NUMERICAL INVESTIGATION OF FLOW AROUND AN AIRFOIL WITH UNSTEADY MOVING

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Abstract

In this study, unsteady aerodynamical effect of accelerated or decelerated two-dimensional airfoil (NACA0012) was numerically examined using a grid-free vortex method. The flow characteristics and aerodynamical forces were compared among various accelerated or decelerated conditions. The results showed that large flow separation occurred under decelerated condition than accelerated condition and constant condition. Furthermore, the lift-drag ratio decreased as the decelerated velocity became high and increased as the accelerated velocity became high.

1 General Introduction

Vehicles like airplane, automobile and fluid machineries are operated under various conditions and they do not usually move at a constant speed. On the other hand, most of the wind tunnel tests or numerical simulations via Computational Fluid Dynamics (CFD) have been carried out for steady states, even though it is well known that the aerodynamic characteristics under unsteady speed condition is different from the one under constant speed condition. In order to realize higher performance vehicles and fluid mechanics, the unsteady characteristics should be considered at the design stage. Since experimental prediction of the effect or real flight test is difficult, new numerical simulation methods which can predict the aerodynamical characteristics of moving geometries are expected.

Vortex methods are grid-free numerical schemes. In the methods, vorticity distributions in the flow fields are represented by using discrete vortex elements and the motion and evolution of vorticity of each element are calculated at each time step. When compared to other computational schemes, vortex methods have the advantage that unsteady distortion of vortical structures in turbulent flows is directly calculated without the numerical diffusion and the method can easily be applied to moving geometries. So the methods are appropriate methods for prediction of unsteady aerodynamical characteristics of moving bodies.

On unsteady aerodynamical characteristics, some pioneering works have already been carried out, Maresca et al. [1] experimentally investigated oscillating airfoils, but unsteady force could not be obtained. Fukuta and Yokoi [2] numerically and experimentally examined flow around in-line oscillating airfoil. The results showed that flow separation was developed from the unsteady effect.

In this study, unsteady aerodynamical characteristics of accelerated or decelerated airfoil (NACA0012) were numerically examined using a grid-free vortex method.

2 Numerical Method

The basic equations of the vortex method in incompressible flow, is the continuity equation and the vorticity transport equation. vorticity transport equation in two-dimensional incompressible flow and Continuity equation are defined by the following equation.

$$\frac{d\boldsymbol{\omega}}{dt} = \nu\nabla^2\boldsymbol{\omega} \qquad (1)$$

$$\nabla \cdot \boldsymbol{u} = 0 \qquad (2)$$

where $\boldsymbol{u}$ is a velocity vector and the vorticity $\boldsymbol{\omega}$ is defined as $\boldsymbol{\omega} = \mathrm{rot}\, \boldsymbol{u}$. In the vortex methods, the time evolution of the flow is represented by the motion and evolution of vorticity strength of each element.

In this study, the viscous term was expressed by the core spreading method proposed by Leonard [3]. The velocity filed was determined by the Biot-Savart law as explained by Wu and Thompson [4].

$$\boldsymbol{u} = \int_V \boldsymbol{\omega}_i \times \nabla_i G dV + \int_S \left[(\boldsymbol{n}_j \cdot \boldsymbol{u}_j) \cdot \nabla_j G - (\boldsymbol{n}_j \times \boldsymbol{u}_j) \times \nabla_j G \right] dS \qquad (3)$$

Here, subscript "i" represents the physical amount at the position r_i present in the region V and boundary surface S. And G is the fundamental solution of the scalar Laplace equation with the delta function. If $\boldsymbol{R} = |\boldsymbol{r} - \boldsymbol{r}_i|$, which is written for a two-dimensional field as $G = -1/(2\pi)\log R$. In Eq. (3), the inner product $n_j \cdot u_j$ and the outer product $n_j \times u_j$ stand for normal velocity component and tangential velocity vector on the boundary surface. They correspond to the source distribution on the surface and the vortex distribution that has the rotating axis in parallel to the surface. The source and vortex corresponding to the second and third terms of right hand side of Eq. (3) are distributed on the boundary surface. On the other hand, with respect to pressure analysis, is used Eq. (4) pressure integral equations obtained from by introducing the $H = p/\rho + |\mathbf{u}|^2/2$ called Bernoulli function pressure Poisson equation.

$$\beta H + \int_S H \frac{\partial G}{\partial n} ds = -\int_V \nabla G \cdot (\mathbf{u}_i \times \boldsymbol{\omega}_i) dV - \nu \int_S \mathbf{n}_i \cdot (\nabla G \times \boldsymbol{\omega}_i) dS \qquad (4)$$

It is possible to determine the pressure by applying the boundary element method to the Eq. (4) to calculate the value of H. Here, β=1 in the flow field and β=1/2 on the boundary S. The exact solution of the Navier-Stokes equation for a straight line vortex filament of infinite length, and the vortex core radius ε radius the rotational speed is the maximum rate of change that time is represented as follows.

$$\frac{d\varepsilon}{dt} = \frac{c^2}{2\varepsilon}, \ (c = 2.242) \qquad (5)$$

Vorticity $\boldsymbol{\omega}_i(\boldsymbol{r})$ is expressed as follows by the $\Delta\Gamma_i$ the circulating volume representing the vortex element i, using the Gauss distribution vorticity distribution.

$$\boldsymbol{\omega}_i(\boldsymbol{r}) = \frac{\Delta\Gamma_i}{\pi\, \varepsilon_i^2} \exp\left(\frac{R^2}{\varepsilon_i^2} \right) \qquad (6)$$

3 Calculation Conditions

In this study, firstly, flow around a two-dimensional wing moving at a constant speed was calculated in order to understand aerodynamical characteristics under the steady-state motion condition. Secondly, flow around the wing moving under accelerated or decelerated condition was calculated in order to examine unsteady aerodynamical characteristics. The numerical model of the wing was expressed by 500 surface panels as shown in Figure 1. Under constant velocity condition, the Reynolds number was set to be $\mathrm{Re}=V_0 C/\nu = 4.0\times10^5$, here V_0 is the constant velocity and C is the chord length. The attack of angle (AoA) was set to be 3.0$^{\mathrm{o}}$ and 5.0°. The non-dimensional time step was $\Delta t V_0/C$=0.0025. Surface vortex panels were set on the surface of the body and the height was 0.004C based on the appropriate height proposed by Ota et al. [5]. For the accelerated or decelerated condition, non-dimensional accelerated velocity was set to be α = 0.1, 0.5, -0.1, -0.5, respectively. For the accelerated or decelerated condition, firstly, calculation at the constant velocity was carried out until the aerodynamical forces became stable, and then the velocity was changed.

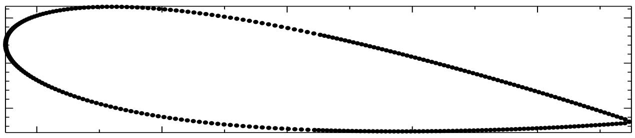


Fig. 1. Numerical model(NACA0012)

4 Results

4-1 Results of AoA=3$^{\mathrm{o}}$

Figures.2-4 show the flow pattern around trailing edge at the same time for each calculation cases of AoA=3$^{\mathrm{o}}$. The color contour shows the vorticity strength of each vortex element. The difference of flow around airfoil was not found at each case.

The analyzed fluid forces under each condition are shown in Figures 5-7. In the accelerated cases, the lift coefficient increased as time went on. On the other hand, in the decelerated cases, the lift coefficient decreased as time went on. The growth rate became high as the accelerated or decelerated velocity became high. About the drag coefficient, in early time, increase and decrease were occurred rapidly. Furthermore, Figure 7 shows that the lift-drag ratio decreased as the decelerated velocity became high and increased as the accelerated velocity became high.

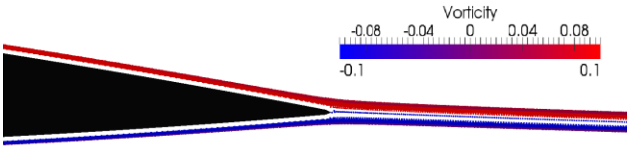
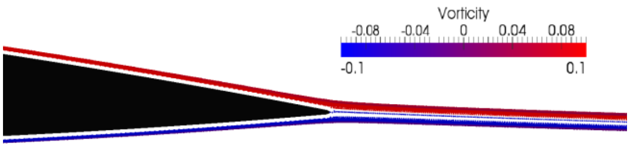


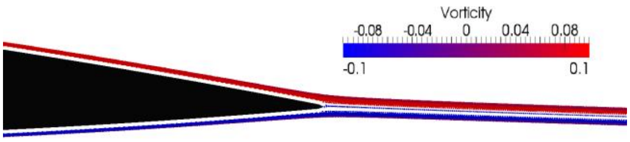
Fig. 2. Flow pattern (AoA = 3°, Constant moving)



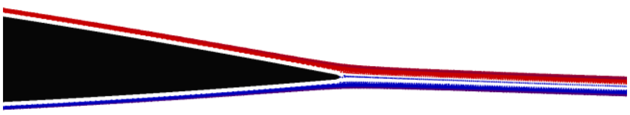
(a) α= -0.1

(b) α= -0.5

Fig.3. Flow pattern (AoA = 3°, accelerated case)



(a) α= -0.1



(b) α= -0.5

Fig. 4. Flow pattern (AoA = 3°, decelerated case)

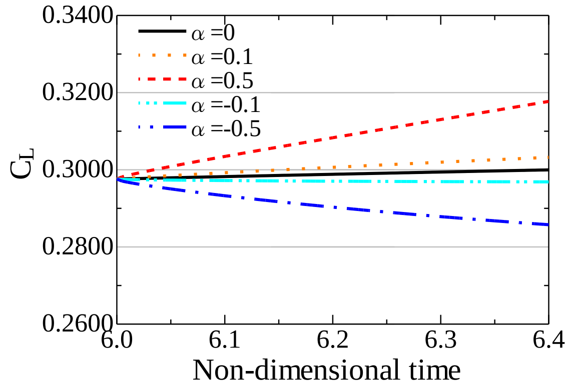


Fig. 5. Time history of Lift coefficient (AoA = 3°)

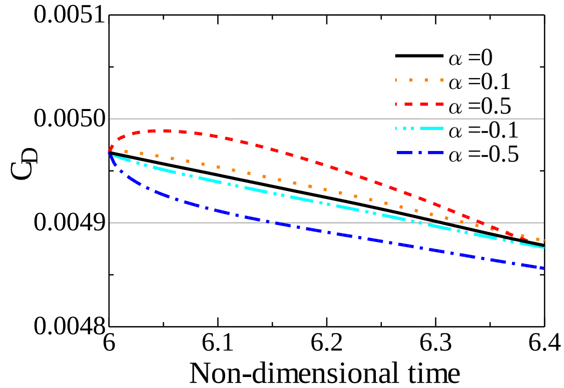


Fig. 6. Time history of Drag coefficient (AoA = 3°)

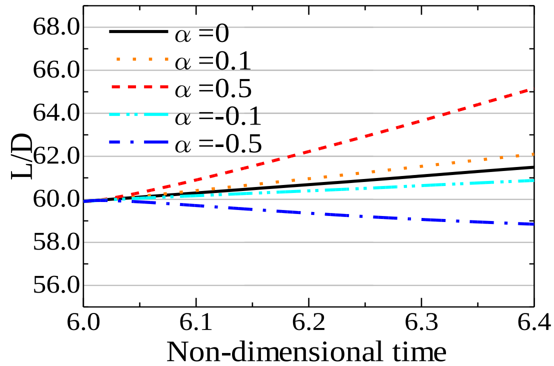


Fig. 7. Time history of Drag coefficient (AoA = 3°)

4-2 Results of AoA=5°

Figures.8-10 show the flow pattern at the same time for each calculation cases of AoA=5°. As compared with constant velocity case and accelerated case, larger vortex structure generated at the trailing edge under decelerated condition. As the non-dimensional decelerated velocity became high, the growth of the vortex structure became rapid.

The analyzed fluid forces under each condition are shown in Figures 11-13. In the accelerated cases, the lift coefficient increased as time went on. On the other hand, in the decelerated cases, the lift coefficient decreased as time went on. The growth rate became high as the accelerated or decelerated velocity became high. About the drag coefficient, in the accelerated cases, the drag coefficient decreased as time went on, and in the decelerated cases, the drag coefficient increased as time went on. The growth rate became high as the accelerated or decelerated velocity became high. Furthermore, figure 13 shows that the lift-drag ratio decreased as the decelerated velocity became high and increased as the accelerated velocity became high.

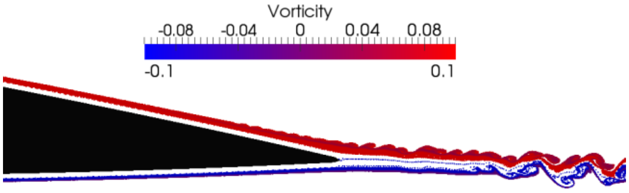
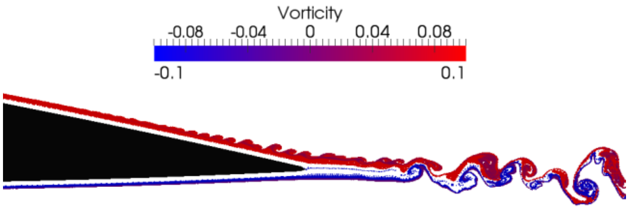
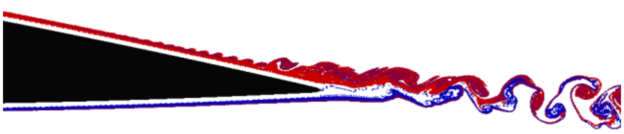


Fig. 8. Flow pattern (AoA = 5°, Constant moving)

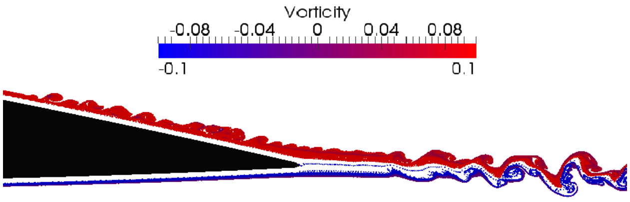


(a) α=0.1

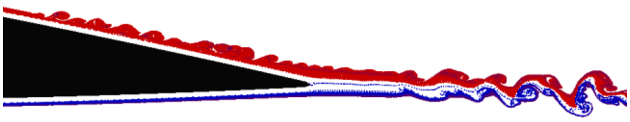


(b) α=0.5

Fig. 9. Flow pattern (accelerated case)



(a) α= -0.1



(b) α= -0.5

Fig. 10. Flow pattern (decelerated case)

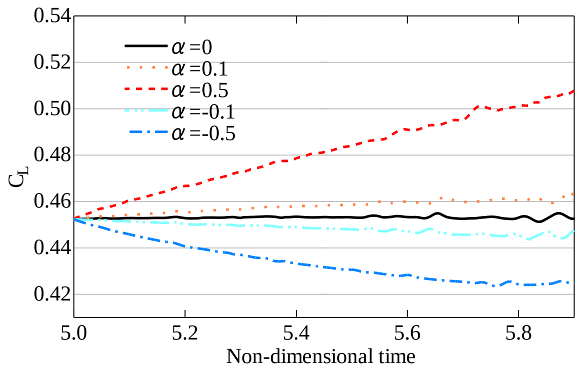


Fig. 11. Time history of Lift coefficient

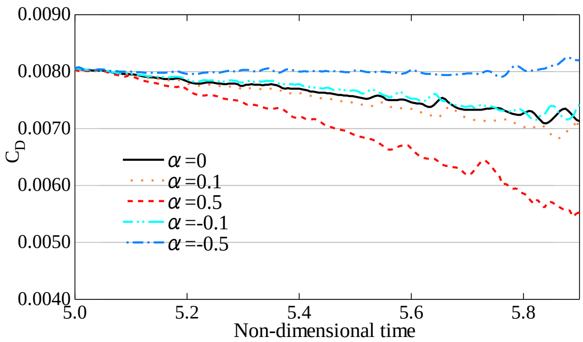


Fig. 12. Time history of Drag coefficient

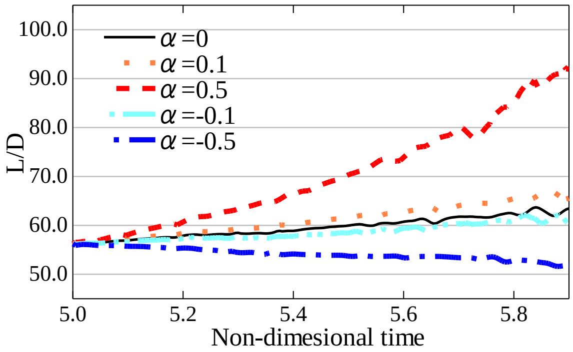


Fig. 13. Time history of Lift-Drag coefficient

5 Conclusions

In this paper, unsteady aerodynamical effect of accelerated or decelerated two-dimensional airfoil (NACA0012) was numerically examined using a grid-free vortex method. The results in the case of AoA=5^o showed that larger vortex structure generated at the trailing edge under decelerated condition than under constant velocity condition and the growth of the vortex structure became rapid as the non-dimensional decelerated velocity became high. Furthermore, it was confirmed that the lift-drag ratio decreased as the decelerated velocity became high and increased as the accelerated velocity became high.

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