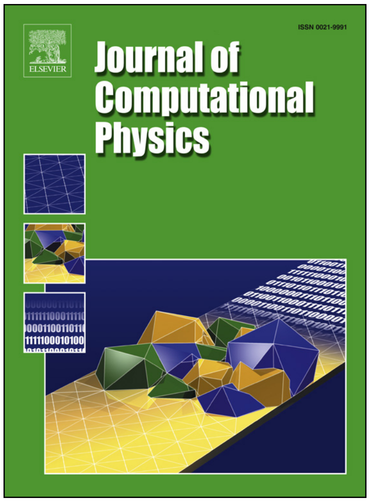

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High-Order Implicit Residual Smoothing time scheme for direct and large eddy simulations of compressible flows

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Abstract

Restrictions on the maximum allowable time step of explicit time integration methods for direct and large eddy simulations of compressible turbulent flows at high Reynolds numbers can be very severe, because of the extremely small space steps used close to solid walls to capture tiny and elongated boundary layer structures. A way of increasing stability limits is to use implicit time integration schemes. However, the price to pay is a higher computational cost per time step, higher discretization errors and lower parallel scalability. In quest for an implicit time scheme for scale-resolving simulations providing the best possible compromise between these opposite requirements, we develop a Runge-Kutta implicit residual smoothing (IRS) scheme of fourth-order accuracy, based on a bilaplacian operator. The implicit operator involves the inversion of scalar pentadiagonal systems, for which efficient parallel algorithms are available. The proposed method is assessed against two explicit and two implicit time integration techniques in terms of computational cost required to achieve a threshold level of accuracy. Precisely, the proposed time scheme is compared to four-stages and six-stages low-storage Runge-Kutta method, to the second-order IRS and to a second-order backward scheme solved by means of matrix-free quasi-exact Newton subiterations. Numerical results show that the proposed IRS scheme leads to reductions in computational time by a factor 3 to 5 for an accuracy comparable to that of the corresponding explicit Runge-Kutta scheme.

Keywords: Time integration, High-order, High-resolution, Direct Numerical Simulation, Large Eddy Simulation

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1. Introduction

Efficient DNS and LES simulations of compressible turbulent flows require a smart combination of numerical ingredients. One of them is the use of high-order spatial discretization techniques, allowing to minimize the number of grid points required to resolve a given wavelength of the numerical solution [1, 2]. On the other hand, computations must be carried out for extended periods of time in order to converge turbulent statistics, so that the choice of a suitable time integration scheme is of the utmost importance for the overall accuracy and efficiency. While explicit schemes provide accurate temporal resolution for LES and DNS, the time step size is dictated by stability constraints of the algorithm rather than by the frequency content of the large-scale structures. This can be particularly severe for low-Mach number and wall-bounded flows [1]. Sources of stiffness that cause severe time step restrictions for explicit schemes include acoustic waves for low-Mach number flows, viscous effects and large variations of the mesh size [3]. In LES of wall-bounded flows, highly stretched meshes are used to capture the fine-scale structures in the turbulent boundary layer [4]. With such small grid sizes, the stability constraint of explicit time-marching methods becomes very restrictive in the near-wall regions, whereas much larger time steps could be applied to mesh elements far from the wall [3]. This means that the time step imposed by stability limits is much

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