Multi-cell hybrid sound packages concepts for improving sound absorption and insulation

Ying Hu, Marie-Annick Galland

10ème Congrès Français d'Acoustique
Lyon, 12-16 Avril 2010

Multi-cell hybrid sound packages concepts for improving sound absorption and insulation

Ying Hu[1 2], Marie-Annick. Galland[1]

[1]LMFA, Ecole Centrale de Lyon, 36 Av Guy De Collongue 69134 Ecully Cedex, {ying.hu, marie-annick.galland}@ec-lyon.fr
[2]Northwestern Polytechnique University, Xi'an China, huying_nwpu@hotmail.com

Finite multilayer structures are widely used for noise control in automobiles, aircrafts, buildings and several other engineering applications. In this work, multi-cell hybrid sound packages which are special examples of the multilayer systems have been presented with combining passive and active control by using porous materials and piezoelectric ceramics. The acoustical transmission performance of these hybrid sound packages which improve sound absorption and insulation is calculated by finite element method in Comsol environment, where the sound propagation in porous materials is formulated with the mixed (*u, p*) formulation based on the displacement in solid phase and the pressure in fluid phase. The involved coupled boundary conditions in a hybrid cell are derived, and the minimum sound power is used as an objective function in active control. The transmission loss of the hybrid sound packages excited by a plane wave is calculated and tested in the condition that the interface between multi hybrid cells is rigid or elastic. The results in numerical examples have shown that with active control the transmission loss of the hybrid sound packages can be improved more than 30dB in low frequencies.

1 Introduction

Finite multilayer systems are widely used for noise control in automobiles, aircrafts, buildings and other engineering applications. Generally, these structures are made up of two elastic plates (called 'an excited plate' and 'a radiating plate' respectively) and a core such as an air gap or highly-dissipative media. Indeed, porous material has been commonly used as a passive core for reducing both structural and airborne sound in the multilayer systems because of its ability to dissipate acoustic energy in the medium. Nevertheless, it is well known that such passive multilayer packages with porous materials are efficient enough at medium and high frequencies but exhibit poor performance at low frequencies, where the resonance inherent to the layer distribution occurs. As an alternative to passive control, active control appears to be an available approach for remedying this problem. Since active control was proposed by Paul Leug [1], many researchers have proceeded to use it for reducing structural vibration and acoustic transmission in low frequencies, and some progress has been achieved. Guigou [2] and Johnson [3] introduced a smart skin for reducing the noise transmitted into an aircraft, using an efficient piezoelectric actuator as secondary sources. A few years later, Carneal [4] developed a robust analytical model of a simply supported plate-air-plate system, finding an optimal position for piezoelectric patches. Lee and his colleagues [5] demonstrated some experimental results obtained with a hybrid concept involving a double-plate panel with a porous material and active control. The LMFA, Centre Acoustique, at the Ecole Centrale de Lyon has developed over the last decade a design of a hybrid broadband absorbing liner which combines the passive properties of absorbent materials and active control [6].

These mentioned multilayer systems combined passive method and active control technique, called the hybrid sound packages, have been validated that their acoustic absorption or/and transmission performance can be improved in a certain extent. However, for controlling the noise in a large-area domain, the single-cell hybrid sound package is ineffective and useless because of its large dimension. In this case, multi-cell hybrid sound packages concept should be developed by compositing these single hybrid cells. In this work, based on a single-cell hybrid structure whose acoustic performance has been validated with numerical and experimental results, the multi-cell hybrid sound packages concept is proposed. The interface between each hybrid cell can be rigid or elastic. In the multi-cell hybrid sound packages, each cell has an error sensor for active control and a minimum sound power can be used as the objective function. Besides, the acoustic absorption and transmission performance have been calculated with the mixed (*u, p*) formulation and finite element method in Comsol environment.

2 Sound propagation in poroelastic medium

The acoustic wave propagation in the hybrid sound packages is calculated by the finite element method and corresponding models can be founded in the Comsol environment. The Comsol provides powerful application modes for acoustic, piezoelectric and elastic problems, but it does not currently provide a specific application mode for the poroelastic medium. Since the coupling between the fluid and solid phases occurs in the poroelastic medium, the partial differential equation (PDE mode) provided by the Comsol is chosen for modeling the poroelastic material [7]. The partial differential equation can be rewritten here as follows,

$$\begin{aligned} &\underline{\underline{\Gamma}} \cdot \underline{\nabla} = \underline{F} \\ &-\underline{\underline{\Gamma}} \cdot \underline{n} = \underline{G} + \left(\frac{\partial \underline{L}}{\partial \underline{U}} \right)^T l \,, \\ &0 = \underline{L} \end{aligned} \tag{1}$$

Here, $\underline{U}$ is the vector of unknowns and $\underline{\underline{\Gamma}}$, $\underline{F}$, $\underline{G}$, $\underline{L}$ are PDE coefficients depending on $\underline{U}$ or its differentiation, $\underline{L}$ and $\underline{G}$ represent the 'Dirichlet' and 'Neumann' vector respectively, l denotes the Lagrange multiplier; $\underline{n}$ is the outward normal unit vector. The first term in Eq. (1) is the partial differential equation of variable $\underline{U}$, and the last two terms denote respectively the Dirichlet and Neumann boundary condition of porous materials.

In Cartesian coordinate system, the displacement of the solid phase is presented by $\underline{u}^s = (u, v, w)$, whereas the pressure of the fluid phase is described by p. Therefore, the motion of poroelastic media can be described by the classical displacement-pressure (u, p) formulation, proposed by Atalla [8] based on Biot's poroelasticity equation, which can be written in the form of

$$div\underline{\underline{\hat{\sigma}}}^s(\underline{u}^s) + \omega^2 \tilde{\rho}\underline{u}^s + \tilde{\gamma}\underline{\nabla}p = 0 \tag{2-a}$$

$$\underline{\nabla}\underline{\nabla}p + \omega^2 \frac{\tilde{\rho}_{22}}{R} p - \omega^2 \frac{\tilde{\rho}_{22}\tilde{\gamma}}{\phi^2} div\underline{u}^s = 0 \tag{2-b}$$

where the tilde symbol indicates that the associated physical property is complex and frequency dependent. In Eq. (2), ω is the angular frequency, $\underline{\underline{\hat{\sigma}}}^s$ denotes the modified partial stress tensor associated with the skeleton particle and only depends on the displacement of the solid phase. ϕ stands for the porosity defined as the ratio between the volume of the fluid phase and the total volume of the porous material, $\tilde{\rho}_{22}$ is the modified Biot's density of the fluid phase accounting for viscous dissipation. $\tilde{\rho}$ is an effective density given by $\tilde{\rho} = \tilde{\rho}_{11} - (\tilde{\rho}_{12})^2 / \tilde{\rho}_{22}$ where $\tilde{\rho}_{11}$ is the modified Biot's density of the solid phase accounting for viscous dissipation. $\tilde{\rho}_{12}$ is the modified Biot's density which accounts for the interaction between the inertia forces of the solid and fluid phases together with viscous dissipation. The coefficient $\tilde{\gamma}$ is given by $\tilde{\gamma} = \phi(\tilde{\rho}_{12} / \tilde{\rho}_{22} - Q/R)$ where Q is an elastic coupling coefficient between the two phases; R is interpreted as the bulk modulus of the air occupying a fraction of the unit volume aggregate. The symbols '-' and '=' mean a vector and a matrix respectively; *'div'* is the abbreviation of divergence.

According to Eq. (2), $\underline{\underline{\Gamma}}$ and $\underline{F}$ can be written as follows,

$$\Gamma = \begin{bmatrix} \Gamma_{ij} \\ \Gamma_{4j} \end{bmatrix} = \begin{bmatrix} \underline{\underline{\hat{\sigma}}}^s(\underline{u}^s) \\ \underline{\nabla}p \end{bmatrix} \tag{3}$$

$$F = \begin{bmatrix} F_i \\ F_4 \end{bmatrix} = \begin{bmatrix} -\omega^2 \tilde{\rho}\underline{u}^s - \tilde{\gamma}\underline{\nabla}p \\ -\omega^2 \dfrac{\tilde{\rho}_{22}}{R} p + \omega^2 \dfrac{\tilde{\rho}_{22}\tilde{\gamma}}{\phi^2} div\underline{u}^s \end{bmatrix} \tag{4}$$

Due to the definition in Ref. [8], the expression of $\underline{\underline{\hat{\sigma}}}^s(\underline{u}^s)$ can be written as

$$\underline{\underline{\hat{\sigma}}}^s(\underline{u}^s) = \left(A - \frac{Q^2}{R} \right) div\underline{u}^s \underline{\underline{1}} + 2N\underline{\underline{\varepsilon}}^s \tag{5}$$

Here $\underline{\underline{1}}$ is a unit diagonal matrix; A is the Lamé coefficient for the elastic solid; Q is an elastic coupling coefficient between the solid and fluid phases; R is interpreted as the bulk modulus of the air occupying a fraction of the unit volume aggregate.

Defining $u^s_{k,k} = div\underline{u}^s = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = u_x + v_y + w_z$, $\underline{\underline{\Gamma}}$ and $\underline{F}$ can be rewritten in details as

$$\Gamma = \begin{bmatrix} 2Nu_x + \hat{A}u^s_{k,k} & N(u_y + v_x) & N(u_z + w_x) \\ N(u_y + v_x) & 2Nv_y + \hat{A}u^s_{k,k} & N(w_y + v_z) \\ N(u_z + w_x) & N(v_z + w_y) & 2Nw_z + \hat{A}u^s_{k,k} \\ p_x & p_y & p_z \end{bmatrix} \tag{6}$$

$$F = \begin{bmatrix} -\omega^2 \tilde{\rho}u - \tilde{\gamma}p_x \\ -\omega^2 \tilde{\rho}v - \tilde{\gamma}p_y \\ -\omega^2 \tilde{\rho}w - \tilde{\gamma}p_z \\ -\omega^2 \tilde{\rho}_{22} p / R + \omega^2 \tilde{\rho}_{22}\tilde{\gamma}u^s_{k,k} / \phi^2 \end{bmatrix} \tag{7}$$

Here $\hat{A} = A - Q^2/R$, N is shearing modulus of the poroelastic medium; the subscripts *'x'*, *'y'* and *'z'* represent the derivation of x, y, z.

The other PDE coefficients, $\underline{G}$ and $\underline{L}$, depend on the couplings between poroelastic/air, poroelastic/elastic and poroelastic/poroelastic. According to the continuity of the total normal stress, displacement, acoustic pressure and fluid flow, the two PDE coefficients were formulated in Ref. [8].

3 Active control

In Comsol environment, a piezo solid mode is used to model the piezoelectric patches glued onto both sides of the excited plate. Suppose P^i_{imp} is the pressure of the incident acoustic wave in the i th single hybrid cell, V^i_{imp} is the voltage imposed on the piezoelectric patches of the i th cell, the active behavior of the multi-cell hybrid sound packages is obtained in three steps in the condition that this sound package is a linear system. For convenience of analysis, herein just considering a two-cell hybrid sound package, two error sensors are used. Figure 1 shows the transfer function schematic of one cell in the hybrid sound packages.

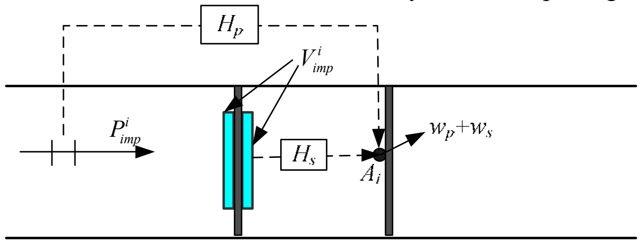


Figure 1: The transfer function schematic

3.1 The primary pathway matrix

The primary pathway matrix is defined as the auto-correlation and cross-correction transfer functions between the primary source and the error sensor in the multi-cell hybrid structures. It can be obtained in two steps as follows.

1) $P^1_{imp} = P_0$, $P^2_{imp} = 0$; $V^1_{imp} = V^2_{imp} = 0$

The pressure P^1_{imp} of the incident acoustic wave in the upper cell is imposed as P_0 , while P^2_{imp} in the down cell is zero, and the voltage V^i_{imp} of each cell is zero, that is, the active control is turned off. The surface pressure of the acoustic wave at point A_i where the error sensors are located can be calculated, represented respectively in $w_{p11}(\omega)$,

$w_{p21}(\omega)$. Then the first column element of the primary pathway matrix can be written as:

$$H_{p11}(\omega)=\frac{w_{p11}(\omega)}{P_0},\quad H_{p21}(\omega)=\frac{w_{p21}(\omega)}{P_0} \tag{8}$$

2) $P_{imp}^1=0$, $P_{imp}^2=P_0$; $V_{imp}^1=V_{imp}^2=0$

The active control is still turned off, but only the pressure P_{imp}^2 of the incident acoustic wave in the down cell is imposed as P_0, the surface pressure of the acoustic wave at point A_i can be represented respectively in $w_{p12}(\omega)$, $w_{p22}(\omega)$. Then the second column element of the primary pathway matrix can be written as:

$$H_{p12}(\omega)=\frac{w_{p12}(\omega)}{P_0},\quad H_{p22}(\omega)=\frac{w_{p22}(\omega)}{P_0} \tag{9}$$

Therefore, the primary pathway matrix can be written as:

$$H_p=\begin{bmatrix} H_{p11} & H_{p12} \\ H_{p21} & H_{p22} \end{bmatrix}, \tag{10}$$

3.2 The secondary pathway matrix

The secondary pathway matrix is defined from the transfer functions between the secondary sources and the error sensors in the multi-cell hybrid structures, which can be also obtained in two steps as follows.

1) $V_{imp}^1=V_0$, $V_{imp}^2=0$; $P_{imp}^1=P_{imp}^2=0$

In this step, no more incident wave transmits in each hybrid cell, and the excited plate in the upper cell is imposed by an electric potential V_0 applied to the piezoelectric patches. Once again, the surface pressures of the acoustic wave can be calculated at point A_i, represented respectively in $w_{s11}(\omega)$, $w_{s21}(\omega)$. Then the first column element of the secondary pathway matrix can be written as:

$$H_{s11}(\omega)=\frac{w_{s11}(\omega)}{V_0},\quad H_{s21}(\omega)=\frac{w_{s21}(\omega)}{V_0} \tag{11}$$

2) $V_{imp}^1=0$, $V_{imp}^2=V_0$; $P_{imp}^1=P_{imp}^2=0$

No more incident wave exists in each hybrid cell, while only an electric potential V_0 is applied to the piezoelectric patches in the down cell. The surface pressure of the acoustic wave at point A_i can be represented respectively in $w_{s12}(\omega)$, $w_{s22}(\omega)$. Then the second column element of the secondary pathway matrix can be written as:

$$H_{s12}(\omega)=\frac{w_{s12}(\omega)}{V_0},\quad H_{s22}(\omega)=\frac{w_{s22}(\omega)}{V_0} \tag{12}$$

Therefore, the secondary pathway matrix can be written as:

$$H_s=\begin{bmatrix} H_{s11} & H_{s12} \\ H_{s21} & H_{s22} \end{bmatrix} \tag{13}$$

3.3 The optimal voltage vector of secondary source

The voltage vector is defined as the electric potential V_s applied to the piezoelectric patches. The total surface pressure vector of the acoustic wave at point A_i can be written as:

$$P=H_pP_{in}+H_sV_s \tag{14}$$

where $P=\begin{bmatrix} P_{A1} & P_{A2} \end{bmatrix}^T$ represent the surface pressures radiating at point A_i; $P_{in}=\begin{bmatrix} P_{imp}^1 & P_{imp}^2 \end{bmatrix}^T$ represent the pressures of the incident acoustic wave transmitting in each hybrid cell; $V_s=\begin{bmatrix} V_{imp}^1 & V_{imp}^2 \end{bmatrix}^T$ represent the voltages imposed on the piezoelectric patches of each hybrid cell.

The sound power of the plane wave can be expressed as:

$$W=P^*P\Big/2\rho_0c_0 \tag{15}$$

Hence, the radiating sound power of the multi-cell hybrid sound packages can be formulated as follows, removing the constant $2\rho_0c_0$:

$$W=P_{A1}^*P_{A1}+P_{A2}^*P_{A2}=P^HP \tag{16}$$

Using Eq. (14), Eq. (16) transforms into:

$$W=V_s^HAV_s+V_s^HB+B^HV_s+C \tag{17}$$

where $A=H_s^HH_s$, $B=H_s^HH_pP_{in}$, $C=P_{in}^HH_p^HH_pP_{in}$; The superscript H denotes the conjugate transpose.

For the minimum sound power, the optimal voltage vector should be equal to:

$$V_s=-A^{-1}B \tag{18}$$

4 Results

4.1 The single-cell hybrid structure with several layers

A single-cell hybrid structure with several air gaps and porous materials is presented in this section (Figure 2). The reason for choosing these layers lies in the fact that this composition is efficient in both absorption and insulation cases [9]. The transmission loss and absorption coefficient of this structure in the numerical and experimental results are shown in Figure 3 and 4 respectively. The 5×5×1, 5×5×2, 4×4×1 3D meshes are applied to the plate, the air gap, the porous and the piezoelectric patches layers. In this case, the minimum power is used as the objective function in active control, that is, the pressure at point A is equal to zero. The experimental data was obtained in the tube with two source-location method, using a dSPACE-DS1103 controller implemented with Simulink for finding the optimal value of the secondary sound source. The resonance frequencies of this single-cell hybrid structure are 320Hz and 420Hz in the numerical results, while 325Hz and 400Hz in the experiment, the relative error between the two methods is less than 5%. In the range of 300~500Hz, a maximum of 15dB has been reached for the transmission loss in the numerical result and experiment, whereas the absorption coefficient has a little offset in both results. Besides, the absorption coefficient in numerical and experimental results exceeds 0.6 in the frequencies more than 500Hz. Moreover, the agreement between the experimental and numerical results has validated that the mixed (*u, p*) formulation and finite element method in Comsol environment is suitable to analyze the acoustic performance of the hybrid structures.

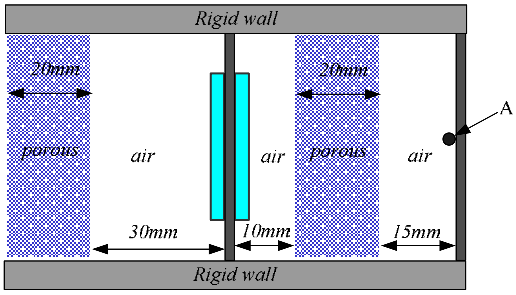
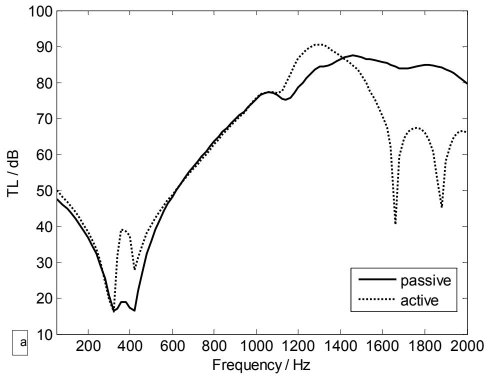


Figure 2: The configuration of the single-cell hybrid structure



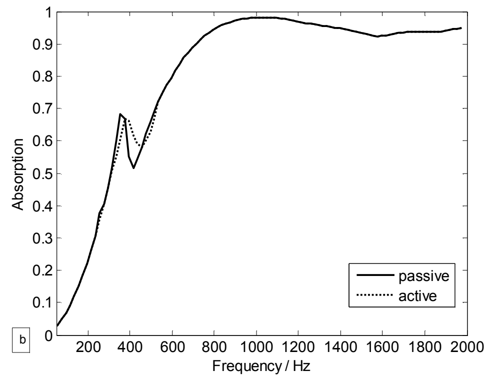
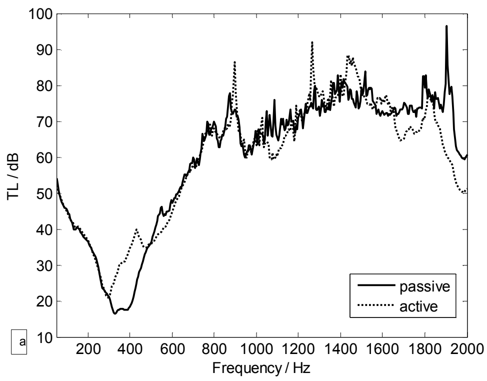


Figure 3: The numerical results of the single-cell hybrid structure with passive and active control. a) the transmission loss; b) the absorption coefficient



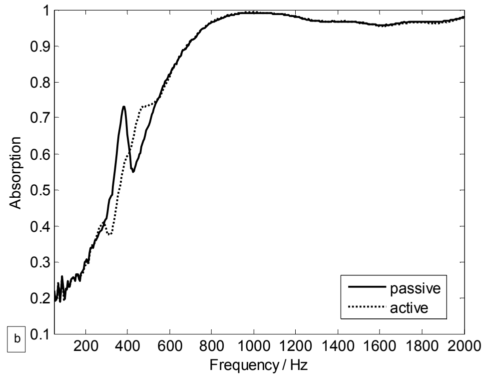


Figure4: The experimental results of the single-cell hybrid structure with passive and active control. a) the transmission loss; b) the absorption coefficient

4.2 The multi-cell hybrid structure with several layers

The configuration of the multi-cell hybrid structure with several layers is shown in Figure 5, considering two cells with rigid or elastic coupling. Two error sensors are positioned at point A and B located respectively in each single cell. In Comsol environment, the same 3D meshes are applied respectively to the plate, the porous material and the piezoelectric patches, and the interface between each single cell is a rigid wall or elastic plate. Figure 6 shows the numerical results of the transmission loss and absorption coefficient in this multi-cell hybrid structure with a rigid interface of 1mm thickness in steel. With active control, the transmission loss of this structure is improved obviously for frequencies lower than 600Hz, whereas the absorption coefficient is reduced compared to passive control in the range 180−600Hz. Near the resonance frequencies, about 30dB gain can be obtained in 340Hz and 480Hz.

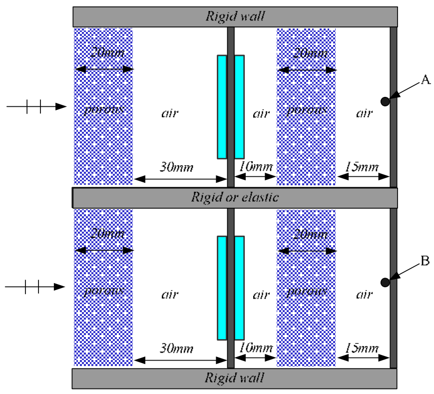
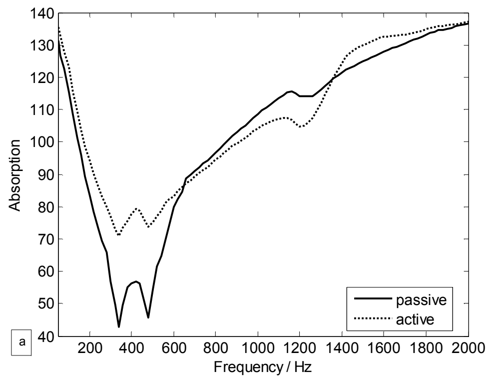


Figure 5: The multi-cell hybrid structure



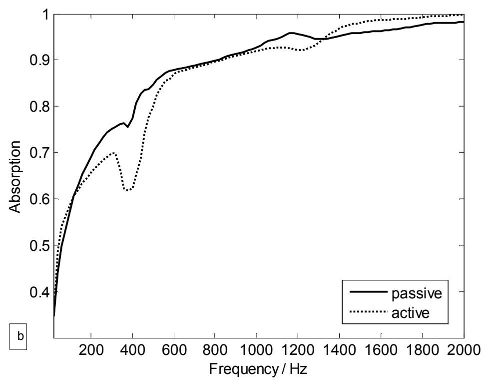


Figure 6: The numerical results of the multi-cell hybrid structure with a rigid interface of 1mm thickness in steel. a) the transmission loss; b) absorption coefficient

Figure 7 shows the numerical results of the transmission loss and absorption coefficient in the similar multi-cell hybrid structure which has an elastic interface of 1mm thickness in steel. Compared to Figure 6, more improvement of the transmission loss has been attained below 800Hz, especially near the resonance frequencies, because the vibration of the elastic interface dissipates sound energy. A maximum gain of 40dB is reached at 340Hz and 480Hz. Besides, the absorption coefficient exceeds 0.8 in active mode and 0.75 in passive mode for frequencies above 200Hz Moreover, comparing to the single-cell hybrid structure, the multi-cell hybrid systems with rigid or elastic interface have better acoustic transmission and absorption performance in full range frequencies than the single-cell structure.

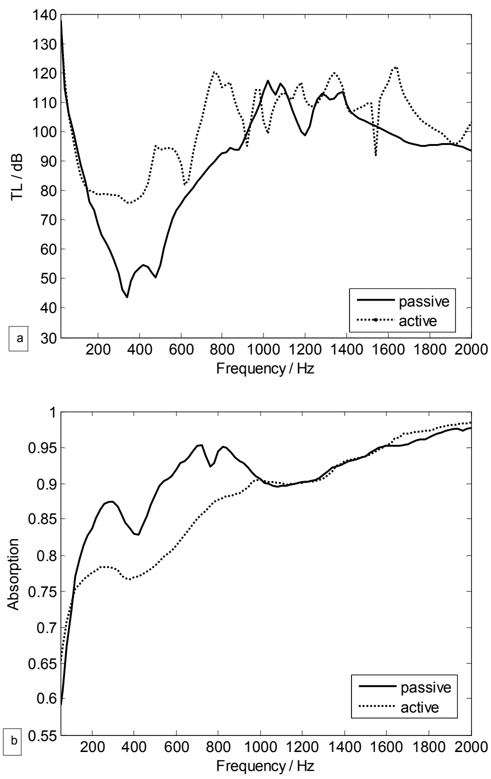


Figure 7: The numerical results of the multi-cell hybrid structure with an elastic interface of 1mm thickness in steel. a) the transmission loss; b) absorption coefficient

5 Conclusion

The acoustic transmission performance of the hybrid sound packages was studied in a plane wave excited. In the numerical method, the poroelastic mixed (*u, p*) formulation based on the displacement in solid phase and the pressure in fluid phase was developed in the Comsol environment for modeling the porous material layer of the hybrid sound packages, and it has been validated by the experimental results. The piezoelectric ceramics is used as the secondary source in active control. In the single-cell hybrid structure, the minimum sound pressure is chosen as an objective function, and it has been shown that the acoustic transmission performance of this structure can be improved with active control in resonance frequencies. The numerical and experimental results agreed with each other well. In the range of 300~500Hz, the transmission loss can be improved by 15dB in the numerical result and experiment, whereas the absorption exceeds 0.6 in the frequencies above 500Hz.

In the multi-cell hybrid structure whose interface between each cell is rigid or elastic, the minimum sound power is chosen as an objective function. The numerical results show that the multi-cell hybrid structure has better acoustic transmission and absorption performance in full range frequencies than the single-cell structure. With a rigid interface, a 30dB gain can be obtained for the transmission loss near the resonance frequencies; whereas with an elastic interface, 40dB is reached. In addition, the experimental validation of the multi-cell hybrid structure will be realized in the future research.

References

[1] P. Leug., Process of silencing sound oscillations, German patent DRP, No. 655508 (1933).

[2] Guigou C., Fuller C.R., “Control of aircraft interior broadband noise with foam-pvdf smart skin”, *J Sound Vib*, *220*, 541-557 (1999).

[3] Johnson B.D., Fuller C.R., “Broadband control of plate radiation using a piezoelectric, double-amplifier active-skin and structural acoustic sensing”, *J Acoust Soc Am*, *107*, 876-884 (2000).

[4] Carneal J.P., Fuller C.R., “An analytical and experimental investigation of active structural acoustic control of noise transmission through double panel system”, *J Sound Vib*, *272*: 749-771 (2004).

[5] Lee J.K., Rhee J.W., Jo C.H., Choi S.B., “Noise reduction of passive and active hybrid panels”, *Smart materials and structures*, *11*, 940-946 (2002).

[6] Galland M.A., Mazeaud B., Sellen N., “Hybrid passive/active absorbers for flow ducts”, *Applied Acoustics*, *66*, 691-708 (2005).

[7] Batifol C., Zielinski T.G, Ichchou M.N., Galland M.A., “A finite element study of a piezoelectric/poroelastic sound package concept”, *Smart Materials and Structures*, *16*, 168-177 (2007).

[8] Atalla N., Panneton R., Debergue P., “A mixed displacement-pressure formulation for poroelastic materials”, *J Acoust Soc Amer*, *104(3)*, 1444-1452 (1998).

[9] Hu Y., Sitel A., Galland M. A., Chen K., “A plane wave study for improving acoustical performance of double wall systems using an active-passive

method", *Noise Control Eng J*, *57(3)*, 193-202 (2009).