Fundamental CFD Analysis on Main-Rotor/Tail-Rotor Interaction Noise of Helicopters

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A fundamental analysis of a simple interaction between a rotor and a vortex externally generated from a vortex generator is numerically performed to clearly understand the phenomenon of main-rotor/tail-rotor (MR/TR) interaction noise of helicopters. A combined method of a 3D unsteady Euler CFD code and an acoustic code based on the FW-H formulation is used. As a result, the effect of intersection angle and interaction position on the noise intensity was understood. The directivity of MR/TR interaction noise was also understood.

NOMENCLATURE

- $C$: vortex generator chord
- $c$: rotor blade chord
- $M_{hp}$: hover tip Mach number
- $r$: radial position
- $R$: rotor blade radius
- $R_v$: core radius of vortex
- $u, v, w$: velocity components in rotor coordinates
- $u_o, v_o, w_o$: components of induced velocity by vortex
- $v_t$: tangential velocity of vortex
- $V_o$: free-stream velocity
- $x, y, z$: rotor coordinates
- $x_c, y_c, z_c$: velocity components of grid movement
- $Z_v$: vortex location in $z$ direction
- $\alpha$: inclination angle of vortex in $y$-$z$ plane
- $\alpha_c$: angle of attack of vortex generator
- $\theta$: inclination angle of vortex in $x$-$z$ plane
- $I^*$: circulation of vortex
- $\mu$: advance ratio, $V_o/\Omega R$
- $\xi, \eta, \zeta$: curvilinear coordinates
- $\xi_o, \eta_o, \zeta_o$: grid metrics
- $\xi_{ob}, \eta_{ob}, \zeta_{ob}$: grid time metrics
- $\phi_{obs}$: observer elevation angle
- $\psi$: blade azimuth angle
- $\psi_{obs}$: observer azimuth angle
- $\Omega$: angular velocity of blade

1. INTRODUCTION

Helicopters are used in various fields such as EMS (Emergency Medical Service), fire fighting, disaster relief, news report, and so on because of the capabilities of hovering and VTOL. However, noise, cost, and VFR (Visual Flight Rules) problems prevent helicopters from being widely used as a means of inter-city transportation in densely populated areas. In Japan, MLIT (the ministry of land, infrastructure and transport) has a plan to enforce IFR (Instrument Flight Rules) to helicopters like fixed wing aircrafts in 2005. If it comes true, all-weather flying will be possible and noise problem will get a great deal of attention because the number of helicopters is expected to grow after the permission.

Helicopters have many kinds of noise sources. One of them is main-rotor/tail-rotor (MR/TR) interaction noise where noise is generated by the sudden change of load on tail rotor blades when they chop the vortices shed from the main rotor blades. This interaction occurs in wide range of helicopter flight condition. As shown in Fig. 1, the envelope of tip-vortex trajectory
fully interacts with the tail rotor in the forward flight condition of more than 60 knots. The intersection angle between a tail rotor and a vortex varies depending on the flight condition and the relative position between main and tail rotors. The curvature and the skewness of vortex at the interaction with the tail rotor are shown in Fig. 2 a) and Fig. 2 b) respectively. Some experimental studies\textsuperscript{4,5} were conducted on the MR/TR interaction noise but the investigations in this field are very limited. In this study, therefore, a fundamental analysis using a CFD technique is performed to obtain better understandings for the phenomenon. A simple interaction between a two-bladed rotor and a vortex externally generated from a vortex generator is considered here.

![Fig. 1 Main rotor tip vortex trajectories during hover and forward flight\textsuperscript{1}] (image)

![Fig. 2 Position of tail rotor and tip vortex geometry of main rotor.](image)

2. CALCULATION METHOD

A method\textsuperscript{6} combining a 3D unsteady Euler CFD code and an acoustic code based on the Formulation \textsuperscript{1} of Flows Williams and Hawking (FW-H) equation is used. The quadrupole term of this formulation is neglected here because the MR/TR interaction noise is mainly generated by the dipole source of blade loading. The Euler equations are discretized in the delta form using Euler backward time differencing. A diagonalized approximate factorization method, which utilizes an upwind flux-split technique, is used for the implicit left-hand-side for spatial differencing. In addition, an upwind scheme based on TVD is applied for the explicit right-hand-side terms. Each operator is decomposed into the product of lower and upper bi-diagonal matrices by using diagonally dominant factorization. For unsteady calculations in forward flight, the Newton iterative method is added in order to reduce residual in each time-step. The number of Newton iteration is 4. The typical dividing number along the azimuthal direction is about 3000/rev. It corresponds to the azimuth angle of about 0.12\textdegree/step. An unsteady calculation is started from a steady solution at the azimuth angle of 90\textdegree. The externally generated vortex is simply represented by the Scully model as follows:

\[
\nu_\rho(r) = \frac{\Gamma}{2\pi} \frac{r^2}{(r^2 + R^2)}
\]

where \(v_\rho\), \(r\), \(\Gamma\), and \(R\) are tangential velocity, radial position, circulation, and core radius of vortex, respectively. The effect of the frozen vortex in the CFD code is modeled by the field velocity approach (FVA)\textsuperscript{8}, in which the effect is taken into account by modifying grid time metrics to include the velocities induced by the vortex. The grid time metrics are modified from

\[
\begin{align*}
\xi_\tau &= -x_i \xi_x - y_i \xi_y - z_i \xi_z \\
\eta_\tau &= -x_i \eta_x - y_i \eta_y - z_i \eta_z \\
\zeta_\tau &= -x_i \zeta_x - y_i \zeta_y - z_i \zeta_z
\end{align*}
\]

to

\[
\begin{align*}
\xi_\tau &= -(x_i - u_i) \xi_x - (y_i - v_i) \xi_y - (z_i - w_i) \xi_z \\
\eta_\tau &= -(x_i - u_i) \eta_x - (y_i - v_i) \eta_y - (z_i - w_i) \eta_z
\end{align*}
\]
\[ \zeta_s = -(x_i - u_i)\zeta_x - (y_i - v_i)\zeta_y - (z_i - w_i)\zeta_z, \]

where \( u_i, v_i, \) and \( w_i \) are the components of induced velocity by the vortex. All the calculations are conducted in the condition of collective pitch angle equal to zero. So, the effect of vortex shed from the blade tip is not considered here. The number of CFD grid is about 162 thousand and the geometry of grid is shown in Fig. 3. Time history of acoustic pressure is calculated by the acoustic code using the pressure distribution on the blade surface obtained by the CFD code.

In this study, calculations are performed using Central Numerical Simulation System (CeNSS), the main part of the third-generation numerical simulator of JAXA. It is composed of high performance UNIX servers, FUJITSU PRIMEPOWER. A crossbar network connects each other of them. CeNSS has 9TFLOPS peak performance, 3TB memory, 50TB disk storage, and 600TB tape archive. It takes about one hour to obtain a fully converged solution of a rotor Euler calculation with about 162 thousand grid points using 18 CPUs.

**Code Validation**

Figure 4 shows the validation of the present method. In this figure, measured and calculated time histories of acoustic pressure in a blade-vortex interaction (BVI) of main rotor are compared in Case 1D shown in Table 1. The horizontal axis shows the index number, where one revolution is divided into 512, and the vertical axis indicates acoustic pressure. The measurement was conducted in the NASA 80- by 120-Foot Wind Tunnel using the experimental set up shown in Fig. 5, in which BVI noise was generated by the parallel interaction between the rotating blade and the vortex shed from the fixed-wing vortex generator. The vortex passes through

![Fig. 3 Geometry of CFD grid.](image_url)

![Fig. 4 Comparison between measured and calculated sound pressure.](image_url)

![Fig. 5 Experimental set up in the NASA 80-by 120-Foot Wind Tunnel.](image_url)

<table>
<thead>
<tr>
<th>Table 1 Calculation condition.</th>
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<td>Case</td>
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<td>1D</td>
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<tr>
<th>Table 2 Characteristics of rotor and vortex generator.</th>
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<tbody>
<tr>
<td><strong>Rotor</strong></td>
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<tr>
<td>Radius, ( R ) [m]</td>
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<tr>
<td>Chord length, ( c ) [m]</td>
</tr>
<tr>
<td>Aspect ratio</td>
</tr>
<tr>
<td>Airfoil</td>
</tr>
<tr>
<td>Pitch angle [deg.]</td>
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<tr>
<td>Twist angle [deg.]</td>
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<tr>
<td>Number of blades</td>
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<tr>
<th><strong>Vortex Generator</strong></th>
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<tbody>
<tr>
<td>Chord length, ( c ) [m]</td>
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<tr>
<td>Airfoil</td>
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0.25C under the rotor parallel to the x axis, where C is the blade chord length. The characteristics of the rotor and the vortex generator are shown in Table 2. The non-dimensional core radius and the circulation of the vortex shed from the vortex generator are 0.054 and 0.374, respectively. The former is non-dimensionalized by C and the latter is done by C and V_0. Microphones are located on the traversing device and they are located in the y-z plane and the elevation angle of each microphone is 26°, 32°, 37°, 43°, 47° from up to down. The distance between the rail of the traversing device and the x axis in Fig. 5 is 3.048m from top view. As a result of the comparison between measured and calculated time histories of acoustic pressure, the present method successfully predicts the wave form of experimental data at every microphone position. Especially, the agreement of the positive peak, which determines the intensity of BVI noise, is quite well. Therefore, this method can be applied to the analysis of MR/TR interaction noise although the intersection angle between blade and vortex of MR/TR interaction is different from that of main-rotor BVI.

3. RESULTS AND DISCUSSION

The effect of intersection angle and interaction position of MR/TR interaction on the noise intensity is analyzed and discussed. Figure 6 shows the schematic of calculation model. The two-bladed tail rotor rotates counter clock-wise around the z axis. The tip Mach number of 0.715 and the advance ratio of 0.198 are same as in Table 1 and the characteristic of rotor is same as in Table 2. The blade interacts with the vortex at the azimuth angle of 180°, which is measured counter clock-wise from the x axis. The non-dimensional circulation and the core radius are also same as those in Fig. 5. The quantity of r/R in Fig. 6 is the span-wise location of interaction non-dimensionalized by R, where R is the rotor radius. The inclination angle of vortex in the plane parallel to the x-z plane and the y-z plane is defined by θ and a, respectively, as shown in Fig. 6. The observer positions indicated by the small circles, Mic.1-4, are chosen to include the direction in which the MR/TR interaction noise strongly propagates. They are located in the y-z plane and the distance between the center of rotor rotation and each circle is 3.515R. Table 3 shows the calculation cases.

Effect of Intersection Angle

Figure 7 shows the effect of intersection angle between blade and vortex in the plane parallel to the x-z plane on the time histories of acoustic pressure at Mic.1-4. The blade chops the vortex at the tip end of the blade itself (r/R =1.0) in these three cases. The inclination angle of vortex, θ, equal to 30°, 0°, and -30° are chosen for Case 1, 2, and 3, respectively, as shown in Table 3. The horizontal and vertical axes indicate the time and the acoustic pressure, respectively. In Case 1, the thickness noise from the blade, which gives negative peak of acoustic pressure, is dominant at the in-plane observer position, Mic.1. The loading noise from BVI, which gives positive peak, is observed at the other three observer positions. The maximum peak appears at Mic.3. BVI noise is not observed in Case 2 while the general trend in Case 3 is almost same as that in Case 1. The reason of missing BVI noise in Case 2 is that the vortex doesn't induce any z component of velocity on the blade surface in this perpendicular interaction while the sudden change of z component of velocity induced by the vortex causes the BVI noise.

<table>
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<th>Table 3 Calculation cases.</th>
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<tr>
<td>r/R</td>
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<td>Case 1</td>
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<td>Case 3</td>
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<td>Case 4</td>
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<td>Case 7</td>
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<td>Case 8</td>
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Fig. 7 Acoustic pressure in Cases 1, 2, and 3.
Figure 8 shows the effect of intersection angle between blade and vortex in the plane parallel to the y-z plane on the time histories of acoustic pressure at Mic.1-4. The span-wise position of interaction is fixed to 0.9R in these three cases. The inclination angle of vortex, α, equal to 30°, 0°, and -30° are chosen for Case 4, 5, and 6, respectively, as shown in Table 3. Almost no signal of BVI noise appears in every observer position in every case. The reason is explained in Fig. 9. The vertical small arrows are the vertical components of velocity on the horizontal plane induced by the oblique vortex. If a blade passes through this field of induced velocity from right to left, which is corresponding to Case 4, the blade doesn’t meet with any drastic change of vertical velocity. On the other hand, if a blade passes through this field from the foreground to the background, which is corresponding to Case 1, the blade feels a dramatic change of vertical velocity from negative to positive. This is the reason why the inclination of vortex in the plane parallel to the y-z plane generates no BVI noise. Therefore, it is effective for reducing MR/TR interaction noise to avoid the occurrence of interactions like Case 1 and Case 3.

**Effect of Interaction Position**

Figure 10 shows the effect of interaction position in the span-wise direction on the time histories of acoustic pressure at Mic.1-4. The inclination angles θ and α are fixed to 30° and 0°, respectively. The span-wise locations of 0.9R and 0.3R are chosen for Case 7 and Case 8 as shown in Table 3. The general trends

![Hemispherical Observer Surface](image)

**Fig. 11** Hemispherical observer surface for finding noise directivity.

![Dirctivity of MR/TR interaction noise in Case 7.](image)

**Fig. 12** Directivity of MR/TR interaction noise in Case 7.
in Cases 7 and 8 are similar to that in Case 1. The thickness noise is dominant at Mic.1 and the BVI noise is observed at the other three observer positions in every case. The maximum peak appears at Mic.3. The positive peak of acoustic pressure caused by the BVI noise is highest in Case 7 at every microphone position of rotor out-of-plane. Therefore, it is effective for reducing MR/TR interaction noise to avoid the occurrence of interaction at about 0.9R. The positive peak observed at Mic.3 in Case 7 is about 30 dB and it stands comparison with the positive peak of main rotor BVI noise because the peak of main rotor noise is about 100 dB even in the severe parallel interaction as shown in Fig. 4. Moreover, MR/TR interaction noise has a possibility of occurring in every flight condition of helicopters while the BVI noise of main rotor is mainly generated in approach to a landing. In addition, the directivity of MR/TR interaction noise in Case 7 is analyzed on the hemispherical observer surface with the radius of 100R in Fig. 11. As a result, the hot spot, where the maximum of peak noise level is observed, appears at the observer azimuth angle of 305° and the elevation angle of 40° as shown in Fig. 12. This is the direction which gives significant impact on the community.

4. CONCLUDING REMARKS

A fundamental analysis of a simple interaction between a rotor and a vortex externally generated from a vortex generator is numerically performed to clearly understand the phenomenon of main-rotor/tail-rotor (MR/TR) interaction noise of helicopters. As a result, the followings were found.

1. When a blade interacts with a vortex in a plane parallel to the x-z plane, the thickness noise of the blade is dominant during perpendicular interaction and the leading noise of MR/TR interaction is remarkable during oblique interaction. Only the thickness noise is observed in rotor plane in every condition.

2. When a blade interacts with a vortex in a plane parallel to the y-z plane, only the thickness noise is remarkable in every condition.

3. The peak of MR/TR interaction noise is highest when the tail-rotor blade chops the vortex at about 0.9 rotor radius and its magnitude stands comparison with that of the BVI noise of main rotor. The direction in which the maximum of peak noise level is observed in this case has a significant impact on the community.

The topic of this study covers only a part of the MR/TR noise. More comprehensive studies in actual conditions of helicopters are required to deeply understand the phenomenon.

REFERENCES