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Transmission loss prediction of silencers by using combined boundary element method and point collocation approach

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ABSTRACT

A technique that combines the boundary element method (BEM) and the point collocation approach is proposed to calculate the transmission loss (TL) of silencers in the absence of mean flow and temperature gradient. A long silencer is first divided into several substructures for analysis purposes. The point collocation approach is applied to produce the impedance matrices of any long substructure that has an axially uniform cross section to produce its impedance matrix. On the other hand, the direct mixed-body BEM is used to produce the impedance matrices of any irregular sections. The point collocation approach employs a modal expansion of the cross-sectional modes extracted by the 2D finite element method (FEM), and then matches the sound pressures and particle velocities at the collocation points on both ends to calculate the impedance matrix. All the substructure impedance matrices are then combined to form the resultant impedance matrix of the whole silencer for TL computation. Several test cases are presented to valid the combined technique and to demonstrate its computational efficiency.

1. Introduction

Both numerical and analytical methods are widely used to predict the acoustic attenuation performance of silencers. Analytical methods have the advantage of high accuracy and computational efficiency. However, they are normally limited to very simple structures only. Selamet et al. [1–3] developed an analytical mode-matching method to predict the transmission loss (TL) of expansion chambers, expansion chambers with extended inlet/outlet tubes, and flow-reversing chambers. The method was also extended to the analysis of concentric-tube packed silencers [4]. On the other hand, numerical methods are more suitable for complex silencers with an arbitrary shape. Peat and Rathi [5] adopted the finite element method (FEM) to analyze dissipative silencers. Mehdizadeh and Paraschivoiu [6] extended the FEM to evaluate the acoustic performance of parallel-baffle silencers. Antebas et al. [7] studied the acoustic properties of dissipative silencers with non-homogeneous absorptive fillings using the FEM. The boundary element method (BEM) was used by Seybert and Cheng [8] to evaluate the four-pole parameters of simple expansion chambers. Wang et al. [9] employed the multi-domain BEM to study the acoustic characteristics of a concentric-tube resonator. Ji et al. [10] extended the BEM to calculate the transmission loss of mufflers with mean flow. The effect of a linear temperature gradient on reactive expansion mufflers was studied by Wang et al. [11] using the multi-domain BEM. For silencers with sound-absorbing material fillings, the multi-domain BEM was used by Ji [12] to calculate the impedance matrix of each homogeneous substructure. Wu and Wan [13] developed the direct mixed-body BEM to eliminate the preprocessing complexity of the traditional multi-domain BEM. Later, the direct mixed-body BEM with a substructuring technique was applied to packed silencers and parallel-baffle silencers [14]. Jiang et al. [15] also extended the method to silencers with multiple sound-absorbing materials.

For large silencers, the FEM or BEM can still be very time consuming due to the large number of degrees of freedom involved. Generally, many industrial silencers in practical use may contain one or several long portions with an axially uniform cross section. For such types of silencers, some hybrid techniques can be used to reduce the computation time. For example, Kirby [16] developed a numerical point collocation approach to analyze dissipative silencers with an axially uniform cross section. To apply the approach, the 2D FEM is first employed to extract the eigenvalues and the associated eigenvectors of the cross section. Then, the point collocation method is used to match the sound pressures and particle velocities at both ends of the silencer chamber to those in the inlet/outlet pipes. Denia et al. [17] extended the point collocation scheme to the transmission loss prediction of dissipative silencers with a transversal temperature gradient and

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mean flow. A numerical mode-matching method was also reported by Kirby [18] to model dissipative silencers with mean flow. In this method, numerical integration is used to enforce the matching conditions over inlet/outlet junction planes. Recently, Fang and Ji [19] used the numerical mode-matching method to calculate and analyze the transmission loss of expansion chambers with extended inlet/outlet tubes. The same method was also extended to predict the transmission loss of double-chamber dissipative silencers with mean flow [20]. Compared to the numerical mode-matching method, the numerical point collocation method is more flexible and may be used to tackle silencers with complex structures such as baffle fairings [21]. The point collocation method is also easy to implement and one may choose less collocation points than the FEM nodes at the cross-sectional plane. However, the original point collocation approach still treats the silencer structure as a whole. Sometimes, a small irregular junction may be inserted between two axially uniform long sections. In that case, the point collocation method cannot be directly used without coupling it to a 3D FEM or BEM model.

Another method that may be considered for long silencers is the direct mixed-body BEM with substructuring [14]. The direct mixed-body BEM has a unique capability to include multiple bulk-reacting materials along with air inside a single BEM domain, and therefore, avoids the tedious zoning and interface matching of the traditional multi-domain BEM. As a result, substructuring can be done naturally in the axial direction. Especially for a long substructure that has an axially uniform cross section, one may just model a small template, and its impedance matrix can “multiply” itself repeatedly using an impedance matrix synthesis procedure to produce the resultant impedance matrix for the long substructure. This template approach can save a lot of computation time. However, computational errors may accumulate if the impedance matrix synthesis procedure is repeated too many times over a very long span.

The objective of the present paper is to propose a combined technique that integrates the numerical point collocation approach [16] into the direct mixed-body BEM with substructuring [14] for the transmission loss prediction and analysis of long silencers without considering mean flow or temperature gradient. A long silencer can be divided into several substructures for analysis purposes. For any long substructure with an axially uniform cross section, the point collocation approach is employed to produce its impedance matrix. On the other hand, the direct mixed-body BEM is used for the remaining irregular sections. All the substructure impedance matrices are then combined to form the resultant impedance matrix of the whole silencer for TL computation. In the point collocation approach, the cross-sectional eigenvalues and eigenvectors may be obtained analytically for simple cross sections. In general, the 2D FEM is used to extract the eigenvalues and eigenvectors numerically for cross sections of an arbitrary shape. To further reduce the computation time, a simplified method based on the modal meshing method [23,24] is also employed in this paper. Several test cases are given to validate the combined technique. The TL predictions are compared to available analytical solutions or the direct 3D BEM solutions. Computational efficiency of the combined technique is also demonstrated.

2. Theory

A typical packed silencer with complex internal components is illustrated in Fig. 1(a). Based on the cross section design in each part, the silencer may be divided into three substructures A, B and C. The direct mixed-body BEM is employed to evaluate the impedance matrices of substructures A and C. For substructure B, the cross section is axially uniform as shown in Fig. 1(b) and thus its impedance matrix may be calculated by point collocation approach.

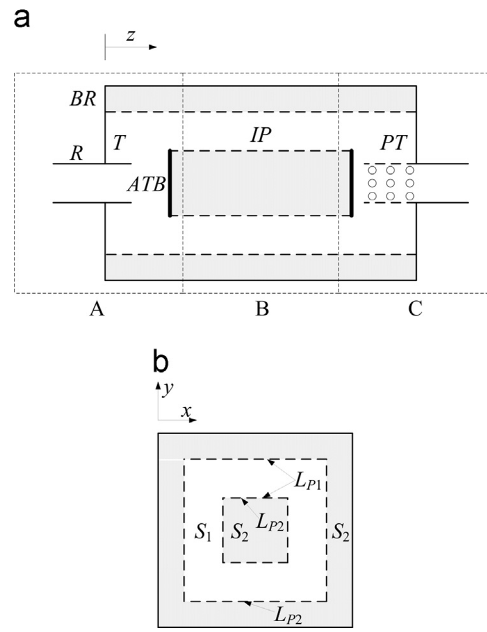

Fig. 1. Configuration of a typical silencer.

2.1. Direct mixed-body BEM

The concept of direct mixed-body BEM begins with the conventional multi-domain BEM by subdividing the acoustic domain into several well-defined homogeneous subdomains. The Helmholtz integral equation is written for each individual subdomain. All the integral equations are then summed to create a single integral equation. The normal-derivative hypersingular integral equation is used to provide an additional equation at any interfaces that have two unknown variables. The method is ideally suited to the acoustical analysis of silencers with complex internal components. The boundary integral equations needed in the paper are listed below and the complete version can be found in Ref. [15].

$$
\begin{aligned}
&\int_R \left(p(r_Q)\frac{\partial G_0(r_P,r_Q)}{\partial n_Q} + jk_0 z_0 v_n(r_Q) G_0(r_P, r_Q) \right) dS \\
&+ \int_{T+PT} \frac{\partial G_0(r_P,r_Q)}{\partial n_Q}(p^+ - p^-) dS \\
&+ \int_{BR} \left(p(r_Q)\frac{\partial \tilde{G}(r_P,r_Q)}{\partial n_Q} + j\tilde{k}\tilde{z} v_n(r_Q)\tilde{G}(r_P, r_Q) \right) dS \\
&+ \int_{IP} \left[p_0 \left(\frac{\partial G_0(r_P,r_Q)}{\partial n_Q} - \frac{\partial \tilde{G}(r_P,r_Q)}{\partial n_Q} \right) - z_0 \tilde{\zeta} v_n(r_Q) \frac{\partial \tilde{G}(r_P,r_Q)}{\partial n_Q} \right. \\
&+ jk_0 z_0 v_n(r_Q) G_0(r_P, r_Q) \\
&\left. - j\tilde{k}\tilde{z} v_n(r_Q)\tilde{G}(r_P, r_Q) \right] dS + \int_{ATB} \left(p_0 \frac{\partial G_0(r_P,r_Q)}{\partial n_Q} - \tilde{p}\frac{\partial \tilde{G}(r_P,r_Q)}{\partial n_Q} \right) dS \\
&= \begin{cases} p(r_P), \ P \in \Omega. \\ 0.5 p(r_P), \ P \in R + BR. \\ 0.5\left[p^+(r_P) + p^-(r_P) \right], \ P \in T + PT. \\ p_0(r_P) + 0.5 z_0 k_0 \tilde{\zeta} v_n(r_P), \ P \in IP. \\ 0.5\left[p_0(r_P) + \tilde{p}(r_P) \right], \ P \in ATB. \end{cases}
\end{aligned}
\tag{1}
$$