Comparison of Pressure-Based and Density-Based Methods for Low Mach Number CFD Computations

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Abstract

Computational fluid dynamic (CFD) methods are usually classified as two distinct families of schemes---pressure-based and density-based methods. Specifically, pressure-based methods, which form the basis of most commercial CFD codes, are well-suited for incompressible and low Mach number flows, while density-based methods have typically dominated transonic and supersonic flowfields encountered in traditional aerodynamics applications. Historically, the two classes of schemes have evolved distinct strategies for the discretization, non-linear relaxation and linear solution aspects underlying the computational schemes. In recent years, however, both classes of schemes have been extended to operate in regimes traditionally dominated by the other scheme. For instance, for low Mach numbers, preconditioned density-based methods have been devised that perform efficiently and accurately at all flow speeds. In many cases, such extensions have also involved dissolution of the some of boundaries that used to distinguish these methods. However, important distinctions and differences still remain and, in particular, some of the critical issues underlying these schemes are still not completely understood.

In this paper, we critically compare the techniques utilized in both classes of schemes and contrast their properties. We investigate, for instance, the formulation of artificial dissipation, the use of under-relaxation versus time-stepping, segregated versus coupled solution procedures and the formulation of the pressure Poisson equation. Using results from von Neumann stability analysis, we show that, for incompressible and low Mach number flows, there is a close relationship between the pressure Poisson solution and the preconditioned density-based solutions. In fact, preconditioning is observed to essentially render the system pressure-based at low Mach numbers, while maintaining the traditional density-based formulation for transonic and supersonic regimes. Stability results are also presented to study the effects of segregated versus fully coupled solution procedures for highly compressible low Mach number situations, for instance, when strong thermal effects (as in combustion) are present. Such results will aid in the better understanding of the inherent strengths and weaknesses of both classes of methods and facilitate the design of optimal and general purpose algorithms.