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Optimal topology of reactive muffler achieving target transmission loss values: Design and experiment

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ABSTRACT

A topology-optimization-based muffler design method for a reactive muffler is proposed and experimentally validated. In a reactive muffler design problem, rigid partitions should be located optimally inside the muffler to improve its acoustical attenuation performance in the target frequency range. In an optimal-performance muffler, the partition volume should be made as small as possible, and the transmission loss value in the target frequency range should be high enough for flow noise reduction in a duct. To this end, a partition-volume-minimization problem achieving target transmission loss values is formulated by using acoustical topology optimization. The formulated muffler design problem is solved for several target frequencies, and the effect of the initial values of the design variables on the optimal topology is investigated. Numerical simulation results show that the proposed formulation requires a smaller volume of partition than the previous topology-optimization-based formulation. The calculated transmission loss curves of the optimal mufflers agree well with the measured transmission loss curves of mufflers made of acrylic.

1. Introduction

Reactive mufflers are widely used to reduce flow noise in the duct or pipes of mechanical systems [1–3]. In general, a concentric expansion chamber muffler, in which the centers of the inlet and outlet of the muffler lie on the same straight line, is mounted onto the cutout area of the duct or pipe so as not to change the original flow loop. The outer dimensions of the muffler are determined depending on the main frequency range and magnitude of the noise. In the case that the height or length of the muffler cannot be increased fully due to space limitations, rigid partitions are inserted inside the muffler to improve its acoustical attenuation performance, which is evaluated with its transmission loss (TL) curve plotted in the frequency domain.

In order to design partition layouts for higher TL values for a given target frequency range, several design methods for the concentric expansion chamber muffler have been proposed. The design methods may be classified into theoretical-analysis-based muffler design methods and optimization-based muffler design methods. Researchers contributing to the former have investigated the effects of the dimensions and shape of mufflers on the TL curves by using the TL formula starting from the acoustic wave equation. Munjal et al. [4–6] used transfer matrix techniques to calculate the TL value and to tune the lengths of the extended inlet/outlet inside the expansion chamber. Selamet et al. [7–9] investigated the effect of the length of the muffler on acoustical attenuation performance and tuned the lengths of vertical/horizontal partitions inside the expansion chamber. Their approaches have been experimentally validated; however, the approaches require that the designers should fully understand the acoustical characteristics of various partition layouts. Researchers developing optimization-based muffler design methods have applied various optimization schemes to muffler design problems. Barbieri et al. [10–13] improved the four-pole parameter method by employing the Galerkin finite element method for numerical simulation and applied the shape optimization method to a reactive muffler design problem. Chiu et al. [14–19] used the generic algorithm or the simulated annealing method to optimally design the size of vertical or horizontal partitions. Their approaches significantly improved the acoustical attenuation performance of the muffler in the target frequency range; however, their method requires a suitable initial partition layout for achieving an optimal partition layout.

Recently, the topology optimization method has been applied to acoustic device design and acoustic control problems because it is less dependent on designers' experiences and the initial shape of the mufflers than previous optimization schemes [20]. Acoustic horns [21], outdoor sound barriers [22], soundproof structures

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Nomenclature

$\overset{N}{\underset{n=1}{\mathbf{A}}}$	finite element assembly operator
c	speed of sound
c_n	speed of sound of the n-th element
d	height of the muffler
d_i	height of the inlet
d_o	height of the outlet
$\mathbf{F}$	nodal vectors of the applied equivalent force
f	frequency
f_t	target frequency
$\mathbf{K}$	stiffness matrix
$\mathbf{k}_n$	element stiffness matrix
L_{obj}	objective function
l	length of the muffler
$\mathbf{M}$	mass matrix
$\mathbf{m}_n$	element mass matrix
$\mathbf{N}_n$	shape function vector of the n-th element
N	number of total finite elements in the muffler
N^{in}	number of associated elements
n	normal direction of the boundary
$\mathbf{P}$	nodal vectors of the acoustic pressure
p	acoustic pressure
p_i	acoustic pressure at point i
R	total number of design variables
R_a	number of allowed rigid body elements
T	total number of target frequencies
TL	transmission loss
$\text{TL}_{f=f_t}$	TL value calculated at the target frequency
$\text{TL}_{\text{target}}$	target TL value
u_x	x component of the particle velocity
$\vec{u}$	particle velocity
x_{12}	distance between the two points in the inlet

Greek symbols

K	bulk modulus
K_n	bulk modulus of the n-th element
ρ	density
ρ_n	density of the n-th element
χ_r	design variable
$\partial\Omega_n^{in}$	inlet boundary
$\partial\Omega_n^{out}$	outlet boundary

[23], and noise barriers [24] have been optimally designed by topology optimization. To control the acoustic mode frequencies for noise reduction, acoustical topology optimization problems have been formulated and solved [25,26]. However, to widen the application area of the acoustical topology optimization method, improvements in the experimental validation and formulation setup are required.

In a reactive muffler design problem, the volume and location of partitions should be determined simultaneously depending on the target frequency and the target TL value at the target frequency. As a first attempt to systematically design the partition layout inside the expansion chamber, Lee and Kim [27] formulated a TL maximization problem by using acoustical topology optimization. They demonstrated the feasibility of the topology-optimization-based muffler design method; however, their approach required that the partition volume in their formulation be pre-determined before optimization. In addition, their optimal designs have not thus far been experimentally validated. In this study, in order to overcome the two primary shortcomings of the previous topology-optimization-based muffler design method [27], the volume of partitions as well as their location is optimized, and the resulting optimally designed mufflers are experimentally validated.

This paper is organized as follows. First, a new reactive muffler design problem is formulated by using acoustical topology optimization. To calculate the TL value at the target frequency, the Helmholtz equation is converted to a finite element matrix equation by using the finite element method. Second, the formulated acoustical topology optimization problem is solved for several design conditions by using a gradient-based optimization scheme, and its performance is investigated by comparing the proposed method with Lee and Kim's method [27]. Subsequently, the calculated TL curves of the optimally designed mufflers are compared with those of the optimal mufflers made of acrylic in the experimental validation stage. Finally, this work is summarized, and the application of this method to an actual muffler design problem is discussed.

2. Muffler design problem set-up by topology optimization

Fig. 1(a) shows the reactive muffler considered in the muffler design problem. The muffler consists of an inlet, an expansion chamber, and an outlet. The center of the expansion chamber coincides with the centers of the inlet and outlet, and its depth (along the out-of-plane z-direction), which is equal to the depths of the inlet and outlets, is so small compared with its height (d) and length (l) that the muffler could be regarded as a 2-dimensional acoustic device. The muffler is divided into the design domain and the non-design domain, where no partition is allowed for fluid passage, as shown in Fig. 1(b).

2.1. Finite element equation

The acoustical attenuation performance of a muffler is evaluated by TL values calculated in the frequency domain. Among

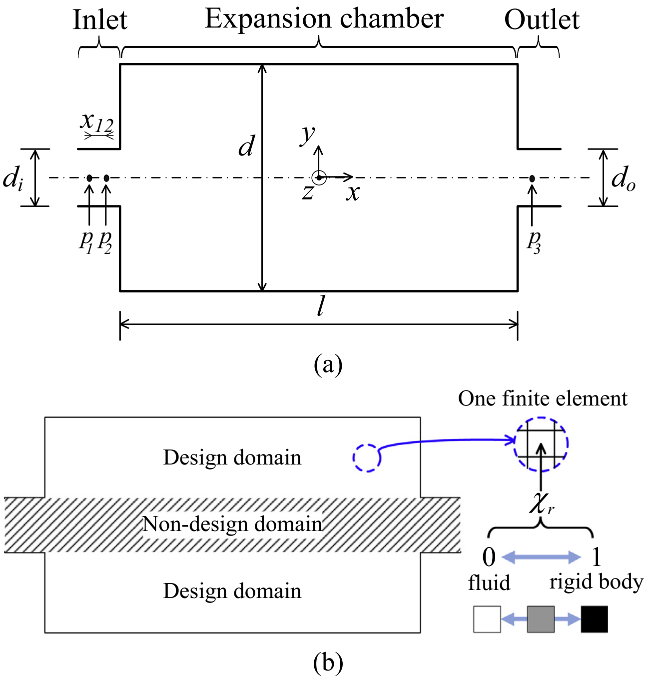

Fig. 1. Reactive muffler in which the centers of the inlet and outlet of the muffler lie on the same straight line. (a) Analysis model (b) Finite element model divided into design domain and non-design domain.