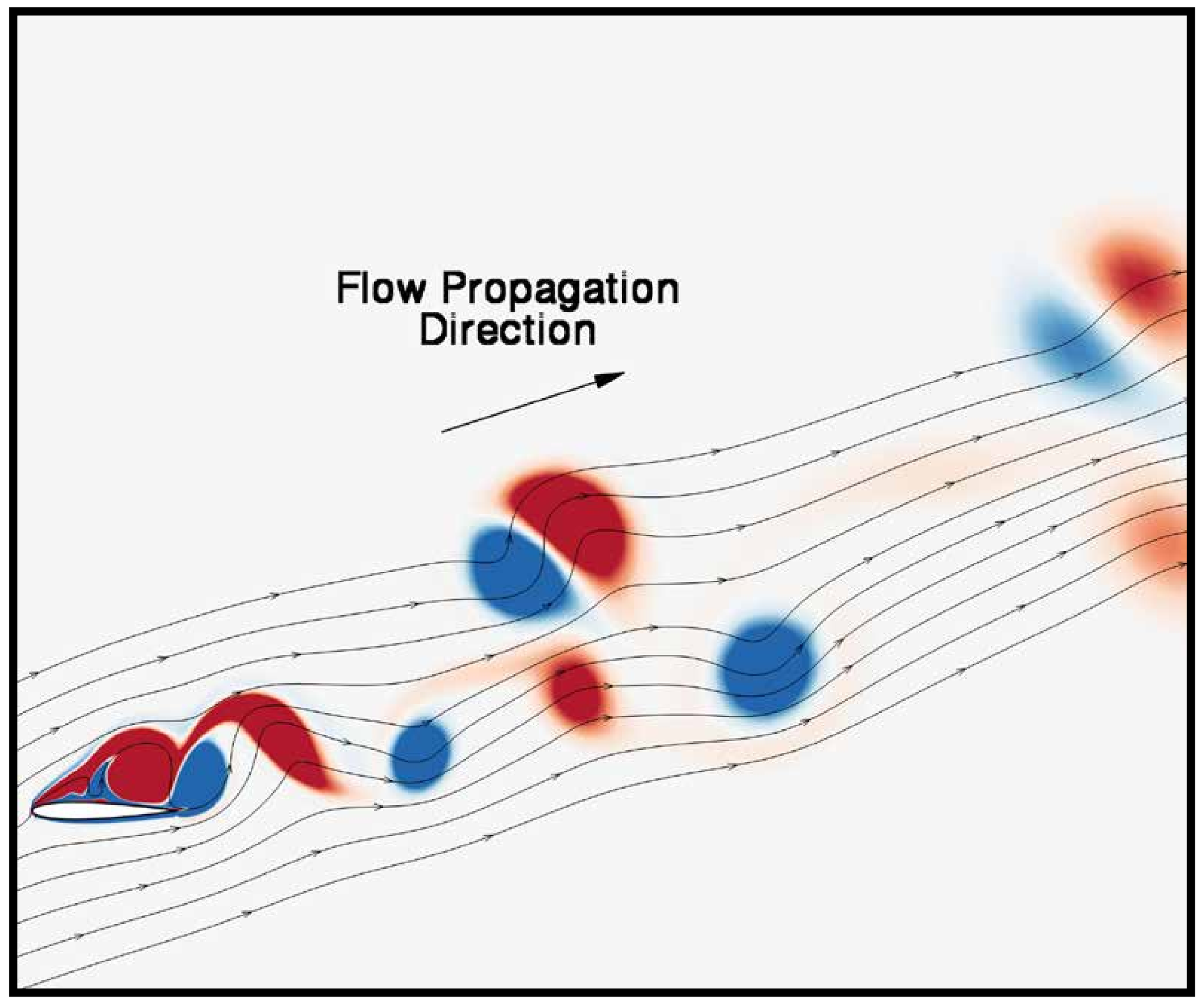
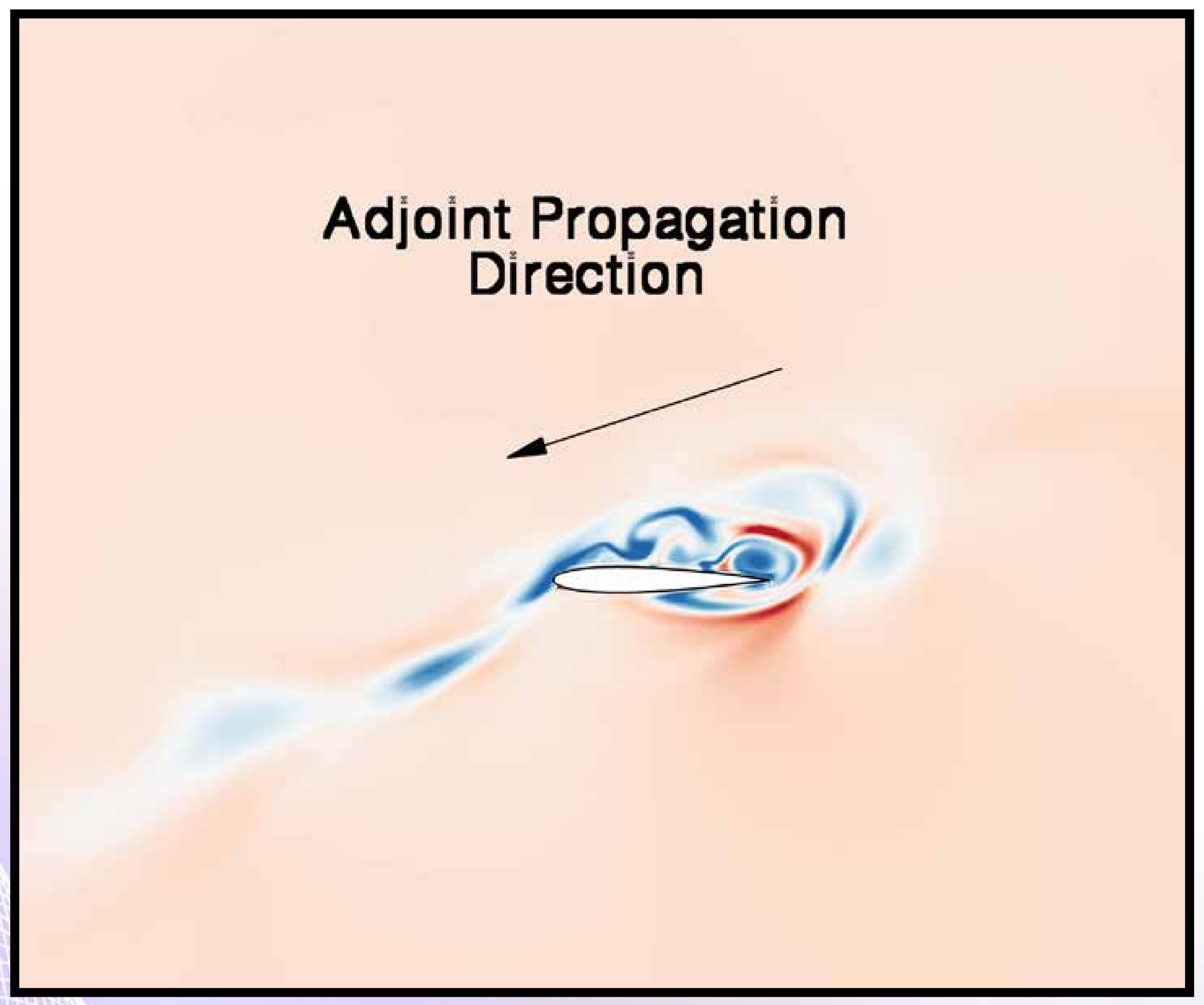
Sensitivity Analysis for Chaotic Fluid Simulations



Snapshot of chaotic shedding from a NACA 0012 airfoil at a high angle of attack. This simple simulation is a testbed for evaluating a proposed approach for sensitivity analysis of chaotic fluid simulations. Although it takes only minutes to solve the conventional governing equations on a standard desktop computer, formal sensitivity analysis for this seemingly trivial simulation pushes the limits of current petascale hardware. *Eric Nielsen, NASA/Langley; Qiqi Wang, Massachusetts Institute of Technology (MIT)*



Snapshot of the discrete adjoint solution computed using the Least Squares Shadowing (LSS) technique. LSS solves a globally coupled version of the linearized equations to determine a bounded adjoint solution that can be used to compute sensitivity information for design optimization, error estimation, and uncertainty quantification. Applying this method to realistic problems will require many orders of magnitude more compute power than currently available. *Eric Nielsen, NASA/Langley; Qiqi Wang, MIT*

The FUN3D development team at NASA's Langley Research Center has performed groundbreaking work in the field of adjoint-based sensitivity analysis for Reynolds-averaged Navier-Stokes (RANS) simulations for over 20 years. The methods developed by the team are used successfully across a broad range of steady and unsteady problems relevant to many NASA aerospace missions across the speed range. However, as high-end simulations begin to encompass eddy-resolving techniques, a long-standing barrier has prevented further extension of these approaches by the sensitivity analysis community.

For simulations that exhibit chaotic behavior, traditional sensitivity analysis techniques break down. This phenomenon is due to the well-known butterfly effect, where simulation outputs are extremely sensitive to initial conditions. In an effort to overcome this barrier, we are partnering with researchers at the Massachusetts Institute of Technology and the National Institute of Aerospace to implement and evaluate a new approach, known as Least Squares Shadowing (LSS).

As a baseline test for this methodology, we simulated shedding flow over a NACA 0012 airfoil at a high angle of attack. The baseline computational fluid dynamics (CFD) problem is trivial, and can be performed in minutes on a desktop computer. However, the computational requirements for LSS simulation are daunting, as the method requires the solution of a global space-time problem based on the linearized governing equations. For example, the LSS formulation for the simple problem presented here results in a matrix system containing billions of equations and many terabytes of input data that must be solved on thousands of processors.

Simulations currently being performed on NASA's Pleiades supercomputer are at least six orders of magnitude larger than the baseline problem presented here. Clearly, the LSS methodology is an ideal candidate for leveraging the next generation of exascale-class hardware.

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