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IMPLICIT WENO EULER SOLVERS FOR WING FLOW COMPUTATIONS WITH PARALLEL IMPLEMENTATION

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Extended Abstract

In this work, 3D inviscid flows over wings are calculated by solving the Euler equations using implicit weighted ENO schemes. t The WENO schemes proposed recently by Liu, et al. [1] and extended by Jiang and Shu [2] can achieve good convergence property while keeping the robustness and high order accuracy of ENO [3,4] schemes. The main idea of ENO scheme is to select the smoothest stencil among several competing candidates to approximate the fluxes to a high-order accuracy and meanwhile to avoid oscillations near discontinuities. However, the freely adaptive stencil is not necessary in smooth solution region and it could change even by a round-off perturbation near zeroes of the solution and its derivatives [1,2]. Numerical experiments with implicit ENO schemes usually suffer slow and even stagnant convergence rate for steady-state solution computations due to this adaptive stencil. Besides, the stencil-choosing step involves frequent usage of logical statements which perform poorly on vector machines. In [5], a class of implicit WENO schemes for the Euler equations has been successfully applied to 2D airfoil flows. Good convergence rate to steady-state solution has been illustrated. In order to improve the efficiency and convergence to the steady state, the lower-upper symmetric Gauss-Seidel (LU-SGS) implicit algorithm [6] is adopted. The details of the present scheme are similar to that given in [5] except that here we extend it to 3D. An extension to compressible Navier-Stokes equations with turbulence model has been given in [7], Several numerical issues regarding to 3D Euler computations have been reported such as the effects of numerical dissipation, inconsistent coarse and fine grid solutions, local and global minimum time stepping, and Kutta conditions [7,8]. The aim of this work is to use implicit WENO Euler solver to tackle these numerical issues by solving several 3D Euler flows. The computations are performed for the subsonic flow over NACA 0015 rectangular wing, transonic flow over ONERA M6 wing and supersonic flow over elliptic delta wing.

The present 3D implicit WENO Euler code was parallelized according to the Single Program Multiple Data (SPMD) paradigm and domain decomposition which means that each process in a parallel run the same code to solve the different regions of the flow domain. This method partitions the fluid domain into several subdomains (zones) and solves the flow equations of each zone independently. Therefore, parallelization of the fluid domain is achieved by assigning one processor to each of the zone in the fluid domain. Each processor solves the flow equations of each zone concurrently. Then the zonal boundaries are updated by exchanging boundary information between neighboring zones. The zonal meshes are patched so that the grid lines are continuous across the zonal interfaces. The numerical flux across cell face at block interface should be treated the same as that for the interior cell interface, which guarantees the flux conservation. To achieve this, the flow data on two grid surfaces normal to the zonal interfaces are needed from the neighboring zones. The data communication between the different processors is accomplished by using the Message Passing Interface (MPI) standard, which is a set of library interface standards for message passing. The advantage of using standard software such as MPI lies in its ability to switch from one implementation to another without modifying the source code. Thus, one only needs to recompile with the new library files.

Several typical results are shown below. The first computation is subsonic flow over a rectangular platform, untwisted, cantelevered NACA 0015 wing with aspect ratio 3.3. Computations were performed at free stream Mach number 0.18 and angle of attack 12.44 degree. The grid system is "O-O" type grid with 129x26x45 grid points. The solutions were calculated using WENO2-Roe and ENO2-Roe schemes at local CFL number 15.0. Fig. 1 shows the convergence histories for WENO2 and ENO2 schemes. After the residuals have decayed for two orders of magnitude, the convergence of ENO2-Roe scheme is leveling off due to the freely adaptive stencil, while monotone convergence is achieved with WENO2-Roe scheme.

The second computation is transonic flow over the ONERA M6 wing at M_∞=0.8395, α =3.06°. The wing is tapered with a taper ratio of 0.56 and has an aspect ratio of 3.8. The airfoil section is an ONERA D symmetric section with 0.1 maximum thickness-to-chord ratio. Extensive wind tunnel test data exist for the ONERA M6 wing, in particular pressure data for transonic flow conditions [11]. Our calculation is performed on an "O-O"-type grid system, containing 161x26x45 grids in the wrap-around, spanwise, and body-normal directions, respectively. The outer boundaries were extended to 30 chord lengths in all directions. The first grid line is at a distance of 0.001 chord length off the wall. The solutions were calculated using WENO2-Roe scheme at local CFL number 20.0. In Fig. 2, we show the pressure coefficients of present scheme as compared with the experimental data [11] and the other calculations by Yoon et al. [12] in which the number of grid points used were 191x33x49. It is shown that results of WENO2-Roe scheme are in good agreement with the experimental data and are more accurate than the results of Yoon et al. The configuration obviously results in the lambda double shock pattern for transonic flow on a swept wing, where the two shocks coalesce to form a single shock near the wing tip. Fig. 3 shows the speed up of the present parallel implementation of the implicit 3D Euler code on a PC cluster with 32 processors. The parallel efficiency is very good. Finally, we present a practical application of the parallel code to a complex aerodynamic geometry, e.g., generic F-16 fighter aircraft. We consider supersonic flow over F-16 fighter aircraft for free stream Mach number 2.0 and with 10 degree angle of attack. An "O-H" grid system with total 370,792 grid points, which consisting of 18 non-equal-size zones was used. The solutions were calculated using WENO2-Roe Euler schemes at local CFL number 20.0 with 1 and 2 processors. In the 2 processors computing, the processor 1 contains 13 zones with total 168,333 cells and processor 2 contains 5 zones with total 168,149 cells. The parallel efficiency is 0.94 for this case. The surface pressure contours are shown in Fig. 4.

We summarize as follows. High resolution implicit WENO Euler codes for solving 3D wing flows have been developed. The present method is based on weighted non-oscillatory spatial operator for convective flux. The time integration of equation is done using the implicit LU-SGS algorithm. Applications to subsonic flow over NACA 0015 rectangular wing, transonic flows over ONERA M6 wing and supersonic flow over elliptic delta wing have been carried out to validate and illustrate the code. It is found that the present implicit WENO Euler solver can achieve much better convergence rate for steady-state calculations as compared with the implicit ENO counterpart. Regarding to the various issues of previous 3D Euler computations such as numerical dissipation of different schemes, inconsistent coarse and fine grid solutions, different time-stepping, the present implicit WENO Euler solvers seem to provide a viable tool to produce accurate, less dissipative and consistent solutions for the inviscid compressible wing flows over a broad range of Mach numbers. Parallel implementation of the present 3D implicit Euler code on a PC cluster is also shown to achieve the desirable accuracy and efficiency.

Acknowledgement

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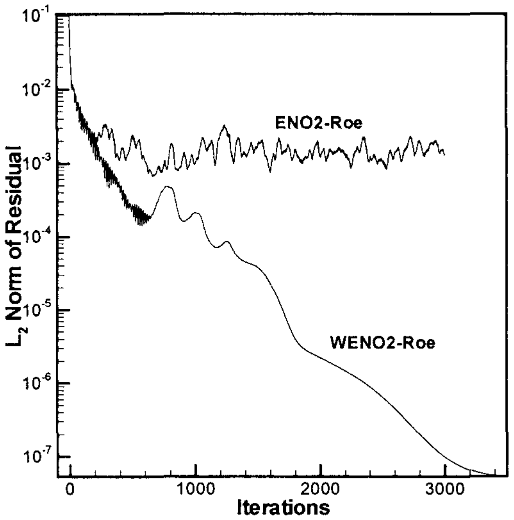

Fig. 1. Convergence history for NACA 0015 rectangular wing at M_∞= 0.18 and. α =12.444

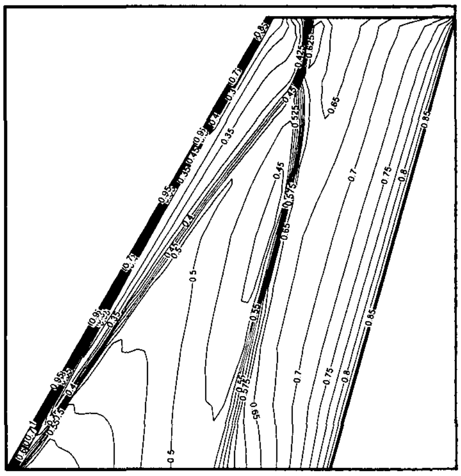

Fig. 2. Upper surface pressure contours for ONERA-M6 wing at M_∞=0.8395 and α =3.06°

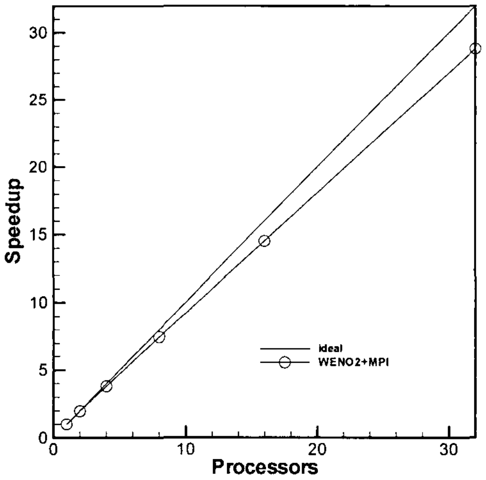

Fig. 3. Speed up of ONERA M6 wing at M_∞=0.8395, and α =3.06°.

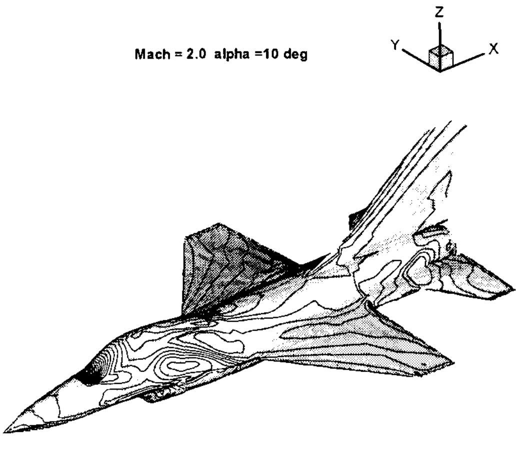

Fig. 4. Surface pressure contours for F-16 fighter aircraft at M_∞=2.0 and α =10°.