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翼身组合体跨音速副翼翁鸣现象数值模拟

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摘　要　本文发展多块网格的生成技术和网格变形方法，通过耦合求解三维薄层 Navier-Stokes 方程与结构运动方程数值模拟翼身组合体跨音速副翼翁鸣现象。整个翼身组合体网格分成 30 块子区，子区之间的流场数据传递通过两层虚拟网格单元来完成。在每一步实时推进计算中，通过内迭代使整个耦合计算的时间精度达到二阶。计算中仅考虑了机翼与副翼的结构变形，在整个计算中副翼网格没有单独分区，而是在主翼与副翼之间引进了“剪刀差”网格，所以这种方法只适合于副翼小变形的情况，但从副翼随时间的变形趋势，可以大致推断是否有副翼翁鸣发生。数值模拟结果表明：对副翼刚性较强的结构模型，在小扰动作用下，副翼结构变形的振幅随时间变化减小，最后结构恢复到平衡态。但对副翼刚性较弱的结构模型，在马赫数 0.98 与 1.05 时，副翼结构变形的振幅随时间发展迅速增大，呈现副翼翁鸣现象。

关键词　Navier-Stokes 方程；多块网格；数值模拟；跨音速；副翼翁鸣

1 Introduction

Because thin wing-sections and control surfaces are necessarily used for the high-speed aircraft from the viewpoint of aerodynamic performance, it is important to predict accurately the transonic nonlinear aeroelastic phenomena such as flutter, buffet, and aileron buzz for the structural design of aircraft. In the last decade, transonic nonlinear aeroelastic analyses have been extensively studied by solving Euler/Navier-Stokes equations coupled with the structural equations of motion [1-3]. However, in these methods, the flow governing equations are only loosely coupled with structural equations of motion and these methods are always only first-order accuracy.

Tightly coupled aeroelastic approach was first put forward by Alonso and Jameson [4] for 2-D Euler aeroelastic simulation, called dual-time implicit-explicit method. In each real time step, the time-accurate solution is solved by explicit Runge-Kutta time-marching method for a steady problem, so all of convergence acceleration techniques such as multigrid, residual averaging and local time-step can be implemented in the calculation. In general, about 100 pseudo-time steps are needed for the explicit iterations to ensure adequate convergence, thus the method is still very time-consuming, so far as the author knows only 3-D Euler results were reported recently [5]. Melville et al [6] proposed a fully implicit aeroelastic solver between the fluids and structures, in which a second-order approximately factorization scheme with subiterations was performed for the flow governing equations, and the structural equations were cast in an iterative form. A fully implicit aeroelastic Navier-Stokes solver with three subiterations has succeeded in the flutter simulation for an aeroelastic wing [7].

In the flutter calculation, due to the deformation of aeroelastic configuration, adaptive dynamic grid needs to be generated at each time step. At present, most of aeroelastic calculations are only done for an isolated wing with single-block grid topology. For the simple flexible geometry, the grid can be completely regenerated with an algebraic method or a simple grid deformation approach. For the complicated aerodynamic configurations, multiblock grids are usually generated for steady flow simulation. However, for aeroelastic application it is impossible to regenerate multiblock grids at each time step due to the limitation of computational cost. Multiblock grid deformation approach needs to be used. Recently Potsdam and Guruswamy [8] put forward a multiblock moving grid approach, which uses a blending method of a surface spline approximation and nearest surface point movement for block boundaries, and transfinite interpolation (TFI) for the volume grid deformation. Wong et al. [9] also established a multiblock moving mesh algorithm. The spring network approach is utilized only to determine the motion of the corner points of the blocks and the TFI method is applied to the edge, surface and volume grid deformations.

In addition, structural data may be provided with plate model, but the flow calculations are carried out for the full geometry. The interpolation between fluid and structure grids is required. Infinite and finite surface splines [10] [11] developed for the plate aerodynamics and plate structural model are still main interpolation tools, only the aerodynamic grid needs to be projected on the surface of structural grid before interpolation.

In the present paper, a fully implicit multiblock Navier-Stokes aeroelastic solver was developed. The main work is to simulate the aeroelastic phenomenon of aileron buzz for a wing-body configuration.

2 Governing Equations and Numerical Method

Flow governing equations are the unsteady, three-dimensional thin-layer Navier-Stokes equations. Second-order linear structural dynamic governing equations are used for the structural calculation.

LU-SGS method, employing a Newton-like subiteration, is used for solving flow governing equations. Second-order temporal accuracy is obtained by utilizing three-point backward difference in the subiteration procedure. The subiteration method is also applied to the structural equations of motion. As the number of subiteration tends to infinity, a full implicit second-order temporal accuracy scheme is formed. For accurate multiblock-grid aeroelastic calculation, the subiteration method is very important not only for eliminating the lagged flowfield induced by lagged multiblock boundary condition but also for removing the sequencing effects between fluids and structures. However, in practical application, only finite subiterations can be used. Our numerical experiments indicate the calculated results are nearly unchangeable as $p \geq 3$. In the following calculation, the number of subiteration is set to 3.

3 Grid Deformation Method

For the aeroelastic application of the wing/fuselage model in the paper, an H-type multiblock grid with 30 blocks is generated and aileron surface is distributed at 12×13 grid points in the span- and chord-wise directions, respectively.

For the multiblock grid deformation, the blocks containing the fuselage surface and the blocks away from the flexible wing can be fixed. The grid deformations only need to be performed for the blocks adjacent to the deforming wing. The TFI method is applied to deform the grid blocks. Based on the known deformations of the flexible body and the parameterized arc-length values of the original grid, 1-D, 2-D and 3-D TFI methods are used to interpolate deformation values in inner grid points. Then the deformations are added to the original grid to obtain the new multiblock grid. For the small and moderate aeroelastic deformation, the present method maintains the grid quality of the original grid and maximizes the re-usability of the original grid. For the aileron deflection, a simple sheared mesh is used and a gap is introduced between the ends of the aileron and wing to allow sufficient space for the moving sheared mesh. The present solver assumes the aileron oscillation of small amplitude. For aileron flutter analyses, the tendency of flow stability can be analyzed from the dynamic response of aileron at relatively small magnitude.

3 Data Transformation

In the present aeroelastic calculations, the structural modal data are provided with the plate model and only normal deformation is considered. However, the real geometry is used for the fluid solution. Then the problem of passing information between the fluid and structural grids becomes very complicated. In the paper, the fluid grid is first projected to the surface of structural grid. Then the deformations on the projected fluid grid points are interpolated by the infinite plate spline (IPS) [10]. The new geometry can then be obtained by adding the deformations to the old one.

IPS is to obtain an analytic function $w(x, y)$, which passes through the given structural deflections of N points $w_i = w(x_i, y_i)$. The static equilibrium equation of $D\nabla^4 w = q$ should be satisfied, where D is the plate elastic coefficient, q is the distributed load on the plate. The solution by superposition of fundamental functions can be written as

$$w(x, y) = a_0 + a_1 x + a_2 y + \sum_{i=1}^{N} F_i r_i^2 \ln r_i^2 \qquad (1)$$

where $r_i^2 = (x - x_i)^2 + (y - y_i)^2$

The $N+3$ coefficients of $(a_0, a_1, a_3, F_1, F_2, \cdots, F_N)$ in Equations 1 can be solved through the function passes the given structural deflections of N and three additional conditions of the conservation of total force and moment:

$$\sum_{i=1}^{N} F_i = 0, \quad \sum_{i=1}^{N} x_i F_i = 0 \quad \text{and} \quad \sum_{i=1}^{N} y_i F_i = 0 \quad (2)$$

Then the deformations of aerodynamic grid points can be evaluated with the function (1). The above linear displacement transformation can be written in the form $\delta S_a = [G]\delta S_s$, where δS_a and δS_s are the displacement vectors defined on the aerodynamic grid and the structural grid, respectively. The force transformation from the fluid to structural grids can be calculated with the principle of virtual work of $F_s = [G]^T F_a$, where F_s and F_a represent the forces on the structural and fluid grids, respectively. The principle of virtual work can guarantee the conservation of energy between the fluid and structural systems.

In the practical application, the LU decompositions of the coefficients matrix and its transpose matrix of the equation groups of (1) and (2), a_0, a_1, a_3, F_1,…, F_N as unknown quantities, are pre-calculated and stored in the code. For the flutter simulation of aileron oscillation on SST, interpolations are applied on the aileron and wing separately since deformation is discontinuous between the zones of the aileron and wing.

5 Results and Discussion

Aileron flutter simulations are performed for two structural models of the supersonic fuselage/wing configuration [12] at three transonic Mach numbers of 0.95, 0.98 and 1.05 under the fixed total pressure of 85 Kpa and angle of attack of 0 degree. In the experimental model, fuselage and main wing are rigid. However, the aileron is attached to the main wing by a spring with different strength to simulate the hinge stiffness. For the weakened structural model, the oscillating mode of aileron has the lowest natural frequency of 30.5 Hz. For another rigid structural model, mode shapes and frequencies are the same as the weakened model except the oscillating frequency of aileron is increased to 220.7 Hz. Aeroelastic calculation starts from the steady flow. A small modal damping coefficient $\zeta_i = 0.02$ was added in the structural equations to damp the unphysical oscillation of small amplitude. The time-step size is taken as 0.01.

Figure 1 shows the comparison of dynamic responses of first sixth modes for the two structural models. For the weakened structural model, the dominant mode is the aileron oscillation mode, which is stable at Mach number of 0.95, but diverges at Mach numbers of 0.98 and 1.05. For the unstable cases, the amplitude of the aileron oscillation becomes larger and larger until the calculation breaks down due to the use of a simple sheared grid deformation for the aileron deflection. For the rigid structural model, the dominant mode is the bending mode of wing, which has the small amplitude of oscillation and decays in time for all of the three Mach numbers. The response of aileron oscillation mode correspond the third mode, which does not produce any significant effect to the dominant mode. The largest amplitude of oscillating angle is only about 0.03 degree.

The flow analyses indicate that, on the upper surface of the wing, the shock wave becomes weaker as the aileron oscillates upward and becomes stronger as the aileron deflects downward, and the flow behaves just contrary on the lower surface of the wing. Corresponding to general theoretical analysis, the flow instability referred to as aileron buzz is induced by a stronger shock alternately moving on the upper and lower surfaces of wing.

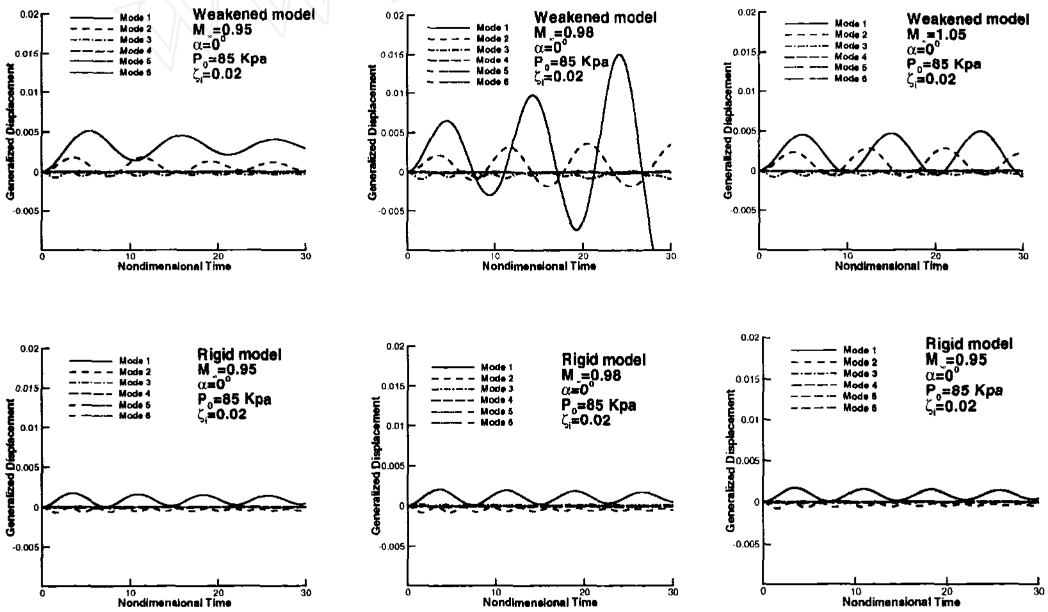

Fig. 1 Dynamic responses of first six modes for SST weakened and rigid structural models

6. Concluding Remarks

A fully implicit aeroelastic solver has been developed for flutter simulation on complex configuration through the tightly coupled solution of Navier-Stokes equations and structural equations of motion. Multiblock grid deformation is performed with the TFI method. IPS and the principle of virtual work are used for data transformation of deformation and force between the fluids and the structures. The phenomenon of aileron buzz has been simulated at the Mach numbers of 0.98 and 1.05 for weakened structural model, which is induced by the movement of the shock wave alternately on the upper and lower surfaces. For the SST rigid structural model, the flow is stable at all calculated Mach numbers as observed in experiment.

References

[1] G. P. Guruswamy: Vortical Flow Computations on Swept Flexible Wings Using Navier-Stokes Equations, AIAA Journal, Vo. 28, 1990, pp.2077-2084.

[2] E. M. Lee-Rausch and J. T. Batina: Wing Flutter Computations Using an Aeroelastic Model Based on the Navier-Stokes, Journal of Aircraft, Vol.33 1996, pp.1139-1147.

[3] S. A. Goodwin, R. A. Weed, L. N. Sankar and P. Raj: Towards Cost-Effective Aeroelastic Analysis on Advanced Parallel Computing Systems, Journal of Aircraft, Vol. 36, No. 4, 1999, pp. 710-715.

[4] J. J. Alonso and A. Jameson: Fully-Implicit Time-Marching Aeroelastic Solutions, AIAA Paper 94-0056. 1994.

[5] F. Liu, J. Cai, Y. Zhu, H. M. Tsai and A. S. F. Wong: Calculation of Wing Flutter by a Coupled Fluid-Structure Method, Journal of Aircraft, Vol. 38, No.2, 2001, pp.334-242.

[6] R. B. Melville, S. A. Morton and D. P. Rizzetta: Implementation of a Fully-Implicit, Aeroelastic Navier-Stokes Solver, AIAA paper 97-2039, 1997.

[7] R. E. Gordiner and R. B. Melville: Transonic Flutter Simulations Using an Implicit Aeroelastic Solver, Journal of Aircraft, Vol.37, 2000, pp.872-879.

[8] M. A. Potsdam and G. P. Guruswamy: A Parallel Multiblock Mesh Movement Scheme for Complex Aeroelastic Applications, AIAA Paper 01-0716. 2001.

[9] A. S. F. Wong, H. M. Tsai, J. Cai, Y. Zhu and F. Liu: Unsteady Flow Calculations with a Multi-Block Moving Mesh Algorithm, AIAA Paper 00-1002. 2000.

[10] K. Sakata: Supersonic Experimental Airplane Program in NAL and its CFD-Design Research Demand, 2nd SST-CFD Workshop, pp. 53-56,2000.

[11] R. L. Harder and R. N. Desmarais: Interpolation Using Surface Splines, Journal of Aircraft, Vol. 9, 1972, pp.189-191.

[12] K. Appa: Finite-Surface Spline, Journal of Aircraft, Vol. 26, 1989, pp.495-496.