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Topology optimization in acoustics and elasto-acoustics via a level-set method

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ABSTRACT

Optimizing the shape and topology (S&T) of structures to improve their acoustic performance is quite challenging. The exact position of the structural boundary is usually of critical importance, which dictates the use of geometric methods for topology optimization instead of standard density approaches. The goal of the present work is to investigate different possibilities for handling topology optimization problems in acoustics and elasto-acoustics via a level-set method. From a theoretical point of view, we detail two equivalent ways to perform the derivation of surface-dependent terms and propose a smoothing technique for treating problems of boundary conditions optimization. In the numerical part, we examine the importance of the surface-dependent term in the shape derivative, neglected in previous studies found in the literature, on the optimal designs. Moreover, we test different mesh adaptation choices, as well as technical details related to the implicit surface definition in the level-set approach. We present results in two and three-space dimensions.

1. Introduction

Topology optimization [1,2] has become nowadays a popular tool in product design. Novel areas of applications constantly appear, in different frameworks of physics and scales ranging from micro-mechanisms (MEMS) to aircraft parts [3]. Moreover, the burst of evolution in additive manufacturing technologies and the consequent breakthrough in fabrication capabilities, permits to realize complex structural shapes and thus take full advantage of topology optimization results.

Beyond the tangible benefits from the incorporation of topology optimization in the product design cycle, such as performance improvement, mass reduction and acceleration of the total design process, its contribution in setting design guidelines is highly acknowledged. In problems involving elaborate physics, such as computational fluid dynamics (CFD), noise-vibration-harshness (NVH) and non-linear mechanics, topology optimization results are used by engineers to gain knowledge on how to improve their designs. Acoustics belong to this category of complex problems, where the strong dependency of the optimal design on the problem data (excitation frequencies, boundary conditions) mitigate the efficiency of concepts based thoroughly on engineers' knowledge and intuition and give rise to the potential gains from employing automated form-finding techniques.

Primal topology optimization approaches [4,5] were based on density methods. In this case, the notion of classical shape is dropped in favor of a density description and one tries to find its optimal distribution inside a working domain [6]. Consequently, assuming that we are not interested for composite materials but for classical geometric shapes char-

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acterized by their boundary position, the mechanical framework needs to be modified in order for the density field to appear in the problem formulation. Although this is classical in several problems, complications may appear in physics frameworks where the precise boundary position is of crucial importance. In such cases, intermediate density values may provide fictituous mechanical results, thus making the optimization results questionable [7]. Although recent advances in projection schemes [8,9] have provided quite satisfying results, geometry-based methods for topology optimization [10–14] seem to be more appropriate to tackle such cases, since the mechanical problem needs almost no modification.

Several works on optimal acoustic design have been presented in the framework of “fictituous” density methods. Yoon et al. [15] used a mixed finite element formulation [16] in order to eliminate the necessity of an explicit boundary representation, by choosing properly the material properties in the acoustic domain. Du and Olhoff [17] minimized the sound power radiated from a bi-material structural surface, making an efficient approximation of the sound power flow. The authors compared the results to those derived by minimizing the dynamic compliance and concluded that although both methods improve significantly the sound performance, differences in the optimized topologies appear for high frequencies. The use of the dynamic compliance for optimal acoustic design has also been proposed in Ref. [18], assuming a one-way coupled system. In Ref. [19] Dühring et al. presented applications of optimal acoustic design in noise reduction of rooms and in the design of sound barriers. The optimal design of elastic wave barriers has also been examined in Ref. [20]. Zhang et al. [21] worked on the minimization of the sound pressure, neglecting the influence of the acoustic problem on the structural system. Wadbro et al. worked on the optimization of an acoustic horn in Ref. [22] and combined their method with shape optimization techniques for optimizing an acoustic horn–lens combination in Ref. [23]. Finally, we highlight the work of Christiansen et al. in Refs. [24–26] on the optimal design and experimental validation of acoustic structures, using a double projection filter to create geometrically robust designs [27].

In the framework of the level-set method for topology optimization, Shu et al. [28] worked on the interior noise reduction considering a coupled acoustic-structural system. Using a phase-field implementation of the level-set method, Isakari et al. [29] have coupled the level-set method with the fast multipole boundary element method and Noguchi et al. [30] have used a mixed formulation for simultaneous design of an elastic structure and a coupled acoustic cavity using a two-phase material model.

In this work, we focus on the implementation of the level-set method for topology optimization [11,14,31] in acoustics and elasto-acoustics problems. Our contribution is twofold. First, from a theory point of view, we highlight some details on the shape derivation of boundary-dependent terms that have been omitted in Ref. [28]. We present two equivalent ways to perform the shape derivation. We also propose an approach for the optimization of the boundary conditions. Then, we focus on the numerical implementation of the method and test several possibilities for the amelioration of its precision, concerning mesh adaptation and approximations of the boundary terms in the implicit level-set description. More specifically, after a short introduction in the shape and topology optimization framework used herein, we start in Section 3 with purely acoustics problems. We use the Helmholtz equation for the acoustic problem and Céa’s method to compute a shape derivative for minimizing the sound pressure. We also propose a smoothing technique [32] to avoid the discontinuity in derivating the position of boundary domains containing different boundary conditions. In Section 4 we treat the fully coupled elasto-acoustics problem. Details on the numerical implementation of the method, directly linked to the level-set description are presented in Section 5 and numerical results in two and three space dimensions are shown in Section 6. This article ends with some general conclusions in Section 7.

2. S&T optimization framework

Several methods for shape and topology optimization have been proposed in the literature. Despite the possible fundamental differences between them, they are all characterized by two main ingredients: a way to describe a shape and a method to evolve it during the optimization process. In this work, we use the level-set method for the shape description, coupled with a shape-sensitivity analysis for computing a notion of shape gradient and applying a type of gradient descent algorithm. We briefly present these two elements in this section.

2.1. Level-set method

The level-set method, developed by Osher and Sethian [33], uses an implicit representation of an evolving front as the zero level-set of an auxiliary function ϕ. More precisely, assuming that the domain Ω of interest is a subset of a large working domain D, the level-set representation of Ω can be defined as:

$$\begin{cases} \phi(x) = 0 & \Leftrightarrow x \in \partial\Omega \cap D, \\ \phi(x) < 0 & \Leftrightarrow x \in \Omega, \\ \phi(x) > 0 & \Leftrightarrow x \in \left(D \setminus \overline{\Omega}\right). \end{cases} \tag{1}$$