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Topology optimization for three-phase materials distribution in a dissipative expansion chamber by unified multiphase modeling approach

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Highlights

- Topology optimization of dissipative expansion chamber with multiphase materials.
- Fully-modeled different constituents—acoustic, poroelastic and elastic materials.
- Unified handling of multiphase material states and their interface couplings.
- Elaborate penalization scheme for material interpolation.
- Optimized designs suitable for practical fabrication.

Abstract

The sound attenuation performance of a dissipative expansion chamber is a combinational result of reflective and dissipative effects. Although it is well known that the performance can be substantially improved by altering the distribution of constituent materials, the process of finding an optimal distribution of the materials still remains a challenge. This work proposes a new design method for interior space of a dissipative expansion chamber by using topology optimization method. Different from the existing topology optimizations for expansion chamber designs based on simplified material modeling, the present design deals with fully-modeled multiphase constituent materials, such as acoustic, poroelastic and elastic one. Difficulties in the optimization formulation for the multiphase material distribution arise from extremely-different acoustic behavior of the materials and the use of various governing equations for different phase materials. To systematically vary the attributes of the chamber interior space, a unified multiphase modeling approach that allows continuous variations between the three-phase materials within the same implementation is employed with an elaborately-derived penalty parameters of material interpolation functions. Various design examples are successfully solved for wide frequency bands and the optimal configurations clearly demonstrate the importance of using specific configurations tuned to different target frequencies.

Keywords: Expansion chamber design; Topology optimization; Poroelastic material; Unified multiphase modeling; Biot's equations

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1. Introduction

As in mufflers or silencers, a dissipative expansion chamber is used as a key functional component in noise reduction systems [1,2]. By combining variation of cross-sectional area, through sudden expansion and contraction at inlet/outlet ports of a chamber, and adding sound absorptive material linings such as porous materials, the resulting reflective and dissipative effects contribute to the sound attenuation of a dissipative expansion chamber. Both the reflective and dissipative effects vary depending on the frequencies of interest [3]. While an increase in sound reflection owing to geometrical changes is suitable for attenuating noise in the low-frequency range, the sound absorptive material linings may be an effective treatment at higher frequencies. This difference in the working frequency makes it difficult to realize wide-frequency noise attenuation with either the reflective effect or the dissipative effect alone. On the other hand, a dissipative expansion chamber is capable of performing a good noise reduction in a wide range of frequencies. Therefore, an optimal combination of the reflective and dissipative effects is the key for a successful design of a dissipative expansion chamber. However, it is difficult to design a dissipative expansion chamber to exhibit such optimal combinations in sound attenuation by traditional trial-error processes.

The objective of the present work is to propose and evaluate a new systematic design method for a dissipative expansion chamber based on the topology optimization method. The process of finding effective combinations of the reflective and dissipative effects is formulated as a problem to design the internal configuration of a dissipative expansion chamber. With some mass constraints, three different-phase materials (i.e., air, elastic solid and poroelastic materials) are to be optimally distributed in a design domain of an expansion chamber as shown in Fig. 1 for maximizing the sound attenuation performance in a wide range of frequency bands. In this work, the multiphase constituent materials are fully modeled, without omitting important degrees of freedom, from both the physical and mathematical viewpoints in order to predict accurately their various physical characteristics.

There have been many works on shaping and sizing expansion chambers by using optimization formulations. The design parameters were the length and the cross-sectional area of a chamber [4–7], extended inlet/outlet tubes in its ports [6–10] and its internal division [10]. Since most of the shape optimization problems did not involve sound absorptive materials inside the expansion chambers, the reflective sound attenuation effect was considered alone. While varying shape parameters of an expansion chamber may effectively reduce noise at a single or a narrow range of frequency, the design range by the shape optimization is limited because the available spatial volume outside of the expansion chamber is constrained in general.

Rather than changing the shape of an expansion chamber itself, the addition of inner structures inside a given expansion chamber may be more efficient in improving noise reduction performance. While there were successful reports to optimize its inner structures by shape optimization [6–10], the topology optimization method that was originally developed for structural compliance minimization [11] can give more freedom in the design (see [12] for general discussion on the method). In this case, the design problem may be formulated as a problem to find an optimal distribution of constituent materials in a design domain. The topology optimization was carried out first by Lee and Kim [13] for the expansion chamber design. The objective was to configure internal partitions in an expansion chamber to maximize its sound transmission loss at single or multiple target frequencies. In their work, only air and a rigid material were considered with the rigid material being modeled as air having very large, artificial values of density and bulk modulus [13]. Similar studies to distribute air and a rigid material in an expansion chamber were performed by Kook et al. [14] and Yoon [15]. In case of [15], a fibrous material represented by an empirical model was considered for the interior design of an expansion chamber.

The governing equation for all materials in [13–15] is the scalar Helmholtz equation alone. Because air was used as the base acoustic material, the rigid solid state in [13–15] and the fibrous material in [15] were expressed as a very hard, artificial air and a strongly-viscous air, respectively. The main limitation in these works is that it was not possible to deal with the multiphase materials, which are rigorously considered in the present study. The main reason is that the scalar Helmholtz equation cannot represent either a purely elastic motion or a coupled motion of elasticity taking place in a biphasic dissipative poroelastic material. This calls for a new topology optimization formation that is capable of handling a complete set of constituent materials, such as air, elastic and poroelastic materials. This work will be mainly focused on this new problem.

Among the three dissimilar materials to be considered in the present dissipative expansion chamber design, air and an elastic solid are obviously single phased while a poroelastic material has two phases, i.e., solid and fluid phases. To deal with multiphase materials effectively in the topology optimization design, a recently-proposed unified multiphase