A STUDY OF ROTORCRAFT NOISE PREDICTION IN MANEUVERING FLIGHT

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Abstract
The coupled flight simulation/noise prediction system (GENHEL–PSU-WOPWOP) has been partially validated for steady noise predictions in this paper. The noise predictions for a utility helicopter matched quite well with wind tunnel measurements of the isolated main rotor. The GENHEL–PSU-WOPWOP system is not capable of blade-vortex-interaction noise prediction, because GENHEL does not account for individual vortices. This limitation was mitigated in this work by choosing flight conditions that are not expected to be dominated by BVI noise. A flight simulation of a complex 80-second was performed. This maneuver, which included a climb, acceleration, 180° coordinated turn, and level flight, demonstrated the complexity of the radiated noise field during maneuvering flight. Care must be taken when interpreting the acoustic signal to account for changes in propagation distance, directivity changes due to aircraft attitude changes, and transient maneuver noise. In general maneuvering flight can be considered as a set of steady flight conditions connected by transient maneuvers. Transient maneuver noise, when present, may contribute dramatically to the radiated acoustic field. Transient maneuver noise is generated during short-duration maneuvers by a multiple sources: aperiodic rotor blade motions; aircraft attitude changes – especially rapid roll maneuvers; and unsteady transient aerodynamic loading on the rotor due to pilot control overshoots, and aerodynamic force overshoots. A more detailed understanding of transient maneuver noise was developed through a set of turn entry maneuvers of different durations.

Introduction
Rotorcraft noise is one of the key objections to rotorcraft deployment in metropolitan areas. Noise regulations designed to reduce community annoyance force rotorcraft to operate within narrow corridors and limited hours of operation. These regulations have constrained the rotorcraft industry from establishing a significantly larger civil presence. In the past two decades, the rotorcraft noise problem has been analyzed and accurate prediction of the noise generated during steady rectilinear flight has been accomplished. However, the present state of the art still does not meet the real-world challenge of maneuvering flight. In order to investigate this problem, a coupled rotorcraft flight dynamics – acoustics prediction system, GENHEL–PSU-WOPWOP, has been developed to predict the rotor-generated noise for rotorcraft in arbitrary motion. In this noise prediction system, the GENHEL flight simulation code provides blade loading and motion data to the PSU-WOPWOP code, which then predicts the noise at arbitrary observer positions. Although this system is currently unable to predict blade-vortex-interaction (BVI) noise, the underlying rotational noise during a maneuver can be studied to gain an understanding of the impact of steady and transient maneuvers on noise generation (especially low-frequency components of the noise).

Approach
A brief description of the coupled rotorcraft flight simulation – acoustic prediction system is given in this section. More details on this system can be found in Ref. 1.

Flight Simulation Code
GENHEL is a flight dynamics simulation tool for a general utility helicopter. The code used in this study is based on the version maintained by NASA/U.S. Army rotorcraft division and it includes following functions:
1. Force model – Models the total forces applied on the helicopter and force generated by rotor disk.
3. Rotor blade dynamic model – The rotor blade dynamic model determines blade flapping, pitching and lagging motions.
4. Pitt-Peters dynamic inflow model.
5. Dynamic models of engine and RPM governor.
6. Control system model – Both pilot controlled stick input and a pilot input model are used by GENHEL to perform maneuvering flight simulation in either real-time or non-real-time environments. The flight control system also models the stability augmentation system (SAS) and flight path stabilization (FAS) system on the aircraft.

7. Rotor aerodynamic model – The rotor aerodynamics model uses blade element theory, in which the blade is divided into sections and the local velocities are calculated based on the blade local Mach number, angle of attack, and yaw angle of the flow. This model is crucial to the acoustics analysis since the acoustics prediction requires aerodynamic forces as input data.

The code provides all of the parameters needed for noise prediction: 1) helicopter motions, including helicopter pitch, roll, and yaw motions as well as the helicopter position data; 2) individual blade motions, including blade pitch, lead/lag and flap; 3) rotor loading data, including blade normal and tangential forces.

**Noise Prediction Code**

The PSU-WOPWOP code is a noise prediction code capable of predicting the rotor noise from multiple rotors for both steady and maneuver flight conditions. PSU-WOPWOP is a source-time dominant implementation of Farassat’s retarded-time formulation \( 1A^4 \) of the Ffowcs Williams–Hawkings (FW–H) equation.\(^5\) When coupled with GENHEL, PSU-WOPWOP predicts both thickness and loading noise for stationary and moving observer locations. The source-time-dominant, retarded-time algorithm and chordwise-compact loading formulation, implemented in the PSU-WOPWOP, have proven to be significantly faster than a previous maneuver version of the NASA WOPWOP\(^6\) code in maneuvering flight. PSU-WOPWOP is able to perform near real-time noise prediction for rotorcraft in maneuvering flight.\(^1\) A more complete description of the PSU-WOPWOP code can be found in Refs. 7, 8, 9, and 10.

PSU-WOPWOP is capable of predicting both BVI noise and high-speed impulsive (HSI) noise, but GENHEL is not capable of computing the needed aerodynamic data for these impulsive noise sources. When BVI noise is predominant, the high-frequency components of noise due to the impulsive loading will not be predicted by the coupled flight simulation – noise prediction system. Even so, the rotational noise (nonimpulsive noise) from the current prediction system is accurately predicted – as will be shown through validation with model rotor acoustic data.

**Noise Prediction System Validation**

There is very little data available to validate the noise of rotorcraft in maneuvering flight. Nonetheless, it is important to demonstrate that the GENHEL–PSU-WOPWOP system can predict noise accurately for steady flight cases. For this purpose, experimental data from a wind tunnel test in the German-Dutch Wind Tunnel (DNW) is chosen was chosen for comparison. The experimental setup and test is described, followed by a comparison of predicted and measured noise at two microphone locations for two flight conditions.

**Experiment Description**

A 1/5-scale United Technologies Corporation contemporary design, 4-blade, pressure-instrumented main rotor was tested while several microphones recorded the noise generated by rotor.\(^1\) The main rotor air-loads and noise were measured at various advancing-tip Mach numbers. The rotor was trimmed to zero blade flapping, but the lag motion during the test was not reported. The rotor test was focused on measuring noise in both BVI and HSI noise conditions—precisely the conditions in which the GENHEL–PSU-WOPWOP system cannot accurately predict noise. Nevertheless, two microphone locations (microphone 1 and 7 in Ref. 11) did not include significant BVI or HSI noise; hence, these two microphones are adopted as observer locations in PSU-WOPWOP noise predictions. Microphone 1 was located in front of the rotor along the rotor centerline (180° azimuth angle). Microphone 7 was also located in the rotor plane 30° from the centerline microphone (150° in rotor azimuth angle), on the advancing side. Both inplane microphones are located three rotor radii from the rotor hub. A schematic of the test setup is shown in Figure 1. The rotational tip Mach number is \( M_{HT} = 0.636 \).\(^1\) In order to focus on the thickness and loading noise prediction, level flight conditions were chosen with advancing-tip Mach numbers \( M_{AT} = 0.690 \) and \( M_{AT} = 0.796 \). With these selections, the influence of any BVI or HSI noise was minimized.

**Figure 1** DNW experiment setup.
The GENHEL flight simulation code is designed to compute the flight dynamics of a full-scale utility helicopter—NOT an isolated rotor in a wind tunnel. The rotor was modeled at full scale in the GENHEL simulation. Simulated level forward flight with a constant forward speed of 15.4 m/s and 51.7 m/s resulted in an advancing-tip Mach numbers of $M_{AT} = 0.690$ and $M_{AT} = 0.796$, respectively, and a constant rotation rate of 258 rpm. Although in the GENHEL simulation, all rotorcraft degrees of freedom were allowed, in level forward flight the rotorcraft attitudes are essentially constant throughout the simulation. The GENHEL simulation predicted some blade flapping, but this was set to zero in the PSU-WOPWOP noise prediction so that the prediction would represent the test more accurately. In effect, only the rotor speed and appropriately scaled blade loading data from GENHEL were used in the PSU-WOPWOP noise prediction.

**Validation Results**

**Case 1: $M_{AT}=0.690$**

In case of advancing-tip Mach number is $M_{AT} = 0.690$, there is no shock generated on the blade surface and therefore HSI noise is not expected in the measured results. However, the measured data contains a small amount of BVI noise for both microphone 1 and 7. (BVI noise can be identified as the narrow impulse(s) just prior to the large negative peak, which is primarily thickness noise.) Figure 2 shows that the predicted total acoustic pressure matches the experimental data at microphone 1 very well – although there is a slight variation between blades that can be seen in the data. In this case the noise is dominated by thickness noise, but loading noise is present, contributing about 20% of the total acoustic pressure amplitude (thickness and loading noise are not shown). Since GENHEL does not provide the impulsive loading generated during a BVI, PSU-WOPWOP is not able to predict BVI noise. A comparison of predicted and measured noise at the location of microphone 7 is shown in Figure 3. Again the noise is predominantly thickness noise, but the measured acoustic pressure history also contains more BVI than at the location of microphone 1. At microphone 7 the agreement between prediction and data are not as good that obtained for microphone 1—the total acoustic pressure magnitude is less than the DNW measured value—but the agreement still quite satisfactory.

**Case 2: $M_{AT}=0.796$**

As the advancing-tip Mach number is increased to $M_{AT} = 0.796$, it is observed from the experimental data that there is still no significant shock generated noise even though the amplitude of the acoustic pressure signal is two to three times that of the earlier case (see Figure 4). For this flight condition, there is now a significant set of BVI impulses in the acoustic pressure history at the microphone 1 location. The PSU–WOPWOP prediction for this condition agrees well in both the shape and amplitude of the acoustic pressure signature, except for the BVI impulses. The acoustic pressure negative peak is somewhat overpredicted, but otherwise is in good agreement. In fact the agreement between the prediction and some of the blades is slightly better than others, due to the blade-to-blade variation in the data. However, in a pure forward flight case with constant speed, each blade passage in the PSU-WOPWOP acoustic prediction is the same because the flight condition is steady. At the microphone 7 location, shown in Figure 5, the negative
thickness noise pulse and the BVI events occur at nearly the same time. Nevertheless, the PSU-WOPWOP prediction for this condition matches the experimental data quite well—especially for the fourth negative peak.

Overall, the results shown in Figures 2–5 demonstrate that the coupled GENHEL-PSU-WOPWOP system prediction matches the experimental data quite well for both forward flight speeds and microphone locations. When BVI occurs, it is not predicted, but the underlying acoustic pressure signal has both the correct shape and amplitude. Further validation out of the rotor plane would be useful, but these results give some confidence in accuracy of the coupled flight dynamics – rotor noise prediction system.

**Maneuver Noise**

Rotorcraft flight can be characterized as series of steady-state flight conditions generally preceded and terminated by short transient maneuvers. Typically, steady, non-accelerating flight is referred to as steady-state flight, while accelerating flight of some sort is thought of as a maneuver. This separation is useful because in accelerating flight the forces, and hence rotor trim, required to maintain the flight state are significantly different from the steady, non-accelerating flight. A further categorization is needed to distinguish maneuvers like rectilinear acceleration or a steady coordinated turn from a short-time transient maneuver like a “pop-up”, “pull-up”, or entry into/exit out of a turn.

In this paper both steady and transient maneuvers are studied, but the main goal of the paper is to understand how the noise generation is modified during a transient maneuver. This objective is complicated by the fact that during a maneuver, both the rotor loading and aircraft/rotor orientation are changing. Hence the acoustic directivity on the ground may change quickly at a specific observer location. Furthermore, the propagation distance to a ground based observer is constantly changing, which results in a change of the strength of the acoustic radiation at the observer location even though the noise generation has not changed. These effects can be separated from each other in the predictions by using observer positions that move with the helicopter and hence remain in a fixed position in the aircraft reference frame.

Another challenge in interpreting maneuver noise is that the time scale is considerably longer than a blade passage period. For this reason it is not useful to examine the acoustic pressure time history of the entire flight. As an alternative, the maneuver noise in this paper is expressed in terms of the overall sound pressure level (OASPL). OASPL is computed from a 0.2 second segment of the predicted acoustic pressure time history. A Hanning window is applied to the data because the signal is not periodic. Finally, a 4.26 dB correction factor is added to the OASPL value to account for the reduction in amplitude a broadband signal would experience after application of the Hanning window. A time history of OASPL is obtained by moving the 0.2 second window through the 80 seconds of data.

**Example: 80-Second Maneuver**

To demonstrate the complexity of the acoustic field during a typical flight profile, an 80-second flight maneuver has been studied. This maneuver, which was first presented by Brentner et al., consists of typical helicopter maneuvers including a climb, a 180° coordinated turn, and a steady acceleration in forward
speed. It is intended that this maneuver should have minimal BVI. A utility helicopter with a four-bladed, swept-tip main rotor and tail rotor was simulated. Only the main rotor, which had a radius of 8.18 m, was included in the acoustic predictions. The gross weight of the helicopter in the simulation was 74800 N.

The 80-second maneuver flight starts at $t = 0$ seconds with a forward flight speed of 20.6 m/s (40 knots). The rotorcraft then enters a climb with a climb rate of 6.1 m/s at $t = 1$ seconds. The climb continues until the helicopter reaches an altitude of 61 m when the helicopter continues in level flight. During the climb and subsequent level flight, the helicopter also experiences an increase in forward speed (acceleration), ultimately reaching 51.5 m/s (100 knots) at $t = 18$ seconds. This forward speed was maintained throughout the rest of the flight. At $t = 22$ seconds, the helicopter performs a 180° coordinated turn, which is completed at $t = 56$ seconds. After the coordinated turn, the helicopter continues in level flight until the end of the simulation. The flight path for the 80-second maneuver and the measurement ground plane with OASPL contours at $t = 35$ seconds are shown in Figure 6.

Table 1. Flight states in 80-second maneuver.

<table>
<thead>
<tr>
<th>Maneuver</th>
<th>Start Time</th>
<th>End Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level</td>
<td>$t = 0$ sec</td>
<td>$t = 1$ sec</td>
</tr>
<tr>
<td>Climb</td>
<td>$t = 1$ sec</td>
<td>$t = 14$ sec</td>
</tr>
<tr>
<td>Acceleration</td>
<td>$t = 1$ sec</td>
<td>$t = 18$ sec</td>
</tr>
<tr>
<td>Level</td>
<td>$t = 14$ sec</td>
<td>$t = 22$ sec</td>
</tr>
<tr>
<td>Coordinated Turn</td>
<td>$t = 22$ sec</td>
<td>$t = 56$ sec</td>
</tr>
<tr>
<td>Level</td>
<td>$t = 56$ sec</td>
<td>$t = 80$ sec</td>
</tr>
</tbody>
</table>

Pilot Control

The pilot plays an important role during maneuvering flight. In the flight simulation a pilot model is used to provide the pilot input. In Figure 7 the time history of the helicopter attitude and pilot input over the 80-second maneuver flight are shown. An examination of the pilot inputs reveals that the most “impulsive” pilot input is the lateral cyclic pitch. This input is required to initiate the roll needed to bank the aircraft in the coordinated turn. The helicopter maintains a roll angle of approximately 28° during the turn. The rapid lateral cyclic pitch input results in a small overshoot in roll which is subsequently corrected – both on the initiation and cessation of the turn. This overshoot phenomenon usually occurs when the pilot is required to perform a maneuver in a short time. Such a rapid change of flight state is associated with significant noise generation. The impact of the various pilot controls, the resulting helicopter response, and its correlation to the radiated sound is investigated in the following sections.

Noise at Single Observer Location

To demonstrate the character and complexity of the noise generated during maneuver and received by a single observer, a computation of the noise for the entire 80-second maneuver has been made at the observer location $\bar{x} = (800, -400, 0)$ m. This observer
location, indicated in Figure 6 by the X on the ground plane, is roughly in the center of the coordinated turn. The time history of both the main rotor normal force (normalized by helicopter gross weight) and thickness and loading OASPL are shown in Figure 8.

One second after the flight simulation is started the helicopter starts the climb and increases its forward speed. The rotor normal force history shows that the initial response to an increase collective pitch is a fairly large increase in rotor thrust that decreases a short time later ($t < 4$). At the end of the climb ($12 < t < 16$), the collective pitch is decreased and the rotor normal force decreases significantly for a short time (similar to the increase at the beginning of the climb). The normal force decreases slightly as the helicopter banks and enters the turn ($t = 22$), but then increases to a steady value about 1.1 times the aircraft gross weight throughout the turn. As the helicopter leaves the turn and levels out ($t = 56$), the rotor normal force rapidly decreases to the gross weight.

At the selected observer location, both the thickness and loading OASPL increased gradually in the throughout the climb ($1 < t < 14$). This increase is due to a combination of several effects: increased noise from the climb maneuver and the acceleration in the forward speed, reduction of distance from the observer, and the directivity change due to the helicopter pitching down. The loading noise does seem to have some increases that correlate with the rotor normal force (the acoustic response is delayed due to propagation time), but the correlation is not a clear. After the climb and accelerating level flight, both thickness and loading OASPL levels decrease as the helicopter enters the turn ($22 < t < 24$). This decrease is probably a result of the change in aircraft pitch and roll angle. This is demonstrated in Figure 9. When the helicopter is in the level flight just before entering the turn, the main rotor tip path plane is approximately parallel to the ground plane and the observer is $6.7^\circ$ below the tip path plane. After the helicopter has rolled $28^\circ$ in the turn, the observer is now $21.3^\circ$ above the rotor tip path plane. In the turn the thickness noise remains nearly constant throughout the turn, but the loading noise decreases. As the helicopter leaves the turn ($t = 56$) both thickness and especially loading noise increase rapidly due to the aircraft attitude change (primarily roll angle). As the helicopter flies farther from the observer ($56 < t < 80$), both thickness and loading noise steadily decrease.

Noise Contours on the Ground Plane
An examination of noise at a single observer location does not give any information about the directivity of the acoustic field. For this purpose the OASPL is plotted on the ground plane. This representation does not eliminate distance effects, but it shows what sound will reach the ground during the simulated flight and it shows the changes in directivity due to aircraft attitude changes. An observer grid of 8181 observers over an area of 1600 by 2000 m was used to visualize the acoustic field on the ground. The thickness, loading, and total noise OASPL contours are shown for several instances of time in Figures 10-12. (Note the times chosen are NOT equally spaced.) A comparison of these figures reveals that the loading noise is dominant over much of the ground plane, but the thickness noise has the highest amplitude in some regions.

Figure 8. Time history of rotor normal force/gross weight (-----) and thickness (top) and loading (bottom) noise OASPL (------) at the ground fixed observer location indicated by X in Figure.

Figure 9. Schematic to show the position of the observer relative to the main rotor tip path plane before (top) and after (bottom) the coordinated turn. (Not to scale.)
In Figure 10 at $t = 3$ seconds, the region of maximum thickness noise is a fairly small region because the helicopter is still close to the ground. Likewise the loading noise radiation is a fairly intense circular pattern. Thickness noise is unaffected by the changes in rotor loading, so as the helicopter climbs ($t = 14$ and $t = 16$) the intensity of the thickness noise on the ground decreases. The loading noise radiation pattern (Figure 11) changes to more of a dipole-like directivity on the ground with intensity increasing as the rotor loading increases. At $t = 22$ seconds the helicopter rolls as it enters the turn and the thickness noise radiation increases as the rotor plane intersects the ground plane. In the turn, the lobe in loading noise that is located on the outside of the turn nearly disappears and the inner lobe is distorted by the aircraft attitude change. This directivity remains constant throughout the turn, except that it follows the helicopter around the turn. The change in directivity due to roll angle is reversed when the helicopter exits the turn ($t = 56$). A comparison of Figures 11 and 12 shows that the total noise is dominated by loading noise, but the thickness noise does influence the total OASPL directivity (i.e., the loading and total OASPL are noticeably different). Figures 9-12 characterize the noise throughout the maneuver on the ground, but they are unable to show the impact of the transient noise, which is by definition

Figure 10  Time history of thickness noise OASPL contours on the ground plane. Axis units are meters. Note: the black circle, which has a radius of $5R$, indicates the position of the helicopter.

Figure 11  Time history of loading noise OASPL contours on the ground plane. Axis units are meters. Note: the black circle, which has a radius of $5R$, indicates the position of the helicopter.

Figure 12  Time history of OASPL (total) contours on the ground plane. Axis units are meters. Note: the black circle, which has a radius of $5R$, indicates the position of the helicopter.

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a short time event. In animations of the ground plane contours, propagating “waves,” which correspond with the roll to enter and exit the turn, are evident in the OASPL contours. To explore this further it is necessary to compute the noise at observer locations fixed in the helicopter reference frame (i.e., moving with the helicopter). Such an observer location will not have any changes in noise due to either distance or relative position changes.

Noise at a Moving Observer Location
Based on the contour plots in Figures 10-12, two moving observer locations were chosen for analysis: \( \tilde{x}_1 \) is located on the advancing side of the rotor, 60° right of the aircraft centerline \( (\psi = 120^\circ) \) and 45° below the rotor tip path plane; and \( \tilde{x}_2 \) is located on the retreating side of the rotor, 60° to the left of the aircraft centerline \( (\psi = 240^\circ) \) and 45° below the rotor tip path plane. Both observers are 30\( R \) from the main rotor hub. These observer locations were chosen to show some of the most dramatic changes in the noise time history.

The predicted OASPL levels are shown for these two observer positions is shown in Figures 13 and 14, respectively. At both observer locations, the most prominent feature in the time history is the presence of “spikes” of up to 15 dB in the OASPL level. These spikes are evident in both the thickness and loading noise OASPL time histories. The rapid change in OASPL is especially impressive when one considers that OASPL is a time integration over 0.2 seconds (slightly less than 1 rotor revolution). Notice that for the advancing side observer, Figure 13, the thickness and loading noise spikes cancel each other to some extent while for the retreating side observer location, Figure 14, the thickness and loading noise are slightly out of phase and hence the amplitude of the total OASPL spike is increased. These spikes in OASPL correspond to the entry and exit from the coordinated turn. In fact, a comparison with the lateral cyclic pitch shows that the spikes correspond to the transient associated when the aircraft rolls. The change in
thickness noise is largely due to the change in the rotor tip path plane relative to the helicopter, but the changes in loading noise are more complicated. These peaks are representative of transient maneuver noise.

A closer examination of Figures 13 and 14 reveals that as the helicopter speed increases ($1 \leq t \leq 22$), the thickness and loading noise both generally increase at each of the observer locations. The loading noise decreases shortly after the climb starts, then starts to increase again. A small pause in the increase in loading OASPL is noted at the end of the climb ($t \approx 14$), but as the helicopter continues to accelerate the loading noise rapidly increases to the impulse at the beginning of the turn.

Upon removing the factors of observer distance and directionality associated with helicopter attitude changes, it is clear that the maneuver noise prediction can be treated as a series of steady flight states connected by transient maneuvers. Schmitz et al. have taken this approach in developing their QSAM method – neglecting the transients. However, it is also noted that between two adjacent steady states, the transient results in OASPL spikes in both thickness and loading noise. The combined OASPL spike has been observed to be as large as 15 dB; at least 8 dB above the steady OASPL level for the advancing side observer. These spikes will be missed in a quasi-steady analysis.

A key parameter then must be the duration time of the transition from one flight state to another. In the 80-second maneuver, the roll to enter and exit the turn occurred over a one second period. The other flight state transitions were somewhat longer duration, as shown in Table 2. This explains why the primary transient noise observed was during the entry and exit of the turn and not during the other transitions. Furthermore, in the 80-second flight, the pilot input overshoot was only observed in short-duration transitions.

Table 2. The transition of maneuver

<table>
<thead>
<tr>
<th>Starting State</th>
<th>End State</th>
<th>Transient Duration (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level</td>
<td>Climb</td>
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</tr>
<tr>
<td>Climb</td>
<td>Level</td>
<td>2</td>
</tr>
<tr>
<td>Level</td>
<td>Turn</td>
<td>1</td>
</tr>
<tr>
<td>Turn</td>
<td>Level</td>
<td>1</td>
</tr>
</tbody>
</table>

Details of Transient Maneuver Noise

It is desired to gain further understanding of the cause of the OASPL spikes or “transient maneuver noise” associated with the helicopter roll maneuver when entering and exiting the turn. A short 10-second flight simulation was conducted to examine the transition from level flight to approximately 30° banked turn. The roll maneuver (part of the entry to the coordinated turn) was initiated at $t = 3$ seconds and was completed in one second. During the maneuver it is known that the blade motion is aperiodic and the time derivative of the surface velocity may introduce additional noise. Also during a maneuver, the loading changes in an aperiodic manner and the loading and its time derivative terms may also introduce additional noise.

To examine the relative importance of these potential sources for transient noise, three fictitious noise predictions were made for the advancing side, moving observer used in the previous section. The first fictitious computation, shown in Figure 15, used blade motions from steady level flight throughout the maneuver while the actual loading from the real transition from level to turn was used in the noise computation. In Figure 15, the thickness and loading noise for this fictitious maneuver are compared with the real maneuver. Notice that both the thickness and loading noise are changed only by a small amount. From this calculation it can deduced that the actual blade motion is not a significant driver of noise at this observer location. The change in thickness noise during the maneuver must be primarily due to the change in rotor velocity due to the aircraft roll motion.

In the second fictitious maneuver, shown in Figure 16, the blade motion from the real maneuver was used...
together with the loading from steady level flight in the noise prediction. In Figure 16, the thickness noise is identical for the real and fictitious cases. This is true because thickness noise only depends on blade geometry and motion. The loading noise, however, is nearly constant throughout the maneuver in the fictitious case—completely different from the real case. This demonstrates that the spike in loading noise is due primarily to a local change in loading, which is not readily seen in the integrated quantity rotor normal force.

In the third fictitious maneuver, shown in Figure 17, the blade motions and the blade loading forces from the actual turn maneuver are used, but the aircraft roll motion is removed from the acoustic computation. In Figure 17, the thickness noise only exhibits a small fluctuation when the aircraft roll is removed, which verifies that the helicopter roll motion is primarily responsible for the negative spike in thickness noise OASPL. Interestingly the loading noise is also affected (increased) if the aircraft roll motion is removed. The importance of aircraft motion can be understood by considering that a rapid roll can impart a significant contribution to the total velocity and acceleration of the blade—two key parameters in the thickness noise computation. The velocity is also a parameter in the loading noise source terms, but with less direct impact.

From these three fictitious noise computations it is apparent that the aircraft roll motion is responsible for the spike in the thickness noise OASPL time history. The aircraft roll motion also reduces the magnitude of the loading noise OASPL spike for this maneuver. The rapid changes in loading during the maneuver apparently are responsible for the spike in the loading noise OASPL time history. The aperiodic blade motion had a very minor influence on the noise at this observer location in this maneuver.

**Impact of Transient Duration**

To investigate the importance of the transient duration in the generation of transient maneuver noise, three variations of the 10-second entry to right turn maneuver with different roll rates were studied. The nominal time from level flight to approximately 30° roll angle and coordinated turn was 0.5 seconds, 1.0 seconds (the case studied previously, which is representative of the 80-second maneuver), and 5 seconds, respectively. In each simulation the right turn was started at \( t = 3 \) seconds and the turn rate at the end of the maneuver is the same. The 0.5-second case represents the most aggressive pilot input and 5-second case is a very smooth transition.

**Helicopter Response**

The pilot model was used to determine the flight controls for each case, shown in Figure 18. The corresponding helicopter roll response is shown in Figure 19, which shows the roll angle and roll rate for
each of the three maneuvers. Notice that for the 0.5-second maneuver, there is an overshoot in roll angle of about 5°; the 1-second maneuver, an overshoot of about 2.5°; and for the 5-second maneuver there is no overshoot in roll. The maximum roll rate for the 0.5-second maneuver just below 70 deg/sec, which is not unreasonable for a military maneuver in this type of helicopter. For the 1-second and 5-second maneuvers the maximum roll rate is substantially less. An overshoot in rotor loading is also evident for the short-duration maneuvers, shown in Figure 20. In the figure, the 0.5-second maneuver first experienced a decrease in rotor normal force followed by a very rapid increase to nearly 1.3 times the helicopter gross weight. The loading then settles down to nearly 1.2 times the gross weight in the turn. Some overshoot in loading is also evident in the 1-second maneuver, but no overshoot exists for the 5-second case. This overshoot in loading is thought to be a significant contributor to the loading component of transient maneuver noise.

Acoustic Response

The noise for 0.5-second, 1-second, and 5-second turn maneuvers was computed at the two moving observer locations fixed to the helicopter reference frame used in the earlier analysis of the transient maneuver noise (45° below the rotor tip path plane, on the advancing, ψ = 120°, and retreating sides, ψ = 240°, of the helicopter) Both the thickness and loading noise OASPL levels are shown for the advancing side observer location in Figure 21, and for the retreating side observer location in Figure 22. As anticipated, the 0.5-second maneuver produces significantly larger changes in the OASPL “spike” levels. For the advancing side observer, the thickness OASPL decreases by over 20 dB in the spike of the 0.5-second case, while the more dominant loading OASPL spike is about 7 dB increase for the same case. The response at the retreating side observer is more complex. Here the thickness OASPL level temporarily increases by over 10 dB during the 0.5-second maneuver and the loading OASPL oscillates ±6 dB relative to the original level. At each observer location the acoustic response is similar but smaller for the 1-second maneuver. The 5-second maneuver is slow enough that there is essentially no transient maneuver noise. This case could be considered by a quasi-steady analysis.

Although the noise computations for the advancing and retreating side observer locations has highlighted the spikes in OASPL that are part of transient maneuver noise. But it is not possible to get a good understanding of how the directivity of noise changes with time unless a large number of observer locations are used. For this reason the acoustic field for each of the 3 turn maneuvers was computed on a portion of a spherical
surface, fixed in the helicopter frame of reference, shown in Figure 23. This surface extends from 70° to 290° in azimuth angle (180° azimuth is directly ahead of the helicopter) and 30° to −70° in elevation angle (0° elevation corresponds to the tip path plane).

Observer locations on the sphere are spaced every 10° in elevation and 13.8° in azimuth and are 30R from the rotor hub. (The previous moving observer locations are points on this spherical surface.) Contour plots of the thickness, loading, and total OASPL are shown in Figures 24-26. Note that in these figures, the azimuth angle is plotted from 290° to 70° so that advancing side observers are on the right and retreating side observers are on the left – the view from behind the helicopter. Also note that the time steps chosen are not equally spaced but rather chosen because they show interesting details.

An examination of all three Figures 24-26 reveals that loading noise is dominant, but that the total noise OASPL level is modified from the loading levels by the addition of thickness noise. Another general observation true in all three figures is that both the 0.5-second and 1-second maneuvers have significant temporal variation, but the 5-second maneuver does not change significantly with time. The primary change to thickness noise during the transient maneuver is to change the shape of the directivity pattern throughout time. The loading noise is more complicated. For the 0.5-second maneuver the loading noise directivity changes dramatically during the maneuver. The overshoots in roll and rotor loading probably account for this change, although more study is needed to fully
explain the detailed behavior. As the helicopter passes through the transient and continues on in the steady coordinated turn, the directivity returns to its original shape, but the levels are higher due to increased rotor loading in the turn. This presentation – on a constant radius, moving spherical surface – gives a clear depiction of the complexity of the addition noise generated during a short-time transient maneuver.

**Conclusions**

This paper has demonstrated some important aspects of the noise of helicopters in maneuvering flight. The acoustic signal received by a fixed observer located on the ground can be very complex. This complexity is due to an ever changing propagation distance, noise directivity changes due to helicopter attitude changes, variation in rotor loading and trim in turning flight, and transient maneuver noise. Of these effects, the least understood is transient maneuver noise, which is the focus of this paper.

The 80-second flight simulation studied in this paper is representative of a typical flight in that it could be considered as a series of steady flight conditions connected with transient flight states. The two shortest duration transients—entry and exit from the coordinated turn—generated a significant amount of transient maneuver noise. Short-duration “spikes” in the overall sound pressure level (OASPL) were observed with magnitudes of 8-10 dB over the steady flight condition, depending on the transient strength and duration. Individual noise components exhibited even larger fluctuations or “spikes” during transient maneuvers.

For the maneuver considered, transient maneuver noise was caused by two primary effects: aircraft motion (roll in particular) and transient rotor loading (including overshoots). The aperiodic rotor blade
motion associated with the transient also contributed to a lesser extent to the transient maneuver noise. Thickness noise changed during the most aggressive maneuver primarily by distorting the original noise pattern, while loading noise changed in a much more complex manner. For the flight maneuvers considered in this study, loading noise was the dominant noise source, but thickness noise did modify the total noise directivity in a significant way.

Although transient maneuver noise can be quite strong in aggressive short-duration maneuvers, it can also be avoided by increasing the duration of the transition time from one flight state to another. Therefore, proper pilot control in the transient maneuver stage could reduce the noise generation from the rotor. Further study is needed to determine the impact transient aircraft and rotor dynamics may have on BVI noise.

Figure 26  Time history of OASPL (total) contours of the turn maneuvers of various durations on the moving spherical surface shown in Figure 23. Note: the time steps are not equally spaced, but each maneuver is shown at the same time — indicated in the right column.

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References


