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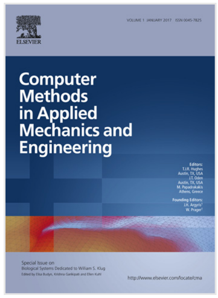

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An Adjoint-Based hp-Adaptive Stabilized Finite-Element Method with Shock Capturing for Turbulent Flows

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Abstract

In this study, an adjoint-based hp-adaptation algorithm has been developed within a Petrov-Galerkin finite-element method. The developed mesh adaptation algorithm is able to perform non-conformal mesh adaptations. To account for hanging nodes in a consistently manner, the constrained approximation method has been utilized. Hierarchical basis functions have been employed to facilitate the implementation of the constrained approximation. The methodology has been demonstrated on numerous cases using the Euler and Reynolds Average Navier-Stokes (RANS) equations, equipped with a modified Spalart-Allmaras (SA) turbulence model. Also, a PDE-based artificial viscosity has been added to the governing equations, to stabilize the solution in the vicinity of shock waves. For accurate representation of the geometric surfaces, high-order curved boundary meshes have been generated and the interior meshes have been deformed through the solution of a modified linear elasticity equation. Fully implicit linearization has been used to advance the solution toward a steady-state. Dirichlet boundary conditions have been imposed weakly and the functional outputs have been modified according to the weak boundary conditions in order to provide a smooth adjoint solution near the boundaries. To accelerate the error reduction in presence of singularity points, an enhanced h-refinement, based on solution's smoothness, has been used. Numerical results illustrate consistent accuracy improvement of the functional outputs for both h- and hp-adaptation, and also capability enhancement in capturing complex viscous effects such as shock-wave/turbulent boundary layer interaction.

Keywords: Adaptation; Adjoint; High Order; Finite Element; Turbulent; Shock Capturing

1. Introduction

After several decades of development, higher-order finite-element methods are now being considered for realistic and large-scale Computational Fluid Dynamics (CFD) simulations. This necessitates further studies on utilization of mesh adaptation techniques in order to reach reliable solutions at minimal computational cost. In many engineering applications, a specific scalar objective, like lift or drag, is of particular interest. The adjoint-based adaptation techniques [1-21] are able to detect regions in the mesh where the discretization errors directly affect the accuracy of the computed objective. Among adaptive high-order finite-element methods being developed for compressible flow problems, the Discontinuous-Galerkin (DG) schemes have been ***arguably*** the most utilized. However, for elements with low polynomial degrees, a Petrov-Galerkin (PG) scheme requires significantly less degrees of freedom (DOFs) and non-zero matrix entries than a DG scheme for comparable accuracy [22-25]. This advantage can be further enhanced using adaptation techniques. Although in the CFD community, a considerable amount of research has been conducted on adjoint-based adaptation for DG schemes [8, 11-13, 18, 20, 26-35], the methodology for PG schemes is still not rigorously established. The objective of the present work is multifold. Here, an adjoint-based adaptation algorithm has been developed for PG schemes such that it can be effectively

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