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An investigation into the acoustic insulation of triple-layered panels containing Newtonian fluids: Theory and experiment

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Abstract

Sound insulation of triple-layered panels consisting of two impervious layers with the middle layer being a Newtonian fluid is studied here both theoretically and experimentally. The progressive impedance model is used to predict the transmission loss (TL) provided by the panel in a normal incidence field. Corrections are then made to obtain the TL values of such panels in random incidence field. A modified B&K impedance tube was constructed for experimental evaluation. Results are presented for a Pyrex glass cylindrical tube containing motor oil, a ferromagnetic nanoparticles fluid (in the absence of a magnetic field) and air. Good agreement is obtained between the measured and analytical results for a wide range of frequencies. Also, a significant difference in TL values, particularly at low frequencies ($f \leqslant 4$ kHz), is observed once the air is replaced by the fluid layer.

Keywords: Noise control; Multiple-layered panels; Transmission loss; Impedance tube

1. Introduction

Multi-layered panels are widely used in aircraft, automotive and building industries. The sound transmission loss (TL) provided by the panels is an important factor in evaluating the acoustical performance of such panels. There are three classical models for predicting the TL values of a multi-layered panel: the progressive impedance model, the progressive wave model and the multiple reflection model.

The first model was derived by Beranek and Work [1]. It was then used by Mangiarotty [2] for optimization of the mass distribution and air spaces in multiple-element sound proofing structures. Beranek and Work were interested only in normal incidence field, which limits the general application of the model. A development of the model to the random incidence field was proposed by Mulholland et al. [3].

The second model was derived by London [4] for random incidence field. The TL values were calculated using Paris' equation. Moreover, London introduced a real part to the panel impedance, i.e. panel resistance was added to the mass reactance term. The model was limited to double panels with air cavities. Ford and Lord [5] presented practical problems of partition design. They modified the TL values derived by previous classical models with empirical correction coefficients. There are two assumptions in the above mentioned models: the panel is infinite in size and the absorption coefficient of the cavity walls is eliminated.

The third model was derived by Mulholland et al. [6]. In this model the sound wave (ray) passing through the first layer bounces back and forth within the cavity walls while transmitted partly out through the second layer. The related reduction in the sound intensity can therefore be evaluated considering the corresponding absorption coefficients of the cavity walls. Good agreement is reported between theory and experiments.

A different model from the classical models was presented by Trochidis and Kalaroutis [7]. They predicted the TL values through double partitions consisting of

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two parallel thin elastic walls with absorptive materials in the middle layer. Relations for sound pressure were obtained combining the equations of motion of the walls and the equations governing the wave propagation in the air space and absorptive material (Helmholtz equation). The wave equations were solved by Fourier transforms. The agreement was good.

Fringuellino and Guglielmone [8] derived the TL values of a multi-layered panel including N walls and $N-1$ air gaps in both normal and random incidence fields. The TL values were calculated using progressive impedance model [1,3]. Craik and Smith [9,10] presented a model for transmission loss of light double-layered panels using SEA method. Tadeu and Mateus [11] studied the TL of several single layered, double-layered and triple-layered glazed openings experimentally by two-room method. The effects of number of layers, wall thickness, air space, and the type of frame were investigated. An experimental study was conducted by Tadeu, Antonio and Mateus [12] wherein the predicted values of the previous models were compared with experimental results. They concluded that the results obtained from analytical solutions were in good agreement with the experiments except for small panels and very low frequencies. Chazot and Guyader [13] studied the TL values finite double-layered panels using a patch-mobility method. Experiments and measurements were carried out on a double aluminum panel.

Mahjoob and Mohammadi [14] derived an analytical model for determining the TL values through a triple-layered panel containing MR/ER fluid in middle layer. The MR/ER fluid behavior was Newtonian in the absence of a magnetic/electric field. The TL values were calculated in a normal incidence field.

The main objective here is to study the TL provided by triple-layered panels containing Newtonian fluids. A modified B&K impedance tube was made for experiments. Results are presented for a Pyrex glass cylindrical tube containing motor oil, a ferromagnetic nanoparticles fluid and air. The nanoparticles fluids behave like a Newtonian fluid in the absence of a magnetic field.

2. The analytical model

The progressive impedance model is used to derive the TL values provided by a triple-layered panel in a normal incidence field. The specific acoustic impedance of the fluid medium is calculated using harmonic solution for the wave equation and then the TL values of the triple-layered panel are derived.

2.1. Wave propagation in Newtonian fluid

The equations governing the wave propagation in a continuum are derived combining three fundamental equations: continuity equations, equations of motion, and state equations. Therefore, the linearized viscous wave equation can be written as

$$\rho_0 u_{tt} - c_0^2 \rho_0 u_{xx} = (2\mu + \lambda) u_{xxt} \tag{1}$$

in which ρ_0 is the static density of fluid and c_0 is the speed of sound. The shear viscosity coefficient (μ) is usually documented for many fluids, but the dilatational viscosity coefficient (λ) is not directly measured. Therefore, by Stoke's condition $\lambda = \frac{-2}{3}\mu$, Eq. (1) is rewritten as

$$\frac{4v}{3c_0^2} u_{xxt} + u_{xx} - \frac{1}{c_0^2} u_{tt} = 0 \tag{2}$$

where v refers to the kinematics viscosity. The complex form of the harmonic solution for the wave equation is

$$u = \mathrm{e}^{\mathrm{i}\omega t}[u_0^+ \mathrm{e}^{(k_I - \mathrm{i}k_R)x} + u_0^- \mathrm{e}^{-(k_I - \mathrm{i}k_R)x}] \tag{3}$$

and

$$p = 2M\rho_0 \cosh[\psi + (k_I - \mathrm{i}k_R)x] \tag{4}$$

where

$$k_R, k_I = \pm \frac{\omega}{c_0} \chi^{-1/4} \left[\frac{1 \pm \chi^{-1/2}}{2} \right]^{1/2}, \quad \chi = 1 + \left(\frac{4v\omega}{3c_0^2} \right)^2 \tag{5}$$

and

$$M = \frac{-\mathrm{i}\omega}{k_I - \mathrm{i}k_R} + \frac{4v}{3}(k_I - \mathrm{i}k_R), \quad \cosh\psi = \frac{u_0^+ - u_0^-}{2} \tag{6}$$

2.2. Specific acoustic impedance

The ratio of acoustic pressure to the associated particle speed is defined as the specific acoustic impedance, i.e.

$$z = \frac{p}{u} \tag{7}$$

From Eqs. (3), (4) and (7), the specific acoustic impedance for the medium containing the viscous fluid is therefore determined:

$$z = z_0 \coth[\psi + (k_I - \mathrm{i}k_R)x], z_0 = M\rho_0 \tag{8}$$

2.3. Infinite triple-layered panels

The panel to be considered is shown in Fig. 1. A normal plane wave is assumed incident onto the first layer, passing through and coming out from the right hand side of the triple layer. The ratio of incident pressure to transmitted pressure and the TL values can now be formulated based on the progressive impedance model [14].

Therefore

$$\frac{p_i}{p_t} = \left\{ \frac{1}{2} \frac{M\rho_0 \coth[\psi_1 - (k_I - \mathrm{i}k_R)d] + \mathrm{i}\omega\sigma_1 + \rho_1 c_1}{M\rho_0 \coth[\psi_1 - (k_I - \mathrm{i}k_R)d] + \mathrm{i}\omega\sigma_1} \right\} \times \left\{ 1 + \frac{\mathrm{i}\omega\sigma_1}{M\rho_0 \coth[\psi_1 - (k_I - \mathrm{i}k_R)d]} \right\} \times \left\{ \frac{\cosh[\psi_1 - (k_I - \mathrm{i}k_R)d]}{\cosh\psi_1} \right\} \times \left\{ 1 + \frac{\mathrm{i}\omega\sigma_2}{\rho_2 c_2} \right\} \tag{9}$$

and