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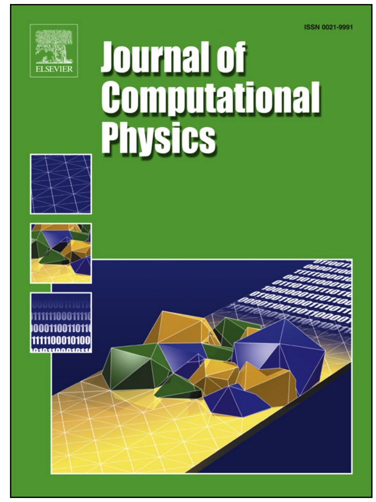

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Output-Based Space-Time Mesh Optimization for Unsteady Flows Using Continuous-in-Time Adjoints

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Abstract

We present a method for estimating spatial and temporal numerical errors in scalar outputs of unsteady fluid dynamics simulations using continuous-in-time adjoint solutions and general time-integration methods. A continuous formulation decouples the primal and adjoint temporal discretizations and allows for the use of standard time-integration schemes for the adjoint. For non-variational methods, a scheme-agnostic temporal reconstruction of the primal and adjoint solutions replaces the functional representation in between time nodes. The output error is still estimated through an adjoint-weighted residual, which takes the form of a space-time integral. Separate temporal and spatial error estimates arise from projection of the adjoint to semi-refined spaces. These estimates drive adaptive refinement, which first requires a calculation of the appropriate cost distribution between the spatial and temporal discretizations. The adaptive mechanics consist of uniform temporal refinement/coarsening, and several localized spatial refinements: order adaptation, hanging-node refinement, and unstructured mesh optimization. Results for scalar advection-diffusion and for the compressible Navier-Stokes equations demonstrate the effectivity of the error estimates, the efficiency of the adaptive refinement, independence of optimized meshes to the starting mesh, and the importance of high-order spatial and temporal approximations.

Keywords: Discontinuous Galerkin, Output Error Estimation, Continuous Adjoint, Unsteady Adaptation, Mesh Optimization

1. Introduction

Solution-adaptive methods can dramatically improve the robustness and efficiency of computational fluid dynamics simulations through error estimates and optimized meshes. In an output-based setting, mesh resolution is automatically dictated by an error estimate for a scalar output of interest, such as a force component or solution integral. Often not all features of the flow need to be well-resolved to accurately predict the scalar output, though sometimes the regions requiring resolution cannot be intuitively predicted. Robust identification of the important regions of the computational domain is possible through the solution of a linear adjoint system, which yields the sensitivity of the output of interest to residual source perturbations. Adaptive refinement schemes can then be designed to target regions where both residual perturbations and the output sensitivity are large, through an adjoint-weighted residual. Much work has been done in this area for steady problems, typically with finite-volume and finite-element methods [1, 2, 3, 4, 5, 6, 7, 8].

Unsteady problems pose additional implementation challenges and computational costs for output-based methods, namely in the solution of the unsteady adjoint equation, which, as a sensitivity problem, must be marched backwards in time. For nonlinear problems, the requisite linearizations also require the state at each time, and this is typically saved to disk at a cost of storage and computational time. In spite of these costs, output-based adaptive methods have been extended to unsteady problems, with various adaptation mechanics, including static-mesh, dynamic-mesh, space-only, and combined space-time refinement [9, 10, 11, 12, 13, 14, 15, 16, 17, 18].

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