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Duct noise attenuation using reactive silencer with various internal configurations

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ABSTRACT

The broadband sound attenuation characteristics of expansion chamber silencers can be altered by their internal configuration. Three-dimensional modeling of such systems, especially in the presence of complex internal partitions, remains a challenging task. In order to tackle the system complexity, this paper presents a systematic approach based on the sub-structuring modeling principle, to investigate the effects of several typical silencer configurations and provide guidelines for possible system optimization. Through numerical examples, the effects of various internal arrangements, including the side-branch partitions, multi-chamber partitions, non-symmetric inlet/outlet, and their combined effects are investigated. Numerical predictions show good agreements with both finite element method (FEM) and experiments. Investigations suggest some critical issues and possible solutions for better silencer design.

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1. Introduction

Noise attenuation inside a duct is an important topic of practical interest. Typical examples are pumps and compressors, induction and discharging pipes, engine exhausts, building ventilation systems, etc. Among various passive noise control measures, expansion chamber silencers [1] have been widely used due to their relatively simple structure and broadband sound attenuation characteristics. The well-known dome-like behavior in the transmission loss (TL) curve, however, neutralizes the silencing effect at the troughs, and the overall attenuation performance is limited by the expansion ratio that can practically be achieved. Moreover, a simple expansion chamber usually has the drawback of inducing high pressure drop due to the sudden cross-sectional change at the expansion and contraction.

In dealing with the above constraints, reactive silencers with various internal configurations have been investigated in the literature [2–9]. For example, Åbom [2] proposed a general analytical approach to evaluate the four-pole parameters of an expansion chamber with extended inlet and outlet. Selamet and Ji [3] showed that the expansion chambers with inlet/outlet extensions combine the broadband domes and extra resonant peaks below the cut-off frequency, which also helps alleviate the induced pressure drop. Huang [4] developed the so-called plate silencers with side-branch cavities covered by flexible plates, which give rise to noise attenuation through wave reflection towards the upstream. The work was later on extended to sandwich plates to facilitate practical implementations [5]. Lee and Kim [6] studied the effect and optimization of additional vertical partitions inside the chamber, which leads to an increased TL, a wider dome-type attenuation and a simultaneous enhancement of flow performance [7]. Middelberg et al. [8] evaluated the acoustic behavior and induced

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pressure drop of dual-chamber mufflers using computational fluid dynamics (CFD) analysis. Meanwhile, in the pursuit of better sound attenuation, hybrid silencers with additional dissipative elements such as sound absorbing materials or perforated linings have also been investigated [10–13].

With the increasing internal structural complexities, effective modeling tools which eventually allow flexible analyses and optimizations are crucial. One-dimensional theory based on plane wave assumption is only accurate in the low frequency range before the onset of multidimensional waves [1]. To deal with higher-order acoustic modes, 2-D/3-D analytical approaches based on the modal matching technique have been employed, which consist in decomposing the pressure field inside each acoustic domain into oppositely propagating acoustic waves and relating the continuity conditions at the corresponding boundaries. Typical work includes circular [1,3], multi-chamber [9], rectangular and elliptical [14] silencers. However, these approaches are confined to relatively simple configurations. When dealing with complex internal layouts with several coupled domains, the number of the continuity equations to be established drastically increases and the modeling procedure becomes very tedious. As an alternative, finite element/boundary element method (FEM/BEM) has also been frequently employed [6,12]. Although FEM/BEM is able to cope with system complexities, it is highly computational intensive when the system dimension is large, and the convergence starts to show problem when the frequency is high. Most importantly, FEM/BEM can hardly provide the efficiency and the flexibility needed for system optimization.

Sub-structuring techniques can possibly provide the most appropriate solution in overcoming these difficulties in the system modeling, and at the same time, offer great potential in performing system optimizations. By disassembling the global system into sub-systems, each sub-system can be characterized before they are coupled together. The assembling treatment can then be performed through rather simple continuity descriptions at the connecting interfaces, and re-calculations are required only for subsystems with changing parameters during the system optimization. When using the existing sub-structuring approaches for silencer applications, however, the inner acoustic domains are usually connected via multiple partial structures (sometimes even flexible ones) with apertures. The co-existence of parallel transmission paths restricts the straightforward coupling treatment when applying simple continuity descriptions, and thus adds tremendous difficulties to the existing sub-structuring techniques. Therefore, it is the aim of this paper to propose a general modeling framework under the sub-structuring principle, with a convenient treatment of mixed separations, to systematically tackle the complexities and difficulties involved in silencer design problems.

Fig. 1(a) shows a typical example of a three-dimensional expansion chamber with complex internal configuration. In this paper, a systematic sub-structuring formulation based on the patch transfer function (PTF) method [15–18] is proposed to calculate the TL, and to investigate the separate and combined effects of several typical internal arrangements. The PTF approach has been demonstrated to be more computational efficient, and capable of covering a much wider frequency range (low to mid-high) than other conventional methods such as FEM/BEM [15,16]. Fig. 1(b) illustrates the decoupling treatment of the global system, where the whole system is divided into multiple sub-domains. To tackle the mixed separation interfaces between acoustic domains, a compound structure treatment is proposed, with the aperture being modeled as an equivalent structural component. As demonstrated later, the unified structural and acoustic component over a mixed interface provides an effective tool to handle multiple internal partitions.

In this paper, the formulation procedure of the proposed modeling framework is first elaborated, along with the subsystem treatment. Using the model, the separate effects of several typical silencer configurations are considered, which include: (a) side-branch cavities with horizontal partitions/extensions; (b) multi-chamber silencer with vertical partitions; (c) non-symmetric inlet and outlet. The combined effects of the above configurations are then analyzed. The accuracy and convergence of the method are verified against FEM results. Physical phenomena corresponding to different configurations are investigated in detail through visualizing the internal pressure field. An experimental validation on a dual-chamber silencer with horizontal partitions is also conducted, showing a good agreement with theoretical predictions.

2. Formulation

The detailed formulation procedure, along with the treatment of subsystem patch transfer functions (PTFs), is illustrated using a silencer example as shown in Fig. 2. The chamber expansion volume is separated by two pairs of extensions at the

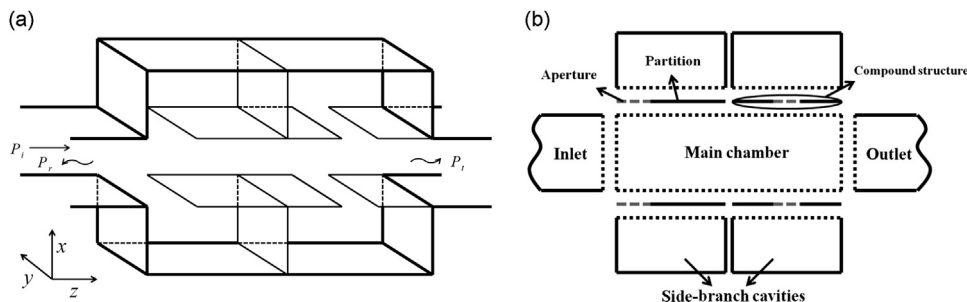


Fig. 1. (a) An example of reactive silencers with complex internal partitions and (b) using sub-structuring technique, the system is divided into uncoupled subsystems.

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