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ABSTRACT

A topology optimization method is developed to optimally design suction mufflers in reciprocating compressors. Suction mufflers should be designed for high noise reduction. The suction mufflers are not easy to systematically design because their outer shape is so complicated and the center axes of the inlet/outlet do not coincide. Muffler researchers in industry have designed the internal configuration of suction mufflers intuitively and experientially. However, since our proposed muffler design method is not restricted to location of the inlet and outlet and to the outer shape of suction muffler, it could be applied to suction muffler design problems. A topology optimization problem is formulated for a finite element model simulating a suction muffler for a reciprocating compressor. Transmission loss value at a target frequency is selected as an objective function and partition volume is constrained. Design variables change continuously from zero to one during optimization process. The material filling one element is an intermediate material between fluid and solid in each iterative calculation and become fluid or rigid body at a final converged stage depending on the value of design variables. Rigid body elements build up partitions or flow path to increase transmission loss. The proposed muffler design method is applied to a suction muffler, which has been introduced at an international conference.

1. INTRODUCTION

A reactive muffler is placed around the refrigerant suction part of a reciprocating compressor to reduce low frequency noise (Lee *et al.*, 2002). The reactive muffler is called as a suction muffler. Since the volume of the suction muffler is determined after other components are designed, its outer shape is complicated and the axes of its inlet and outlet do not coincide with each other in many cases. Therefore, conventional muffler design methods (Selamet and Radaivich, 1997, Selamet and Ji, 1999), which have been introduced so far, are not easy to apply to suction muffler design problems. Many reciprocating compressor developing companies have difficulty in designing the internal configuration of a suction muffler to increase its noise attenuation performance in a target frequency range. In many cases, new suction mufflers, which have been reported in the International Compressor Engineering Conference at Purdue, reflect designers' intuition and experience, and require a lot of time and many trials and errors. Hence, a new muffler design method is required to figure out the current difficulties in compressor companies.

Topology optimization has been widely used in structural design problems (Bendsøe and Sigmund, 2004). The topology optimization design method has a lot of advantages over shape and size optimizations. The utmost advantage among them is that the topology optimization design method does not depend on designers' intuition and experience. Therefore, a creative optimal design can be obtained by topology optimization. Lee and Kim (2009a, 2007a) formulated acoustical topology optimization problems for acoustic device design. Especially, they (2009b, 2007b) showed that the topology optimization method can be applied to reactive muffler design problem: internal partitions should be optimally located in a muffler to increase a transmission loss value at a target frequency. In this work, Lee and Kim's suggested method (2009b, 2007b) is extended to suction muffler design problems.

This paper is outlined as follows: first, a suction muffler design problem is reformulated as an acoustical topology optimization problem; then the formulated design problem is solved at a single target frequency for various partition volumes; and future work is discussed for practical application. The suction muffler, which has been reported previously in other conference (Svendsen and Møller, 2005), is selected as an analysis model and is assumed as a 2 dimensional model for computation time reduction. The finite element model of the suction muffler is employed for acoustical analysis and optimization. One finite element is filled with intermediate material between rigid body and fluid, which is expressed as a function of design variables, during optimization process. Design variables are updated by using a gradient-based optimization algorithm (Svanberg, 1987).

2. REFORMULATION OF SUCTION MUFFLER DESIGN PROBLEM

An acoustical topology optimization problem is formulated for the 2-dimensional suction muffler in Figure 1. The outer shape of the suction muffler is obtained from the 3-dimesional suction muffler which Svendsen and Møller (2005) used for noise reduction. Refrigerant enters the right end of the muffler and goes out into the upper end, and the outer shape is too complicated to easily locate some partitions for transmission loss increase. The internal area in the suction muffler is divided into a design domain and a non-design domain. For refrigerant passage, a non-design domain is assumed to be filled with refrigerant during optimization. Some partitions, which are built up during optimization, will be located optimally in the design domain.

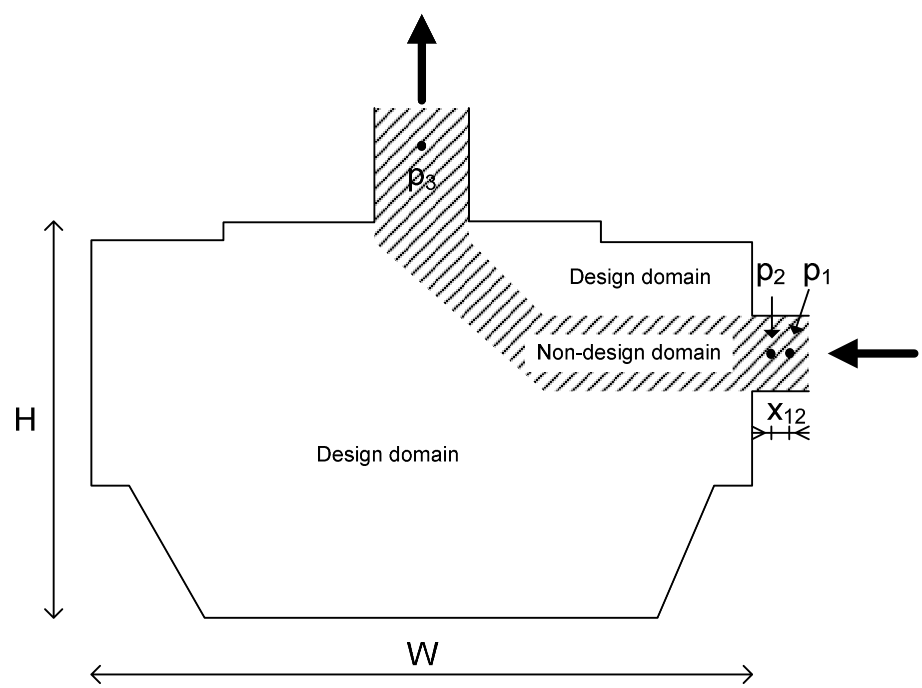


Figure 1: Suction muffler with right-end inlet/upper outlet

To reformulate the suction muffler design problem, the acoustical topology optimization problem in Lee and Kim's method (2009b, 2007b) is recalled. The transmission loss value at a target frequency is selected as an objective function in Equation (1) and the volume ratio between partitions and the suction muffler is constrained in Equation (2). The density and bulk modulus of one finite element are expressed as functions of design variables in Equation (3). The design variables change continuously from '0' to 1'. The finite element is filled with an intermediate material between rigid body and fluid during optimization process and pushed to rigid body or fluid by the interpolation functions in Equation (3). The design variables converge '0' or '1' at a converged topology. The transmission loss value at each iterative calculation is calculated by using the three-point method (Wu and Wan, 1996) in Equation (4).

$$\underset{\boldsymbol{\chi}_\mathbf{e}}{\text{Max}}\, \text{TL}_{f=f_t} \tag{1}$$

where TL represents a transmission loss value at a target frequency, f_t is a target frequency, and $\boldsymbol{\chi}_\mathbf{e}$ is a design variable vectors.

$$\left(\int_V \chi_e dV\right) / V \le V_r \tag{2}$$

where χ_e is a design variable, V is the total volume of suction muffler, and V_r is the volume ratio between allowed partitions and the suction muffler.

$$\begin{aligned} 1/\rho_e(\chi_e) &= 1/\rho_{fluid} + \chi_e \cdot (1/\rho_{rigid} - 1/\rho_{fluid}) \\ 1/K_e(\chi_e) &= 1/K_{fluid} + \chi_e \cdot (1/K_{rigid} - 1/K_{fluid}) \end{aligned} \tag{3}$$

where ρ is the density and K is the bulk modulus ($K = \rho c^2$).

$$\text{TL} = 20 \cdot \log_{10}\left| \frac{1}{p_3} \frac{p_1 - p_2 \cdot e^{jk \cdot x_{12}}}{1 - e^{j2k \cdot x_{12}}} \right|, \qquad k = \frac{2\pi f}{c} \tag{4}$$

where p_1 and p_2 are acoustic pressures at two points in the inlet area of Figure 1 and p_3 is an acoustic pressure at one point in the outlet area. Symbols of x_{12} and c are the distance between two points in the inlet area and sound speed, respectively.

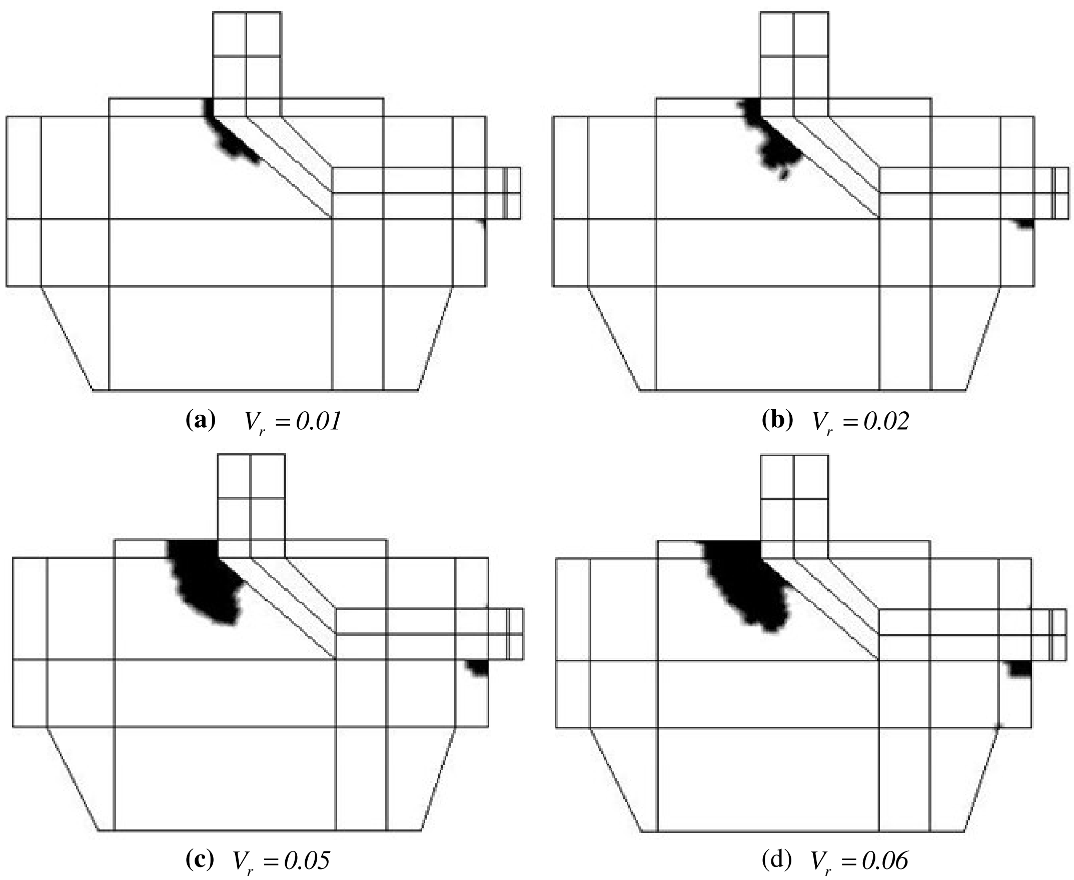
To calculate transmission loss at a target frequency, finite element method is employed. The finite element analysis is implemented by using Olesen *et al.*'s method (2006). Design variables are updated by the Method of Moving Asymptotes (Svanberg, 1987) during optimization process. The method is required the sensitivity analysis of the objective function and the constraint with respect to each design variable. The sensitivity analysis is performed by the Adjoint method (Duhring *et al.* 2008).

3. OPTIMAL SUCTION MUFFLERS

The formulated topology optimization problem for suction muffler design is solved at $f_t = 900$ Hz for four different volume ratios ($V_r = 0.01, 0.02, 0.05, 0.06$). Fluid passing through the suction muffler is assumed to be air. Specific values in Table 1 are used in the optimization. The density and sound speed of rigid body are determined by using the criteria suggested by Lee and Kim (2009c). Figure 2 shows optimal mufflers obtained by solving the topology optimization problem. Black areas are filled with rigid bodies, which build up the partitions. In all optimal mufflers, partitions were built up around an inlet and an outlet. The partition located around the outlet helps increasing the transmission loss value at the target frequency better than the partition located around the inlet. An interesting point is that the partitions are built up below the non-design domain connecting the inlet and the outlet. The location of the partitions could not be found without the topology optimization based design method. Figure 3 compares the transmission loss curves of the four optimal mufflers with the reference muffler ($V_r = 0.00$)

Table 1: Specific values used in the optimization

Symbols	**Physical meanings**	**Specific values**
ρ_{fluid}	Density of fluid	1.21 kg/m^3
$\rho_{rigid\ body}$	Density of rigid body	1.21 $\times 10^7$ kg/m^3
c_{fluid}	Sound speed in fluid	343 m/s
$c_{rigid\ body}$	Sound speed in rigid body	3430 m/s
x_{12}	Distance between two points in the inlet	0.001 m
H	Height of the muffler	0.085 m
W	Width of the muffler	0.14 m



(a) $V_r = 0.01$ **(b)** $V_r = 0.02$

(c) $V_r = 0.05$ (d) $V_r = 0.06$

Figure 2: Optimal topologies

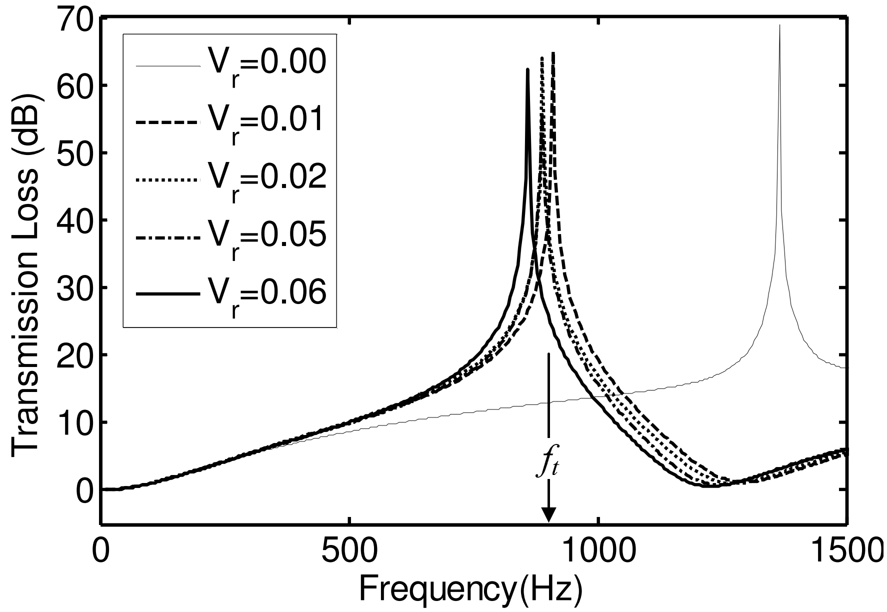


Figure 3: Comparison of transmission loss curves of four optimal mufflers and the reference muffler.

4. CONCLUSIONS

In this work, the topology optimization based muffler design method suggested by Lee and Kim (2009b) was applied to a suction muffler design problem. Optimal mufflers were obtained for various volume ratios between partitions and muffler. The transmission loss values at target frequency are increased dramatically in the four optimal mufflers compared with the reference muffler. Although the current approach was applied to two-dimensional mufflers for reducing the computation time, it could be applicable to three-dimensional muffler design problems without modification.

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