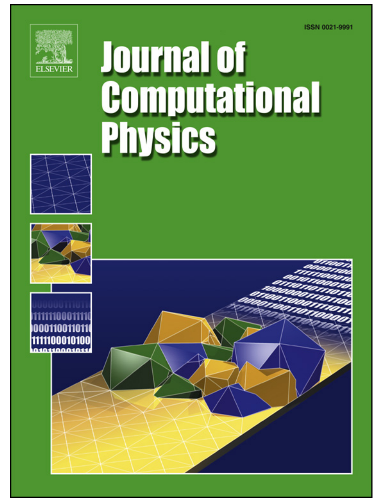

A high-order semi-explicit discontinuous Galerkin solver for 3D incompressible flow with application to DNS and LES of turbulent channel flow

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A high-order semi-explicit discontinuous Galerkin solver for 3D incompressible flow with application to DNS and LES of turbulent channel flow

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Abstract

We present an efficient discontinuous Galerkin scheme for simulation of the incompressible Navier–Stokes equations including laminar and turbulent flow. We consider a semi-explicit high-order velocity-correction method for time integration as well as nodal equal-order discretizations for velocity and pressure. The non-linear convective term is treated explicitly while a linear system is solved for the pressure Poisson equation and the viscous term. The key feature of our solver is a consistent penalty term reducing the local divergence error in order to overcome recently reported instabilities in spatially under-resolved high-Reynolds-number flows as well as small time steps. This penalty method is similar to the grad-div stabilization widely used in continuous finite elements. We further review and compare our method to several other techniques recently proposed in literature to stabilize the method for such flow configurations. The solver is specifically designed for large-scale computations through matrix-free linear solvers including efficient preconditioning strategies and tensor-product elements, which have allowed us to scale this code up to 34.4 billion degrees of freedom and 147,456 CPU cores. We validate our code and demonstrate optimal convergence rates with laminar flows present in a vortex problem and flow past a cylinder and show applicability of our solver to direct numerical simulation as well as implicit large-eddy simulation of turbulent channel flow at $Re_\tau = 180$ as well as 590.

Keywords: Discontinuous Galerkin, Incompressible Navier–Stokes equations, Turbulent flow, Matrix-free implementation, Splitting method

1. Introduction

The discontinuous Galerkin (DG) method has attained increasing popularity for simulation of the compressible Navier–Stokes equations due to a series of highly desired properties, which are stability in the convection-dominated regime, high-order capability using unstructured meshes, geometrical flexibility on curved boundaries as well as efficiency on massively parallel high-performance computers. This unique combination makes DG a very attractive approach for many high-Reynolds-number applications, e.g., direct numerical simulation (DNS) [1, 2], large-eddy simulation (LES) [2, 3, 4] as well as RANS and URANS [5, 6, 7] of turbulent compressible flows. Applications range from internal turbomachinery flows [8], computation of high-lift configurations of an entire aircraft [9] to environmental flows [10, 11].

Applications governed by the incompressible Navier–Stokes equations are frequently computed using standard compressible codes at small Mach numbers to avoid compressibility effects, see, e.g., [2, 12, 13] and the comparison [14], coming along with significant time step restrictions [12], or artificial compressibility methods, see, e.g., [15] (LES), [16] (URANS) and [17] (RANS). Fully incompressible numerical schemes in the context of LES have so

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