Development of Method for Predicting the Influence of Elastic Porous Materials on Coincidence Frequency of Walls for Sound Insulation Based on Composite Structures

Snejana Pleshkova-Bekiarska, Aleksandar Vasilev Kirechev,

Abstract. *Coincidence effect of wall structures for sound insulation have important role when the transmission loss between two rooms is considered. Often the coincidence frequency range is at high frequencies where the human earing is more sensible. In order to reduce dips of transmission loss at coincidence frequency range the elastic porous materials are added to the sound insulation wall structures. The goal of this article is to develop a suitable method for predicting the influence of elastic porous materials on coincidence frequency of composite sound insulation wall structures. The solid, porous, fluid layers and their corresponding interfaces between the layers of used composite sound insulation wall structures are presented with appropriate models. The proposed models are used in numerical calculations for some chosen composite wall structures made of medium density fiberboard (MDF), elastic porous material and gypsum board. In calculations and prediction of influence of the elastic porous materials on coincidence frequency are proposed to use the Transfer Matrix Method (TMM). The main efforts in calculations are directed to investigate and analyze the influence of the thickness of an elastic porous material on coincidence frequency. The results from simulations and carried out experimental measurements with the proposed models of solid, porous and fluid layers of the used composite sound insulation wall structures are deeply analyzed and compared. The main achievements from these analysis and comparisons are summarized in the conclusion.*

Keywords: Sound insulation; Composite wall structures; Elastic porous material; Coincidence frequency influence; Transmission loss; Transfer Matrix

1. Introduction

The sound radiation efficiency of wall structure is dependent upon the coupling of sound wave in the air and flexural waves in the plate. Optimum efficiency is achieved when the banding wave velocity of the plate is equal to the velocity of acoustic waves in the air. To reduce the efficiency of radiation the elastic porous materials are applied between two solid layers. The influence of the thickness of the elastic porous material is calculated and the numerical results are compared to experimental date.

2. Development of Composite Sound Insulation Wall Structure Model

a. Definition of Solid Layer in proposed Sound Insulation Wall Structure Model

In solid layers the main incident and reflection waves that propagate are longitudinal and shear waves. The acoustical field in the material is described using four amplitudes of those waves. The associated displacement potentials are written as:

$$\varphi = \exp(j\omega t - jk_1 x_1)[A_1 \exp(-jk_{13} x_3) + A_2 \exp(jk_{13} x_3)] \quad (1)$$

$$\psi = \exp(j\omega t - jk_1 x_1)[A_3 \exp(-jk_{33} x_3) + A_4 \exp(jk_{33} x_3)] \quad (2)$$

Where k_{13} and k_{33} are the wave number vectors. The acoustic fields in the elastic solid layer can be predicted if these four amplitudes are known. Instead of these parameters, four mechanical variables may be chosen to express the sound propagation in the medium. The V^s is a vector written as:

$$V^s(M) = [v_1^s(M)\ v_3^s(M)\ \sigma_{33}^s(M)\ \sigma_{13}^s(M)]^T \quad (3)$$

Where v_1^s and v_3^s are the x_1 and x_3 components of the velocity at point M , respectively σ_{13}^s and σ_{13}^s are the normal and tangential stresses at point M. The vectors are connected to vector A by matrix $[\Gamma(x_3)]$. The vectors in point M and M' can be written as:

$$\begin{cases} V^s(M) = [\Gamma(0)]A \\ V^s(M') = [\Gamma(h)]A \end{cases} \quad (4)$$

The transfer matrix $[T^s]$ which relates $V^s(M)$ and $V^s(M')$ is definite by:

$$[T^S] = [\Gamma(-h)[\Gamma(0)]^{-1} \quad (5)$$

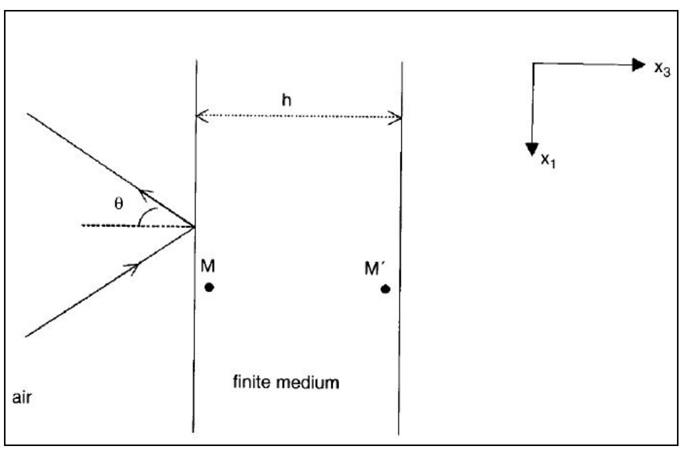


Fig. 1. Plate wave impinging on a domain of thickness h

b. Definition of Porous layer in proposed Sound Insulation Wall Structure Model

In porous layers, three kinds of waves can propagate in a porous medium: two compressional waves and a shear wave. The wave number vectors of compressional waves are denote by k_1, k_2, k_3 and the wave number vectors of shear wave by k'_1,k'_2, k'_3. The nonprime vectors correspond to waves propagating forward while the primed vectors correspond to waves propagating backward. The frame displacement potentials of compressional waves, is written as:

$$\varphi_i^s = A_i \exp[(j(\omega t - k_{i3}x_3 - k_t x_1)] + A'_i \exp[(j(\omega t - k_{i3}x_3 - k_t x_1)] \quad i = 1,2 \quad (6)$$

The displacements induced by the rotational waves are parallel to the x_1 and x_3 plane, and only the x_2 component of the vector potential is different from zero. The component is written as:

$$\psi_2^s = A_3 \exp[(j(\omega t - k_{33}x_3 - k_t x_1)] + A'_3 \exp[(j(\omega t - k_{33}x_3 - k_t x_1)] \qquad (7)$$

The air displacement potentials are related to the frame displacement potentials by:

$$\varphi_i^f = \mu_i \varphi_i^s \quad i = 1,2 \qquad (8)$$

and

$$\psi_2^f = \mu_3 \varphi_2^s \qquad (9)$$

The acoustic field in the porous layer can be predicted if the six amplitudes are known. Instead of these parameters, six independent quantities may be chosen to express the sound propagation in the medium. The six acoustic quantities that have been chosen are tree velocity components and tree elements of the stress tensors. The V^p is a vector written as:

$$V^p(M) = [\upsilon_1^s(M)\ \upsilon_3^s(M)\ \upsilon_3^f(M)\ \ \sigma_{33}^s(M)\ \sigma_{13}^s(M)\ \sigma_{13}^f(M)]^T \qquad (10)$$

Where v^s_1 and v^s_3 are the and components of the velocity of the frame, v^f_3 components of the velocity of the fluid, the two components σ_{13}^s and σ_{33}^s of the stress tensor of the frame, and σ_{33}^f in the fluid. The transfer matrix $[T^p]$ which relates $V^s(M)$ and $V^s(M')$ is definite by:

$$[T^P] = [\Gamma(-h)[\Gamma(0)]^{-1} \qquad (11)$$

c. Definition of Fluid layer in proposed Sound Insulation Wall Structure Model

The acoustic field in a fluid medium is completely defined in each point M by the vector:

$$V^f(M) = [p(M), \upsilon_3^f(M)]^T \quad (12)$$

where p and v_3^f are pressure and the x_3 component of the fluid velocity. Determine the parameters of the medium at point M' is given as:

$$V^f(M) = [T]V^f(M') \quad (13)$$

Where the transfer matrix *[T]* is given by:

$$[T] = \begin{bmatrix} \cos(k_3 h) & j\dfrac{\omega\rho}{k_2}\sin(k_3 h) \\ j\dfrac{k_2}{\omega\rho_3}\sin(k_3 h) & \cos(k_3 h) \end{bmatrix} \quad (14)$$

d. Interface between solid-fluid layers in proposed Sound Insulation Wall Structure Model

When the adjacent layers have different nature, the continuity equations may be used to relate the two interface matrices $[I_{sf}]$ and $[J_{sf}]$ to field variable vectors at M_2 and M_3:

$$[I_{sf}]V^{(s)}(M_2) + [J_{sf}]V^{(f)}(M_3) = 0 \quad (15)$$

The continuity conditions are given by:

$$\upsilon_3^s(M_2) = \upsilon_3^f(M_3) \quad (16)$$

$$\sigma_{33}^s(M_2) = -p(M_3) \quad (17)$$

$$\sigma_{13}^s(M_2) = 0 \quad (18)$$

And the matrices *[I]* and *[J]* are given as:

$$[I_{sf}] = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (19)$$

$$[J_{sf}] = \begin{bmatrix} 0 & -1 \\ 1 & 0 \\ 0 & 0 \end{bmatrix} \quad (20)$$

Matrices [I] and [J] must be interchanged for a fluid-solid interface.

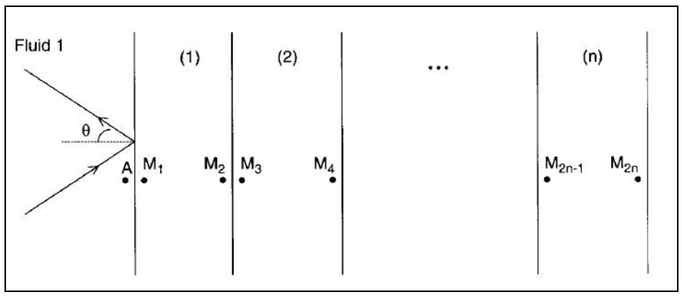


Fig. 2. Plate wave impinging on a multilayer domain

e. Interface between fluid-solid layers in proposed Sound Insulation Wall Structure Model

The continuity equations relate the two interface matrices *[Isp]* and *[Jsp]* to field variable vectors at M_2 an M_3 is written as:

$$[I_{sp}]V^{(s)}(M_2) + [J_{sp}]V^{(p)}(M_3) = 0 \quad (21)$$

The continuity conditions are given by:

$$\upsilon_1^s(M_1) = \upsilon_1^s(M_3) \quad (22)$$

$$\upsilon_3^s(M_1) = \upsilon_3^s(M_3) \quad (23)$$

$$\upsilon_3^s(M_1) = \upsilon_3^f(M_3) \quad (24)$$

$$\sigma_{33}^s(M_2) = \sigma_{33}^s(M_3) + \sigma_{33}^f(M_3) \quad (25)$$

$$\sigma_{13}^s(M_2) = \sigma_{13}^s(M_3) \quad (26)$$

And the matrices *[I]* and *[J]* are given as:

$$[I_{sp}] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (27)$$

$$[J_{sp}] = -\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \qquad (28)$$

f. Global transfer matrix

The calculation of transfer and interface matrices cannot generally be used to calculate physical processes of a complex wall structure. Hence the global transfer matrix has to be assembled for particular case. In our case of study we have semi-infinite fluid termination condition. The conditions for semi-infinite fluid are expressed as:

$$[I_{(n)f}]V^{(n)}(M_{2n}) + [J_{(n)f}]V^{f}(B) = 0 \qquad (29)$$

g. Transmission coefficient and transmission loss

The transmission coefficient T and the reflection coefficient R are related by:

$$\frac{p(A)}{1+R} - \frac{p(B)}{T} = 0 \qquad (30)$$

For a plane wave of incidence Θ, the transmission loss is defined by:

$$TL = -10\log\tau(\theta) \qquad (31)$$

where

$$\tau(\theta) = \left|T^{2}(\theta)\right| \qquad (32)$$

is the transmission coefficient for the angle of incidence Θ.

h. Coincidence frequency

The definition of the coincidence frequency is important for this case of study. The coincidence effect occurs when the wave bending velocity c_b of excited structure match the velocity of the incidence free bending sound wave c. At this frequency the radiation of sound true the structure reaches maximum level. The coincidence frequency is given by:

$$f_{coin}^{2} = \frac{12c^{4}\rho}{EI^{3}\sin^{4}\theta(1-\upsilon^{2})} \quad (33)$$

where the Θ is the angle of incidence.

The coincidence frequency range appears in high frequencies. Considering that the human ear is more sensible at frequencies between 1kHz and 4kHz the coincidence effect is very important for subjective result of the installed system. In order to move coincidence frequency and recuse its effect the porous material with high density and low Yang's module has to be used.

3. Experimental results

For the experimental part the source room with dimensions of 350x250x180cm and the receiving room with dimensions 300x250x180 are used. The testing chamber did not match ISO standard 140-1 and 140-2 but the acoustical field match the demanded parameters for this experiment. In the testing opening is built a partition wall from steel frame and middle decency fiberboard (MDF).The properties of the MDF are presented on "Table 1". The thickness of the wall is 40mm. In order to reduce flanking transmission from side walls true the testament the wall is separated from the other element by 10mm SBR granulated rubber pads.

First part of measurement is made only with MDF install at the testing opening. The sound pressure level different is measured between source room and receiving room. The results are presented on "Fig. 3".

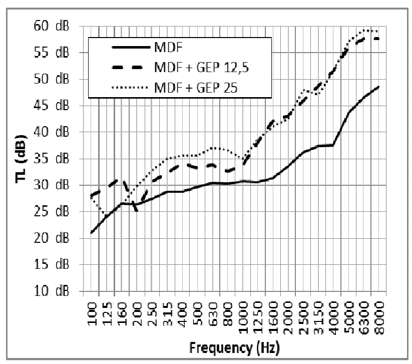
The second part of the experiment measured the sound pressure level different of the MDF wall with installed composite panel. The panel is made of elastic porous material with thickness of 12,5mm and solid gypsum board with thickness of 12,5mm (GEP 12,5). All three layers are glued to each other with polyurethane foam glue. The properties of used materials are presented on "Table 1". The results of the measurements are presented on "Fig. 3"

The third part of the experiment measured the sound pressure level different of the same wall structure but with change thickness of the elastic porous material to 25mm (GEP 25). The results are presented on "Fig. 3".

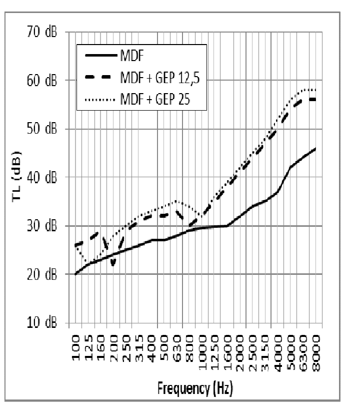
Type of material	Parameters				
	Thickness (mm)	*Density (kg/m^3)*	*E (GPa)*	*Coeff. Of Poisson*	*Internal loss*
MDF	40	605	2,5	0,10	0,10

Type of material	Parameters				
	Thickness (mm)	*Density (kg/m^3)*	*E (GPa)*	*Coeff. Of Poisson*	*Internal loss*
Elastic porous material	12,5	220	6.10^{-5}	0,02	0,25
Elastic porous material	25	220	6.10^{-5}	0,02	0,25
Gypsum board	12,5	670	2,1	0,24	0,01

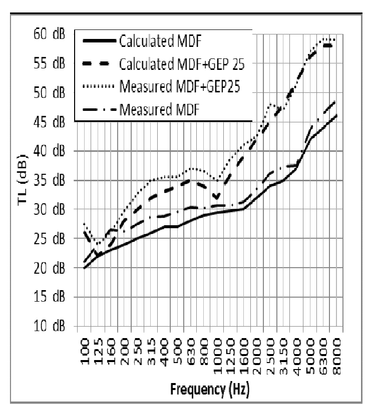
Table 1. Properties of testament materials



(a)



(b)



(c)

Fig. 3. Results of experimental test end numerical calculations of transmission loss of different combination of materials. (a) Experimental results for TL. (b)

Numerical results for TL. (c) Comparison between numerical and experimental results.

The numerical and experimental results did not show as a coincidence frequency drop when we consider only MDF wall. The reason behind this is because the coincidence frequency of MDF is above frequency range.

When we install the two types of panels the drop of TL appears at middle frequencies. Numerical and experimental results confirm that the coincidence frequency for the two types of panel appears at the same frequency. The results show as that if we doubled the thickness of elastic porous material the drop of TL appears at higher frequency and his nominal volume is higher. The different of volumes of TL at the coincidence frequency between two panels is not significant – below 3dB and the frequency is in the human hearing range.

4.Conclusion

In this paper the transfer matrix method for prediction of transmission loss of a complex wall structure was developed. The calculated volumes are compared with experimental results. The good agreement is observed between the numerical and the experimental results. The results show as that that if we double the thickness of elastic porous material the coincidence frequency of the structure appears to be between human hearing ranges. If we want to improve the TL more different approach has to be considered. For example to use different porous layer with high internal losses. The next step of investigation is to consider the how different methods of installation of porous material to the solid material influence the results of TL.

Acknowledgement

This work was supported by Technical University – Sofia inner program to research projects under 161ZF0003-07: “Methods and tools for the study of audio signals”.

References

[1] M. Abid, M. S. Abbes, J.D.Chazot, L.Hammemi, M.A.Hamdi, M.Haddar „Acoustic Response of a Multilayer Panel with Viscoelastic Material”, International Journal of Acoustics and Vibration, Vol. 17, No. 2, 2012

[2] Anoop RG,Prof. M R Sarathchandradas”Study of analysis of sound transmission through multilayered structures using generalized matrix method”International jurnal of emerging research in management and technology ISSN: 2278-9359(Volume-4, Issue-11)

[3]Jean F. Allard, Noureddine Atalla “Propagation of sound in porous media: Modelling sound absorbing materials,secound edition” Universty of le Mans,France ,University of de Sherbrooke,Qc, Canada. Published 2009, John Wiley and Sons Ltd ISBN: 978-0-470-746615-0

[4] Sastry, J. S. and Munjal M. L.” A transfer matrix approach for evaluation of the response of a multi-layer infinite plate to a two-dimensional pressure excitation.” Journal of Sound and Vibration, 182(1), 109–128, (1995).

[5] Guofeng Bai, Pei Zhan, Fusheng Sui, Jun Yang “Research on sound insulation of multiple-layer structure with porous material and air-layer” Key Laboratory of noise and vibration research, Institude of Acoustics, Chines Academy of Sciences

[6] Lee,C. M. and Xu, Y. A modified transfer matrix method for prediction of transmission loss of multilayer acoustic materials. Journal of Sound and Vibration, 326, 290–301,(2009).

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