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Numerical Simulation of Flow Past Oscillating Airfoil Using Oscillation of Flow Boundary Condition

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The present study is devoted to an approximate modeling for numerical simulation of flows past oscillating airfoils. In this study, it is shown that the harmonic oscillating objects can be studied by simple numerical codes that are unable to solve moving grids. Instead of using moving grids for the simulation of the flowfield around an oscillating airfoil, this unsteady flow is solved on a fixed grid having oscillated its free stream velocity vector on the boundaries. It is shown that, with a time shift, resulting airfoil forces have a good agreement with moving grid results. This time shift, which is not noted by others, is the time that takes for the flow to move from upstream boundary and pass the airfoil completely. Resulting C_l *-* α *ellipse diameter using this approximate modeling, is only a little bigger than the experimental results. This modeling is applicable in simple codes that are not able to model moving grids.*

NOMENCLATURE

c	Airfoil chord length
C_l	Lift coefficient
C_N	Normal force coefficient
dt	Time step
k	Reduced frequency ($k = \frac{\omega_\alpha c}{2V_\infty}$)
M	Mach number
P_∞	Free stream pressure
Re	Reynolds number
t	Time
T	Time period of oscillation
V_∞	Free stream velocity
α	Angle of attack
α_m	Angle of attack at t=0
α_p	Amplitude of oscillation
ω_α	Angular velocity of oscillation

INTRODUCTION

Unsteady flows passing moving objects (e.g. oscillating airfoils) can be modeled using two approaches. One uses a moving grid which results in a more accurate solution[1,2], and the other uses an approximate modeling which will be discussed in this paper. Moving grid methods implement mesh changing algorithms[3]. If at each time step, the boundary movement is smaller than the minimum mesh size in the domain, local grid restructuring methods[4] can be used. With respect to the high cost of mesh insertion and deletion in such methods, the idea of dynamic meshes was introduced [5,6], which implements mesh smoothing instead of insertion and deletion of near boundary grids. Mesh smoothing is used until mesh quality has not degraded. Mesh quality depends on several criteria. Some of these criteria have been discussed in Ref. 7. In problems involving large displacements of moving objects, Chimera grids can be applied [8,9]. The main point in this method is implementation of accurate conservative interpolations.

The simplest approach to approximate modeling of unsteady flow is quasi steady solution. In this approach, at each time step it is assumed that flow (e.g. over an airfoil) is locally steady. With this assumption, at each time step, C_l is equal to the C_l of an airfoil that

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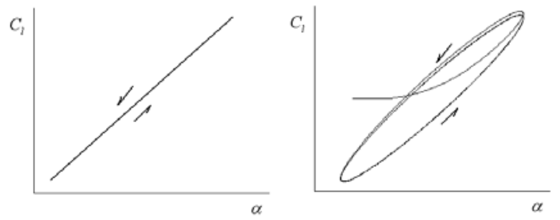

Figure 1. C_l- α curve for a: very low speed oscillation, and b: high speed oscillation.

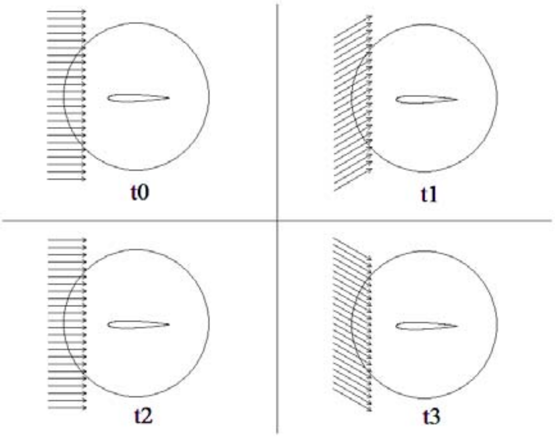

Figure 2. Oscillatory change of free stream velocity vector orientation.

is fixed at the same angle of attack. Therefore, during the airfoil pitch up or pitch down periods, C_l will be the same at an equal angle of attacks. As a result, the curve of C_l- α will be a straight line (Figure 1a).

The quasi steady assumption will be valid only if the airfoil oscillation is negligible with respect to flow velocity. In cases where the speed of airfoil oscillation is in the order of flow speed or higher, the flow field about the oscillating airfoil can not be assumed steady at each time step, and therefore quasi steady assumption would not be valid. In such cases, the C_l - α curve will become elliptic; see Figure 1b.

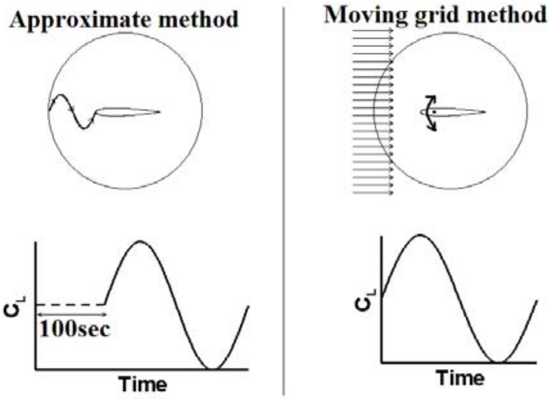

Figure 3. Difference between C_l -time curves of flow over an oscillating airfoil and oscillating flow over an airfoil.

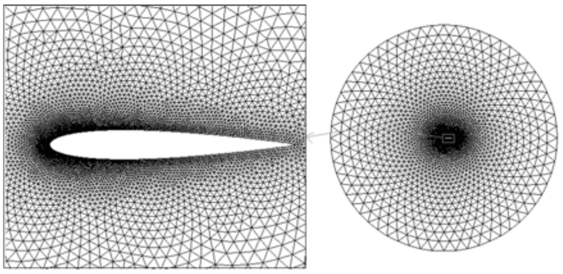

Figure 4. Domain and the generated mesh for NACA0012.

The main purpose of this paper is to demonstrate the capability of an approximate modeling and its drawbacks to analyze the flow field around an oscillating airfoil by oscillating farfield boundary conditions. In this paper, details of this approach and the differences between this modeling and the moving grid method are described, physically and numerically by comparing the results of these two methods.

MODELING OF FLOW PAST OSCILLATING AIRFOIL

A simple way for modeling flow past oscillating airfoil is to oscillate the free stream velocity vector at the farfield boundary instead of oscillating the airfoil itself; see Figure 2.

It must be noticed that from a physical point of view, steady free stream flow past oscillating airfoil is different from an oscillating flow past a fixed airfoil. To show this, assume that an airfoil with 1m chord is located in a circle domain with a radius of 1000m. A flow at a speed of 10m/s passes over this airfoil at zero incidence. In this case, if the airfoil oscillates in a sinuous fashion with a time period of 1s, the C_l -time curve will be in a sinuous form with the same time period. Now, if we model this problem assuming a fixed airfoil and an oscillating free stream velocity vector, the results will be different. In this case, the airfoil will not produce any lift at the first 100s, however after this, a sinuous C_l -time curve with the time period of 1s will be formed (Figure 3). The main difference between the two methods is the delay time required for flow to travel from the boundary to the airfoil in the second method. This time delay, which is about 100s, depends on the flow speed (V_∞) and the distance between outer boundary and the airfoil (L); i.e. $\Delta t = \frac{L}{V_\infty}$.

The above analysis is studied numerically by considering flow past a NACA0012 airfoil. The angle of attack varies as $\alpha(t) = \alpha_m + \alpha_p * \sin(\omega_\alpha * t)$, and the pitching angular velocity, defined in terms of reduced frequency k, is given by: $\omega_\alpha = 2k * V_\infty / c$, where k=0.0814, α_m =0.016 deg, α_p =2.51 deg, and the flow parameters are M_∞ =0.755, P_∞ =1 atm, and T_∞ =298 k. The present modeling is performed using a prepared coupled unsteady Euler solver. The Euler equations are solved implicitly using first order upwind scheme. The airfoil chord length is c=1m and the circular outer

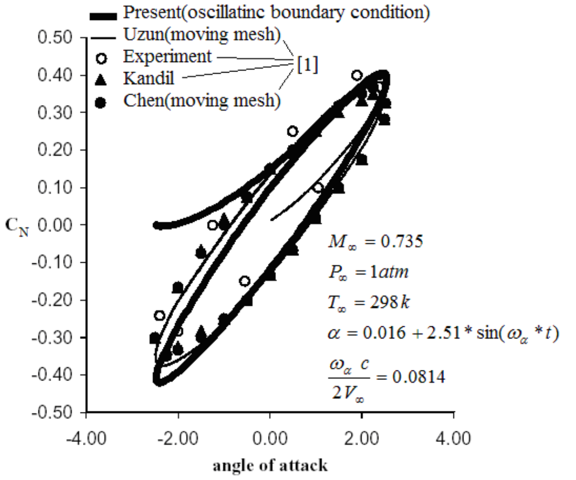

Figure 5. Numerical results of inviscid flow past NACA0012 airfoil.

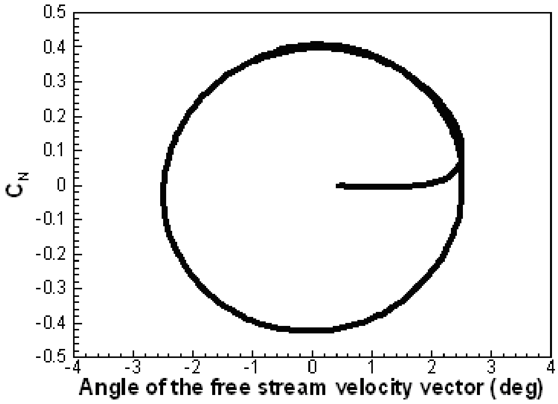

Figure 6. Numerical results of inviscid flow past NACA0012 airfoil (Present modeling without time delay correction).

boundary has a radius of r=10 m (Figure 4). Using a grid generation code, the domain is discretized into unstructured triangular meshes including 15000 cells.

Experimental and numerical results of this problem are given in Ref. 1. As discussed before, we would like to solve this problem on a fixed grid having oscillated its free stream velocity vector on the boundaries. Using Eq. (1), the angular velocity vector of oscillation would be ω_α =42.53 rad/s, which is equivalent to a time period of T=0.148s. Having chosen dt=0.001s, each cycle will include 148 time steps. Since the velocity of free stream is V_∞ =261m/s and the radius of outer boundary is 10m, after 0.0383s the airfoil surface will feel the change of angle of attack. In Figure 5, the present results are compared with the experimental data and other CFD results of Ref.1. According to the above analysis, we have implemented the time delay of 0.0383s by correcting the airfoil angle of attack as: $\alpha_{airfoil} = \alpha_m + \alpha_p \sin(\omega_\alpha(t - 0.0383))$. As seen earlier, except for the result of the first cycle, which is due to the transient nature of the problem, the result of the rest of the solution has an acceptable accuracy. Without considering this time delay, the resulting $C_N - \alpha$ curve will not be correct (Figure 6). In fact in Figure 6, the angle of attack of airfoil and the angle of free stream velocity vector on the boundary are the same.

The C_N values obtained by the present modeling at the extremum points are higher than the experimental data. This is because of the nature of the present modeling. In fact, at a particular time, the flow angle varies along the airfoil; see Figure 7. At very low speed flows, wave length of the oscillating flow is in the order of the airfoil chord. In this case, the present results will be different from other numerical results obtained by other moving grid methods. But in most oscillating airfoil problems, flow speed is high. For example, in our test case, wave length is 39m and the chord length is 1m. Therefore, the difference between the airfoil leading edge and the trailing edge angle of attacks is negligible (Figure 7b).

The computed instantaneous pressure coefficient distributions on the airfoil surface at the angle of attacks of 2.34 and -2.41 are given in Figures 8 and 9, respectively. As can be observed from these figures, the computed instantaneous pressure coefficient distributions are in good agreement with the experimental pressure coefficient distributions [1].

In our second test case, the compressible viscous

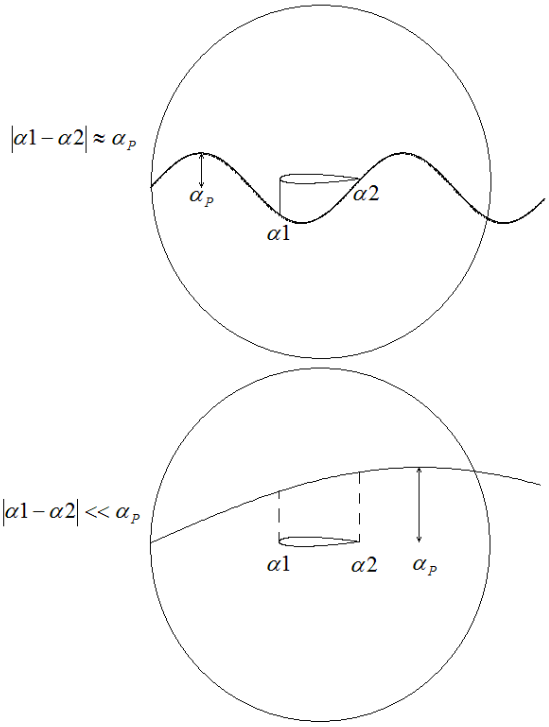

Figure 7. Oscillating free stream flow passing over the airfoil with a) short wave length and b) long wave length.

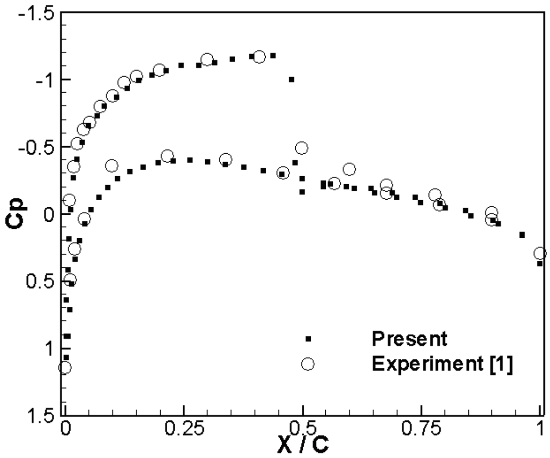

Figure 8. Pressure coefficient distribution at $\alpha = 2.34^o$ over oscillating NACA0012 airfoil.

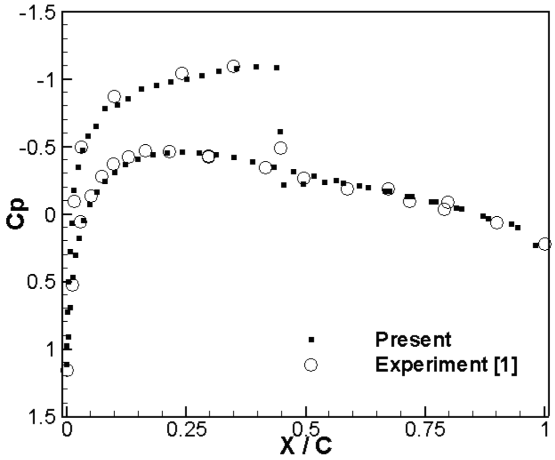

Figure 9. Pressure coefficient distribution at $\alpha = -2.41^o$ over oscillating NACA0012 airfoil.

flow of $M_\infty = 0.796$ and Re $= 12.5 * 10^6$ passes a 1 meter chord NACA64A010 airfoil. Airfoil oscillates at zero mean angle of attack with an amplitude of $\alpha_p = \pm 1.01^o$, and the reduced frequency of k=0.212. In this test case, the wave length of the sinuous oscillating flow is 15m. As in the case of the previous problem, this wave length is large enough in comparison to the airfoil chord. This problem is solved by the present modeling, using 200*50 C-type mesh (50 node normal to airfoil; see Figure 10) and a second order upwind discretization scheme of an implicit coupled solver with RNG $k-\epsilon$ turbulence modeling.

In this case, the so-called time delay is 0.015s. Considering this time delay, the resulting C_l - α curve is compared with the experimental data and the numerical results of Ref. 2 in Figure 11. With the dt of 0.0002s and T=0.093s, each cycle will contain 465 time steps. As in the case of the previous test, the diameter of C_l - α ellipse is bigger than that of the experimental data. As seen earlier, the present results have acceptable accuracy in cases that one can not access moving mesh codes.

CONCLUSION

In the present work, numerical modeling of flow past oscillating airfoils is studied. Instead of using moving grid solvers to model flow over oscillating airfoils, in this modeling orientation of the velocity vector at the free stream boundary is oscillated. Using this modeling, the resulting force on the airfoil shows good agreement with the results of a moving grid solver and the experimental data. Also, the computed instantaneous pressure coefficient distributions are in good agreement with the experimental pressure coefficient distributions. The resulting C_l - α ellipse diameter using this modeling is a bit larger than that of the experimental data. However, since the present modeling is applicable to all simple codes that are not able to solve moving grids, this overshoot is tolerable.

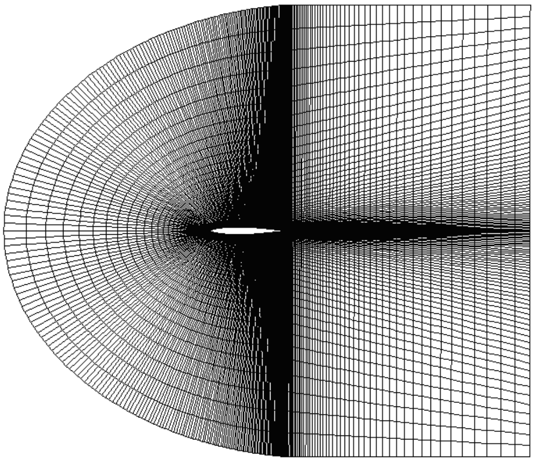

Figure 10. Generated grid for NACA64A010 airfoil.

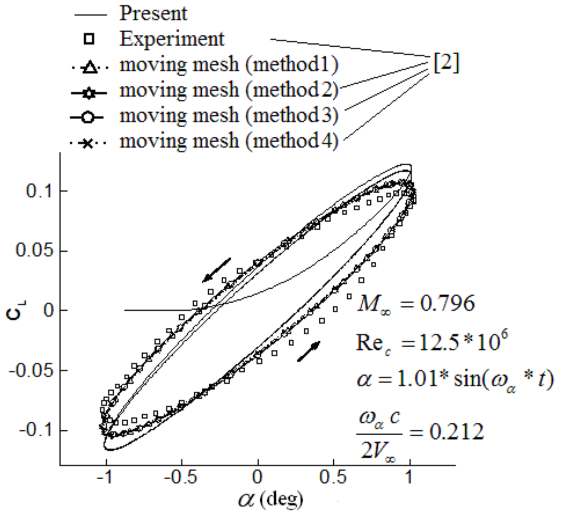

Figure 11. Present results for viscous flow past NACA64A010.

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