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Continuum Shape Sensitivity Analysis with Spatial Gradient Reconstruction for Fluid-Structure Interaction

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Research was performed to develop a computational method to calculate the sensitivity of aeroelastic response with respect to changes in vehicle shape, which facilitates efficient design optimization of high-fidelity, aeroelastic models. Continuum sensitivity analysis (CSA) was implemented in a nonintrusive manner to enable use of black-box (commerical) solvers for nonlinear fluid-structure interaction (FSI) analysis. Accuracy of this CSA boundary velocity formulation was ensured through spatial gradient reconstruction (SGR), while avoding the need to differentiate the FSI Jacobian matrices.

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FINAL PERFORMANCE REPORT

15 December 2018

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CONTINUUM SHAPE SENSITIVITY ANALYSIS WITH SPATIAL GRADIENT

RECONSTRUCTION FOR FLUID-STRUCTURE PROGRAM

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CONTINUUM SHAPE SENSITIVITY ANALYSIS WITH SPATIAL GRADIENT RECONSTRUCTION FOR FLUID-STRUCTURE PROGRAM

Robert A. Canfield

Abstract

The objective of this research was to develop a computational method to calculate the sensitivity of aeroelastic response with respect to changes in vehicle shape. An efficient and accurate continuum sensitivity analysis (CSA) method was developed to compute shape design derivatives for nonlinear aeroelastic structures. These design derivatives facilitate efficient design optimization of high-fidelity, aeroelastic, computational models. CSA differentiates the nonlinear governing fluid-structure interaction (FSI) partial differential system of equations to arrive at a linear system of partial differential *continuum sensitivity equations* (CSEs). FSI boundary conditions were differentiated to specify the sensitivity boundary conditions. Accuracy of this CSA *boundary velocity formulation* was ensured through spatial gradient reconstruction (SGR) to overcome inaccuracy compared to domain velocity or discrete analytic formulations. The benefit is that geometric sensitivity, known as design velocity, is not required in the domain. In contrast to the usual discrete sensitivity approach, a principal advantage of CSA is that mesh sensitivity and differentiation of the discrete Jacobian system matrix is avoided. An important consideration is to distinguish design velocity from grid velocity at the FSI interface for arbitrary Lagrangian-Eulerian (ALE) reference frames, which are often needed for aeroelastic gust response involving rigid body motion. A novel continuum-discrete *hybrid adjoint* formulation was derived to efficiently handle the case of many design variables. This original CSA method with SGR was developed in a nonintrusive manner for gust response, enabling use with common FSI analysis tools. Recovery of the analysis rate of convergence was often achieved for CSA.

Summary

AFOSR awarded the grant in Dec 2015. This grant builds upon research begun in AFOSR grant begun in FY11. The research goal was to derive, implement, and demonstrate a novel method to compute shape sensitivity of flexible aircraft. Just as finite differences are popular because they treat analysis tools as black boxes to approximate derivatives, the proposed approach is to efficiently compute accurate design derivatives by post-processing analysis results in a nonintrusive manner, obviating the need to modify analysis source code. The three-year follow-on research effort has further developed the computational algorithms for efficient analysis and design optimization of aeroelastic models in several areas.

Progress in the first year was in three areas: 1) nonintrusive implementation of continuum sensitivity analysis (CSA) for finite volume computational fluid dynamics (FV-CFD) demonstrated for the commercial Fluent CFD solver, 2) convergence rate studies of spatial gradient reconstruction (SGR) for FV-CFD flow analysis, and 3) CSA derivation for an arbitrary Lagrangian-Eulerian (ALE) reference frame for fluid-structure interaction (FSI).

Results for rates of convergence for SGR and CSA obtained for a lid-driven cavity flow and for a NACA 0012 airfoil are presented in the following Section 2 attached to this annual report. Figure

2.16 illustrates that second-order rate of convergence is achieved for the cavity flow using SGR patches of at least two layers, based on reconstructing results for a manufactured solution. Figures 2.35 and 2.36 indicate that in general second-order, and sometimes not even first-order, rate of convergence for spatial derivatives was not achieved, based on reconstructing FV-CFD results from SU2 flow solver. Consequently, less than first-order rate of convergence was achieved for shape derivatives of lift coefficient (Figure 2.40), while first-order rate was achieved for drag coefficient derivatives (Figure 2.41) with respect to airfoil shape parameters.

In the second year, additional study of boundary conditions and their material derivatives was undertaken, based on the generally first-order rates of convergence reported for finite volume CFD in the first year. In particular, boundary condition enforcement and additional layers in SGR patches are being investigated as a means to improve reconstruction of flow state variables and their spatial derivatives, which drive the shape derivative CSA.

In the third year, CSA-SGR was implemented in the AFRL MSTC computational environment with design velocity for parametric shape change and meshing driven by the Computational Aircraft Prototype Syntheses (CAPS) program. In contrast to the usual discrete sensitivity approach, a principal advantage of CSA is that mesh sensitivity in the domain is avoided and the system Jacobian matrix is not perturbed or regenerated. Also, progress in the last year was achieved in deriving FSI CSA in an arbitrary Lagrangian-Eulerian (ALE) reference frame, which is often needed for aeroelastic gust response involving rigid body motion. This original CSA method with SGR has been developed in a nonintrusive manner for gust response, enabling use with common FSI analysis tools.

Accomplishments

Four journal articles [1–4] were published, one submitted for publication [5], and one dissertation published [6] were published, documenting the funded research. Three conference papers were presented during the performance period [7–9]. The funded research supported two doctoral students and one post-doctoral research assistant.

Several significant contributions to the state of knowledge were made for the application of CSA. Although they were posed in support of the sensitivity analysis of FSI problems, some findings are more general and more fundamental than the application to FSI. Some of accomplishments, as a result of our AF-funded research, are summarized as follows.

- Hybrid Continuum-Discrete Adjoint for Boundary Velocity CSA
    - Treats Large Numbers of Design Variables
    - Same Numerical Answer as Direct CSA, but more efficiently
    - Acts on Boundary Velocity CSA RHS Pseudo-Load using Discrete Adjoint Vector
- CSA-SGR for Finite Volume
    - Fluent and SU2
    - Non-Intrusive for Fluent w/o Full Jacobian
- K-exact Reconstruction compared with SGR
    - Same Accuracy up to 2nd-Order Finite Volume
- CSA Derived for Arbitrary Lagrangian-Eulerian (ALE) Frame 1st Time for FSI
    - Incompressible Linear and Compressible Nonlinear Full Potential ALE CSA Derivation
- CSA-SGR implemented at AFRL MSTC using ASTROS, NASTRAN & SORCER

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