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ALGORITHM AND CODE DEVELOPMENT FOR UNSTEADY THREE-DIMENSIONAL NAVIER-STOKES EQUATIONS

Shigeru Obayashi

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MCAT Institute
3933 Blue Gum Drive
San Jose, CA 95127

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Introduction

In the last two decades, there have been extensive developments in computational aerodynamics, which constitutes a major part of the general area of computational fluid dynamics.[1] Such developments are essential to advance the understanding of the physics of complex flows, to complement expensive wind-tunnel tests, and to reduce the overall design cost of an aircraft, particularly in the area of aeroelasticity.

Aeroelasticity plays an important role in the design and development of aircraft, particularly modern aircraft, which tend to be more flexible. Several phenomena that can be dangerous and limit the performance of an aircraft occur because of the interaction of the flow with flexible components. For example, an aircraft with highly swept wings may experience vortex-induced aeroelastic oscillations. Also, undesirable aeroelastic phenomena due to the presence and movement of shock waves occur in the transonic range. Aeroelastically critical phenomena, such as a low transonic flutter speed, have been known to occur through limited wind-tunnel tests and flight tests.

Aeroelastic tests require extensive cost and risk. An aeroelastic wind-tunnel experiment is an order of magnitude more expensive than a parallel experiment involving only aerodynamics. By complementing the wind-tunnel experiments with numerical simulations, the overall cost of the development of aircraft can be considerably reduced. In order to accurately compute aeroelastic phenomenon it is necessary to solve the unsteady Euler/Navier-Stokes equations simultaneously with the structural equations of motion. These equations accurately describe the flow phenomena for aeroelastic applications.

At Ames a code, ENSAERO, is being developed for computing the unsteady aerodynamics and aeroelasticity of aircraft and it solves the Euler/Navier-Stokes equations. The purpose of this cooperative agreement was to enhance ENSAERO in both algorithm and geometric capabilities. During last five years, the algorithms of the code have been enhanced extensively by using high-resolution upwind algorithms and efficient implicit solvers. The zonal capability of the code has been extended from a one-to-one grid interface to a mismatching unsteady zonal interface. The geometric capability of the code has been extended from a single oscillating wing case to a full-span wing-body configuration with oscillating control surfaces. Everytime when a new capability was added, a proper validation case was simulated and the capability of the code was demonstrated.

Previous Results

Streamwise Upwind Algorithm and Its Higher-Order Extension

The initial cooperative agreement implemented an upwind algorithm into ENSAERO. The existing ENSAERO code had the central-difference scheme with the second and fourth order dissipation terms. It used the diagonal Beam-Warming approximate factorization implicit solver. The new upwind algorithm implemented into the code was the streamwise upwind algorithm that accounted for the multidimensionality to construct the numerical flux. The computed results demonstrated the improved accuracy and robustness of the code over the previous central-difference option.[2-4]

Freestream Capturing

When the governing equations are transformed to generalized coordinates, satisfaction of the discretized conservation law is not trivial because of the numerical evaluation of the metrics. It has more importance in moving grid cases. In this work, source of the error was identified and a correct numerical procedure was presented.[5]

Shock-Vortex Interaction on a Flexible Delta Wing

The upwind version of ENSAERO was applied to transonic flows over a clipped delta wing at moderate angles of attack. Due to the wing planform with a highly swept leading edge, a strong leading-edge vortex can form. This vortex can interact with a shock wave at transonic Mach numbers. Simulations were performed for both rigid and flexible wings successfully. It was found that the flexibility of the wing would delay occurrence of vortex breakdown during the ramp motion of the wing.[6]

Oscillating Control Surfaces

Geometric capability of the code was extended to simulate oscillating control surfaces. Single-grid approach and zonal approach were proposed. In this study, the model geometry was slightly modified to place a gap between the wing and the control surface. The gap region was used to shear the grid as the control surface oscillated. The zonal approach utilized a mismatching zonal interface. Test cases were chosen from the previous clipped delta wing with a trailing-edge control surface. The result demonstrated the first successful three-dimensional Navier-Stokes computation with a moving grid system.[7]

Wing-Body Configuration with Oscillating Control Surfaces

In parallel to the control surface work, the code had been extended for unsteady Navier-Stokes simulations of transonic flows over a wing-body configuration. The code inherited the one-to-one matching zonal interface capability from the Transonic Navier-Stokes code, TNS. After the control surface work was done, the geometric capability of the code was extended to a full-span wing-body configuration, specifically an arrow-wing configuration of supersonic transport-type aircraft with oscillating control surfaces. Four zones were used and the total number of grid points were about one million. Comparison of computed response characteristics between symmetric and antisymmetric control surface motions on the right and left wings was studied.[8]

Virtual Zones

To simulate the control surface oscillation without changing the model geometry, an idea of virtual zones were implemented into the code. Virtual zones are zones of zero thickness (for a finite volume formulation) which serve to transfer solid wall (or other) boundary conditions to an interface condition. Thus multiple boundary conditions can be imposed on a block face with the same flexibility as an interface condition. The orginal zoning capability of the ENSAERO code was extended by including the above capability of multiple interface conditions on a single block face. The virtual zone computation provided a detailed flow field with fewer grid points than those necessary for the single grid.[9]

Johnson-King Turbulence Model

To improve the accuracy of turbulent flow calculations, several turbulence models were tested for transonic flows past the ONERA M6 wing. Our experience indicates that correctly formulated models give poor prediction in general. However, the models that include a coding error or wrong formulation sometimes predict the flow field perfectly. In addition, the amount of artificial dissipation determines the performance of turbulence models. It is very difficult to draw any concrete conclusion from those observations. The computed results were submitted to CFD Validation Database.

Current Results

Under the extension period of this cooperative agreement since September 1993, new capabilities have been added to ENSAERO to perforce static aeroelastic simulations efficiently. Unsteady calculations are still too expensive for the current industrial needs. To satisfy the near-term needs, the present research has been performed to improve the static aeroelastic option of the code. The flow solver for solving the Navier-Stokes equations is completely rewritten with a combination of the LU-SGS (Lower-Upper factored Symmetric Gauss-Seidel) implicit method and the modified HLLE (Harten-Lax-van Leer-Einfeldt) upwind scheme. A pseudo-time marching method is used for the structural part of the code to improve overall convergence rates for static analysis. Results are demonstrated for transonic flows over rigid and flexible wings (see attachment).[10]

Concluding Remarks

The capabilities of the code, ENSAERO, have been greatly enhanced both in numerical algorithm and in geometric flexibility. The code has been validated through a number of numerical simulations and comparisons with experiment. The code can solve both static and dynamic aeroelastic problems using the Navier-Stokes equations over wing, wing-body, wing-control, and wing-body-control configurations.

The main future research will be to extend the code toward a complete aircraft. The next mile stone in the geometric extension is Navier-Stokes computation with engine thrust. In the algorithm development, second-order extension in time by using the Newton iteration will be the next step. For the code validation, good experimental data will be required.

Research in turbulence modeling is still ongoing. Further improvements should be studied for reliability.

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