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Short Communication

Acoustic length correction of closed cylindrical side-branched tube

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Abstract

A numerical approach based on the three-dimensional boundary element method (BEM) is developed to determine the acoustic length correction of closed cylindrical side-branched tube mounted perpendicular to a cylindrical main pipe. The effects of Helmholtz number and finite length of side-branched tube on the acoustic length correction are examined, and a curve-fitting expression is provided for the acoustically long side-branched tube. For a pipe-mounted concentric Helmholtz resonator, the transmission loss and resonance frequency are predicted by using the 3-D BEM and the corrected 1-D analytical approach to assess the accuracy and applicability of the latter, as well as to illustrate the importance of acoustic length correction for an accurate prediction of resonance frequency of the pipe-mounted resonator.

1. Introduction

Side-branch and Helmholtz resonators are used widely to suppress the low-frequency narrow band noise in pulsating internal flows. The sound field inside the main pipe and side-branch near the junction is three-dimensional, but the one-dimensional approach may be used to obtain an approximate prediction because the higher order modes are evanescent and only the planar mode propagates below the cut-off frequency of the main pipe. In order to improve the accuracy of one-dimensional prediction, the acoustic length correction of side-branch, which accounts the three-dimensional wave effects associated with the generation of evanescent modes, is required [1].

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The objective of the present work is then to employ the three-dimensional boundary element method to determine the acoustic length correction of the side-branch on a main pipe both with the cylindrical geometry, and then suggest an approximate expression for the acoustic length correction. Finally, the corrected one-dimensional analytical solutions of transmission loss and resonance frequency for a Helmholtz resonator are compared with the three-dimensional BEM predictions and experimental results to assess the accuracy and applicability of the corrected 1-D analytical approach.

2. Formulation

Consider a closed cylindrical branched tube mounted perpendicular to a cylindrical main pipe as shown in Fig. 1. The frequency is assumed to be sufficiently low (compared to the cut-off frequency of the main pipe) so that only the planar mode propagates, whereas the higher order modes are evanescent [2–4]. If the side-branch is long enough, then the input impedance of the evanescent modes is "inductive". The inertance can be classically written as a "length correction" for the side-branch. For the linear wave propagation, the length correction of a side-branch resonator may be determined by measuring or calculating resonance frequency f_r, which may be expressed as

$$f_r = c_0/4(l_b + \delta), \tag{1}$$

where l_b is the length of side-branch, δ is the acoustic length correction and c_0 is the speed of sound.

In the present study, the three-dimensional BEM is employed to calculate the transmission loss of side-branch resonators, and then the resonance frequency may be determined from the transmission loss curve. The transmission loss and resonance frequency are correctly predicted without any correction to the real dimensions of the duct system. The transmission loss calculation procedure is identical to those used earlier [5] and will not be repeated here.

In order to satisfy the plane wave condition at the inlet and outlet of main pipe, the frequency considered needs to be lower than the plane wave cut-off frequency of the main pipe so that the higher order modes are evanescent.

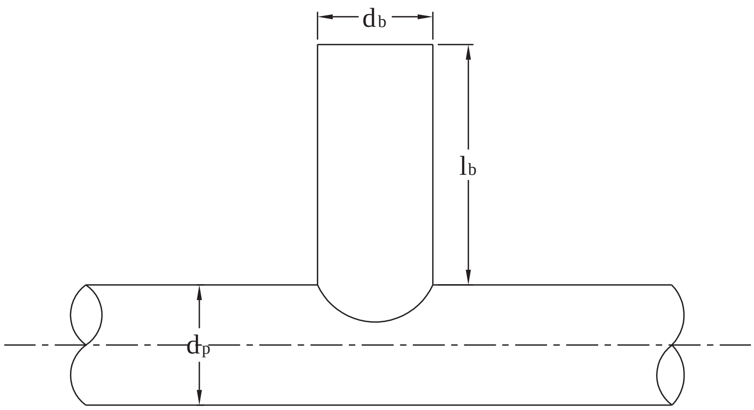

Fig. 1. Side-branched tube mounted perpendicular to a cylindrical main pipe.

3. Results and discussion

The studies of Dubos et al. [3] for a rectangular duct and Dalmont et al. [4] for a cylindrical duct with an open branched tube demonstrated that the Helmholtz number ka_p has an influence on the acoustic length correction of side-branch. Similarly, Figs. 2 and 3 show the effect of ka_p on the acoustic length correction of the closed cylindrical side-branched tubes for two different diameter ratios with $d_b/d_p = 0.5$ and 1.0. The acoustic length correction is increased as the increase of ka_p or

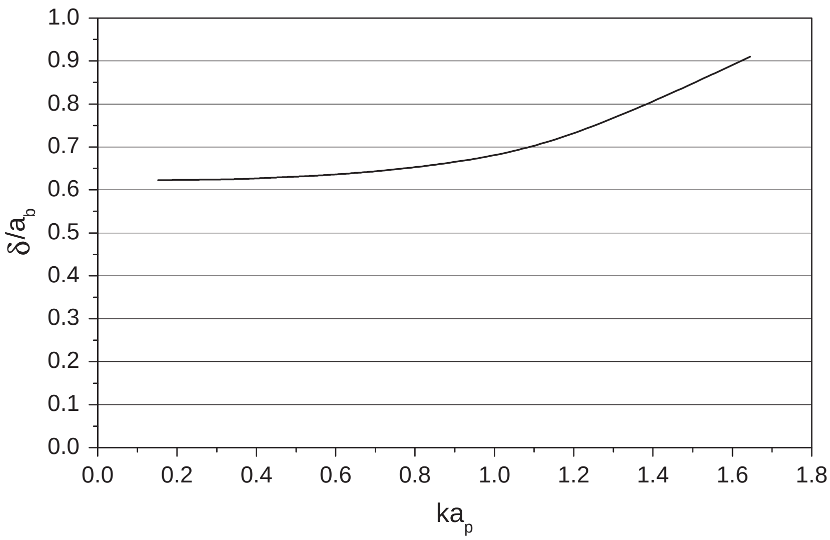

Fig. 2. Effect of Helmholtz number on the acoustic length correction of side-branched tube ($a_b/a_p = 0.5$).

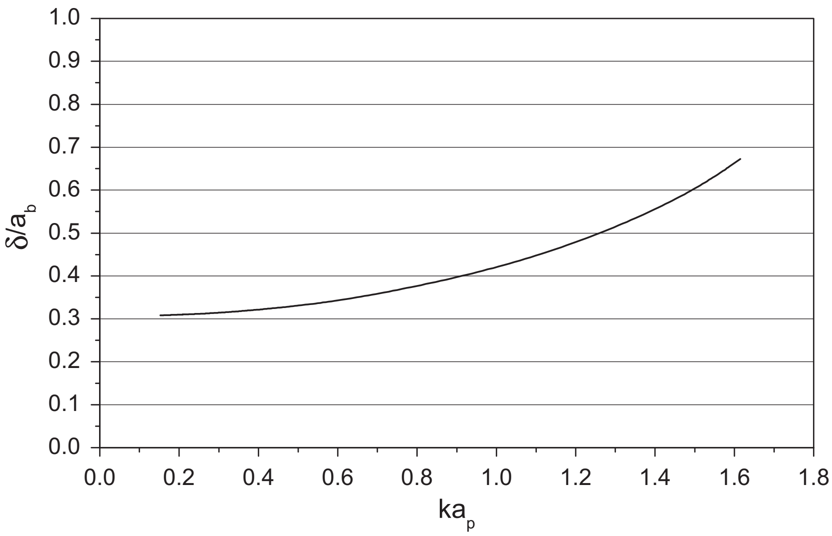

Fig. 3. Effect of Helmholtz number on the acoustic length correction of side-branched tube ($a_b/a_p = 1$).

frequency for a fixed diameter of the main pipe. However, the difference of the length correction in the low Helmholtz number range (for example, less than 0.5) is very small and negligible.

The finite length effect on the acoustic length correction of side-branch resonator is examined next. Figs. 4 and 5 present the acoustic length correction predictions of the side-branch resonators for the cases of $d_b/d_p = 0.5$ and 1.0, respectively. It can be remarked that for the short lengths, the resonance frequencies are high, and the results indirectly give the length correction with respect to frequency. For this case, the "length correction" is not a convenient quantity, instead of the inertance. The detail analysis and discussion have been presented by Dubos et al. [3], and are not

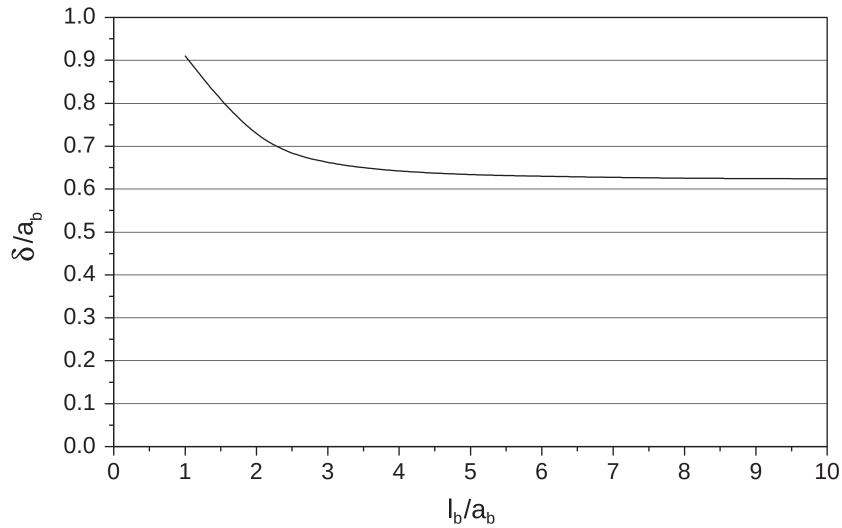

Fig. 4. Finite length effect on the acoustic length correction of side-branched tube ($a_b/a_p = 0.5$).

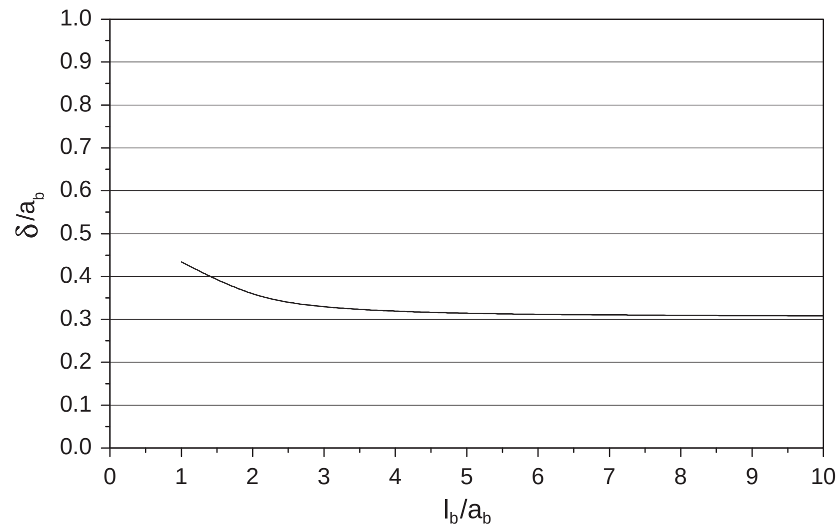

Fig. 5. Finite length effect on the acoustic length correction of side-branched tube ($a_b/a_p = 1$).

repeated here. With increasing the length of side-branched tube, the ''acoustic length correction'' is decreased and converged to a fixed value for a given diameter ratio. Thus in applying the modified one-dimensional approach, the lower limit of length-to-diameter ratio for side-branched tube needs to be considered to ensure that the finite length effect is negligible. If the frequency is lower than the plane wave cut-off frequency, the sound pressure attenuation of the mode (1, 0) within the side-branched tube will be

$$e^{-jk_{10}l_b} = e^{j\sqrt{k^2-(\alpha_{10}/a_b)^2}l_b} = e^{-\sqrt{\alpha_{10}-(ka_b)^2}(l_b/a_b)}. \tag{2}$$

For example, considering the case of $ka_b = 0.5$ and $l_b/d_b = 2.0$, the wave attenuation of the mode (1, 0) within the side-branched tube is $e^{-jk_{10}l_b} = 0.00084$. So that, if taking $ka_p \leqslant 0.5$ and the length of side-branched tube and each sections of main pipe are more than twice of their diameters, all of high-order modes may be considered to be attenuated fully within the side-branched tube. In the following calculations, the lengths of main pipe and side-branched tube will be selected to be above double their diameters to ensure the plane wave condition at inlet and outlet of the main pipe and exclude the effect of finite length.

Fig. 6 shows the length correction calculations using BEM and Eq. (1). A curve-fitting expression is suggested as

$$\delta/a_b = \begin{cases} 0.8216 - 0.0644(a_b/a_p) - 0.694(a_b/a_p)^2, & a_b/a_p \leqslant 0.4, \\ 0.9326 - 0.6196(a_b/a_p), & a_b/a_p > 0.4 \end{cases} \tag{3}$$

and plotted with solid line in Fig. 6. The relative errors between BEM calculations and Eq. (3) are within 1%. For the limited case of $a_b/a_p = 0$, the length correction $\delta/a_b = 0.8216$ from expression (3) is same as calculated results by Kergomard and Garcia [6] and Norris and Sheng [7]. A comparison of formulas (4) and (5) in Ref. [4], deduced from Refs. [2,3], with Eq. (3) in the present paper leads to the same value for small diameters, but Eq. (3) gives a larger value for large

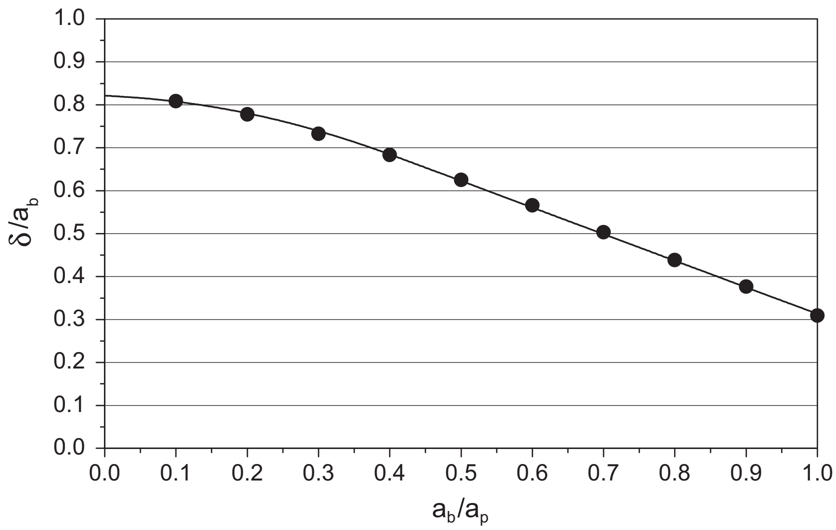

Fig. 6. Acoustic length correction of closed cylindrical side-branched tube: ●, BEM; —, Eq. (3).

diameters. To verify the calculated results using the BEM, we recalculate the transmission loss of the side-branched resonator with $d_b/d_p = 1.0$ using the FEM in Sysnoise software package to determine the acoustic length correction, and a very closed value is obtained with the relative error less than 0.5%.

Finally, the corrected one-dimensional approach is used to predict the transmission loss and resonance frequency of a pipe-mounted concentric Helmholtz resonator ($l_v = 24.420$ cm, $d_v = 15.319$ cm, $l_c = 8.50$ cm, $d_c = 4.044$ cm, $d_p = 4.859$ cm) as shown in Fig. 7. The neck length is modified by adding a length correction factor for each end, thereby replacing l_c by $l'_c = l_c + \delta_v + \delta_p$, δ_v and δ_p being the added lengths corresponding to the neck and cavity volume as well as neck and main pipe interfaces, respectively. The acoustic length corrections are determined from expression (21) of Ref. [8] for the neck and cavity volume connection and expression (3) of the present paper for the neck and main pipe connection. The transmission loss results from the corrected one-dimensional approach and BEM are depicted in Fig. 8. For comparison purposes, Fig. 8 also includes the experimental results. It is observed that the transmission loss predictions from the corrected one-dimensional approach agree very well with the BEM predictions and experimental results. The one-dimensional approach without end corrections predicts the resonance frequency 96.7 Hz, while the corrected one-dimensional approach, BEM and experiment provide very close resonance frequency values 87.8, 88.0 and 88.5 Hz, respectively. The difference in transmission loss and resonance frequency between the calculated and experimental results is currently being assessed in relation to neglected viscous effects in the computational approach, and minor geometrical imperfections in the experimental set-up (for example, the slight deviation of the junction of neck and main pipe from the ideal connection interface). Using the experimental value of the resonance frequency, the total length correction $\delta_v + \delta_p = 1.752$ cm is obtained, while the BEM and corrected 1-D analytical approach yield the total length correction $\delta_v + \delta_p = 1.875$ and 1.919 cm, respectively.

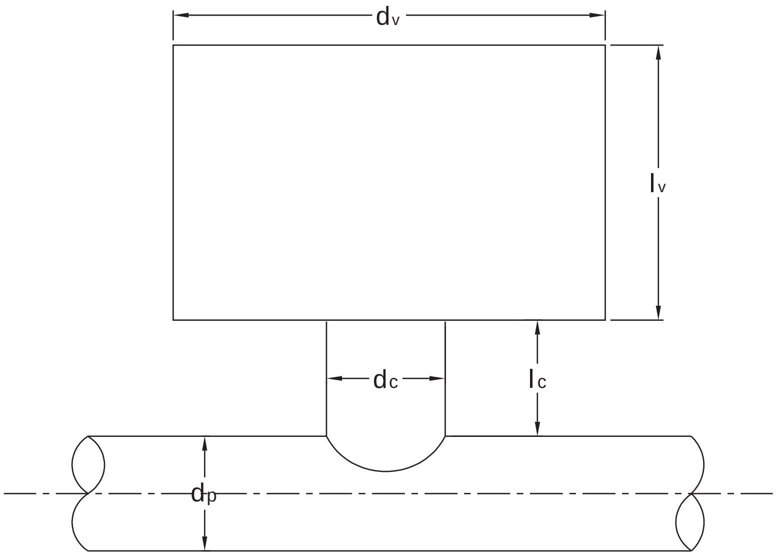

Fig. 7. Pipe-mounted concentric Helmholtz resonator.

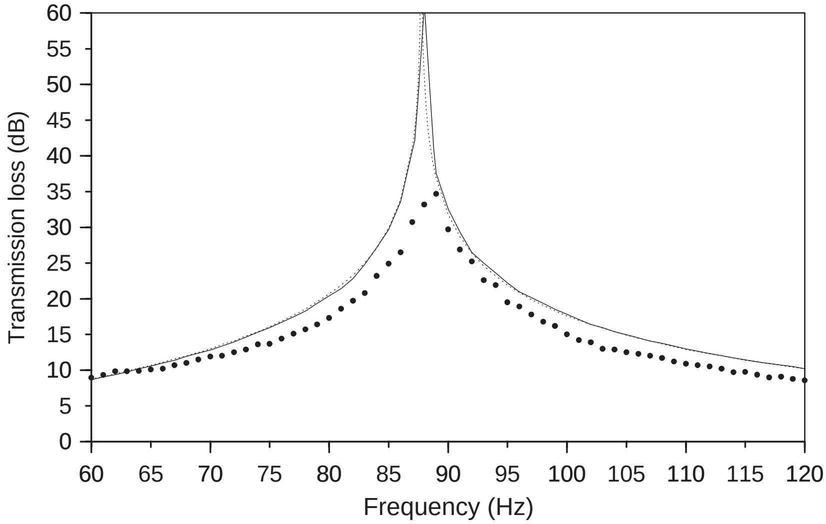

Fig. 8. Transmission loss of pipe-mounted concentric Helmholtz resonator: ..... , corrected 1-D approach; —, BEM; ●, experiment.

To conclude, the present study (1) provides a simple expression for the acoustic length correction of closed cylindrical side-branched tube mounted perpendicular to a cylindrical main pipe; (2) examines the effects of the Helmholtz number and finite length on the acoustic length correction of side-branched tube; (3) compares the 3-D boundary element predictions and the corrected 1-D analytical solutions to assess the accuracy and applicability of the latter; and (4) illustrates the importance of acoustic length correction for an accurate prediction of resonance frequency of the pipe-mounted resonator.

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