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Topology optimization for enhancing the acoustical and thermal characteristics of acoustic devices simultaneously

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ABSTRACT

In this study, an optimal design method was developed using topology optimization for an acoustic device in the presence of temperature gradient. Although acoustic properties were strongly affected by temperature distribution, many topology optimization problems for optimal acoustic devices were formulated under the assumption that temperature was uniformly distributed in the design domain or that heat transfer through boundaries was negligible. An acoustically optimized topology could negatively influence the heat transfer characteristics of a mechanical device. To figure out this issue, thermo-acoustical topology optimization problems were formulated for an optimal design of the acoustic device. A general form of a finite element equation was developed for acoustical and thermal analyses, and interpolation functions were carefully selected to obtain a black-and-white topology in the final step. Optimal design examples were solved for various acoustical and thermal design requirements, and the physical characteristics of an optimal muffler obtained using the proposed approach in the present study were compared with those of a well-known existing design.

1. Introduction

Various acoustical topology optimization problems have been formulated since Bendsøe and Kikuchi [1] successfully applied a topology optimization method to a structural design problem. Topology optimization was used to systematically design acoustic horns [2,3], outdoor sound barriers [4], soundproof structures [5], mufflers [6], and noise barriers [7]. Extended acoustical topology optimization problems were introduced for the optimal design of coupled structural-acoustic systems [8,9] and minimization of sound radiation [10,11]. A multi-physics-based topology optimization problem was developed for an acoustic device [12]. In these problems, the limiting values of acoustic properties, such as density and bulk modulus, were fixed assuming that the temperature was uniform in the design domain or that the temperature distribution did not change during the optimization. However, when a fluid with thermal energy passes through an actual acoustic device, such as a vehicle exhaust muffler, a temperature gradient is present inside the device due to conduction or convection, and its distribution also changes with its thermal resistance depending on topology during the optimization process. Therefore, a thermo-acoustical topology optimization framework is required to obtain an optimal topology that reflects the thermal effect on acoustical phenomenon.

Several researchers conducted acoustical analyses of acoustic devices in the presence of a temperature gradient. Cummings [13], Munjal and Prasad [14], Prasad and Crocker [15], and Peat [16] proposed theoretical methods to

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obtain approximate or exact solutions for linear temperature gradients inside a duct. Kumar and Sujith [17] considered quadratic temperature profile inside a duct to develop the exact solution of acoustic pressure inside a straight pipe. Kim et al. [18] theoretically and numerically calculated the acoustic pressure of an expansion chamber muffler with a steady temperature gradient. Wang et al. [19] applied the boundary element method to an acoustical analysis of a silencer in the presence of a linear temperature gradient. Although the results of these extant studies definitely contributed to the development of thermo-acoustical analysis on acoustic devices, they did not result in an optimal design of an acoustic device.

Recently, design methods based on numerical calculations were widely applied to mechanical device design problems. Barbieri and Barbieri [20,21] used a shape optimization method to determine the partition length of a muffler for a higher transmission loss (TL) value at the target frequency. Bängtsson et al. [22] formulated an acoustical shape optimization problem to design an acoustic horn. Additionally, Lee et al. [23] formulated an acoustical topology optimization problem for the optimal distribution of three-phase materials in a dissipative expansion chamber. Lee et al. [24] enhanced sound radiation and scattering of thin body structures using topology optimization with generic algorithms. However, they did not consider the temperature gradient in the design domain. In the area of thermal design, Li et al. [25,26] optimized heat paths to reduce the temperature of a plate model by employing the evolutionary topology optimization method. Gao et al. [27] formulated a conduction problem using topology optimization to consider the design-dependent thermal load effect. Iga et al. [28] applied the topology optimization method to the heat convection problem. Ryu et al. [29] reformulated the path-planning problem for a point robot moving in a planar environment as a heat conduction topology optimization problem. The design results of the fore-mentioned previous studies demonstrated that optimization-scheme-based design methods result in better performance. However, the optimization problems formulated in extant studies were based on single mechanics (either acoustics or thermodynamics), and their optimal results overlooked changes due to interactions between acoustic wave propagation and heat transfer.

This study develops a thermo-acoustical topology optimization framework for the optimal design of an acoustic device in the presence of a temperature gradient. The paper is divided into the following sections. Section 2 introduces the heat transfer issue in acoustical topology optimization. The unified form of a finite element equation is derived to carry out acoustical and thermal analyses in Section 3. In Sections 4 and 5, three thermo-acoustical topology optimization problems are formulated and solved for several design conditions. Finally, the physical characteristics of the obtained optimal topologies are discussed and compared with those of a side-branch resonator and a conventional muffler in Section 6. In this study, it is assumed that the flow speed of fluid passing through the muffler is so slow that the effect of flow on the acoustical attenuation performance could be neglected, and the heat transfer inside the muffler could be governed by conduction. An expansion chamber muffler with an offset inlet/outlet is used as an analysis model, and all numerical results are obtained using MATLAB, unless otherwise mentioned.

2. Heat transfer issue in acoustical topology optimization

The goal of this section is to discuss the heat transfer issue in acoustical topology optimization by using extant research. Thus, only several key equations on design problem formulation, and analysis/solving procedure are presented briefly in this section. Further details on the equations and procedure are given in the following sections (Sections 3 and 4). Two temperature distributions are considered in the formulation of a muffler design problem by using acoustical topology optimization.

In order to investigate the effect of temperature gradient on the optimal topology in an acoustic device design problem, the acoustical topology optimization problem formulated by Lee and Kim [6] for the muffler design was used with a finite element model in Fig. 1(a) as follows:

$$\min_{0\le\chi_r\le 1} L = -TL_{f=f_t}, \tag{1}$$

subject to

$$\sum_{r=1}^{R}\chi_r/R \le V_a, \tag{2}$$

$$1/B_r(\chi_r) = 1/B_{\mathrm{air}} + \chi_r(1/B_{\mathrm{rigid}} - 1/B_{\mathrm{air}}), \tag{3a}$$

$$1/\rho_r(\chi_r) = 1/\rho_{\mathrm{air}} + \chi_r(1/\rho_{\mathrm{rigid}} - 1/\rho_{\mathrm{air}}), \tag{3b}$$

where $TL_{f=f_t}$ denotes the TL value calculated at the target frequency (f_t) by using a three-point method [30]. A design variable (χ_r) was assigned to each finite element in the design domain and changed continuously between “0” and “1”. The number of finite elements in the design domain in Fig. 1(a) was denoted by R, and V_a represents the allowed volume ratio between the partition and the design domain. The bulk modulus (B_r) and density (ρ_r) of the r-th finite element were determined by the interpolation functions in Eqs. (3a) and (3b), which are functions of a design variable. The subscripts “air” and “rigid”