THE JOURNAL OF THE ACOUSTICAL SOCIETY OF KOREA VOL.25, NO.2E 2006. 6 pp. 85~88

Validation of Free-Vortex Embedded CAA Method for Airfoil Vortex Interaction

Seong-Yong Wie*, Duck-Joo Lee*
*Department of Aerospace Engineering, KAIST
(Received Jun 9 2006; Accepted Jun 13 2006)

Abstract

Blade-vortex interaction (BVI) is one of the most important phenomena in rotor flow since it causes undesirable intense vibration and noise. Since three dimensional Euler or Navier-Stokes solutions to BVI require very high computational cost, BVI has been approximated by airfoil-vortex interaction (AVI) in chordwise planes. To describe more realistic situations with AVI, three dimensional vortex informations such as position, core size and strength are embedded artificially to Computational Aeroacoustics (CAA) calculation at each computational time step. To implement this requirement, in this paper, a technique called free vortex embedded method was used. And the solution by this method was compared with the solution by conventional method for interaction between freely convected vortex and airfoil. For the application to three dimensional free vortex embedded CAA, two dimensional free vortex embedded CAA method was validated in advance.

Keywords: *Computational aeroacoustics, Blade vortex interaction, Vortex embedded method, Compact scheme*

I. Introduction

As recognition about advantages of helicopter's hovering and low speed flight increase, techniques about helicopter performance have been vigorously researched and developed. Particularly, noise control of helicopter has been very important requirement technique because of environment noise restriction. Among the noise sources of helicopter, the most serious one is Blade Vortex Interaction (BVI) at descending, forwarding and maneuvering flights.

Extensive studies of rotor's aerodynamics and acoustics about BVI have been executed actively. Srinivasan [1, 2] researched two dimensional BVI by using embedded method. Hardin and Lamkin [3] researched parameters governing BVI. Lee [4] studied vortex core distortion during BVI procedure. The other researches of BVI also have been studied. [5, 6, 7, 8]

Corresponding author: Duck-Joo Lee (djlee@kaist.ac.kr)
KAIST, Guseong-dong, Yuseong-gu, Daejeon, 301-701. Korea

BVI means that blade tip vortex occurred at rotor blade interacts the following blades. This causes unsteady aerodynamic and acoustic characteristics. These characteristics depend on parameters of vortex, such as vortex strength, vortex core size and miss distance. Therefore, to reduce BVI noise, proper condition of BVI should be controlled.

To simulate BVI phenomena realistically, vortex parameters and flow conditions have to be considered very carefully. But numerical method using 2D Euler equation can not consider time variation of 3D vortex parameters. For that reason, we can use the other method including vortex variation. This method that can treat 3D vortex information use perturbed Euler equation including embedded vortex flow and perturbed flow generated by vortex. As perturbed variables in perturbed Euler equation are difference between total flow field properties and embedded vortex field properties, total flow properties are calculated by adding perturbed part to vortex part.

As the embedded vortex convects, flow and acoustic noise are changed. 3D vortex informations obtained from time marching free wake method are embedded in 2D computational aeroacoustic solver. A high order high resolution of optimized compact scheme is used for the flow-acoustic calculation. The vortex informations are substituted before all calculation of CAA and are added to the perturbed quantity calculated. The vortex embedded CAA and conventional CAA results are compared and discussed. To apply 3D vortex embedded method, 2D vortex embedded method should be executed in advance.

II. Governing equations and numerical schemes

The embedded method is governed by perturbed Euler equation [1]. Total conservative variables, Q, of Euler equation are decomposed of embedded vortex known Q_v and unknown flow variable $Q'(= Q-Q_v)$.

$$\frac{\partial}{\partial t}(Q-Q_V)+\frac{\partial}{\partial x}(E-E_V)+\frac{\partial}{\partial y}(F-F_V)=0 \tag{1}$$

wthere

$$Q=\begin{bmatrix}\rho\\ \rho u\\ \rho v\\ \rho e_t\end{bmatrix},\quad E=\begin{bmatrix}\rho u\\ \rho u^2+p\\ \rho uv\\ (\rho e_t+p)u\end{bmatrix},\quad F=\begin{bmatrix}\rho v\\ \rho uv\\ \rho v^2+p\\ (\rho e_t+p)v\end{bmatrix} \tag{2}$$

$$Q_v=\begin{bmatrix}\rho\\ \rho u\\ \rho v\\ \rho e_t\end{bmatrix}_{vortex},\quad E_V=\begin{bmatrix}\rho u\\ \rho u^2+p\\ \rho uv\\ (\rho e_t+p)u\end{bmatrix}_{vortex},\quad F_V=\begin{bmatrix}\rho v\\ \rho uv\\ \rho v^2+p\\ (\rho e_t+p)v\end{bmatrix}_{vortex} \tag{3}$$

$$(e_v = p_v/(\gamma-1)+\rho_v(Q_\infty^2+V_\theta^2)/2)$$

Using Jacobian-metric relation, the perturbed Euler equation for Q' is transformed into below equation.

$$\frac{\partial}{\partial t}(\hat{Q}-\hat{Q}_V)+\frac{\partial}{\partial \xi}(\hat{E}-\hat{E}_V)+\frac{\partial}{\partial \eta}(\hat{F}-\hat{F}_V)=0 \tag{4}$$

$$\hat{Q}=\frac{Q}{J},\quad \hat{E}=\frac{1}{J}(\xi_x E+\xi_y F),\quad \hat{F}=\frac{1}{J}(\eta_x E+\eta_y F) \tag{5}$$

where $J=\dfrac{1}{x_\xi y_\eta - x_\eta y_\xi}$

A generalized coordinate system is used to simulate BVI.

Using velocity induced by vortex, pressure and density are calculated for vortex part. Equations below indicate velocity, radial momentum and enthalpy relation. As shown in equation (6), Scully vortex model is employed for vortex velocity field. Pressure and density field of vortex are determined by equation (7) and (8). If vortex part is known, the unknown Q' are obtained in equation (4) at each time. Finally, the unknown part can be predicted by solving (4).

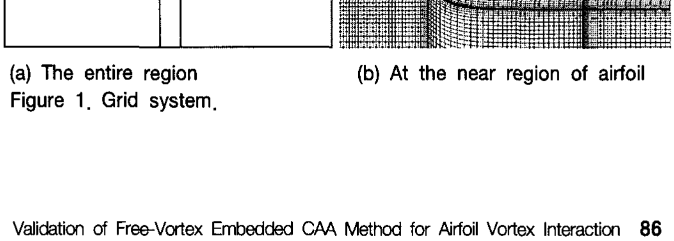
$$V_\theta=\frac{\Gamma}{2\pi r_c}\frac{r/r_c}{(1+(r/r_c)^2)} \tag{6}$$

$$\text{Radial momentum equation}:\ \frac{dp_v}{dr}=\frac{\rho_v V_\theta^2}{r} \tag{7}$$

$$\text{Enthalphy relation}:\ \frac{\gamma}{\gamma-1}\frac{p_v}{\rho_v}+\frac{1}{2}(Q_\infty^2+V_\theta^2)=H_t \tag{8}$$

During vortex passing near airfoil, interaction between airfoil and vortex generates acoustic wave. Then to investigate wave radiation more precisely, high order high resolution scheme for CAA is used to simulate BVI. In this paper, optimized forth-order compact scheme [9] is used for evaluation of spatial derivative. And 4th order Runge-Kutta scheme is used for integration in time.

Inflow, outflow boundary and airfoil wall condition are implemented by general characteristics boundary condition. [10] To reduce spurious oscillation and capture shock correctly, adaptive nonlinear artificial dissipation (ANAD) is used. [11] Figure 1 shows grid used for numerical procedure. Grid system is composed of nine blocks. And the number of total node is about 123400.



(a) The entire region (b) At the near region of airfoil

Figure 1. Grid system.

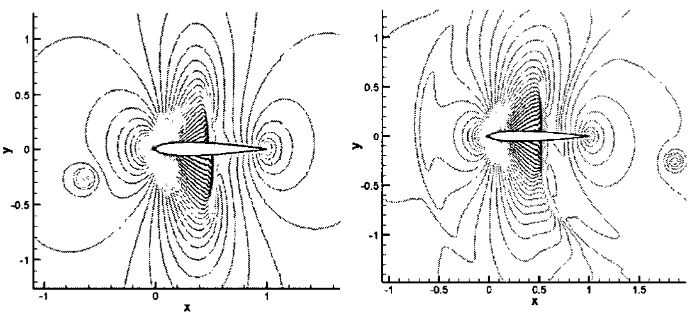
III. Numerical results

To simulate the BVI process, initial condition of vortex is given in Table 1. Vortex used by the embedded method moves at the same free stream velocity (M=0.8). Then comparison with freely convecting vortex is possible. The vortex embedded CAA method results are compared with Euler solutions by Oh, et al. [12] and Srinivasan [1]. Compared quantities are lift coefficient with vortex position variance and pressure coefficient at vortex position (x_v=1).

Table 1. Initial condition.

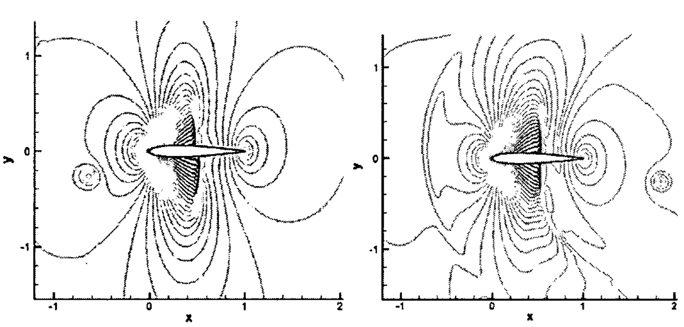
Xv(starting position)	Yv(starting position)	vortex strength $\Gamma/(u_\infty chord)$	vortex core size r / $chord$
-5.0	-0.26	-0.2	0.05

Figure 2, 3 are pressure contours during BVI. In Figure 2, 3, we can confirm that pressure fields induced by embedded vortex accord with pressure fields induced by free convected vortex. During interaction, pressure fluctuation is mainly generated at the leading edge. And shock at the airfoil surface tremble. This tremor makes acoustic wave and nonlinear characteristics of acoustic fields.



(a) x_v=-0.6 (b) x_v= 1.8

Figure 2. Pressure contours. (Free convected vortex)



(a) x_v=-0.6 (b) x_v= 1.8

Figure 3. Pressure contours. (Embedded vortex)

Figure 4 is lift coefficient and Figure 5 is pressure coefficient at vortex position x_v=1. Both show good agreement with the other results.

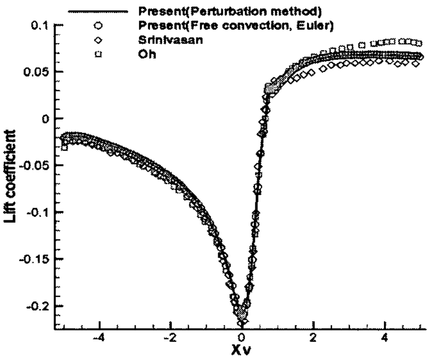


Figure 4. Lift coefficient.

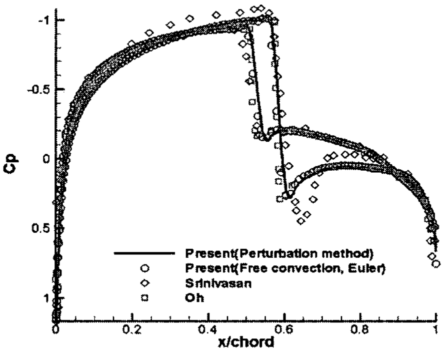


Figure 5. Pressure coefficient at x_v=1.

For detecting acoustic waves, acoustic pressures are directly measured at 5 times chord length apart from the aerodynamic center. Maximum peaks from among the acoustic pressures can represent directivity of acoustic field. In Figure 6, we can confirm that directivity pattern is dipole. Because of this characteristic, acoustic waves at the upper and lower airfoil are strong. Figure 7 shows that acoustic pressure at the fixed position varies with vortex position (x_v). In Figure 7, two pulses are shown. One is from leading edge. And another is from trailing edge. Pulse from leading edge is stronger than that from trailing edge. And acoustic pulses at the upper and lower part are more dominant.

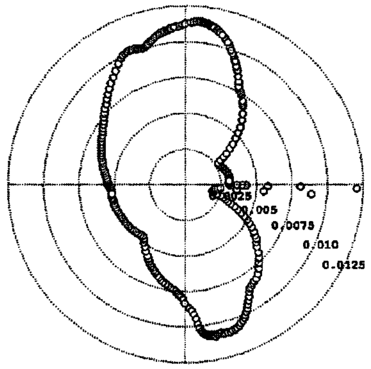


Figure 6. Directivity.

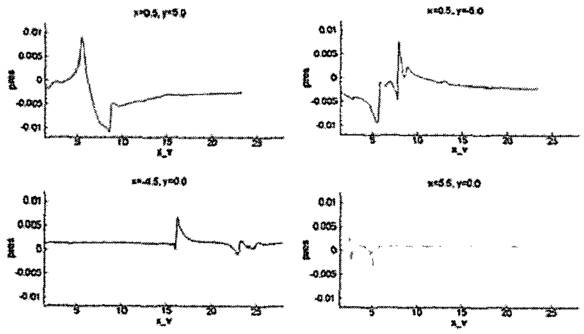


Figure 7. Acoustic pressure variation at fixed position.

IV. Conclusions

Lift and pressure coefficient of the vortex embedded CAA method accords with the other results very well. Therefore this method is validated. The vortex embedded CAA method can simulate acoustic waves including vortex variation effects. In Figure 2,3 , we can find acoustic waves generated at mainly leading edge. BVI noise is governed by acoustic waves induced interaction between leading edge and vortex. [14] We can confirm the vortex embedded CAA method is possible for BVI noise.

In three dimensional BVI, vortex position and strength are changed relatively in chordwise planes at each time because vortex filament has curved line geometry. Since the vortex embedded CAA method has advantage to change vortex information, two dimensional simulation in chordwise plane with vortex embedded CAA method is so useful. Three dimensional informations (vortex strength, trajectory) can be obtained from the other method such as free wake method.

References

1. G. R. Srinivasan, "Numerical Simulation of the interaction of a Vortex with Stationary Airfoil in Transonic Flow," AIAA 22nd Aerospace Sciences Meeting, 1984.
2. G. R. Srinivasan, "Aerodynamics of Two-Dimensional Blade-Vortex Interaction," AIAA Journal, **24** (10) 1986.
3. J. C. Hardin, and S. L. Lamkin, "Concepts for Reduction of Blade Vortex Interaction Noise," Journal of Aircraft, **24** (2) 1987.
4. D. J. Lee and C. A. Smith, "Effect of Vortex Core Distortion on Blade-Vortex Interaction," AIAA Journal, **29** (9) 1991.
5. J. S. Preisser, T. F. Brooks and R. M. Martin, "Recent Studies of Rotorcraft Blade-Vortex Interaction Noise," Journal of Aircraft, **31** (5) 1994.
6. Y. H. Yu, B. Gmelin, W. Splettstoesser, J. J. Philippe, J. Prieur and T. F. Brooks, "Reduction of Helicopter Blade-Vortex Interaction Noise by Active Rotor Control Technology," Progress in Aerospace Science, **33** 647-687, 1997.
7. K. S. Brentner and F. Farassat, "Helicopter Noise Prediction: The Current Status and Future Direction," Journal of Sound and Vibration, **170** (1) 1997.
8. Y. H. Yu, "Rotor blade-vortex interaction noise," Progress in Aerospace Science, 2000.
9. J. W. Kim and D. J. Lee, "Optimized compact finite difference schemes with maximum resolution," AIAA Journal, **34** (5) 1996.
10. J. W. Kim and D. J. Lee, "Formulation and Application of Generalized Characteristic Boundary Conditions for Computational Aeroacoustics," AIAA Journal, **38** (11) 2000.
11. J. W. Kim and D. J. Lee, "Adaptive Nonlinear Artificial Dissipation Model for Computational Aeroacoustics," AIAA Journal, **39** (5) 2001.
12. W. S. Oh, J. S. Kim and O. J. Kwon, "Numerical Simulation of Two-Dimensional Blade-Vortex Interactions Using Unstructured Adaptive Meshes," AIAA Journal, **40** (3) 2002.
13. T. H. Pulliam and J. L. Steger, "Implicit Finite Difference Simulation of Three-Dimensional Compressible Flow," AIAA Journal, **18** (2) 159-167, 1980.
14. D. J. Lee, "Surface Pressure Fluctuations due to Impinging Vortical Flows upon an Airfoil," AIAA/ASME/SIAM/APS 1st National Fluid Dynamics Congress, 1988.

[Profile]

•Seong-Yong Wie
2004 : B.S. degree in Aerospace Engineering, KAIST
2006 : M.S. degree in Aerospace Engineering, KAIST
2006~present : Ph.D. course, Department of Aerospace Engineering, KAIST

•Duck-Joo Lee
1977 : B.S. degree in Aerospace Engineering, Seoul National University
1980 : M.S. degree in Aero&Astronautics, Stanford University
1985 : Ph.D. degree in Aero&Astronautics, Stanford University
1985~1987 : NRC Fellow, NASA Ames Research Center
1988~present : Professor, Department of Aerospace Engineering, KAIST