JOURNAL OF AIRCRAFT
Vol. 42, No. 5, September–October 2005

Engineering Notes

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Deforming Grid Technique Applied to Unsteady Viscous Flow Simulation by a Fully Implicit Solver

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Nomenclature

C_l	=	lift coefficient
C_m	=	pitching moment coefficient
C_p	=	instantaneous pressure coefficient
c	=	chord length of airfoil
k	=	reduced frequency of pitching motion
M_∞	=	freestream Mach number
Re	=	Reynolds number
α	=	angle of attack
α_m	=	mean angle
α_0	=	amplitude of oscillation
Δt	=	real time step

Introduction

THE unsteady flows associated with moving boundaries have long been of interest to aerodynamic research. For most unsteady problems, the computational grid has to conform to the instantaneous shape of a moving body. Thereby, grid regeneration, or movement techniques, becomes an important issue.

Rotating the grid system rigidly can easily treat rigid-body motions, but this approach is inapplicable if the body deforms, if the block boundaries have to be fixed for a multiblock grid system, or if the relative motion of a multicomponent configuration is to be considered. A simple way is to regenerate a grid at each physical time step. Obviously, this process will be very time consuming. It is a much more relatively difficult task when a three-dimensional problem must to be taken into account. An efficient grid-movement technique seems to be crucial for such problems, by which the grid system will be only deformed once per time step rather than regenerated completely in unsteady flow simulations.[1]

The present work attempts to develop an unsteady viscous flow simulating method for moving boundary problems with deforming grids in a multiblock grid system. The grid movement is mainly based on a transfinite interpolation (TFI) algorithm. The TFI technique is a very popular algebraic grid-generation technique that can effectively interpolate grid points in the computational domain from prescribed points along the block boundaries. This method can be seen as a perturbation method that is flexible and independent of the initial grid generation. Therefore, the TFI process allows the overall quality of the original grid to be retained longest.[1] When the TFI technique is used, the grid-deformation process becomes completely independent of the generation of the initial grid, for which any suitable technique can be used.[2]

In this paper, the TFI technique is employed to obtain the grid at each time step for oscillating pitching airfoils. The deforming-grid technique is intentionally placed into the multiblock framework, although only simple two-dimensional applications are considered. The flow solver developed in Ref. 3 has been modified to solve the moving boundary problems. The dynamic grid algorithm that is coupled with the flow solver moves the computational grid to conform to the instantaneous position of the moving boundary.

To verify the efficiency of the present technique for a multiblock grid, the unsteady viscous flow about the oscillating NACA0012 airfoil is numerically simulated. The results obtained for the test case have shown that the grid-deformation method is very effective and robust for solving the unsteady flow problems. This TFI technique provides an efficient way of deforming the grid during an unsteady flow calculation. This method has also been successfully applied to the grid treatment for icing problems.[4]

Flow Solution

The unsteady compressible Navier–Stokes (N–S) equations for a moving control volume can be expressed as

$$\frac{\partial}{\partial t}\int_{V(t)} \boldsymbol{U}\,\mathrm{d}V + \int_{S(t)} \boldsymbol{F}\cdot\boldsymbol{n}\,\mathrm{d}S = \frac{1}{Re}\int_{S(t)} \boldsymbol{F}_v\cdot\boldsymbol{n}\,\mathrm{d}S$$

where $V(t)$ is the moving control volume, $S(t)$ its boundary, and $\boldsymbol{n}$ the unit outward normal vector to the boundary. Let $\boldsymbol{q}_b$ be the velocity of the moving boundary, then the convective flux can be expressed as $\boldsymbol{F} = \boldsymbol{F}_i - \boldsymbol{U}\boldsymbol{q}_b$. Here the variables $\boldsymbol{U}$, $\boldsymbol{F}_i$, and $\boldsymbol{F}_v$ are the flow variable vector and the corresponding inviscid and viscous flux terms, respectively. The equation of state for the perfect gas completes the governing equations.

A fully implicit method, which employs a dual-time approach, is used to solve the unsteady N–S equations. A full description about the present method may be found in Ref. 5.

The grid cell areas vary in time with the deforming grid. Therefore, it is very important to maintain the conservative properties of the numerical scheme. With reference to Ref. 5, a geometric conservation law is also introduced to avoid the numerical errors in the present viscous flow simulations.

Deforming Grid Approach for Multiblock Applications

In the framework of the multiblock grid, the flow domain is decomposed into blocks and then the structured subgrids are generated in each block. The grid generation in each block is made easier with such an approach. It is evident that the overall quality of the grid will be greatly improved at a low cost if the grids in adjacent blocks can be made to match smoothly at common interfaces.

At each time step, the dynamic grid algorithm moves the grid to conform to the instantaneous position of the moving boundary. Some attractive methods, which are based on the algebraic interpolation of

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Presented as Paper 2005-1221 at the AIAA 43rd Aerospace Sciences Meeting and Exhibit, Reno, NV, 10–13 January 2005; received 5 April 2005; accepted for publication 31 May 2005.

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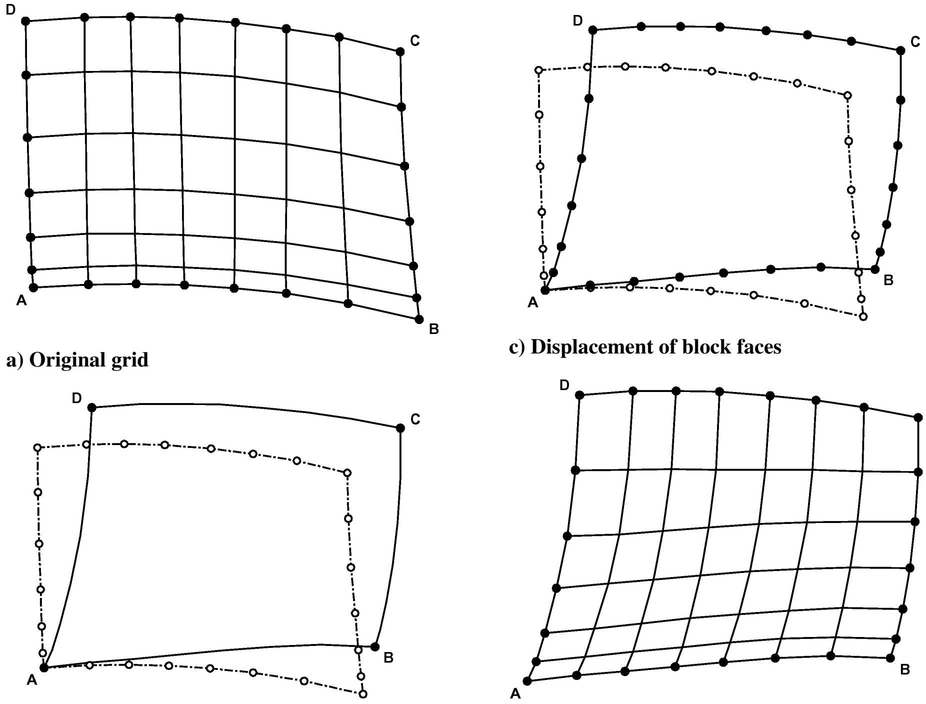

a) Original grid

c) Displacement of block faces

b) Displacement of corners

d) Displacement of interior points

Fig. 1 TFI method based on grid displacements.

the grid displacements, generally preserve the overall quality of the initial grid, as well as being cheap to calculate and easy to formulate. A modified TFI method, which is based on the interpolation of the block corner displacements, is employed here to deform the grid in each moving block.[1]

According to the displacement of the block corners, the displacement of the block faces and then of the interior points within each block can be interpolated. When the same interpolation procedure is used at all block boundary interfaces, perfect matching of the block boundaries will be guaranteed even if the blocks are treated independently.[1] The main ideas of the TFI method of grid perturbations are shown in Fig. 1. First, to determine the displacements of the four block corners, see Fig. 1b. Then, interpolate the displacement of all of the points along the block boundary according to the displacements of the four corner points, as shown in Fig. 1c. Following the original formulation of the TFI algorithm, the displacements of the interior grid points are finally obtained by the general TFI method, which usually results in a recursive algorithm. Details of the modified TFI algorithm may be found in Refs. 1 and 2. In Ref. 1, the TFI method was employed for unsteady inviscid flow simulations, including an airfoil oscillating in pitch and a multi-element airfoil with an oscillating flap.

Results for NACA0012 Airfoil

The current method has been applied to unsteady transonic flow simulation over pitching NACA0012 airfoil. The test case examined here is selected from the AGARD database.[6] For the computation, one order of magnitude drop in residual is used to control the subiterations at each time step for the pseudotime marching. In the present study, it takes a few iterations (typically about five) to achieve the stopping criterion. A nondimensional time step, $\Delta t = 0.05$, is used for the unsteady flows. The unsteady calculation usually takes three to four periods to get the solution fully periodic, when starting from its corresponding steady-state simulation.

The computation has been performed using a structured C-type grid. The grid is generated with an elliptic grid-generation method that uses a forcing function control technique.[7] It consists of 285×110 grid cells with 180 cells on the airfoil surface and 110 cells in the normal direction. The distance of the first grid line off the airfoil surface is about 2×10^{-6} chord lengths. As shown in Fig. 2, the grid system is intentionally partitioned into eight blocks, four inner blocks and four outer blocks, and only the four inner blocks are allowed to deform. For the deforming grid, the grid speeds are not known analytically and must be approximated to the desired degree of accuracy by evolving grid coordinates at several time levels. In the present study, the grid speeds are computed numerically employing a second-order backward temporal approximation.

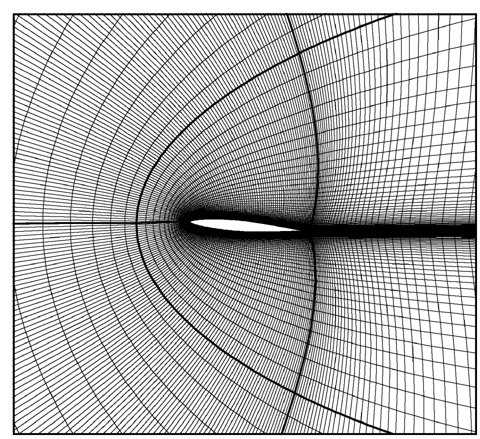

Fig. 2 Deformed grids for pitching airfoil.

For the selected case, the incidence as a function of time is given by $\alpha(t) = \alpha_m + \alpha_0 \sin(2kt)$. The analysis was performed with the conditions $M_\infty = 0.6$, $Re = 4.8 \times 10^6$, $\alpha_m = 4.86$ deg, $\alpha_0 = 2.44$ deg, and $k = 0.081$. The results for the lift and moment loops are shown in Fig. 3. Detailed comparisons between simulations and experiments for the instantaneous C_p distributions are presented in Fig. 4. Because of the high value of the freestream Mach number, a shock appears in the leading-edge region of the airfoil. The shock strengthens as the airfoil pitches up and then weakens and disappears during the downward part of cycle.

In general, a good prediction of the unsteady lift coefficient and the pressure distributions has been achieved. The computed moment coefficient differs from the measured data to a certain extent. The discrepancy is likely caused by the following facts. In this test case, the position of the cut line at the airfoil trailing edge has a different orientation with the movement of the grid system. This may affect the flow solution in the wake region, as well as the pressure at the

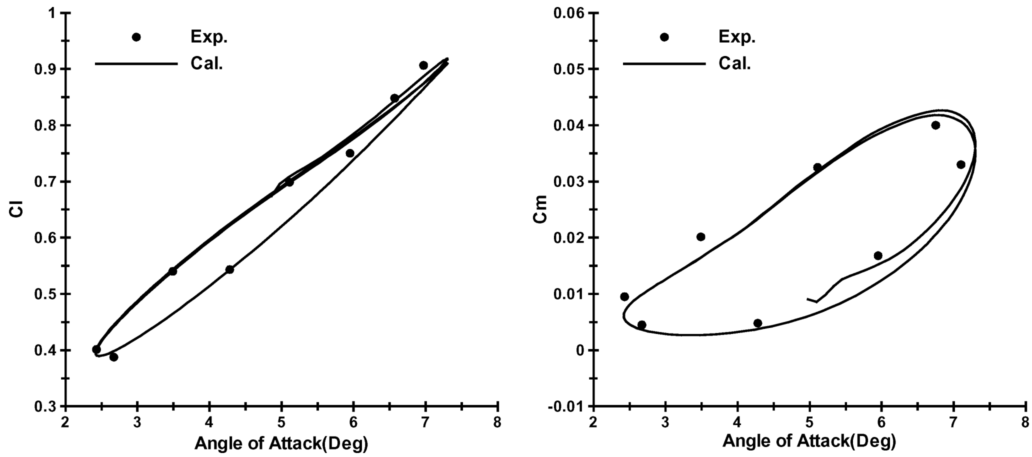

Fig. 3 Unsteady C_l and C_m variation with angle of attack for NACA0012 airfoil.

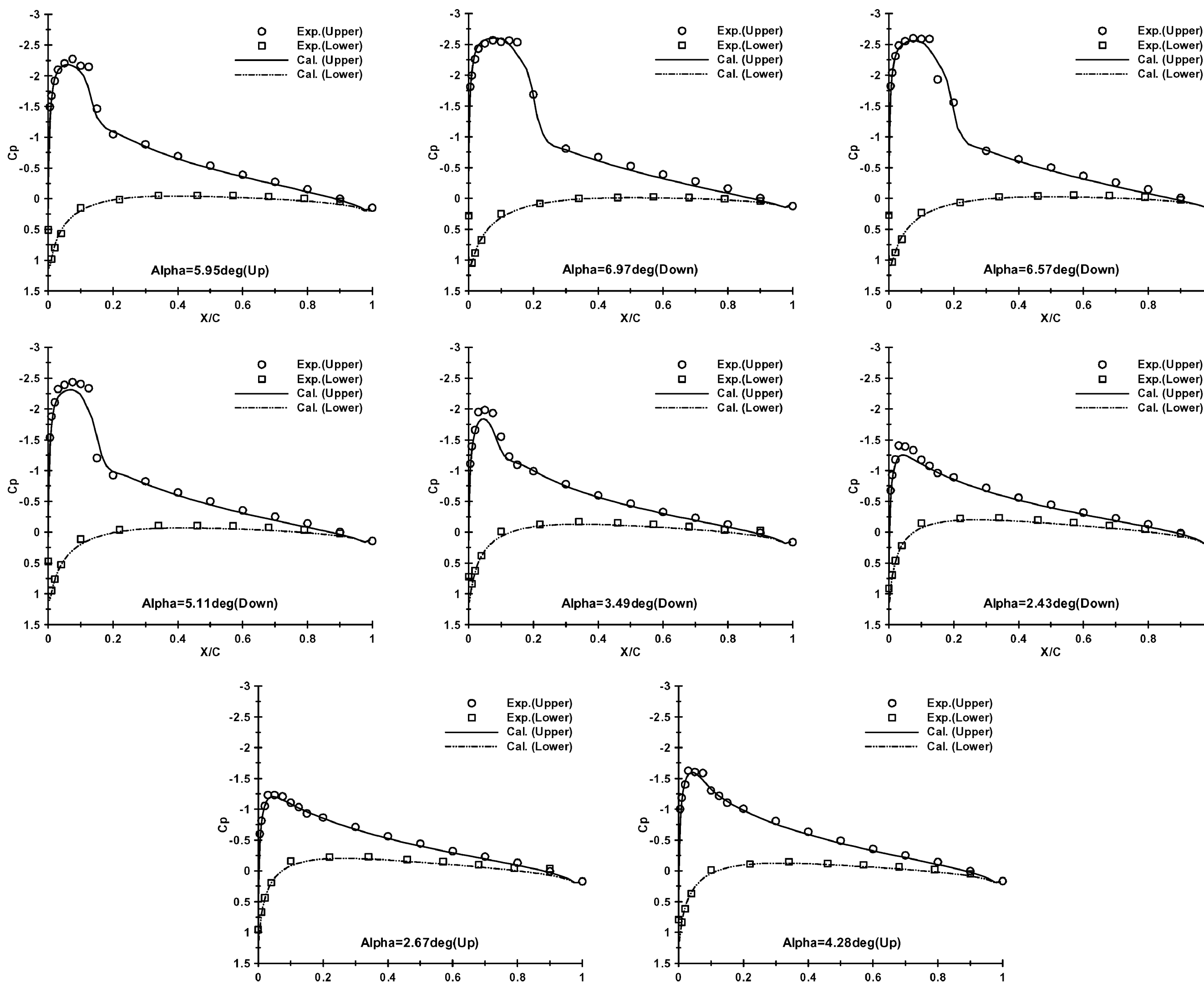

Fig. 4 Instantaneous pressure distributions for NACA0012 airfoil.

airfoil trailing edge, thus causing a small variation of the shock position and strengthening as the airfoil pitches to high incidences.[1] This difference is subsequently reflected on the C_l and C_m coefficients.

In contrast to the rigid-grid method, the deforming grid technique would result in a more distorted grid in the near-wall region if all of the deformation has to be absorbed by a smaller region. To maintain the general quality of the grid, it is suggested that the flow domain must be carefully divided to avoid smaller blocks.

Conclusions

The main objective of the present paper is to document the extension of a grid-movement approach to unsteady viscous flow simulations. The grid-deformation technique based on a modified TFI algorithm is employed to the grid displacements for the oscillating airfoil. This method can be seen as a perturbation method that is independent of the initial grid generation.

The present work is intentionally placed into a multiblock framework although only a simple test case is performed. For each moving block, the grid deformation is determined by the TFI perturbations according to the displacement of the block boundaries. The advantages of using interpolated displacements are being fast and simple. Another important feature of the approach is that it allows the overall quality of the initial grid to be maintained. This method provides an efficient way of deforming the grid during an unsteady flow calculation.

The current application mainly evaluates the deforming-grid technique for unsteady viscous flow simulation in multiblock grid system. The test results have shown that the deforming-grid technique is very effective and can be employed to the more general motions, for example, deforming airfoils.

To demonstrate the performance of this method for the general multiblock case, the next work is to extend it to three-dimensional unsteady viscous flows about a complex multicomponent configuration. This work is currently underway.

Acknowledgments

This work was partially sponsored by the fund of "The Developing Program for Outstanding Persons" at Northwestern Polytechnical University for the first author. The authors express their gratitude for the support of this research by Jianhong Dong of the First Aircraft Institute of China Aviation Industry Corporation I. Many useful discussions with Jiangtao Si and Shengju Jiang are also gratefully acknowledged.

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