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

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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 convection vortex and airfoil. For the application to three dimensional free vortex embedded CAA, two dimensional free vortex embedded method was validated in advance.

▪ 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.

Recent studies of rotor's aerodynamics and noise 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]

BVI means that blade tip vortex occurred at rotor blade interacts the following blade. 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 shown in Figure 1. 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.

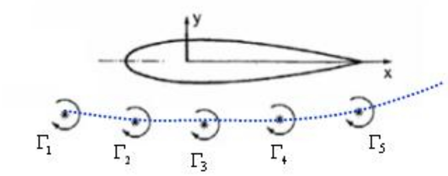


Figure 1 Vortex trajectory and strength variation

- **Governing equation**

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_f. ($Q = Q_V + Q_f$)

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

where

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

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

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

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

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

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

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.

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

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

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

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_f are obtained in equation (4) at each time. Finally, the unknown part can be predicted by solving (4), then we can confirm flow variation occurred by vortex.

▪ Numerical procedure

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. The central compact scheme used is shown below.

$$\beta f_{i-2} + \alpha f_{i-1} + f_i + \alpha f_{i+1} + \beta f_{i+2} = c\frac{f_{i+3} - f_{i-3}}{6\Delta x} + b\frac{f_{i+2} - f_{i-2}}{4\Delta x} + a\frac{f_{i+1} - f_{i-1}}{2\Delta x} \tag{9}$$

where

$$\begin{aligned} a &= 1.279672797796143 \\ b &= 1.051191982414920 \\ c &= 0.04475268855213291 \\ \alpha &= 0.5900108167074074 \\ \beta &= 0.09779791767419070 \end{aligned} \tag{10}$$

4th order Runge-Kutta scheme is used for integration in time. Procedure of this scheme is shown below.

$$\frac{\partial f}{\partial t} = F(f) \tag{11}$$

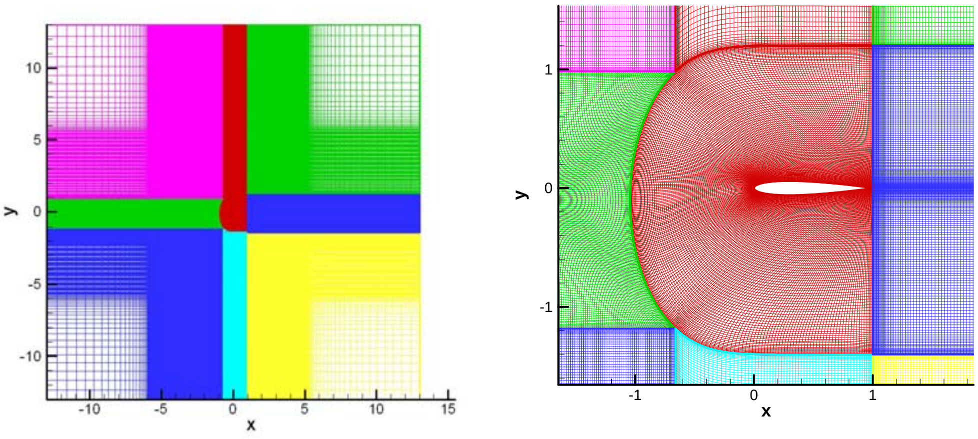
$$\circ \ \text{For} \quad m = 1...4, \qquad K^m = F(f^n + k_m K^{m-1})\Delta t \qquad\qquad \circ \ \text{Then,} \qquad f^{n+1} = f^n + K^p \tag{12}$$

where

$$k_1 = 0, \quad k_2 = \frac{1}{4}, \quad k_3 = \frac{1}{3}, \quad k_4 = \frac{1}{2} \tag{13}$$

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 2 shows grid used for numerical procedure. Grid is composed of nine blocks. And the number of total node is 245800.



(a) (b)

Figure 2 Grid (a) The entire region (b) At the near region of airfoil

▪ Results

Before finding solution of BVI problem, steady solutions are obtained without vortex. At Mach number = 0.8, NACA0012 airfoil type, angle of attack (AOA) = 0°, pressure coefficient is shown in Figure 3.

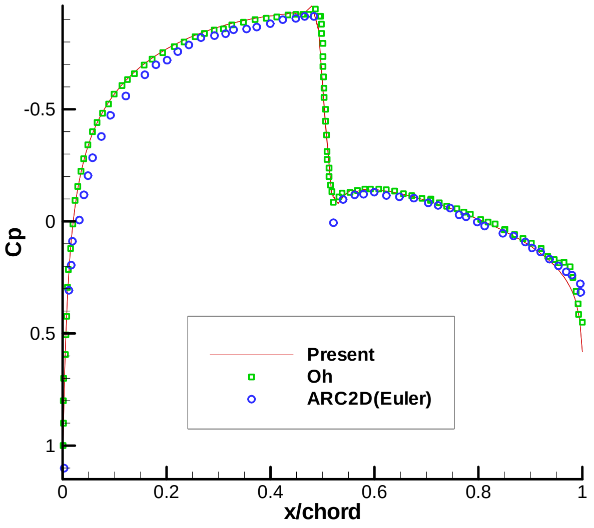


Figure 3 Pressure coefficient (NACA0012, M=0.8, AOA=0°)

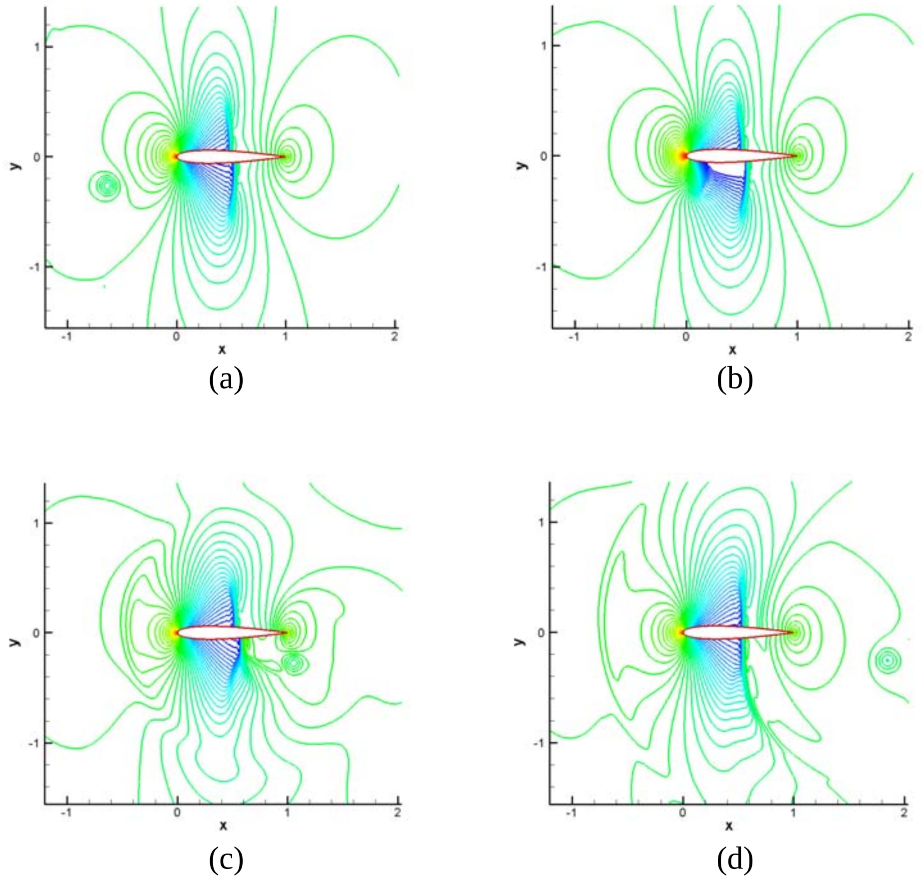
Present solution using high order high resolution scheme is compared with Oh et al.[12] and ARC2D[13]. This result accords with the other results.

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

Table 1 Vortex initial condition

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 embedded 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).

Figure 4 (a), (b), (c) and (d) are pressure contour during BVI. It is shown that acoustic waves are generated during interaction for the high resolution calculation. Figure 5 is lift coefficient and Figure 6 is pressure coefficient at vortex position x_v=1. Both show good agreement with the other results.



(a) (b)

(c) (d)

Figure 4 Pressure contours during BVI (a) x_v=-0.6 (b) x_v=0.2 (c) x_v=1 (d) x_v=1.8

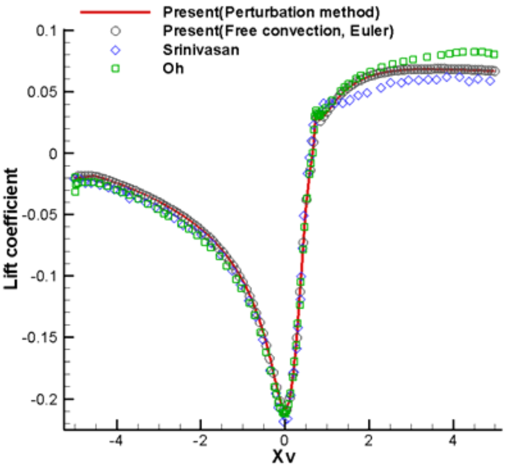


Figure 5 lift coefficient

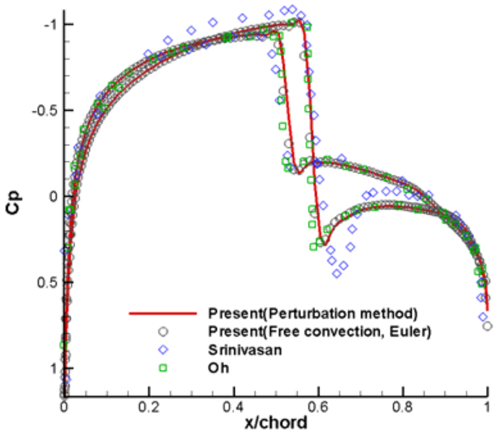


Figure 6 pressure coefficient at x_v=1

▪ Discussion

Unsteady pressure fluctuation is occurred at surface owing to blade vortex interaction. And in Figure (4) (a)-(d), we can find pressure variation generated at mainly leading edge. BVI noise is governed by interaction between leading edge and vortex. [14]

Lift and pressure coefficient of the embedded method accord with the other results very well. Therefore the embedded method using 3D vortex information is validated. We can confirm the 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 embedded method has advantage to change vortex information, two dimensional simulation in chordwise plane with embedded CAA method is so useful. Three dimensional variations of vortex strength and position can be obtained from the other method such as vortex free wake method shown in Figure 6.

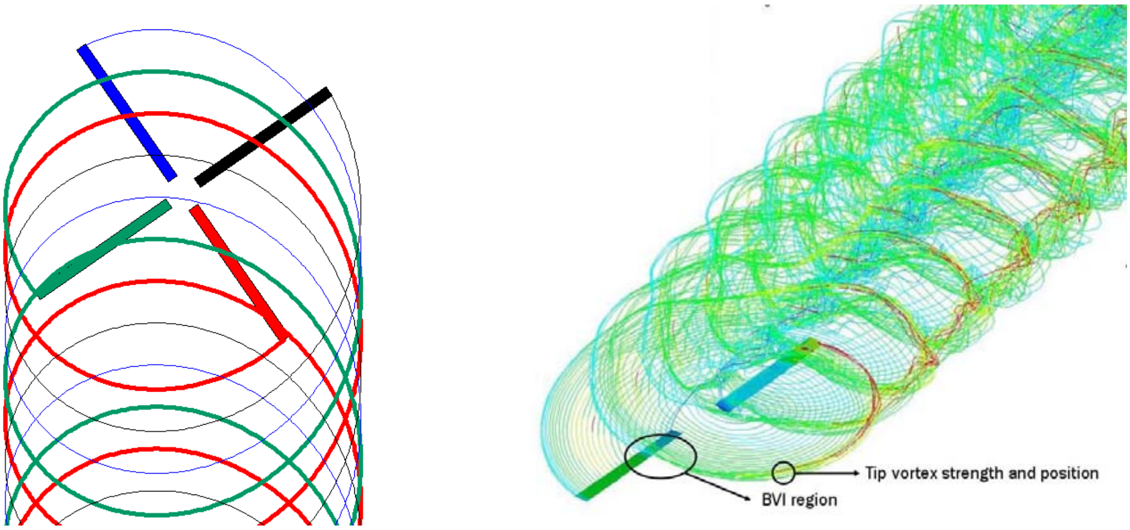


Figure 6 tip vortex geometry (a) trajectory of tip (b) solution of free wake method

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