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A Schur–Newton–Krylov solver for steady-state aeroelastic analysis and design sensitivity analysis

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Abstract

This paper presents a Newton–Krylov approach applied to a Schur complement formulation for the analysis and design sensitivity analysis of systems undergoing fluid–structure interaction. This solution strategy is studied for a three-field formulation of an aeroelastic problem under steady-state conditions and applied to the design optimization of three-dimensional wing structures. A Schur–Krylov solver is introduced for computing the design sensitivities. Comparing the Schur–Newton–Krylov solver with conventional Gauss–Seidel schemes shows that the proposed approach significantly improves robustness and convergence rates, in particular for problems with strong fluid–structure coupling. In addition, the numerical efficiency of the aeroelastic sensitivity analysis can be typically improved by more than a factor of 1.5, especially if high accuracy is required.

Keywords: Aeroelasticity; Design optimization; Sensitivity analysis; Three-field formulation

1. Introduction

Today, the utility of high-fidelity analysis methods for the design of engineering devices and systems is widely recognized [1,2]. This particularly applies to problems, which are dominated by nonlinear effects and subject to multi-physics phenomena, such as fluid–structure interaction (FSI) and electrostatic–mechanical

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coupling. However, high-fidelity analysis methods are most often used to only verify the final design. Large computational costs prevent these tools from being applied in the iterative design development process, requiring multiple analyses and sensitivity analyses. This paper is concerned with computational strategies that increase the computational robustness and efficiency of high-fidelity analysis and sensitivity analysis for FSI problems, and the implementation of these strategies within a formal design optimization framework.

In the past decade, computational FSI methods for aeroelastic and hydro-elastic problems have significantly advanced. The predominant amount of work has focused on algorithms for transient analysis in order to simulate, for example, the behavior of realistic aircraft configurations [3]. Recently, these high-fidelity computational models have been augmented by sensitivity analysis methods, and transient solution techniques have been adopted for design optimization purposes [4–7]. For practical reasons, however, design optimization problems are typically based on quasi-static models, approximating dynamic load effects by equivalent static load conditions. So far, most analysis and sensitivity analysis algorithms for solving quasi-static FSI design optimization problems rely either on direct solvers [7,8], which are therefore only applicable to idealized and small-scale problems, or are based on loosely coupled and segregated solvers, which have been proven to be accurate and efficient for transient problems but may be inefficient for quasi-static problems.

The latter methods follow nonlinear block Gauss–Seidel schemes typically using an approximate aeroelastic Jacobian, due to implementation and computational cost issues, and under-relaxation techniques for stability purposes. These schemes allow for solving the FSI problem by algorithms and software modules, which are tailored to the structure and fluid subproblems. Applications of such schemes in the context of aeroelastic design optimization have recently been reported in the literature [6,9–11]. However, this approach lacks robustness and efficiency, in particular when the FSI problem is strongly coupled and the aeroelastic system is close to static divergence, that is the aeroelastic Jacobian becomes singular. In these cases, the convergence highly depends on the under-relaxation factor, whose optimal value is in general unknown.

Only few approaches have been presented for the analysis of nonlinear aeroelastic problems and applied to design sensitivity analysis that overcome the shortcomings of block Gauss–Seidel schemes. Ghattas and Li [12] present a modified Newton scheme for a two-field formulation of the quasi-static FSI problem. The linear subproblem in each Newton step and the global sensitivity equations are solved by a generalized minimal residual (GMRES) algorithm [13]. The authors propose to precondition the linearized system with an approximate Jacobian by dropping the off-diagonal terms that couple the structural displacements and the fluid variables. This approach is applied to the analysis and sensitivity analysis of a two-dimensional flow around an infinite elastic cylinder with variable flow and structural parameters. As the discretization is rather coarse, that is the total number of unknowns is less than 10,000, the applicability to realistic FSI problems cannot be assessed.

Heil [14] follows a similar Newton approach that simultaneously advances the state variables of a two-field formulation of the quasi-static FSI problem. The author studies different preconditioners, based on block-triangular approximations for the aeroelastic Jacobian, for solving the linearized system by a GMRES algorithm. This approach is applied to an incompressible, low Reynolds number, two-dimensional flow inside a tube with flexible walls.

Kim et al. [15] present a general framework for the analysis of coupled multi-physics problems using existing solvers. Their approach is based on a multi-level Newton scheme for simultaneously solving the set of coupled nonlinear equations. While in the upper level all variables are simultaneously advanced by a Newton correction, in the lower level only the variables of the related subproblems are solved for by Newton's method. A Krylov method is used to solve the Jacobian system of the multi-level Newton residual. The authors apply this approach to a three-field formulation of the quasi-static FSI problem. The robustness and numerical performance are demonstrated with a laminar, low Reynolds number,