Differentiable Fluid Dynamics for Shape Optimization in Compressible Flows

[1]Deniz A. Bezgin*; [1]Aaron B. Buhendwa; [1]Steffen J. Schmidt; [1,2]Nikolaus A. Adams;

[1]Technical University of Munich, School of Engineering and Design, Chair of Aerodynamics and Fluid Mechanics, Boltzmannstraße 15, 85748 Garching bei München, Germany

[2]Technical University of Munich, Munich Institute of Integrated Materials, Energy and Process Engineering, Lichtenbergstraße 4a, 85748 Garching bei München, Germany

Abstract

Shape optimization in compressible flows plays a crucial role in various engineering applications, such as improving the aerodynamic efficiency of airfoils or designing scramjet engine intakes. Traditional methods for aerodynamic shape optimization include solving (manually derived and implemented) adjoint equations or adaptive numerical experimentation. In this work, we demonstrate that the automatically differentiable computational fluid dynamics solver JAX-Fluids enables efficient shape optimization in shock-dominated flows. JAX-Fluids, a Godunov-type finite-volume solver for compressible flows, utilizes a level-set-based immersed boundary formulation for an accurate and efficient description of fluid-solid interfaces. By utilizing JAX-Fluids, we compute gradients of the objective functions with respect to free parameters of the level-set field directly through automatic differentiation. The resulting AD gradients ensure exact differentiation of the entire algorithmic representation of the chosen numerical approximation of the governing conservation laws. The combination of nonlinear shock-capturing discretizations and the level-set method ensures an accurate description of the flow physics and the fluid-solid interface. We validate our approach on canonical problems, including supersonic ramp flows. In particular, we show that analytical solutions obtained from gas dynamical relations are recovered by the AD-based optimization. Extensions of the proposed approach to more complex configurations are also discussed.

Keywords: Computational Fluid Dynamics, Compressible Flows, Automatic Differentiation, Immersed Boundary Method, Shape Optimization.