ICCFD8

Eighth International Conference on Computational Fluid Dynamics
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Book of Abstracts

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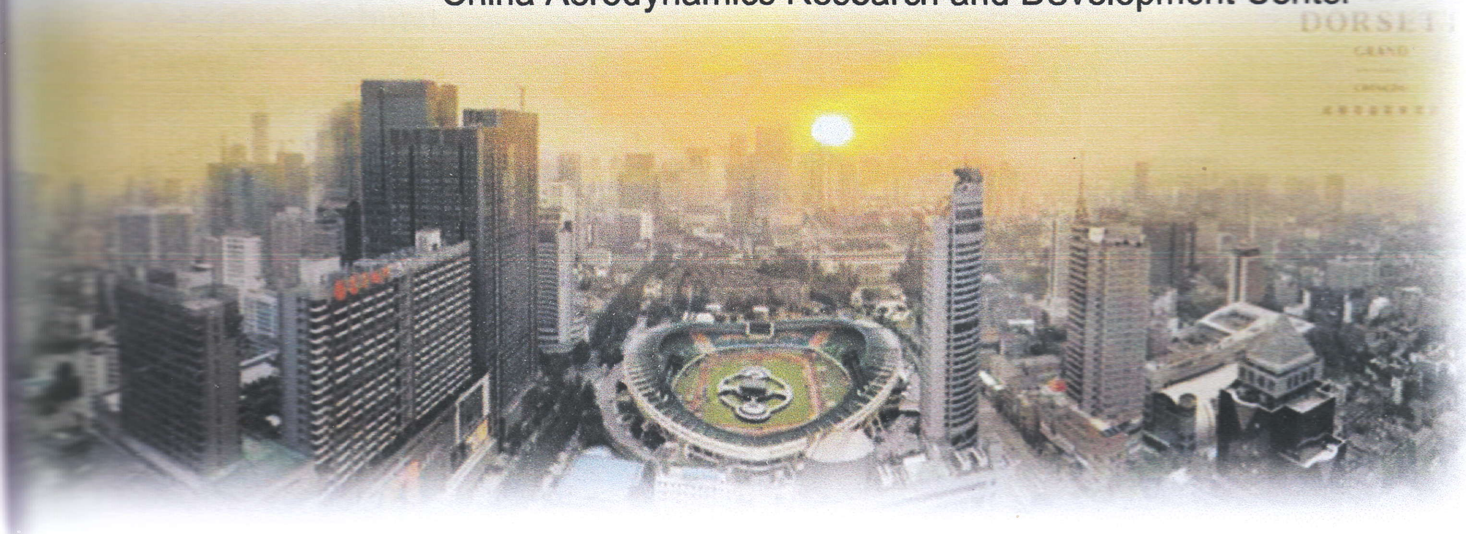

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Inertia terms for all Mach number Godunov-type schemes: Behavior of unsteady solutions at low Mach number

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Abstract: Inertia terms are introduced in a Godunov-type scheme. The resulting scheme, called AUSM-IT, is designed as an extension of the AUSM$^+$-up scheme, in order to allow full Mach number range calculations of unsteady flows. In line with the continuous asymptotic analysis, the AUSM-IT scheme satisfies the exact conservation of the discrete linear acoustic energy in the low Mach number limit. Its capability to properly handle low Mach number unsteady flows, that may include acoustic waves or discontinuities, is numerically illustrated.

Keywords: All Mach number flows, Low Mach number flows, Godunov-type schemes, AUSM, Momentum interpolation.

Convective and acoustic waves may propagate together in compressible flows, at time and space scales that may be very different, and with possible interactions. Design of numerical methods able to handle properly these complex phenomena remains a challenging task, even if viscous effects are neglected. With a co-located arrangement of the unknowns, accuracy and robustness of the numerical method heavily depend on the way of interpolation on the cell or element faces. Two broad categories of methods can be identified, according to the equations they are derived from: (1) Methods solving a Riemann problem at each face by using characteristic equations (these methods are referred to as Godunov-type schemes in the present study); (2) Momentum interpolation methods, that are derived from the momentum equation. In our opinion, the relations between these two approaches merit investigation in order to improve their respective capabilities.

The difficulties arising at low Mach number when Godunov-type schemes are used have been widely studied, mainly for steady flows (see *e.g.* [1, 2, 3, 4]). Denoting by $\mathrm{M_r}$ a reference Mach number in the flow, it has been recognized that avoiding the checkerboard decoupling problem needs an $1/\mathrm{M_r^2}$−scaling of the pressure gradient term in the face velocity or the face mass flux. This $1/\mathrm{M_r^2}$−scaling implies that the thermodynamic and the acoustic pressures are constant in space at the convective scale, which conforms to the continuous asymptotic analysis (see *e.g.* [3, 5]), provided that suitable boundary conditions are adopted. For AUSM-type schemes, it was shown in [1] that the $1/\mathrm{M_r^2}$−scaling is also necessary to verify that no spurious acoustic waves are created when starting from so-called well-prepared initial conditions. However, there is experimental evidence that this property does not guarantee accurate calculation of acoustic propagation in low Mach number flows. In our earlier work [6], it was thus observed that for unsteady low Mach number flows, the presence of the time-step in the pressure-velocity coupling coefficient of the face velocity is required, as for momentum interpolation. Based on this observation, an improvement of the AUSM$^+$-up scheme was then proposed in [7], by mimicking the pressure-velocity coupling of the momentum interpolation. However, we noted that the quality of the momentum interpolation, if properly defined for unsteady calculations in a Rhie-Chow-like manner (see [6, 8, 9]), was not reached for some tests at low Mach number.

Observing that the main difference between the scheme proposed in [7] and the momentum interpolation is the presence of inertia terms in the face velocity expression, we propose in the present study to introduce these inertia terms in the face velocity of Godunov-type schemes. The momentum interpolation is used as a guideline to accommodate these terms. The resulting pressure-velocity coupling exhibits then the suitable $1/\mathrm{M}_r^2$−scaling for low Mach number steady flows, as well as the time-step dependency with the proper Mach number scaling suitable for unsteady flows, as shown in [6, 7]. Moreover, the inertia terms are introduced such that the steady state solution, if it exists, does not depend on the time-step.

The high quality of the calculation results thus obtained for acoustic waves in low Mach number flows is about the same as by momentum interpolation. The reason for this good performance is that the way the inertia terms are introduced in the Godunov-type scheme allows exact conservation of the discrete linear acoustic energy in the low Mach number limit for periodic boundary conditions, which conforms to the continuous asymptotic analysis. The superiority of the proposed Godunov-type scheme over the momentum interpolation technique for Riemann problems is numerically demonstrated on a low Mach number test.

The proposed approach, which consists in the introduction of inertia terms in the face velocity expression, is applied in the present study to the AUSM$^+$-up scheme [4]. The resulting scheme, called AUSM-IT (IT for *Inertia Terms*), allows full Mach number range calculations, since it is an extension of the AUSM$^+$-up scheme which is retrieved if the local Mach number is larger than unity. Nevertheless, taking into account inertia terms for velocity interpolation is applicable in principle to any Godunov-type scheme. Thus, the approach proposed in the present study to design the AUSM-IT scheme can be applied to any Godunov-type scheme, in order to obtain full Mach number range high quality calculations.

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