Numerical Study on the Blade-Vortex Interaction of Helicopter Rotor with Lateral Blowing

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ABSTRACT

As a method to reduce Blade-Vortex Interaction (BVI) noise of helicopter rotor, the effects of lateral wing-tip blowing were analyzed for the generation and behavior of tip vortical flow. Three-dimensional compressible Euler/Navier-Stokes solver were used to calculate the effect of blowing air from blade tip on the tip vortex of fixed single blade at the various flow and jet conditions. The numerical results include the position of the vortex center along the vortical flow, the size and strength of the rolled tip vortex, and circulation and maximum tangential velocity of the tip vortex. Jet blowing from the wing-tip can diffuse the tip vortex in the way to make larger core sizes and less velocity gradients, which can be effective way to reduce BVI noise of the rotary wing. The predictions of Blade-Vortex Interaction (BVI) noise were performed using a combined method of an unsteady Euler code with an aeroacoustic code based on Ffowcs-Williams and Hawkings formulation. A moving overlapped grid system with three types of grids (blade grid, inner and outer background grid) was used to simulate BVI of helicopter with two OLS-airfoil blades in forward/ descending flight condition. The calculated waveform of BVI noise clearly shows the distinct peaks caused by the interaction between blade and tip vortex and the effect of lateral blowing at tip to reduce BVI noise.

1 Introduction

1.1 BVI noise in helicopter

The mechanism of BVI noise generation is impulsive change in the pressure distribution over the interacting blade preceding pressure jump, as shown in Figure 1. These sudden changes in pressure propagate sound to far field observer. In general, the interactions occur in descent flight conditions, especially during approach to a landing. The noise generated by the interactions radiates mostly below the helicopter's tip-path plane in the direction of forward flight. The acoustic signal is generally in the frequency range most sensitive to human subjective response (500 to 5000Hz). The BVI noise, therefore, prevents that the commuter helicopter is widely used in the densely populated area.

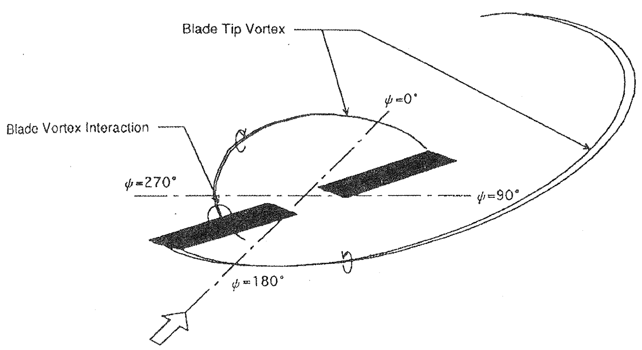


Figure 1. Diagram of BVI

An example of typical waveform of noise spectrum from microphone in Figure 2[1] shows dominant regions for four individual source mechanisms. Compared to other noises, BVI generates critically high noise depending flight conditions.

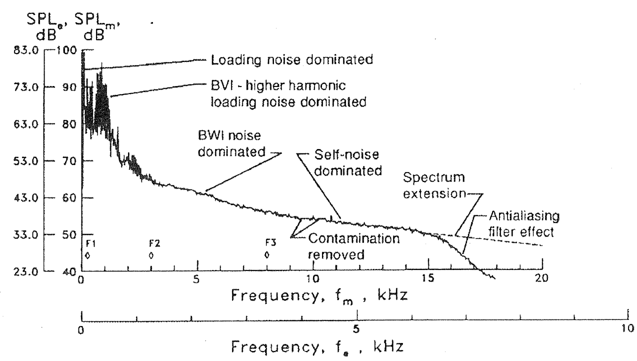


Figure 2. Waveform of noise

Several methods which couple aerodynamic and aeroacoustic codes have been developed to predict the BVI noise by the Aeroflight-dynamics Directorate (AFDD) of the U.S.Army, DLR of Germany, ONERA of France, and ATIC of Japan, respectively. Tadghighi et al. [2] developed a procedure for BVI noise prediction, based on a coupling among a lifting-line code (to provide the vortex wake geometry), a three-dimensional unsteady full-potential code (to provide blade surface pressure), and an acoustic code using Farassat's 1A of the Ffowcs Williams and Hawking (FW-H) formulation. Several research groups have been also developing prediction code using various combinations of analytical codes to obtain wake geometry, airload or blade surface pressure, and acoustic signature[3]. Yu et al.[4] summarized the comparisons of the analytical results for Operational Loads Survey (OLS) model rotor. The activity of the BVI working group by Caradonna et al.[5] is also reported, and their work provided a plenty of progress in the helicopter noise research.

BVI is function of many geometrical and aerodynamic parameters, such ad hover-tip speed, advance ratio, wake geometry, vortex strength and core size, miss distance, blade deformations, intersection angle and so on. The intensity of the BVI noise is strongly affected by the factors, 1) the local strength of the tip vortex, 2) the core size of the tip vortex, 3) the local interaction angle between the blade an vortex line, and 4) the miss-distance between the vortex and the blade. Each research has approached to one of these parameters to reduce BVI noise.

Passive devices have been considered to suppress high noise levels by rotor tip design and leading edge modification. Many researchers have been trying to modify the blade-tip planform to limit shock-wave generation and stall occurrence on the advancing rotor blade. Active devices in BVI noise have been employed such as Individual Blade Control (IBC) method, Higher Harmonic Control (HHC) method and Tailing Edge Flap (TEF) method. These methods are concerned with changing miss distance by disturbing blade or tip vortex. Another way in active control is changing vortex core size or strength using jet-blowing from the tip or attaching Canard wing at the blade tip.

As one of active control method to reduce the BVI noise, method of jet-blowing from a blade-tip, as shown in figure 3, has been tried by many researchers. The idea of mass injection to control the tip vortex started in the area of fixed wing. Lee et al.[6] have used a wing tip modified with a long single slot to produce a spanwise jet sheet. The effect of this sheet appears to be modification of the lift distribution similar to that produced by an increase in aspect ratio. Unfortunately, the fundamental nature of the tip vortex for the modified wing does not appear to be appreciably altered. Wu and Vakili[7] examined the use of discrete wingtip jets for fixed wing to disperse the wake vortex. They have shown that the concept of discrete jets has the potential to effectively disperse the vorticity present in the coherent wing tip vortices. The mechanism for the change appeared to be the formation of multiple auxiliary vortices that decreased the tip vortex strength and introduced increased instability into the flow field. Gowanlock[8] and etc. and other many researchers conducted experimental studies to show jet blowing from a blade-tip can be effective in reducing the strength and velocity gradients of tip vortices. Mineck[9] conducted comprehensive experimental and analytical studies to assess the potential aerodynamic benefits from spanwise blowing at the tip of a moderate-aspect-swept wing.

For the application to helicopter rotor blade, Tan et al.[10] conducted wind tunnel test to reduce BVI noise by blowing compressed air from blade tip of helicopter rotor. They showed that the vortex intensity is reduced while the vortex location is moved outward which resulted in lower BVI noise level. Yamada[11] conducted parametric study using three-dimensional compressible Euler code to calculate the effect of blowing air from blade tip on the tip vortex of single fixed or rotary blade at the various free stream velocities and blowing conditions, such as injection angle, mass flow rate of jet blowing. Yang et al.[12] conducted comprehensive numerical and experimental investigation of the lateral tip-blowing to reduce BVI noise. The results showed that blowing from the wing-tip could diffuse the tip vortex and displace it outward causing the increased 'wing-span'.

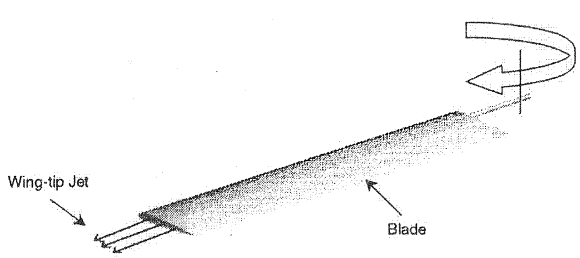


Figure 3. Diagram of wing-tip blowing jet of rotor

1.2 Motivation and Objectives

The results obtained so far, coupled with blowing optimization capabilities, clearly show the potential benefits of discrete jet blowing as means of active control of wingtip vortex flow to reduce BVI noise. For the control of BVI phenomena or BVI noise, it is necessary to get an exact solution of near filed flow of rotor and far field flow. This makes it difficult to set up experimental system and needs a huge computing power.

Main objective of this research work is to study lateral tip-jet blowing as one of method to reduce BVI noise using compressible flow solver with overlapped grid system. For this purpose, first numerical analysis technique will be constructed to solve the BVI phenomena of the helicopter rotor in forward flight. Quantitative calculation will be compared with experimental data. Then using the code developed, BVI analysis will be conducted with various jet blowing conditions to construct basic database of predicting optimal condition.

Numerical Wind tunnel (NWT) of NAL in Japan will be used to get an accurate aerodynamic flow solution near the rotor blade. The NWT is a parallel super computer that consists of 166 processing elements (PEs). The performance of an individual PE is 1.7 GFLOPS, and each PE had a main memory of 256MB. High-speed crossbar network connect 166 PEs to make the total peak performance to be about 280GLOPS and the total capacity of main memory as much as 45GB. For the calculation, the typical dividing number along the azimuthal direction is about 2000/rev. The NWT makes it possible to conduct parametric study of the effect of the lateral jet blowing on the intensity of the BVI noise.

2 Numerical methods

2.1 Compressible Euler/Navier-Stokes solver

The inviscid flux vectors are discretized using Roe's flux difference splitting (FDS) method. The flux difference across a cell interface is divided into components associated with each characteristic wave with third order accuracy using TVD scheme. TVD scheme has a good capability of capturing the shock wave without adding artificial dissipation. Roe's approximate Riemann solver does not satisfy the entropy condition and thus permits physically inadmissible expansion shock. To remedy this problem, entropy correction is applied.

For time integration, Euler Backward Implicit Time Integration was used in the conventional delta form. In order to obtain the unsteady solution in the forward flight condition of helicopter rotor, the Newton iterative method was applied.

In the beginning of the calculation, the steady calculation is conducted at the azimuth angle, $\psi = 90^\circ$ by using the implicit time-marching method. Then, the unsteady calculation is started from this initial condition by using the Newton iterative method. Four iterations are sufficient to reduce the residual at each time-step. The typical dividing number along the azimuth direction is about 2000 per revolution.

2.2 Far-field acoustic prediction method

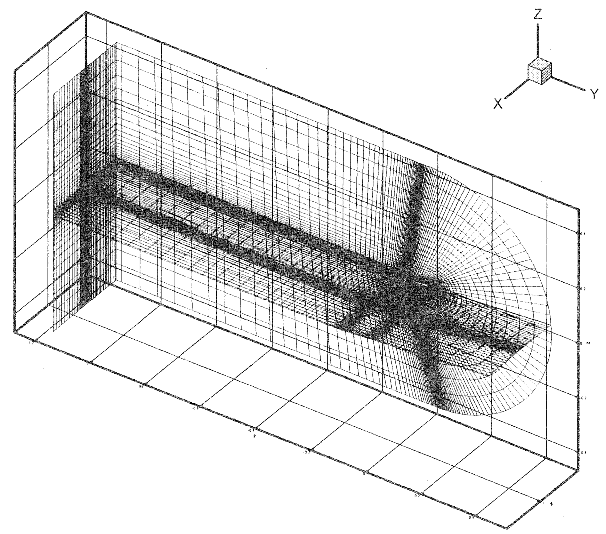
The aeroacoustic code is based on the Ffowcs-Williams and Hawkings formulation without quadruple term[13]. The pressure distribution data on the blade surfaces calculated for every 0.5 degree in azimuth angle by the CFD code were used as the input data in noise calculation.

3 Study on jet blowing with single blade

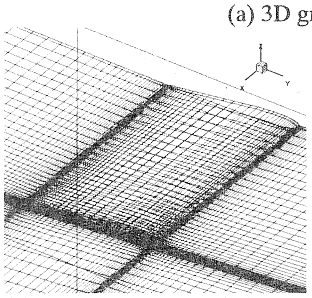
3.1 Grid system and various jet blowing parameters

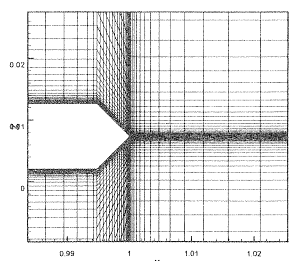
Figure 4 shows a grid system used for single blade calculation to see the effects of tip blowing. The length of wake region after trailing edge was set to be 10-chord length. As a sectional airfoil model, OLS blade (modified BHT 540) was used, which will be used for calculation with overlapped grid to get BVI noise data. This model also has been used for full-scale aerodynamics and noise testing by NASA[14]. C-H-type grid system was used with the number of (chord ×normal ×span = 181 ×56 ×71 =) 719,656 grid points without twist angle.

Blade tip was simplified to be sharp edge as shown in figure 4 (c) with condensed grid near tip to apply jet boundary condition.



(a) 3D grid system





(b) Grid system near blade (c) Sectional grid of blade tip

Figure 4. Three-dimensional grid systems for OLS single blade

Flow conditions were simplified from the data of one of the flight condition of helicopter model-rotor experiments, which were conducted at DNW[14]. Free stream Mach number was set to be 0.5 and 0.8 with the angle of attack to be 5 degree to free stream flow.

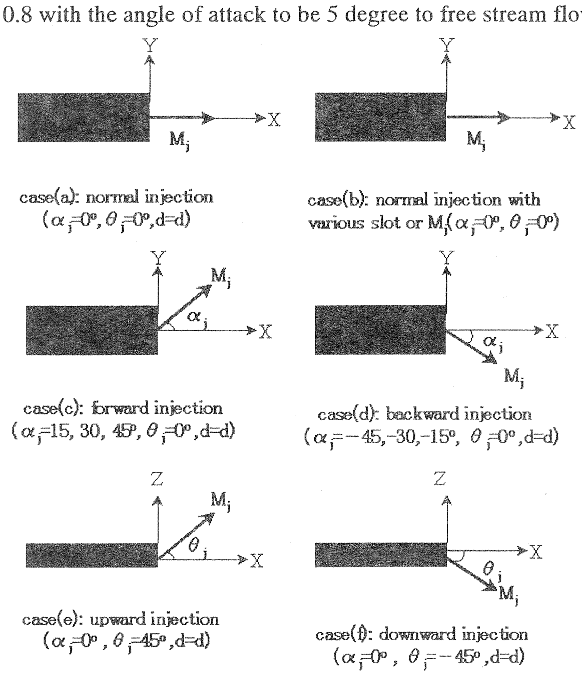


Figure 5. Diagram of cases with various direction of tip jet

Various jet conditions, as shown in figure 5, were used to see the effect of jet direction, jet Mach number, jet slit area, etc. With the results of preliminary calculation, more specified jet condition in forward/backward jet direction were calculated. Jet slit geometry begins 20% of chord length and ends up 65% chord length from the leading edge, and has about 20, 30% thickness of airfoil section.

3.2 Calculations of single blade with Euler solver

Inviscid flow solutions were calculated with Euler solver for various flow conditions to show the effect of tip jet blowing on tip vortex for single blade. Figure 6 shows the comparison of vortex core size for fixed wing with various jet directions (M=0.8, M_{jet}=0.6)

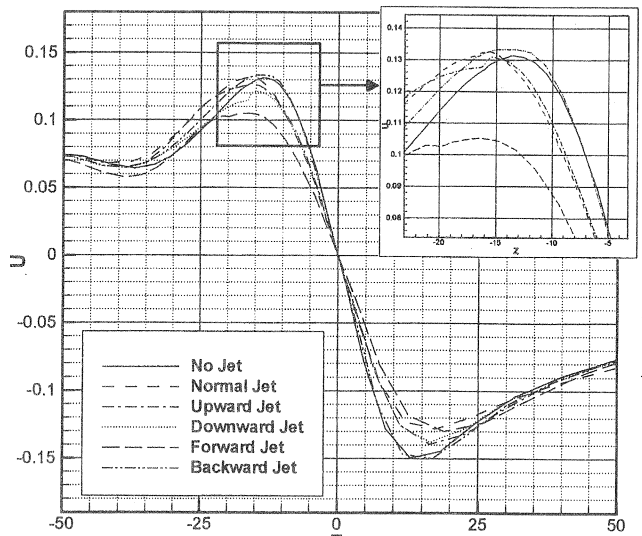


Figure 6. Comparison of tangential velocity distributions at L=10C according to jet directions (M=0.8, M_{jet}=0.6)

When various jets were applied, the core sizes of tip vortex were enlarged and the strength of tip vortex, which can be presented by the slope of tangential velocity at the center of vortex, became smaller.

As shown in figure 7, the effects of jet Mach number and slit area, larger jet area and high jet Mach number makes bigger disturbance into tip vortex to make larger core size and less vortex strength.

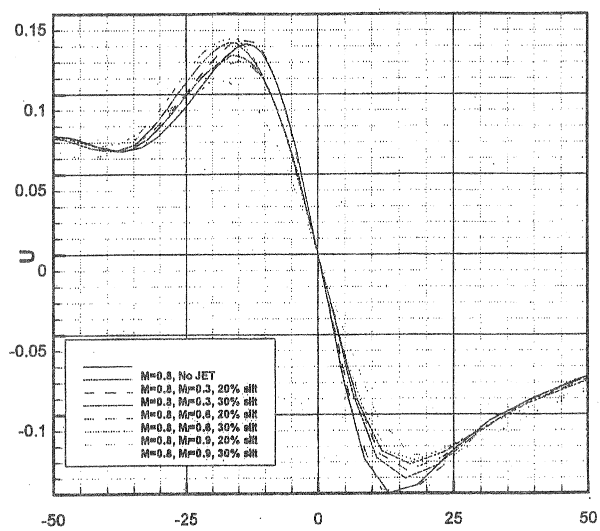
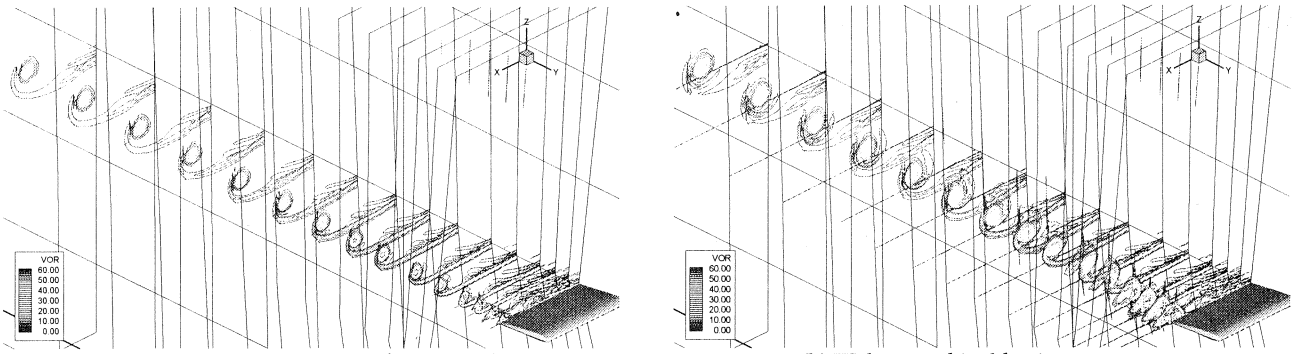


Figure 7. Comparison tangential velocity distributions at L=10C according to jet Mach number and slit area (M=0.8)



(a) Without jet blowing (b) With normal jet blowing

Figure 8. Comparison of vorticity contours up to L=10C distance for with/without jet blowing (M=0.8, M_{jet}=0.6)

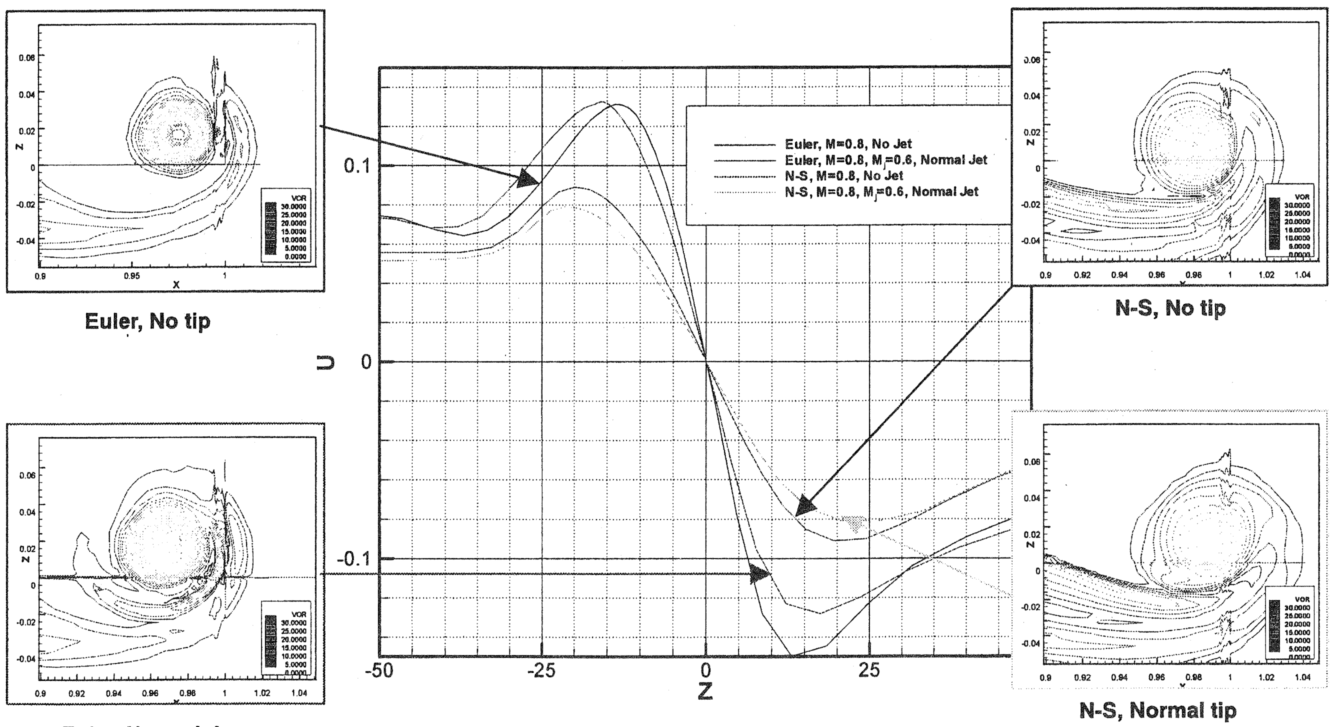


Figure 9. Comparison tangential velocity distributions at L=10C for inviscid/viscous solutions (M=0.8, M_{jet}=0.6)

Figure 8 shows the difference of tip vortex when jet blowing was applied with the wake region of 10 chord length. Compared to the small clear tip vortex of figure 8(a), jet effect make tip vortex disperse not only near tip region but also up to quite a far wake region to show bigger vortex size.

3.3 Calculations with Navier-Stokes solver

Viscous effect was examined with the solution using Navier-Stokes solver for similar flow and jet conditions as Euler calculations. The viscosity of Navier-Stokes calculations makes more dissipations to produce less vortex strength and larger core size, but the jet blowing shows same tendencies on tip vortex just as Euler cases, as shown in figure 9.

4 Study on Jet blowing with Two Blades in Overlapped Grid

4.1 Overlapped grid system of two blades

The predictions of Blade-Vortex Interaction (BVI) noise were performed using a combined method of an unsteady Euler code with an aeroacoustic code based on Ffowcs-Williams and Hawkings formulation. A moving overlapped grid system with three types of grids (blade grid, inner and outer background grid) was used to simulate BVI of helicopter with two OLS-airfoil blades in forward/ descending flight condition[15].

Inner Background grid	(x ×y ×z) 290 ×230 ×50 = 3,335,000
Outer Background grid	(x ×y ×z) 83 ×79 ×49 = 321,293
Blade grid	(chord ×normal ×span) ×blade (81 ×34 ×140) ×2 = 771,120
Total	4,427,413 points
Grid spacing of Inner background Grid in rotor disk	0.19c (=0.0105R)

Table 1. Specifications of grid systems

The body-fitted blade grid, which is O-H topology, moves with the blade motion including rotation, flapping, feathering, and lagging. The inner background grid in Cartesian system is placed around rotor disk to include blade grid. The outer background grid in Cartesian system covers all computational domain, including inner background grid and blade grid. Table 1 shows the specifications of each grid system. In order to get high resolution along tip vortex and BVI phenomena, huge number of grid points was given in inner background grid.

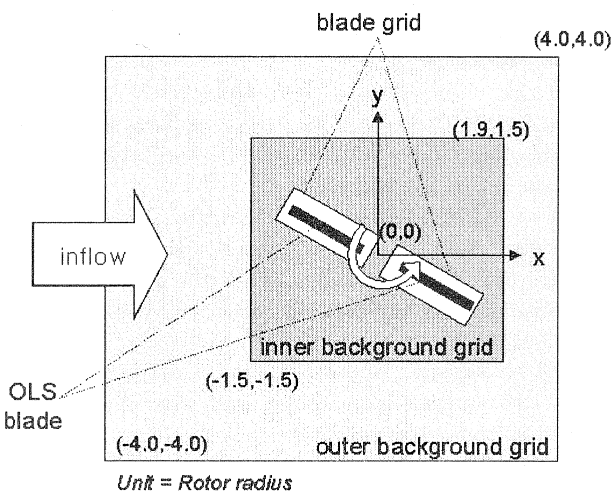


Figure 10. Geometric dimensions of computational domain of inner and outer background grid

The model rotor blades were set to be AH1-OLS blades, which also have been used for full-scale aerodynamics and noise testing by NASA. The rotor motion was also set to be one of the test cases of NASA experiment as shown in table 2.

Tip Mach Number, M_H	0.664
Advance ratio,	0.164
Tip path plane angle	4.74
Collective pitch angle, α_{m0}	4.06
Lateral cyclic pitch angle, α_{mc}	-3.47
Longitudinal cyclic pitch angle, α_{ms}	1.57
Flapping angle	2.30

Table 2. Operating conditions

4.2 Study on the effect of jet blowing

Figure 11 shows vorticity contour at several sections together to visualize the trace of tip vortex in forward/descending flight condition. It shows the trace of tip vortex clearly which were generated by two rotors, and also shows the interaction of blade and tip vortex. According to azimuth angles, each rotor blade experiences unsteady pressure history, which has a sudden change when blade-vortex interaction happens. After applying aeroacoustic code based on Ffowcs-Williams and Hawkings formulation, we can get sound pressure history for one revolution of rotor.

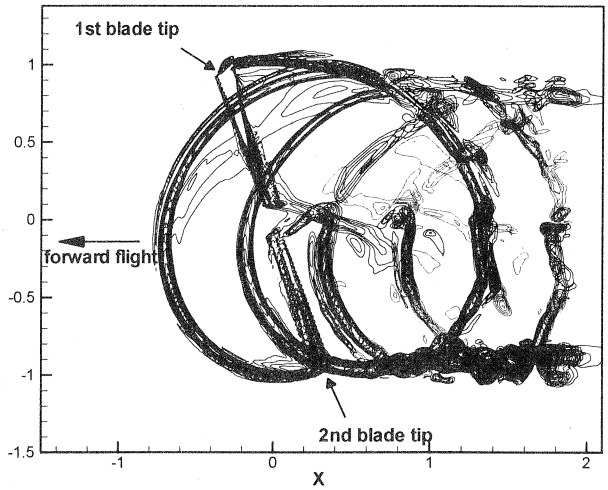


Figure 11. Visualized tip vortices of vorticity contours (M=0.8, M_{jet}=0.6, Normal Jet)

As shown in figure 12 of sound pressure level, maximum BVI noise peak (position **B**) was reduced when jet blowing was applied at rotor tip. When converted into sound level, the maximum decrease in BVI noise is 2.06 dB. Even the other BVI noise (position A) increased owing to jet blowing, the method to use jet blowing is effective to reduce the peak BVI noise, which is more critical to human's hearing.

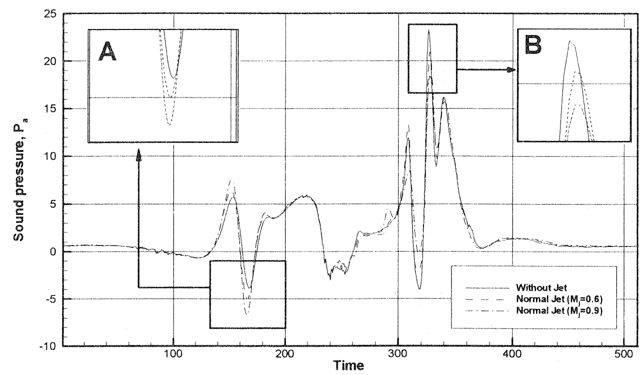


Figure 12. Comparison of sound pressure level (SPL) between cases with overlapped grid system.

From the results with overlapped grid system above, the effect of jet blowing direction was not so big to change the BVI noise, compared with the big difference as results with fixed blade. The reason was supposed to be the periodic alternation of flow condition of rotor owing to rotor rotation during forward flight.

	SP (W/m^2)	Noise (dB)	Difference (dB)
No Jet	23.32	121.33	-
Normal Jet (M_J=0.6)	20.92	120.39	0.94
Normal Jet (M_J=0.9)	18.40	119.27	2.06

Table 4.4 Comparison of BVI noise reductions for several cases

It is necessary to study more about the effect of discrete jet blowing according to flight condition and rotor movement.

5 Summary and Conclusions

As a method to reduce Blade-Vortex Interaction (BVI) noise of helicopter rotor, the effects of lateral wing-tip blowing were analyzed for the generation and behavior of tip vortical flow.

Three-dimensional compressible Euler/Navier-Stokes solver were used to calculate the effect of blowing air from blade tip on the tip vortex of fixed single blade at the various flow and jet conditions. The numerical results include the position of the vortex center along the vortical flow, the size and strength of the rolled tip vortex, and circulation and maximum tangential velocity of the tip vortex. Jet blowing from the wing-tip can diffuse the tip vortex in the way to make larger core sizes and less velocity gradients, which can be effective way to reduce BVI noise of the rotary wing.

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With these results above, the method to use jet blowing can be effective way to reduce the peak BVI noise, which is most critical to human's hearing.

6 Acknowledgement

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