

Simulation of Enclosures Including Attached Duct Work

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ABSTRACT

Partial enclosures are commonly utilized to reduce the radiated noise from equipment. Often, enclosure openings are fitted with silencers or louvers to further reduce the noise emitted. In the past, the boundary element method (BEM) has been applied to predict the insertion loss of the airborne path with good agreement with measurement. However, an alteration at the opening requires a new model and additional computational time. In this paper, a transfer function method is proposed to reduce the time required to assess the effect of modifications to an enclosure. The proposed method requires that the impedance at openings be known. Additionally, transfer functions relating the sound pressure at one opening to the volume velocity at other openings must be measured or determined using simulation. It is assumed that openings are much smaller than an acoustic wavelength. The sound power from each opening is determined from the specific acoustic impedance and sound pressure at the opening. The method has been validated using a simulation model for an enclosed engine.

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INTRODUCTION

Partial enclosures are commonly utilized to attenuate the radiated noise from equipment and machinery. Openings in enclosures may be intentional, such as for ventilation or equipment function, or unintentional, such as leaks and gaps.

Several models have been developed in the past. Ver [1] proposed a simple analytical model to predict the acoustic performance of partial enclosures and noted that the insertion loss is likely to be negative at the Helmholtz frequency. Ivanov and Kurtsev [2] developed a similar model, which included expressions to account for the effect of the near sound field.

Apart from the aforementioned simple models, numerical approaches such as the boundary element method (BEM) have been utilized. For example, Augusztinovicz et al. [3] assessed the insertion loss of engine enclosures using the BEM where the source was modeled as number of equivalent monopole sources. Sound absorptive material was not included due to the software limitation at that time. Although the models proved to be qualitatively correct and demonstrated the feasibility of the method, significant discrepancies between the measurement and prediction in one-third octave bands were identified. Zhou et al. [4] used the BEM to model the airborne path of a partial enclosure and concluded that enclosures can amplify the sound at low frequencies, and the frequencies for negative insertion loss

can be predicted. In addition, they investigated the effect of changing the enclosure size, opening size, opening position, absorption coverage, and absorption positioning.

However, it is often inevitable that sound at the enclosure openings will need to be further attenuated by attaching mufflers and silencers. In that case, a BEM model will need to be prepared for each successive modification. In this paper, an approach is detailed that permits the insertion loss of an enclosure to be determined quickly using a transfer function method. The method requires that transfer functions relating the sound pressure at an opening to the volume velocity at another be calculated first. Additionally, the impedance of new attachments can be calculated using transfer matrix theory. It is assumed that openings are much smaller than an acoustic wavelength. Accordingly, the approach is more appropriate at low frequencies. After the transfer functions and impedances are determined, new designs can be easily assessed by using the existing data and computed impedance of the attachments.

Noise reduction (*NR*), transmission loss (*TL*) and insertion loss (*IL*) are common metrics to characterize the acoustic performance of partial enclosures [5]. However, the sound power insertion loss (*IL_W*), hereafter referred to simply as the insertion loss is the most commonly used measure to assess the effectiveness of partial enclosures and is defined as the difference between the sound power radiated by the source in the presence of the partial enclosure (*L_{pe}*) and in the absence

of the partial enclosure (L_{WO}). It denotes the measure of the reduction in sound power due to the partial enclosure and can be written as

$$IL_W = L_{WO} - L_{WE} \quad (1)$$

Insertion loss will be the metric used in this paper.

TRANSFER FUNCTION METHOD

The proposed method is based upon the same principles as transfer path analysis (TPA) [6,7,8,9,10,11,12,13,14]. The method described can be generalized for any number of openings. However, the development shown here is limited to three openings as shown in Figure 1. First, assume that the enclosure is closed and that the three openings are replaced by three sources having volume velocity Q_i for opening i . The enclosed source is considered as a distribution of sources having volume velocity Q_j^s for each patch j on the source surface. In that case, the sound pressure at each opening can be expressed as

$$p_1 = H_{11}Q_1 + H_{12}Q_2 + H_{13}Q_3 + \sum_{j=1}^n H_{1j}^s Q_j^s \quad (2)$$

$$p_2 = H_{21}Q_1 + H_{22}Q_2 + H_{23}Q_3 + \sum_{j=1}^n H_{2j}^s Q_j^s \quad (3)$$

$$p_3 = H_{31}Q_1 + H_{32}Q_2 + H_{33}Q_3 + \sum_{j=1}^n H_{3j}^s Q_j^s \quad (4)$$

where H_{ij} ($i, j = 1, 2, 3$) denotes the transfer function relating the sound pressure p_j at opening j to the volume velocity Q_i at opening i , H_{ij}^s represents the transfer function relating the sound pressure at patch j to the volume velocity at opening i , and Q_j^s is the volume velocity at patch j on the source surface.

The transfer functions (H_{ij}), which relate the sound pressure at one opening to the volume velocity at another, can be determined either by BEM simulation or experimentally. These transfer functions should be determined with the source turned off (i.e., $\sum_{j=1}^n H_{ij}^s Q_j^s = 0$ for each source i).

Then, the partial or blocked sound pressure at each opening i due to the source (i.e., $p_i^B = \sum_{j=1}^n H_{ij}^s Q_j^s$) can be determined by blocking the openings and measuring the sound pressure at the opening locations. Alternatively, BEM can be used provided that the source is well defined.

The impedance at the openings can be determined based on analytical solutions or by using plane wave theory if a duct is attached. These impedances can be modified for different treatments.

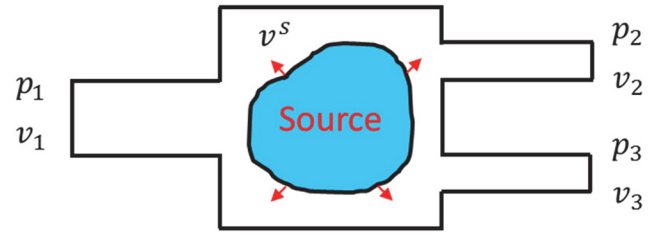


Figure 1. Schematic showing a source in a partial enclosure with three openings.

Transfer Function Calculations

The transfer functions (H_{ij}), which relate the sound pressure at one opening to the volume velocity at another, are most easily determined using BEM. In order to determine the transfer functions, a unit velocity boundary condition is defined at one opening with the other remaining openings closed. The sound pressure at opening i and the other openings is then obtained.

Imposing the uniform velocity to opening 1, one obtain

$$H_{11} = \frac{p_1}{Q_1}, H_{12} = \frac{p_2}{Q_1}, H_{13} = \frac{p_3}{Q_1} \quad (5)$$

Similarly, applying the velocity boundary condition to opening 2, the transfer functions are found as

$$H_{21} = \frac{p_1}{Q_2}, H_{22} = \frac{p_2}{Q_2}, H_{23} = \frac{p_3}{Q_2} \quad (6)$$

and for opening 3 as

$$H_{31} = \frac{p_1}{Q_3}, H_{32} = \frac{p_2}{Q_3}, H_{33} = \frac{p_3}{Q_3} \quad (7)$$

Partial Pressure Contributed by Source

The enclosed source plays an important role in the radiated sound from the openings. With the enclosed source turned on and the three openings rigid, the partial or blocked sound pressures can be found as

$$p_1^B = \sum_{j=1}^n H_{1j}^s Q_j^s \quad (8a)$$

$$p_2^B = \sum_{j=1}^n H_{2j}^s Q_j^s \quad (8b)$$

$$p_3^B = \sum_{j=1}^n H_{3j}^s Q_j^s \quad (8c)$$