Numerical Simulation of Two-Dimensional Parallel Blade-Vortex Interactions Using Large Eddy Simulation

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Abstract

In this paper, an unsteady, two-dimensional, parallel blade-vortex interaction (BVI) has been calculated using large eddy simulation (LES) and the predicted pressures are compared with experimental measurements. The BVI is a primary source of rotor vibratory loading and rotorcraft noise. The LES technique provides a promising tool for obtaining the unsteady wall-pressure fields, aerodynamic coefficients, and acoustic functions. The dynamic sub-grid scale stress model, the low diffusion Roe flux-difference splitting scheme, and second order accuracy in the time and space are used. The simulation was performed for $M_{tip}=0.714$ and $Re = 2.2 \times 10^6$, on a case where the miss distance equals 0, which will be referred to as a strong BVI. The simulation was first run until a unsteady compressible fully-developed turbulent flow field was achieved for the non-lifting NACA 0012 airfoil. Then, the Scully vortex, which has been widely used, was added to the fully-developed turbulent flow field as a perturbation. In the present computation, the spatial resolution close to the surface was very good. The wall $y^+$ was smaller than 0.6. The LES method can accurately preserve the characteristics of the vortex. The simulation which was low dissipative had a good agreement with the experimental results (C. Kitaplioglu, 1999). Moreover, the vortex had an important influence on the aerodynamic performance of the blade.

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1. Introduction

The major source of rotorcraft noise is generated by the rotor blades interacting with the vortices trailed from the preceding blades. This blade-vortex interaction (BVI) generates high amplitude impulsive noise that is particularly intense under certain flight conditions such as low speed descent and manoeuvres [1]. When the rotor blade and the tip vortex are very close and nearly parallel to each other, the interaction is particularly strong (though usually of short duration). This type of interaction is usually referred to as a parallel blade-vortex interaction [2]. At the simplest level, a parallel BVI problem can be reduced to a two-dimensional airfoil–vortex interaction and is the subject of this numerical investigation.

Numerical simulation is an important tool used to study the BVI at present. Most previous studies simulated the BVI using unsteady Euler equations or URANS. Marcel Ilie [3, 4] simulated the two-dimensional blade-vortex interaction using large eddy simulation first. These studies focused on only low speed incompressible flow. Thom [1] performed high-resolution simulations of parallel BVI using the solution of the compressible Euler equations on overset meshes. In order to simulate a BVI accurately, at first the vortex structure must be preserved accurately as the vortex convects through the blade. Furthermore, the numerical dissipation that is inherent in CFD simulations should be minimized. An approach aiming at overcoming the difficulty is large eddy simulation which is a powerful and promising tool in direct computation of aero-acoustics, as well as in complex turbulent flow [5, 6].

1. Computational method and models

In the present work, the 2-D simulations were performed for Re=2.2e6, Ma=0.714 on the tip, and the miss distance equals 0 at a zero angle of attack. A body conforming C topology mesh was used to discretize the domain of a NACA 0012 airfoil. To accurately simulate the BVI, the large eddy simulation, the dynamic sub-grid scale stress model, the low diffusion Roe flux-difference splitting scheme and second order accuracy in the time and space are used.

The simulation is first run until an unsteady compressible fully-developed turbulent flow field has been achieved for the non-lifting NACA 0012 airfoil. Then, the Scully vortex which has been widely used is added to the fully-developed turbulent flow field as a perturbation. These parameters are obtained from the experimental work of McAlister and Takahashi [7], where the vortex trailed from a NACA 0015 wing was studied. The approach of using the McAlister vortex data to simulate the Caradonna experiments has been widely used before in similar simulations, however, most previous studies have imposed the vortex as a moving, constant strength perturbation from the velocity field [1]. In the present work, the vortex is free to convect and deform, allowing a strong interaction case where the vortex directly impacts upon the blade to be realistically simulated. The vortex was initiated two chords ahead of the airfoil.

2. Results and discussion

Before simulations, the mesh must be refined in order to keep $y^+$ smaller than 1. The Fig 1 shows the results of no vortex, instantaneous, compressible, and fully-developed turbulent flow field at dimensionless time 15.5 using LES method. These results were used to the initial flow field of the BVI simulations. Fig 1 (a) shows the entropy contours. Entropy generation is high in the region close to the airfoil. Fig 1 (b) shows the root mean square of the pressure coefficient fluctuations on the surface of the airfoil. It can be seen that the intensity of turbulence become strong near the tail, and the details of turbulence flow can be gained by the LES. The wall $y^+$ was smaller than 0.6. Thus, the mesh is fine enough for the simulations.
After gaining the initial flow field, the dimensionless physical time was reset to zero, and the Scully vortex was superimposed as a perturbation. Fig 2 shows the flow time history of lift and drag during the BVI process. The lift and drag coefficients is affected by the press distribution over the airfoil surface. From Fig 2 (a), it can be seen that the lift become decreased as the vortex core arrives near the leading edge of the airfoil. At that time, the blade and vortex start to interact. The vortex continues to move downstream, arriving at the airfoil leading edge, the minimum value of lift will come out. At that time, the interaction is the strongest. After vortex core passes the leading edge, the lift coefficient has a sudden change, and the lift starts to increase. The sudden change can produce the BVI noise. As the vortex core arrives near the tip of the airfoil, the lift coefficient has maximum value. After that, the lift coefficient becomes decreased. Because the vortex core moves away from the airfoil, and the interaction becomes weak. At last, the lift coefficient is zero as the same as before interacting, and the interaction is over. The time history of lift coefficient has agreement with the incompressible LES results [3].
From Fig 2 (b), the time history of drag coefficient is almost the same as the lift coefficient. But drag coefficient has more drastic changes, and is different with the incompressible LES results [3]. Maybe, the compression effect has big effect on the drag coefficient, has small effect on the lift coefficient.

Fig 3 (a) shows the profile of vortex velocity as vortex converts from initial position at the five different dimensionless time 0.042, 0.065, 1.043, 1.46, and 2.10. At the time 0.042, the vortex just starts to move downstream. At the time 2.10, the vortex and airfoil start to interact. After the time 2.10, the vortex will deform and be broken. From the Fig 3 (a), before BVI, the characteristics Scully vortex can be preserved. So the numerical dissipation of these simulations is low enough.

Fig 3 (b) shows the wall pressure distribution on the lower surface of the airfoil at the dimensionless length 0.02. This point on the airfoil surface is the closest to the leading edge of the experimental measurement set, and is subject to the sharpest pressure gradients. Note that the solution time of the two-dimensional simulation has been converted to the equivalent of rotor azimuth to directly compare against experiment. Also the pressure value has been offset to best correspond with the experimental data [1]. From Fig 3 (b), it can be seen that, in the range of equivalent of rotor azimuth from 170 degree to 190 degree, the simulated pressure has good agreement with the experiment data, in spite of this being two dimension simulation.

3. Conclusions

In this paper, the two-dimension, parallel, blade vortex interaction was numerical simulated using LES. The LES results show that LES can predict the detail of the turbulence flow accurately; the lift and drag coefficients was effected by the vortex; when the vortex was free to convect and deform before starting to interact, LES can preserve the characteristics of the vortex; the LES results which were low dissipative had a good agreement with the experimental results.

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