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Optimization of fluid-structure systems by eigenvalues gap separation with sensitivity analysis

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ABSTRACT

The design optimization process is frequently accompanied by repetitive time-consuming operations, through the design analysis with a few modifications in its parameters, until the required system is encountered. Whenever possible, it is more convenient to use the sensitivity analysis during the optimization, which permits a fast evaluation of the model performance without doing a completely new analysis. In this work, one methodology for obtaining dynamic optimal structural shape through parameters changing was developed for coupled fluid-structure systems, which took advantage of the modal sensitivity analysis and available nonlinear programming tools. The objective of this work is to maximize the gap between two adjacent eigenvalues in coupled fluid-structure systems, in order to avoid the resonance phenomena at a specific natural frequency interval, taking the height of the cross-section of the beam structural elements as design variables with some dimensional constraints and a constant structural volume. The sequential quadratic programming algorithm was used for solving the constrained nonlinear optimization problem, and the modal sensitivity analysis was considered for the modal prediction of the modified design, as well as for the gradient evaluation of the objective function and system's constraints, throughout the optimization. The study was verified in two-dimensional coupled fluid-structure systems, where the structural system is modeled as a beam. The implemented methodology can be applied to avoid resonant situations or to improve the vibroacoustic comfort, for example, in cabins and reservoirs.

1. Introduction

It is common to find problems with two or more physical systems interacting with each other. In many of these situations, an independent modeling of a single system without the simultaneous participation of the others is not realistic. These systems are known as coupled ones, such as systems involving fluid–structure interaction, where both systems cannot be solved independently, because of the existence of interface forces.

The adequate selection of the system variables is fundamental for solving fluid-structure coupled problems. The structural equations are commonly expressed in terms of displacements, while the fluid domain can be described using displacements, pressures, potential of velocities, potential of displacements or combinations of them, [1].

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For instance, the coupled vibrations of a submerged structure in a compressible fluid is studied in [2], using finite elements discretization, with a non-symmetric matrix formulation in structural displacement **u** and fluid pressure **p**.

On the other hand, many techniques have been proposed for analyzing the modal sensitivity of a structural system, e.g., the method of finite differences, the modal method of Fox and Kapoor [3], the method of Nelson [4], the modified modal method of Wang [5], among others.

The method of Fox and Kapoor is based on the modal superposition, but the precision decreases when the higher modes are omitted. Nelson's method analyzes the modal sensitivity in strict way, but it requires solving a different equation for each mode. The modified modal method of Wang employs the modes in acceleration and modal superposition. These methods are based on the symmetrical dynamic formulation of structural systems, but they can also be generalized for non-symmetric systems using the concepts of right and left eigenvectors.

In coupled systems, Ma and Hagiwara (cf. [6]) applied right and left eigenvectors for the modal solution of acoustic-structural systems in a non-symmetric **u**-**p** formulation. They exploited the modal superposition technique and proposed a method for calculating the sensitivity of eigenvalues and eigenvectors. Afterward, Hagiwara and Ma (cf. [7]) proposed an improvement of this approach after canceling the upper and lower modes.

According to Luo and Gea (cf. [8]), a relation between right and left eigenvectors must be previously established by symmetrization of the unsymmetric eigensystem for the modal analysis of a coupled acoustic-structural system, and then the method of Nelson can be used for calculating the sensitivity of eigenvalues and eigenvectors.

Whereas the optimization of structural problems has been researched in different ways following the size, shape and topological approaches, there is a minor quantity of works concerning to the optimization of coupled systems. In the structural domain and concerned to this work, the gap maximization between adjacent natural frequencies of a free-fixed beam with a mass on the free end is exemplified in [9], while in the field of simultaneous shape and topology optimization, the difference between two eigenfrequencies is maximized in [10].

Jog (cf. [11]) worked on the reduction of vibrations of structures under periodic loading through the minimization of the dynamic compliance, reducing the noise radiated from a structure and obtaining attenuation in the vibration level by moving the natural frequencies. Lately, Aghajari and Schäfer (cf. [12]) presented shape optimization tools for fluid-structure problems using the Sequential Quadratic Programming (SQP) approach.

The structural optimization with the criterion of eigenvalues separation in a two-dimensional fluid-structure coupled system is analyzed in [13]. The optimality criterion method is considered during the optimization, but the main disadvantage is the difficulty to choose the convergence parameter to stabilize the optimization process. Pal and Hagiwara (cf. [14,15]) studied the noise level reduction in a coupled structural-acoustic problem, using the sensitivity analysis in a modal base and ignoring the upper and lower modes.

Marburg et al. (cf. [16]) demonstrated the potential of the application of normal modes in external acoustics for optimization of a radiating finite beam, but the optimization strategy does not guarantee that the global minimum has been found. However, they emphasized that, for technical applications, it is often more relevant to find an improved solution in a short time than to run a long search looking for a global minimum.

Many systems may need to model the fluid–structure interaction phenomena, such as fuel reservoirs, electric transformers, vehicle cabins, piping and pressure vessels. These systems can enter in resonance because of the effect of certain excitements, being preferable to prevent it in the design phase. For example, Marburg and Hardtke (cf. [17]) intended to decrease the vehicle interior noise by maximizing the first eigenfrequency through shape optimization of a vehicle hat-shelf, while Yuksel et al. (cf. [18]) developed a methodology to improve the SPL inside the vehicle cabin modifying the thickness of the most influential radiating panels.

The topology optimization has also been used in multiphysics systems, as it can be observed on aeroelastic structures [19], soundproof structures [20], periodic microstructures [21], acoustic-porous-structure systems [22,23], acoustic metamaterials [24], acoustic-structure problems [25,26], fluid–structure interaction systems [27,28], among others.

Global optimization techniques have been also applied in vibroacoustic systems, such as the parallel genetic algorithm and a distributed computing network used by Howard et al. (cf. [29]) to optimize the locations and parameters for combined Helmholtz resonators and tuned mass dampers in an aerospace application. In other context Ranjbar and Marburg (cf. [30]) proposed a fast vibroacoustic optimization using artificial neural networks to make analytical approximations of the objective function concerned with the reduction of radiated SPLs and the method of simulated annealing as the optimizer tool.

On the other hand, using a scheme that comprises both global and local optimization methods, Vogel (cf. [31]) established that acoustic related stresses and structural mass can be simultaneously reduced in structural-acoustic aerospace applications.

However, according to Marburg (cf. [32]) in the field of approximation optimization, Sequential Quadratic Programming (SQP) as local approximation seems to possess the highest potential for optimization and its performance should be compared with that of stochastic methods to clarify which method performs best for certain applications.

In this work, a new methodology is developed for modal optimization of fluid-structure problems in a non-symmetric **u**-**p** formulation, where the modal sensitivity of the system relative to the design variables are used for the modal prediction of the modified design, and also for the gradient evaluation of the objective function and constraints of the system.

The objective of this work is the control of vibroacoustic characteristics in coupled systems, composed by an elastic structure filled with a compressible fluid, through the positioning of its natural frequencies. For that purpose, the