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Stress-based topology optimization method for steady-state fluid–structure interaction problems

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Highlights

- We solve the stress based topology optimization considering fluid–structure interaction.
- The singularity issue of the fluid–structure interaction is resolved by the qp-relaxation.
- The maximum von-Mises stress of structures due to fluidic force is constrained.
- The design domain is important because the fluid force is dependent on the design domain.

Abstract

This research developed a new stress-based topology optimization method (STOM) for a steady-state fluid–structure interaction (FSI) problem that minimizes the volume subject to the local stress constraints. Despite numerous studies on STOM, challenging optimization issues related to stress-based topology optimization (TO) procedures for fluid–structure multiphysics systems still exist. Critical issues involved in creating a successful TO for an FSI structure include: the interpolation approach between the fluid equation and the structure equation with respect to locally defined design variables, the mutual multiphysics coupling boundary conditions at dramatically evolving interfacing boundaries, and a clear interpretation of the governing equations and the interaction boundary conditions for spatially varying intermediate design variables. In addition to these three issues, which are related to multiphysics equations, there are three important considerations related to the STOM: the stress singularity issue, the issues of multiple constraints and the highly nonlinear behavior of the stress constraints. To resolve all of the aforementioned issues, we applied a monolithic analysis, integrating the *qp*-relaxation method and the global p-norm approach. Using the present method, we created optimal layouts that minimize the volume constraining local stress values for a steady-state fluid and structural interaction system.

Keywords: Stress-based topology optimization; Fluid–structure interaction; Monolithic approach

1. Introduction

Multiphysics simulations of transient or steady-state fluid–structure interactions (FSIs) are an important topic with a very wide range of scientific and engineering applications. The difficulties inherent in important FSIs have led to

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many numerical analysis procedures that can be categorized as either staggered or monolithic analysis procedures, depending on the differences in the coupling manner between fluid and structure (see [1–4] and the references therein for reviews of various representative numerical analysis procedures for FSI systems). Based on a review of the numerical analysis procedures, we found that many size and shape structural optimization methods for FSI systems do not seriously consider the topological connectivity alternation between the fluidic domain and the structural domain. Indeed, it is difficult to develop a topology optimization (TO) that allows for topological alternations between the fluid domain and structural domain. In [5], a new monolithic approach using the deformation tensor was introduced for the TO of FSI. Subsequent research extended this to include an electro-fluid-thermo-compliant multiphysics actuator design [6]. In [7], Andreasen and Sigmund proposed a saturated poroelastic actuator and FSI problem in poroelasticity for shock absorbers. In [2], dynamically tunable fluidic devices were optimized using the hydrodynamic lattice Boltzmann method by neglecting the structural deformations due to fluidic forces. In [8,9], a TO method for the internal structure of an aircraft wing was presented with and without FSI. In [10], a structural optimization design for composite laminated plates subject to FSI was developed. In [11], the aeroelastic optimization of a membrane micro air vehicle wing was designed through TO. For pressure-loaded problems, many studies have been conducted with using an explicit boundary between the fluid and structure [12–16]. In [17,18], mixed formulation was employed for pressure-loaded problems. In [19], the stress constraint was considered with design-dependent loading. In [20,21], turbulent flow, for which the turbulence model is the RANS Spalart–Allmaras turbulence model, was the primary consideration in connection with the heat transfer problem in TO. This was a novel approach for turbulence TO with OpenFOAM and the FVM-based adjoint sensitivity analysis. In those studies, the authors proposed to add the element density based-damping factor to the nonlinear turbulence model equation to calculate the turbulent viscosity as well as the momentum equations. In [3], David et al. presented an optimization method for designing the optimal layout of flow channels in micro-mixers using the lattice Boltzmann method. In [22,23], topological optimization for micro mixers was developed. In [24], a new TO method for unsteady incompressible Navier–Stokes flows is developed. In addition, many studies regarding fluid-related problems in TO have been conducted [4,8,25–30]. However, to the best of our knowledge, no study has focused on local stress values in an FSI multiphysics system, and many theoretical and numerical issues still need to be resolved [31–43]. Based on the recently developed monolithic analysis approach [5,6] and the STOM theories for linear structures [44–49], we present a new stress-based TO framework for FSI systems.

1.1. Issues related to topology optimization (TO) for fluid–structure interactions (FSIs)

Several important issues need to be addressed for a successful STOM for an FSI system. In a structural TO method, the general procedure begins by optimizing the spatially varying density variables assigned to each finite element as shown in Fig. 1. In the solid isotropic material with penalization (SIMP) method, very weak Young's moduli are assigned to finite elements for void domains, and nominal Young's moduli are assigned to finite elements for structural domains to simulate morphological alternations in pure structural optimization problems for stiff structure or compliant mechanism, as shown in Fig. 2(a). This artificial material usage method is also used for other TO problems with other areas of physics such as thermal, electric, magnetic and fluid physics. Unlike pure structural optimization problems, the TO simulation procedure for FSI systems is complicated and ambiguous because the material properties of the Navier–Stokes equation and the linear elasticity equation, as well as the two governing equations themselves must be interpolated with respect to the assigned density design variables, as shown in Fig. 2(b). Another related complication is that, there is ambiguity in interpolating the governing equations and the coupling boundary conditions for FSI for intermediate design variables; however, this issue is not related to the intermediate design variable, i.e., gray element or postprocessing, after optimization convergence. Because of these mathematically ambiguous conditions, the state-of-the-art staggered or monolithic computational analysis methods developed to date for FSI systems have many difficulties and limitations that restrict the locally defined stress constraints. Although several new analysis and optimization methods have been proposed for STOMs for linear and geometrically nonlinear structures, the STOM issues for this particular multiphysics system remain problematic and require further mathematical and scientific modifications and contributions.

Overcoming the aforementioned interpolation issues for the two governing equations and the intermediate design variables, we based on our previous research, which analyzed the finite element-based monolithic analysis procedure on FSI systems [5,6]. The most important differences between our monolithic analysis and the existing staggered and