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On Effective Implementation of Block LU-SGS Scheme on Hybrid Unstructured Grid for Hypersonic Flow

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Abstract

This paper describes a new implementation of Block LU-SGS cell-centered scheme on hybrid unstructured grid, which aims at hypersonic flow simulation. Several solutions to some hypersonic key issues (such as large CFL caused computation instability, over-expansion on leeside, etc.) are also presented in this paper, which are proved to be effective in hypersonic computations with some test case. To confirm the fast convergence of Block LU-SGS scheme versus original LU-SGS scheme, and to demonstrate the flexibility of the solver, numerical results are given for several hypersonic problems.

Hypersonic vehicles have become more and more complex, which makes it difficult to generate multi-block structured grid for CFD simulation. What's more, the complexity of grids increases along with the complexity of geometry, and sometimes it's nearly impossible to meshing a whole vehicle with structured grid. So unstructured grid becomes more and more popular on demand. An unstructured zone can be meshed with mixed volume type such as hexahedral, prism, pyramid, or tetrahedral, which is very flexibility on complex vehicles. With the development of mesh generator, the unstructured meshing process is also more and more automatic and intellectual, which save more manpower on pre-process, thus unstructured grid is widely used in hypersonic vehicle design.

But for hypersonic flow, the time step in each cell is relatively small compared to low-speed case due to the restriction of CFL condition, so the numerical evolution of flow field is slow in most case. To break the CFL restriction on time step, implicit schemes are developed for faster convergence. LU-SGS scheme is a typical time-implicit scheme on both structured and unstructured grid, which uses local Lax-Friedriches flux on the left side of discrete scheme and the flux jacobian reduced into a single spectral radius neatly.

As an implicit scheme, LU-SGS is welcomed by many CFD researcher due to its simplicity. But its convergent speed is actually slowed down by the heavily reduced flux jacobian. In this paper we use ROE flux on the left side, which helps restore the full flux jacobian in to the discrete scheme (which is named as Block LU-SGS scheme by Wang[1]). But strict approximate LU factorization is used to construct a forward and backward sweep instead of Wang's sub-iteration method to reduce the time consumption in sweep process. The test case indicates that full flux jacobian plays an important role in convergent process and converges much faster the original LU-SGS scheme.

In hypersonic flow there some special physical phenomena which is detrimental to the stability of computation. Strong over-expansion on leeside is one of them, especially on computation startup. It will rapidly drains the density into negative. We carefully inspect the draining process and found that if we keep the same amount of numerical dissipation on both wall boundary and interior face, the negative density is less likely to happen. So we use a unified numerical flux method for both wall boundary and interior face in this paper. Computation results shows the over-expansion phenomena is apparently alleviated and seldom happen anymore.

Another problem is that, larger CFL number is difficult to achieve due to the heavy non-linearity caused by strong shockwaves. Some cells in the zone will lost stability in computation process. To achieve larger time step, local time-stepping is used as well as an adaptive CFL (ACFL) tuning mechanism. If the computation fails in some cell, we reduce the CFL of the cell to 10% of its previous value, and

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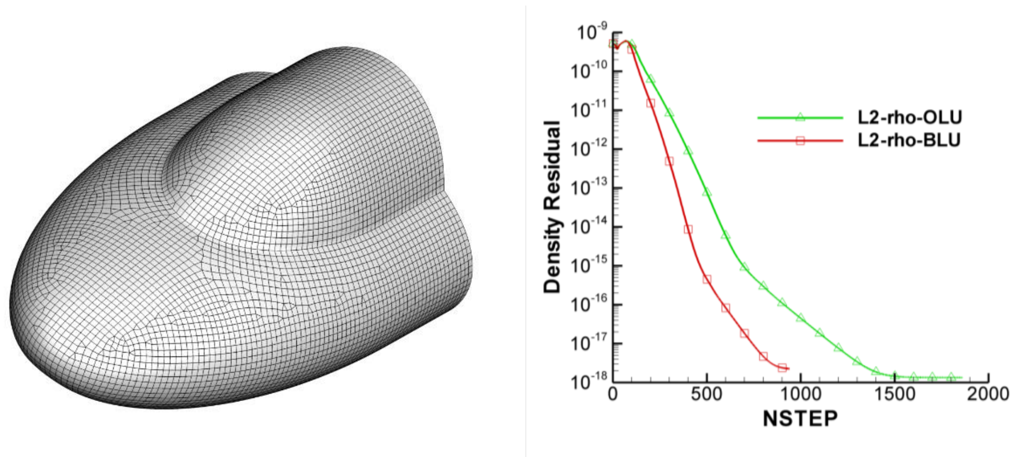
increase it gradually to the global CFL number after the computations becomes stable. Test case confirms that it's quite effective under large CFL situation.

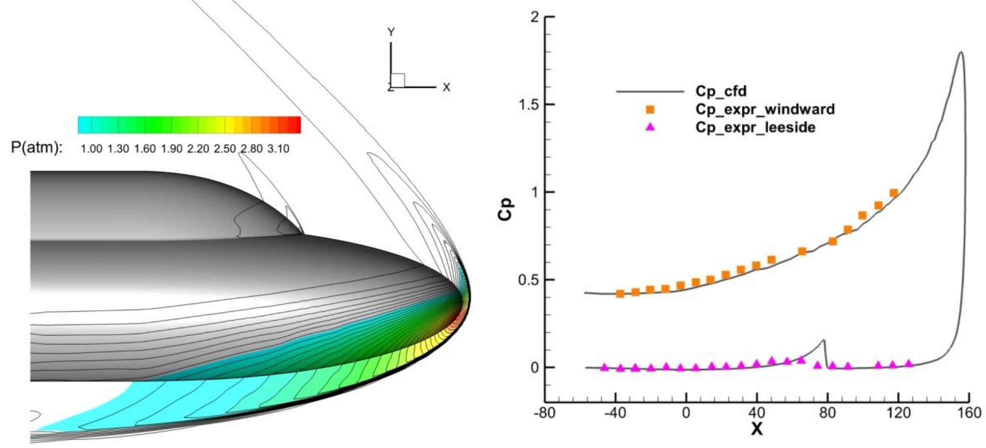
Several test cases are presented in this paper. A standard double ellipsoid case[2] is computed and the result is compared with experiment data. A hybrid grid of about 1 million is used in this case. The surface grid of mixed type is shown only in Fig.1 (a). The inflow condition is as follows,

$$M_\infty = 8.15,\ T_\infty = 56\text{K},\ \text{Re} = 1.67\text{E7/m},\ T_w \text{ (wall temperature)} = 288\text{K},\ \text{AoA} = 30\ ^\circ.$$

From Fig. 1(b) it's clear that for original LU-SGS scheme, 1500 steps are required to achieve a convergent state, while only 1000 steps are required for Block LU-SGS scheme. It's worth noting that the initial condition is copied from inflow boundary, thus causing strong draining effect on the leeside, but the solver runs smoothly due to our special treatment of numerical dissipation on wall boundary. In computation, CFL number increased from 0.1 to 10 in 100 steps, which is mild for LU-SGS scheme. But for Block LU-SGS the CFL number is large enough to trigger ACFL mechanism in the first 100 steps, and after 200 steps CFL of whole field becomes identical. From Fig.1 (d) it can be seen that pressure coefficient on both windward and leeside agree well with experiment data.



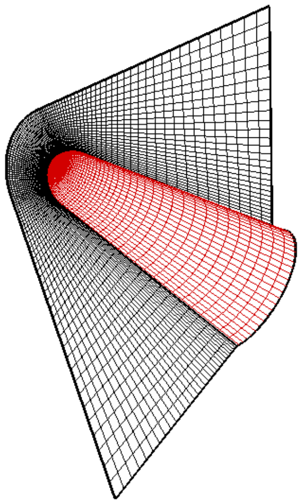
(a) Surface grid.　　(b) Convergence history (unnormalized)



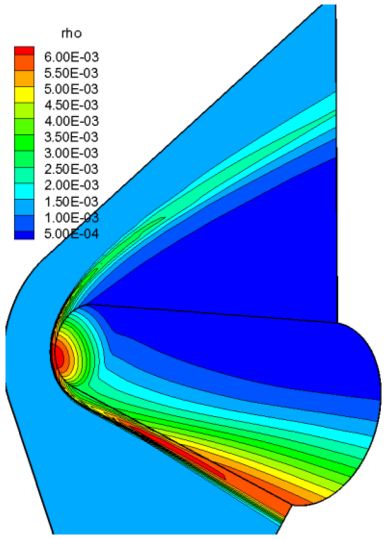
(c) Pressure contour　　(d) Comparison of pressure coefficient computed by Block LU-SGS scheme with experiment.

Fig 1. Double-ellipsoid case.

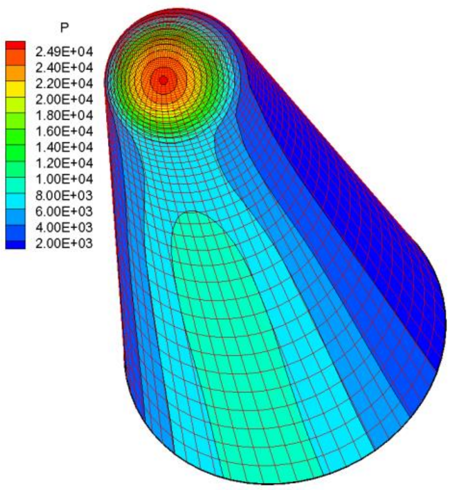
Another blunt cone simulation is present by this paper. The nose radius is 152mm, the half angle of the cone is 9 degree, and the total length is 1295mm. It's assumed the blunt cone flies at 50km altitude with a velocity of 5200m/s. The angle of attack is 16 degree. Fig.2 (a) shows the grid used in this case which is a universal hexahedral grid. Stagnant pressure calculated by Newtonian theory is 25556.23 Pa. CFD result by Block LU-SGS is slightly lower than the theoretical by -2.5%. Strong over-expansion on leeside also exists on startup, but the solver overcome this problem successfully. What's more the shockwave is captured with acceptable resolution and pressure contour is smooth in stagnant region, as shown in Fig. 2(b) and Fig.2(c). CFL strategy is the same as double-ellipsoid case, but Block LU-SGS schemes requires fewer time steps compared to original LU-SGS. ACFL mechanism is also triggered when computing with Block LU-SGS.



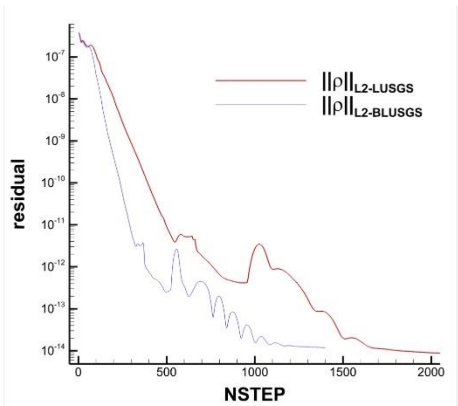
(a) Grid



(b) Density contour



(c) Pressure contour on windward side.



(d) Convergent history(unnormalized)

Fig 2. Single cone case

By the above work done, this paper presents an implementation of Block LU-SGS scheme by using ROE flux in the left side of implicit LU-SGS scheme to restore a full flux jacobian. The strong over-expansion is carefully treated on leeside of the vehicle, and adaptive CFL tuning mechanism is introduced to increase the time step. After several test case, it's proved to be a stable implementation for hypersonic flow with faster convergence.

Keywords: *Block LU-SGS, Hypersonic, Unstructured Grid*

References

1. Chen, R.F., Wang, Z.J., An Improved LU-SGS Scheme With Faster Convergence for Unstructured Grids of Arbitrary Topology, AIAA-99-0935
2. Desideri, J.A., Glowinski, R., Périaux, J., Hypersonic Flows for Reentry Problems Volume II: Test Cases — Experiments and Computations Proceedings of a Workshop Held in Antibes, France, 22–25 January 1990