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Evolutionary topology optimization for natural frequency maximization problems considering acoustic–structure interaction

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ABSTRACT

This paper aims to extend the evolutionary methods of topology optimization to free vibration problems of acoustic–structure systems. The interacting fluid and structure fields are governed by the acoustic wave equation and the linear elasticity, respectively. Both domains are solved with the finite element method. The coupling conditions are the equilibrium and kinematic compatibility at the acoustic–structure interfaces. The proposed bi-directional evolutionary structural optimization (BESO) method seeks to maximize the first natural frequencies of the acoustic-structural model by switching elements into solid, fluid or void condition. It allows the acoustic–structure boundaries to be modeled and modified straightforwardly, addressing design-dependent loads on the topology optimization problem with simple finite element formulations. The proposed methodology extension is justified by various possible applications to free vibration of acoustic–structure systems such as tanks/reservoirs, acoustic-structural devices, passengers compartments in automobiles and aircrafts and pipelines. Numerical results show that the evolutionary methods can be applied to this kind of multiphysics problem effectively and efficiently.

1. Introduction

Structural Topology Optimization method for continuum structures [1,2] has gained in popularity and now is used daily as a design tool in industry and academy. The basic idea is to find an optimal distribution of material in a structural design domain considering an objective function and constraints. Commercial topology optimization tools have been developed based on special Finite Element Method (FEM) solvers or have been added in standard commercial packages, many of them concerning stiffness or natural frequencies maximization.

Although the optimization procedures have reached a satisfactory level of maturity, many topics are still open to research. An important group consists of multiphysics problems. Commercial FEM packages often contain solvers for multiphysics problems, however they do not enable optimization.

Through the last 10 years, the methods of topology optimization have been under a considerable scientific effort to be extended to different physical phenomenon problems. One may cite aerolastic structures [3], acoustics design [4–6], thermo-elastic stresses [7], fluid flows [8] and fluid–structure interaction [9–11], acoustic–structure responses [12–14], multiscale analysis [15,16] and others.

The presented work aims to contribute to the design of multiphysics systems, more specifically in acoustic–structure interaction design problems. Yoon et al. [12] proposed a mixed element formulation to model acoustic–structure responses. The method approximated both acoustic and solid domains in an overlapped mixed model, allowing the solid isotropic material with penalization (SIMP) method to be applied. Vicente et al. [14] developed a new sensitivity analysis for the bi-directional evolutionary structural optimization (BESO) method for frequency responses minimization of acoustic–structure systems. The authors considered the minimization of pressures and displacements under harmonic loads. Different from [12,14], herein no loads are applied and free vibration of coupled acoustic–structure systems is considered for eigenvalues maximization. The fluid and solid fields considered here are modeled with the classic finite element formulation from Zienkiewicz and Bettess [17], currently and widely used in commercial codes. In the coupled eigenproblem both acoustic and structural fields strongly influence the vibration modes of the system in all directions since no harmonic excitation is applied. This type of modal analysis has been explored in optimization for purely structural analysis [18–21], but not for free vibration of acoustic–structure problems using the classic formulation.

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In order to allow the switch between solid, fluid and void elements, the BESO method is applied. The discrete update scheme of the evolutionary methods allows the use of separate and different governing equations during the optimization problems, such as proposed by Picelli et al. [22]. This overcomes a well known challenge of the classic density based methods in dealing with moving multiphysics loads and interfaces [23,24]. Thus, in the context of multiphysics optimization, the BESO method presents great potential applications specially considering classic formulations, which can be advantageous for the combination of commercial FEM packages and the optimization codes.

The technique so-called Evolutionary Structural Optimization (ESO) was first introduced in the 90s with Xie and Steven [25]. The ESO method was initially proposed as a gradual removal of inefficient material from the design domain until the remaining structure converges to the optimum topology. Material elimination is done after a sensitivity analysis. A later development of this method was called Bi-directional ESO (BESO), in which elements are also added in void positions near to the elements with the highest sensitivity numbers [26]. In the evolutionary optimization methods, the elemental sensitivity number is a local index and represents the sensitivity of the objective function when the element is added or removed. Papers considering the BESO method have presented convergent and mesh independent solutions [27], natural frequencies constraints [20] and others. Recently, Sigmund and Maute [28] and Deaton and Grandhi [29] have cited the evolutionary methods as one class of the main structural topology optimization methods.

The paper is organized as follows: Section 2 presents the governing equations and the finite element model for the acoustic–structure coupled system. In Section 3, the topology optimization problem for free vibration is formulated and the sensitivity analysis is carried out. Details of the method are also described. Section 4 shows the numerical results achieved with the proposed methodology. Finally, conclusions are drawn in Section 5.

2. Acoustic–structure interaction: governing equations and finite element model

Herein, the analyzed systems are limited to free vibration of flexible structures in contact with acoustic fluids. For this system, the structure can be described by the differential equation of motion for a continuum body assuming small deformations and the fluid by the acoustic wave equation [17,30,31]. The governing equations for the fluid and structural domains as well as the coupling boundary conditions are defined as follows.

2.1. Acoustic domain

In this paper, the fluid is considered inviscid, irrotational and only under small translation conditions. The governing equation for the pressure field in a homogeneous acoustic fluid medium can be described by the acoustic wave equation

$$\frac{1}{c_f^2}\frac{\partial^2 p_f}{\partial t^2} - \nabla^2 p_f = 0 \quad \text{in } \Omega_f, \tag{1}$$

where p_f is the acoustic pressure and c_f is the speed of sound in the acoustic domain Ω_f. In this paper, the following boundary conditions are considered:

$$p_f = p_0 \quad \text{on } S_p, \tag{2}$$

$$\nabla p_f \cdot \mathbf{n}_f = 0 \quad \text{on } S_f, \tag{3}$$

representing the pressure Dirichlet boundary condition, Eq. (2), applied on the portion of the boundary S_p, where p_0 is the constrained pressure, and the hard wall natural boundary condition, Eq. (3), applied on S_f, as shown in Fig. 1.

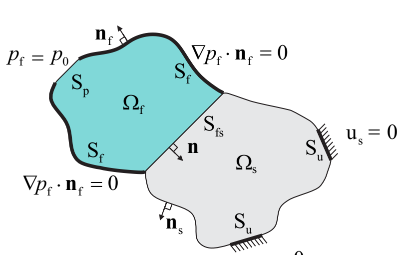

Fig. 1. The coupled acoustic–structure system: the acoustic fluid domain Ω_f and the structural domain Ω_s coupled by integrals over the acoustic–structure interface S_{fs}.

2.2. Structural domain

We consider the equilibrium of a linearly elastic structure in the domain Ω_s. The solid domain is governed by the equilibrium equation

$$\nabla \cdot \sigma_s - \rho_s \frac{\partial^2 \mathbf{u}_s}{\partial t^2} = 0 \quad \text{in } \Omega_s, \tag{4}$$

where $\nabla \cdot \sigma_s$ is the divergence of the Cauchy stress tensor, ρ_s is the structural mass density and $\mathbf{u}_s$ is the structural displacement vector field. In this work the Dirichlet boundary conditions are applied as follows (see Fig. 1):

$$\mathbf{u}_s = 0 \quad \text{on } S_u, \tag{5}$$

2.3. The coupled acoustic-structural system

At the interface S_{fs} between the structural and fluid domains, the fluid and the structure move together in the normal direction of the boundary. The normal vector $\mathbf{n} = \mathbf{n}_f = -\mathbf{n}_s$ (see Fig. 1) can be used in order to guarantee the equilibrium condition between fluid pressures and structural tractions on S_{fs}:

$$\sigma_s \mathbf{n}_s = p_f \mathbf{n}_f \quad \text{on } S_{fs}, \tag{6}$$

With relations derived from the governing equations and the previous coupling conditions, the interface forces may be obtained. Using an approximation based on the finite element method (FEM), the force acting on the structure provided by the fluid pressure is [17,30,31]

$$\mathbf{f}_{fs} = \int_{S_{fs}} \mathbf{N}_s^T \mathbf{n} \mathbf{N}_f \, dS_{fs} \, \mathbf{p}_f \tag{7}$$

and the excitation acting on the fluid domain can be expressed in terms of the structural acceleration

$$\mathbf{f}_{sf} = -\rho_f \int_{S_{fs}} \mathbf{N}_f^T \mathbf{n} \mathbf{N}_s \, dS_{fs} \, \ddot{\mathbf{u}}_s \tag{8}$$

where $\mathbf{p}_f$ is the vector of nodal pressure in the fluid elements, ρ_f is the mass density of the fluid, $\mathbf{u}_s$ is the vector of structural displacements in the structural elements and $\mathbf{N}_s$ and $\mathbf{N}_f$ contain the finite element shape functions for structural and fluid elements, respectively.

The introduction of a spatial coupling matrix, $\mathbf{L}_{fs}$, where

$$\mathbf{L}_{fs} = \int_{S_{fs}} \mathbf{N}_s^T \mathbf{n} \mathbf{N}_f \, dS_{fs} \tag{9}$$

allows the coupling forces to be written as

$$\mathbf{f}_{fs} = \mathbf{L}_{fs} \mathbf{p}_f \tag{10}$$