Journal of Fluids and Structures 57 (2015) 298–313

Contents lists available at ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs

Efficient shape optimization for fluid–structure interaction problems

Nima Aghajari, Michael Schäfer *

Institute of Numerical Methods in Mechanical Engineering, Technische Universität Darmstadt, Dolivostr. 15, 64293 Darmstadt, Germany

ARTICLE INFO

Article history:
Received 9 February 2015
Accepted 18 June 2015
Available online 25 July 2015

Keywords:
Fluid–structure interaction
Shape optimization
Reduced order modeling

ABSTRACT

An approach for the shape optimization of fluid–structure interaction (FSI) problems is presented. It is based on a partitioned solution procedure for fluid–structure interaction, a shape representation with NURBS, and sequential quadratic programming approach for optimization within a parallel environment with MPI as direct coupling tool. The optimization procedure is accelerated by employing reduced order models based on a proper orthogonal decomposition method with snapshots and Kriging. After the verification of the FSI optimization, the functionality and efficiency of the reduced order modeling as well as the corresponding optimization procedure are investigated.

1. Introduction

Fluid–structure interaction (FSI) problems play an important role in many technical applications, for instance, wind turbines, aircrafts, injection systems, valves, or pumps. Thus, the optimization of such kind of problems is of high practical importance.

While a lot of work regarding the numerical methods for FSI problems has been published in recent years, developments dealing with the shape optimization of such problems are still limited. The few existing publications are mainly devoted to the shape optimization of aeroelastic applications. For instance, Maute and Allen (2004) developed a method for the aerodynamic optimization of an airfoil by manipulating the topology of the structure. Shape optimization by computing sensitivities with finite differences is considered by Giunta and Sobieszczanski-Sobieski (1998). Maute et al. (2003) proposed a partitioned ansatz for the computation of sensitivities in the context of an optimization problem. Lund et al. (2003) deal with the CAD-based optimization of an academic fluid–structure interaction problem with strong coupling. Schäfer et al. (2010) as well as Hojjat et al. (2010) presented a partitioned approach for a NURBS-parameterized shape optimization of partitioned fluid–structure interaction. Etienne and Pelletier (2005) use a monolithic formulation to determine sensitivities.

In the present paper we consider a modular approach for the shape optimization of fluid–structure interaction problems involving reduced order modeling to accelerate the optimization process. The method is based on a partitioned solution procedure for fluid–structure interaction, a shape representation with NURBS, a sequential quadratic programming approach for optimization, and a proper orthogonal decomposition method with snapshots and Kriging for the set up of several reduced order models. The procedure is realized within a parallel programming environment with the Message Passing Interface (MPI) as coupling tool.

* Corresponding author.
E-mail address: schaefer@fnb.tu-darmstadt.de (M. Schäfer).

http://dx.doi.org/10.1016/j.jfluidstructs.2015.06.011
0889-9746/

The FSI optimization procedure is verified by comparison with reference solutions. Afterwards, the quality of the approximations from the reduced order modeling and the influence of relevant parameters are investigated. Finally, the performance of the optimization procedure with reduced order modeling is investigated by a comparative study.

2. Basic equations

We consider fluid–structure interaction problems in a domain Ω consisting of a fluid part Ω_f and a solid part Ω_s with boundaries Γ_f and Γ_s, respectively, and a fluid–structure interface Γ_i.

For the fluid domain part Ω_f we assume a flow of an incompressible Newtonian fluid. In this case, the basic conservation equations governing transport of mass and momentum for a fluid control volume V_f with surface S_f are given by

$$\int_{S_f} (\boldsymbol{v}-\boldsymbol{v}^g)\cdot\boldsymbol{n}\,\mathrm{d}S_f = 0, \tag{1}$$

$$\frac{\partial}{\partial t}\int_{V_f}\rho_f\boldsymbol{v}\,\mathrm{d}V_f + \int_{S_f}\rho_f(\boldsymbol{v}-\boldsymbol{v}^g)(\boldsymbol{v}\cdot\boldsymbol{n})\,\mathrm{d}S_f = \int_{V_f}\rho_f\boldsymbol{f}_f\,\mathrm{d}V_f + \int_{S_f}\boldsymbol{T}_f\cdot\boldsymbol{n}\,\mathrm{d}S_f, \tag{2}$$

where $\boldsymbol{v}$ is the velocity vector with respect to Cartesian coordinates $\boldsymbol{x}$, t is the time, ρ_f is the fluid density, $\boldsymbol{n}$ is the outward normal vector and $\boldsymbol{f}_f$ are external volume forces (e.g., buoyancy forces). $\boldsymbol{v}^g$ is the velocity with which S_f may move (grid velocity) due to displacements of solid parts. The Cauchy stress tensor $\boldsymbol{T}_f$ for incompressible Newtonian fluids is defined by

$$\boldsymbol{T}_f = \mu_f\left(\nabla\boldsymbol{v}+\nabla\boldsymbol{v}^T\right) - p\boldsymbol{I}, \tag{3}$$

with the pressure p, the dynamic viscosity μ_f, the vector gradient ∇ and the identity tensor $\boldsymbol{I}$.

For the structure we denote a material point in the reference configuration as $\boldsymbol{X}$ whose position in the current configuration is given by

$$\boldsymbol{x} = \boldsymbol{\chi}(\boldsymbol{X}, t). \tag{4}$$

The displacements are evaluated by

$$\boldsymbol{u} = \boldsymbol{x} - \boldsymbol{X}. \tag{5}$$

The basic balance equation for momentum for the solid domain Ω_s can be written as (e.g. Truesdell and Noll, 2004)

$$\nabla\cdot(\boldsymbol{F}_s\boldsymbol{S}_s^T) + \rho_s\boldsymbol{f}_s = \rho_s\ddot{\boldsymbol{\chi}}, \tag{6}$$

where $\ddot{\boldsymbol{\chi}} = \partial^2\boldsymbol{\chi}(\boldsymbol{X},t)/\partial t^2$ is the acceleration, $\boldsymbol{S}_s$ denotes the second Piola–Kirchhoff stress tensor, ρ_s is the density of the solid, and $\boldsymbol{f}_s$ are external volume forces acting on the solid (e.g., gravitational forces). $\boldsymbol{F}_s = \partial\boldsymbol{\chi}/\partial\boldsymbol{X}$ denotes the deformation gradient.

In the present investigation we consider the Saint Venant–Kirchhoff material law

$$\boldsymbol{S}_s = \lambda_s\,\mathrm{tr}\,\boldsymbol{E}\,\boldsymbol{I} + 2\mu_s\boldsymbol{E}, \tag{7}$$

with the Green–Lagrangian strain tensor

$$\boldsymbol{E} = \tfrac{1}{2}\left(\boldsymbol{F}_s^T\boldsymbol{F}_s - \boldsymbol{I}\right), \tag{8}$$

as kinematic property. λ_s and μ_s are the two Lamé constants, which are related to the elasticity modulus E_s and the Poisson ratio ν_s by

$$\lambda_s = \frac{E_s\nu_s}{(1+\nu_s)(1-2\nu_s)} \quad\text{and}\quad \mu_s = \frac{E_s}{2(1+\nu_s)}. \tag{9}$$

The problem formulation has to be closed by prescribing suitable boundary and interface conditions. On solid and fluid boundaries Γ_s and Γ_f, standard conditions as for individual solid and fluid problems can be prescribed. For the velocities and the stresses on a fluid-solid interface Γ_i we have the conditions

$$\boldsymbol{v} = \dot{\boldsymbol{\chi}} = \boldsymbol{v}_b \quad\text{and}\quad \boldsymbol{T}_f\,\boldsymbol{n} = \boldsymbol{T}_s\,\boldsymbol{n}, \tag{10}$$

where $\boldsymbol{v}_b$ is the velocity of the interface and $\boldsymbol{T}_s = \boldsymbol{F}_s\boldsymbol{S}_s\boldsymbol{F}_s^T/\det\boldsymbol{F}_s$ is the Cauchy stress tensor.

We consider the optimization of problems governed by the above coupled fluid–structure interaction equation systems. We define the optimization problem in general form as

$$\min_{\mathbf{d}\in\mathbb{R}^n} J(\mathbf{w}(\mathbf{d}),\mathbf{d}), \tag{11}$$

subject to the conditions

$$\mathbf{R}(\mathbf{w}(\mathbf{d}),\mathbf{d}) = 0, \tag{12}$$