a “fried egg” plot. A “fried egg” plot for a notional light helicopter is shown in Fig. 2a. The high BVI noise region is shaded on the plot and is defined in terms of airspeed and rate of climb. The operator can use this information to develop noise abatement procedures that avoid the BVI noise region, such as the proposed quiet approach highlighted in red on the plot. This approach starts with a steep descent at constant speed, followed by decreasing airspeed at a high rate of sink to pass below the high BVI noise region, resembling a Category A approach for FAA Part 29 (transport category) rotorcraft.

The data normally used to generate the “fried egg” plot are typically collected by the helicopter’s manufacturer for a helicopter operating in steady flight at a particular test location (typically at sea level) and configuration. However, recent research has demonstrated that there are many factors
Fig. 2: “Fried egg” plots for a helicopter under standard (a) and alternate (b) operating conditions.

d That influence where BVI noise occurs for a particular type of helicopter. These factors include: maneuvers such as accelerations, turns, and pitch ups; sideslipped flight; ambient atmospheric conditions; gross weight; and drag. Figure 2b shows some examples of how these effects can influence the boundary of the BVI region marked on the “fried egg” plot. Deceleration of the helicopter causes BVI to occur at more shallow rates of descent, since the rotor disk must tilt backward, increasing its angle of attack relative to the air mass. Conversely, steady turning flight increases the thrust on the rotor causing the rotor wake to be pushed further below the rotor disk and moving the BVI noise region to steeper descent rates. At high altitude, the reduction in air density results in a proportional reduction in aerodynamic loads; therefore, the trim states where BVI occur happen at higher true airspeeds. These effects can cause a noise abatement procedure developed from the manufacturer-provided data to cross through the high BVI noise region. Recent research has resulted in methods to account for these effects, allowing noise abatement procedures to be developed that are effective under a wide range of helicopter operating conditions. Unfortunately, the specific operating conditions the helicopter will encounter cannot be predicted easily ahead of the operation, requiring this information to be generated at the time of use. However, due to the complexity of BVI noise, it is not feasible for the pilot to consider all of these effects while also flying the helicopter.

To solve this problem, helicopter operators require tailored real time feedback as to the community noise impact of their operations. The objective of this paper is to describe a new real time approach to modeling the noise of helicopters which can be used by pilots to reduce community noise impact. This modeling approach is intended to allow the pilot of a helicopter to see how the current operating state results in noise on the ground. In addition to giving the pilot feedback tailored to the current operating condition of the helicopter, the model output will allow the pilot to identify the regions where annoying levels of noise are radiated, so that operations can be adjusted to direct noise away from densely populated or noise sensitive areas.

2 APPROACH

The noise measurements used to generate vehicle specific “Fly Neighborly” guidance are typically conducted for a helicopter in a single configuration, at a single test site, and under a limited set of steady flight conditions. However, accurate noise prediction requires that the noise radiation characteristics of the helicopter are known throughout the entire range of operating conditions that will normally be experienced by the helicopter. The Fundamental Rotorcraft Acoustic Modeling
from Experiments (FRAME) technique was developed by the author to solve this problem. FRAME constructs models of rotor noise radiation by fitting a nondimensional aeroacoustic model to measured acoustic data from both wind tunnel and flight experiments. Because a computational model of the major rotor harmonic noise sources is constructed, noise estimates can be obtained at flight conditions and radiation directions that were not originally measured, allowing a single set of source noise data to be generalized across the entire operating range of the helicopter. The FRAME model was later extended to maneuvering flight conditions by introducing a dynamic prescribed vortex wake model for BVI noise. The model showed good agreement with measured data for several transient maneuvers and could be run in real time for a single observer; however, the generation of ground noise contours for assessing the community noise impact of helicopter flight procedures typically requires noise calculations for hundreds to thousands of observers—far too many for the model to be practically applied in the design and evaluation of low noise mission profiles. To provide a practical noise model for use in planning helicopter operations, the hybrid FRAME-QS model was developed. The FRAME-QS model combines the FRAME method of generalizing measured acoustic data to other operating conditions using physics-based modeling with a quasi-static equivalence between the acoustic state of the helicopter and its operating condition.

The nondimensional FRAME model must be calibrated to a set of measured steady-flight data for a particular helicopter. In this paper, the model is calibrated to data collected by NASA and the US Army for the AS350 helicopter. The calibrated model is then used to generate an extensive database of spherical representations of the steady-state harmonic noise radiation of the helicopter at different operating conditions. Both the main and tail rotor are included in the model; the tail rotor operating condition is assumed to track with changes in the main rotor operating condition. Using the quasi-static equivalence, the performance state of the helicopter is determined from measurements of the velocity and acceleration of the helicopter and the appropriate sphere is selected from the precomputed database. This sphere is then oriented with the measured orientation of the helicopter. In this paper, the position, velocity, acceleration, and orientation inputs are provided to the model from a commercially-available flight simulator of the SA342 Gazelle helicopter, which has a similar main rotor system and dynamic characteristics to the modeled AS350. The FRAME-QS model, being quasi-static, does not consider the hysteresis of the wake; however, previous research has indicated that the dynamic distortion of the wake has little effect on noise radiation and accounts for perhaps a 1 dBA difference between advancing side and retreating side maneuvers. Finally, the noise levels from the surface of the sphere are interpolated and propagated instantaneously to the ground. The propagation time delay from the source to the observer is neglected so as to reflect the acoustic impact of the current state of the helicopter. By precalculating the FRAME noise data, ground noise levels can be computed rapidly.

This approach was validated against experimental maneuvering flight noise data collected by NASA and Bell Helicopter for the Bell 430 in 2011 and was shown to capture the effects of maneuvering flight on helicopter noise radiation with good accuracy. For example, Fig. 3 plots a comparison of predicted A-weighted Sound Pressure Level (SPL) to measured data at a microphone location ahead of the helicopter for the Bell 430 executing both a fast pitch up maneuver (Fig. 3a) and a roll-in to an advancing side turn (Fig. 3b). In both cases, the FRAME-QS model provides excellent agreement with the measured data in contrast to predictions with a conventional source noise model based on empirical data for a single set of operating conditions. The FRAME-QS model accurately predicts the large increase in A-weighted noise levels caused by the increase in BVI due to the transient maneuver, whereas the conventional model underpredicts the SPL by as much as 10 dBA.
A simplified straight-ray propagation model\textsuperscript{18} is used with FRAME-QS to further decrease the computational time required to evaluate each maneuver. When the FRAME sphere database is constructed, the predicted pressure time history at each emission angle is converted to a frequency-domain power spectrum. From this spectrum, the A-weighting curve is applied to each main and tail rotor harmonic; the A-weighted SPL can then be computed on the sphere surface by summing the energy in each of these weighted harmonics. Additionally, an excess atmospheric attenuation factor can be computed for each A-weighted SPL on the sphere by applying the frequency-domain atmospheric absorption correction of Bass et al.\textsuperscript{19} to the spectra for a reference distance of 1 m. The resulting spectra can also be A-weighted and summed, since both the atmospheric absorption and the A-weighting filters are linear. The difference between the A-weighted noise level and the A-weighted noise level including 1 m of atmospheric attenuation is the excess atmospheric attenuation factor. The excess atmospheric attenuation factor represents the attenuation of the A-weighted level due to atmospheric absorption for each meter of propagation, and is calculated separately for the spectrum associated with each emission angle and flight condition of the helicopter in the database. This approach requires only a single calculation for straight ray propagation from the source spheres to an observer on the ground, instead of requiring a separate calculation for each harmonic contained in the original frequency spectrum. Each evaluation of this model takes approximately 20 microseconds to execute on a single 2.5 GHz Intel Core i7 CPU core.

Instead of computing noise levels at all locations near the helicopter, the computational efficiency can be further improved by limiting calculations to only those required to identify the region on the ground where the helicopter is likely to annoy people. In this paper, an SPL of 65 dBA will be used as an “annoyance threshold.” The annoyance region at any time of emission is then identified by computing the range where the 65 dBA level is reached along each bearing. This calculation is performed using an efficient bracketing line search method,\textsuperscript{20} which generally requires fewer than ten evaluations (200 microseconds) of the FRAME-QS noise model to identify a range with an SPL within 0.1 dBA of the “annoyance threshold” value. In this paper, the annoyance range is calculated every ten degrees (36 bearings) at a rate of 60 Hz, using less than 5% of the available CPU capacity and less than 500 MB of memory to store the database of preprocessed noise spheres.

Figure 4 shows an annotated picture of one possible way to visualize the current noise state of the helicopter predicted by the real time model. This display consists of several elements superimposed
on a moving map. In the center of the display is a marker showing the current position of the helicopter. The marker is filled with a solid color to indicate the relative noise intensity—in mean SPL—over the noise sphere associated with the current operating condition of the helicopter. The color transitions from blue, for quiet states, to red, for loud states. This represents the noise intensity at the source irrespective of the position and orientation of the helicopter relative to the ground. A 65 dBA “annoyance threshold” contour is plotted around the helicopter; the boundary of the contour represents the 65 dBA range and the interior of the contour is filled with colors from blue to red to illustrate that the ground noise levels will increase above 65 dBA for observers closer to the helicopter than the 65 dBA range. No contour is displayed when the helicopter does not radiate noise above the 65 dBA level on the ground, such as when flying at high altitude. In the case shown, the helicopter is in high speed level cruising flight, and the A-weighted noise levels are primarily set by tail rotor noise, which radiates directly ahead of the vehicle.

On the right hand side of the display is a simple BVI avoidance guidance indicator. Because the noise data are precalculated, the accelerations and rates of climb where BVI noise occurs are known for all airspeeds. As the pilot approaches a high BVI noise flight condition, the indicator will begin to fill. When the rotor tip vortices are below the rotor disk, the indicator will fill from the midpoint toward the top of the display, indicating that the pilot should climb and/or accelerate to increase the separation between the rotor blades and the vortices to reduce BVI. Likewise, when the vortices are above the rotor disk, the indicator will fill toward the bottom of the display, indicating that the pilot should descend and/or decelerate to avoid BVI noise. A textual indication of the BVI avoidance guidance, either “Accel/Climb” or “Decel/Descend,” will also appear on the display as the pilot nears a high BVI operating condition. Fig. 5 shows an example of the noise display output during a descending flight condition where the helicopter is near the maximum BVI rate of sink. High levels of BVI are radiated ahead of the helicopter, increasing the extent of the annoyance region. The guidance indicator is nearly full, and indicates that the pilot should accelerate or reduce the rate of
sink in order to move to a lower noise operating condition. Another example is shown in Fig. 6 during a level flight turn toward the advancing (left hand) side of the helicopter. The helicopter has decelerated as it enters the turn, increasing BVI noise radiation relative to the cruise condition shown in Fig. 4, and directing it toward the outside of the turn.

3 CONCLUDING COMMENTS

A real time helicopter noise model was developed in this paper and demonstrated as part of a pilot community noise awareness display. The helicopter noise model is computationally efficient, and can easily be run in real time on a device such as a tablet or modern helicopter “glass cockpit” avionics. The community noise awareness display will allow helicopter pilots to consider the acoustic impact of their operations, accounting for the specific configuration, ambient conditions, and flight condition of the helicopter at the current time. In combination with a flight simulator, the real time helicopter noise modeling could also be used to provide real time feedback when training helicopter pilots on effective noise abatement procedures.

Further human factors research should be conducted to identify the most effective way to communicate community noise information to the pilot of the helicopter without undue increase in pilot workload. The display should then be integrated into the cockpit of a helicopter, and the acoustic radiation on the ground measured, in order to assess the efficacy of the display in causing a reduction in helicopter noise radiated in the community. The situational awareness of the pilot could be further improved by integrating the community noise awareness information and guidance into one of several Helmet Mounted Optical Devices (HMOD) currently under active development.\textsuperscript{21,22} Further developments of the noise model could also include additional propagation effects such as wind and terrain, which would increase computational cost but offer additional mechanisms that could be exploited to effect further reductions in community noise levels.
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