MADRID
inter.noise 2019
June 16 - 19
NOISE CONTROL FOR A BETTER ENVIRONMENT

Sound transmission between cavities via an elastically mounted panel with apertures

Wang, Gang[1]
School of Mechanical and Electric Engineering, Soochow University
Suzhou, 215131, China

Li, Wenlong[2]
Advanced Information Services
Ningbo, China

Feng, Zhihua[3], **Ni, Junfang**[4]
School of Mechanical and Electric Engineering, Soochow University
Suzhou, 215131, China

ABSTRACT

The sound transmission between cavities via an elastically mounted panel with apertures is predicted in this paper. The vibro-acoustic coupling system is obtained by substructure technique in which the sub-domain of the system is invariably expressed as a modified Fourier series expression. The sound pressure in the cavities and the displacement of the hole-panel is expressed as 3D and 2D Fourier series, respectively, with supplements which is adopted to accelerate the convergence of the series. Unlike the traditional modal superposition methods, the continuity of the normal velocities is faithfully enforced on the interfaces between the flexible panel and the acoustic media. The sound transmission between cavities via the hole-panel could be easily derived by setting the thickness of the hole on the panel to infinitely small. The continuity of the sound pressure on the two-side of the hole is fully studied. Several numerical examples are presented to validate the system model and study the influence of the mounting conditions of the panel and the position of the hole on the sound transmission characteristics of the vibro-acoustic system.

Keywords: Vibro-acoutics, sound transmission, apertures.
I-INCE Classification of Subject Number: 43

1. INTRODUCTION

The cavities coupled by panel with apertures are extensively used in aeronautical, mechanical and civil structures. The characteristics of the sound transmission between those cavities have been studied for many years.

Early studies meanly forced on the sound transmission between two infinite sound spaces coupled by a rigid wall with apertures on it [1-4]. Dowell [5] studied the natural

[1] wanggang81@suda.edu.cn
[2] wli@nb-ais.com

frequencies and mode shapes of two cavities coupled by an aperture. The aperture was realized by setting the density and Young's modulus of the virtual panel to zero in which the virtual panel was adopted to build a coupled system between sound spaces. The sound transmission between cavities coupled by flexible panels with cut-outs was studied by Guyader [6-8], in which the virtual panel was adopted and the sound isolation of the panel with apertures was fully analysed. The sound transmission through slits and openings between rooms was analysed by considering the influences of the slit dimensions, opening position and room properties[9]. Yu and Cheng[10-12] studied the sound transmission among acoustic media through mixed separations, consisting of both rigid/flexbible structure with aperture in which a virtual panel treatment is adoped to consider an apertures as an equivanlent structural components. Wang [13] studied the break-out sound from a cavity via an elastically mounted panel by adopting the spectro-geometric method in which the solution over each sub-domain is invariably expressed as a modified Fourier series expansion.

In this present work, the spectro-geometric method is proposed to treat the aperture as a virtual panel element. By considering the aperture as an equivalent structure component, this treatment allows handling mixed interface in a more efficient way, especially when packaged as a subsystem module under the sub-structuring modelling framework. In this paper, the accuracy of the present method is validated with finite element method by using two cavities coupled with mixed structures. Several numerical results are given and the influences of the parameters in the coupling systems are studied.

2. THEORETICAL FORMULATION

Figure 1 shows a coupling system consisting of two rooms and one flexible panel with aperture on it. The sound pressure in these two sound spaces are coupled by the mixed separation. The virtual panel treatment is adopted to consider the apertures as an equivalent structural components.

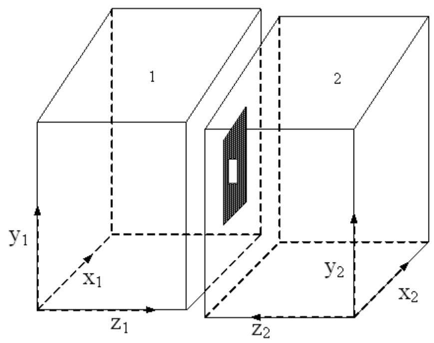


Figure 1 Sound transmission through the flexible panel with apertures

In this paper, the spectro-geometric method (SGM) is adopted to study this vibro-acoutic system, in which each sub-domain should be expressed as modified Fourier series. The sound field in these two rectangular rooms could be expressed as

$$p_1(x,y,z)=\sum_{m_x=0}^{Mx1}\sum_{m_y=0}^{My1}\sum_{m_z=0}^{Mz1}P_{1m_xm_ym_z}\cos\lambda_{m_x}x\cos\lambda_{m_y}y\cos\lambda_{m_z}z+\zeta_{2L_z}\sum_{m_x=0}^{Mx}\sum_{m_y=0}^{My}b_{2m_xm_y}\cos\lambda_{m_x}x\cos\lambda_{m_y}y, \tag{1}$$

$$p_2(x,y,z)=\sum_{m_x=0}^{Mx2}\sum_{m_y=0}^{My2}\sum_{m_z=0}^{Mz2}P_{2m_xm_ym_z}\cos\lambda_{m_x}x\cos\lambda_{m_y}y\cos\lambda_{m_z}z+\zeta_{2L_z}\sum_{m_x=0}^{Mx}\sum_{m_y=0}^{My}b_{2m_xm_y}\cos\lambda_{m_x}x\cos\lambda_{m_y}y, \tag{2}$$

where $P_{m_xm_ym_z}$ and $b_{m_xm_y}$ denote the complex Fourier expansion coefficients, $\lambda_{m_s}=m_s\pi/L_s$ (s=x, y or z) and $\zeta_{2L_z}=L_z(z/L_z)^2(z/L_z-1)$. By the fact that $\zeta_{2L_z}{}'(L_z)=1$, one can readily see that the second term (or the coefficients $b_{m_x m_y}$) is actually the cosine series representation of the normal velocity distribution of the acoustical particles on the panel-cavity interface.

The displacement of the panel could be expressed as

$$w(x,y)=\sum_{m=0}^{M}\sum_{n=0}^{N}A_{mn}\cos\lambda_{am}x\cos\lambda_{bn}y+\sum_{j=1}^{4}(\xi_b^j(y)\sum_{m=0}^{M}c_m^j\cos\lambda_{am}x+\xi_a^j(x)\sum_{n=0}^{N}d_n^j\cos\lambda_{bn}y), \qquad (3)$$

where $\lambda_{am}=m\pi/a$, $\lambda_{bn}=n\pi/b$, and A_{mn}, c_m^j and d_n^j represent the unknown Fourier expansion coefficients to be determined. The supplementary functions $\xi_b^j(y)$ and $\xi_a^j(x)$ are introduced to overcome the potential discontinuities encountered when the displacement function and its lower-order derivatives are periodically extended onto the entire *x-y* plane, as mathematically implied by the Fourier expansion. As an immediate numerical benefit, the Fourier series in Eq. (3) will converge uniformly at an accelerated rate.

Once suitable forms of solutions have been chosen, the Rayleigh-Ritz procedure will be employed to calculate the unknown expansion coefficients. The Lagrangian for the panel structure can be written as

$$L_{panel}=U_{panel}-T_{panel}+W_{c\&p}-W_{out}, \qquad (4)$$

where U_{panel} is the total potential energy associated with the transverse vibration of the panel and the deformations of the restraining springs; T_{panel} denotes the total kinetic energy of the panel, $W_{c\&p}$ represents the work done by the interior sound pressure, and W_{out} is the work done by the exterior pressure.

Also the Lagrangian for the cavities can be written as

$$L_{cavity1}=U_{cavity1}-T_{cavity1}+W_{c2\&p}+W_{p2-source}, \qquad (5)$$

$$L_{cavity2}=U_{cavity2}-T_{cavity2}+W_{c2\&p}+W_{p2-source}, \qquad (6)$$

in which U_{cavity} and T_{cavity} are the potential energy and kinetic energy of the sound filed in cavities, $W_{p\text{-}source}$ is the energy of the sound source.

Substituting Eqs. (1-3) of the plate displacement into Eqs. (4-6) and minimizing the resulting equations against the unknown Fourier coefficients will lead to a set of couple system

$$\left\{\begin{bmatrix}\mathbf{K_{room1}} & \mathbf{0} & \mathbf{0}\\ \mathbf{C_{r1\&P}} & \mathbf{K_{P\_h}} & \mathbf{C_{r2\&P}}\\ \mathbf{0} & \mathbf{0} & \mathbf{K_{room2}}\end{bmatrix}-\omega^2\begin{bmatrix}\mathbf{M_{room1}} & \mathbf{-C^T_{r1\&P}} & \mathbf{0}\\ \mathbf{0} & \mathbf{M_{P\_h}} & \mathbf{0}\\ \mathbf{0} & \mathbf{-C^T_{r2\&P}} & \mathbf{M_{room2}}\end{bmatrix}\right\}\begin{Bmatrix}\mathbf{P_1}\\ \mathbf{W}\\ \mathbf{P_2}\end{Bmatrix}=\begin{Bmatrix}\mathbf{F_p}\\ \mathbf{0}\\ \mathbf{0}\end{Bmatrix} \qquad (7)$$

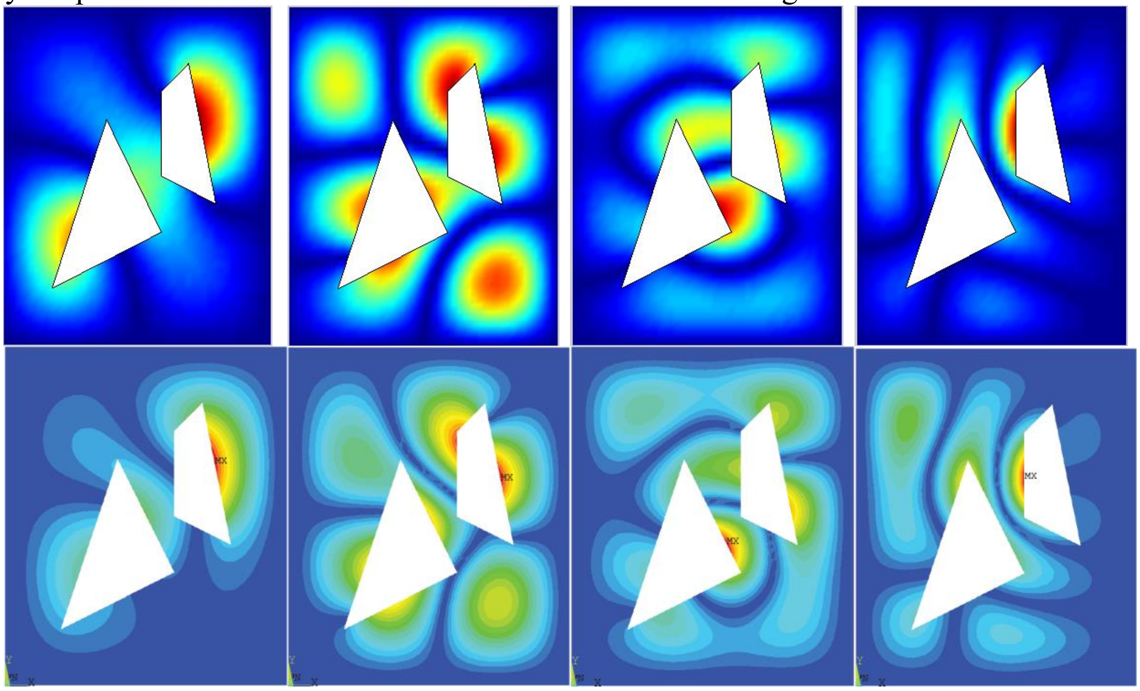
By solving Eq. (7), the natural frequency, the mode shapes and the forced response of the coupling system could be obtained.

It should be noted that the apertures could be obtained with the virtual panel treatment in which the density and Young's modulus of the panel are setting to zeros.

3. RESULTS AND DISCUSSIONS

The accuracy of the present method is first validated against finite element method. A coupling system is conducted with the dimensions of these two cavities: $a_1\times b_1\times c_1$= 2×2.2×2.4 m for cavity 1 and $a_2\times b_2\times c_2$= 2.2×2.4×2.6 m for cavity 2. The length of the panel is 1×1.2 m with parameters thickness 0.005m, Young's modulus 70.3GPa, density 2700 kg/m^3 and passion ratio 0.3.

The free vibration of the panel with apertures are first validated against the results obtained by FEM. Figure 2 shows the mode shapes of the panel with apertures derived by the present method and FEM. It could be seen that a well agreement is obtained.



a b c d

Figure 2 Comparison of the modal shapes of the simply supported panel with two holes (upper plot: current, lower plot: FEM; a: 4nd order; b: 7th order; c: 9th order; d: 12th order)

Table 1 shows the comparison of the natural frequencies of the coupled system by setting the panel as a virtual panel, in which the density and Young's modulus of the panel is setting to zeros. Finite element method (LMS Virtual Lab) is adopted to validate the accuracy of the present method. First 16th orders of the natural frequencies are given and the results match well.

Table 1 Comparison of the natural frequencies obtained by these two methods (Hz)

Order	FEM	Present method	Order	FEM	Present method
1	26.071	28.297	9	103.889	104.455
2	67.227	67.442	10	105.833	106.415
3	71.665	71.853	11	109.101	111.296
4	77.294	77.725	12	114.013	115.891
5	79.268	79.972	13	115.586	116.161
6	83.842	86.783	14	125.263	126.231
7	86.665	87.340	15	133.115	133.960
8	98.921	99.539	16	136.327	137.423

The mode shapes obtained by the present method and FEM are shown in Figure 3. In Figure 3, 1st , 2nd , 3rd and 10th order mode shapes are plotted, separately. Also the force response of sound pressure in cavities obtained by the present method are compared with those derived by FEM. It is clearly seen that those two results agree well.

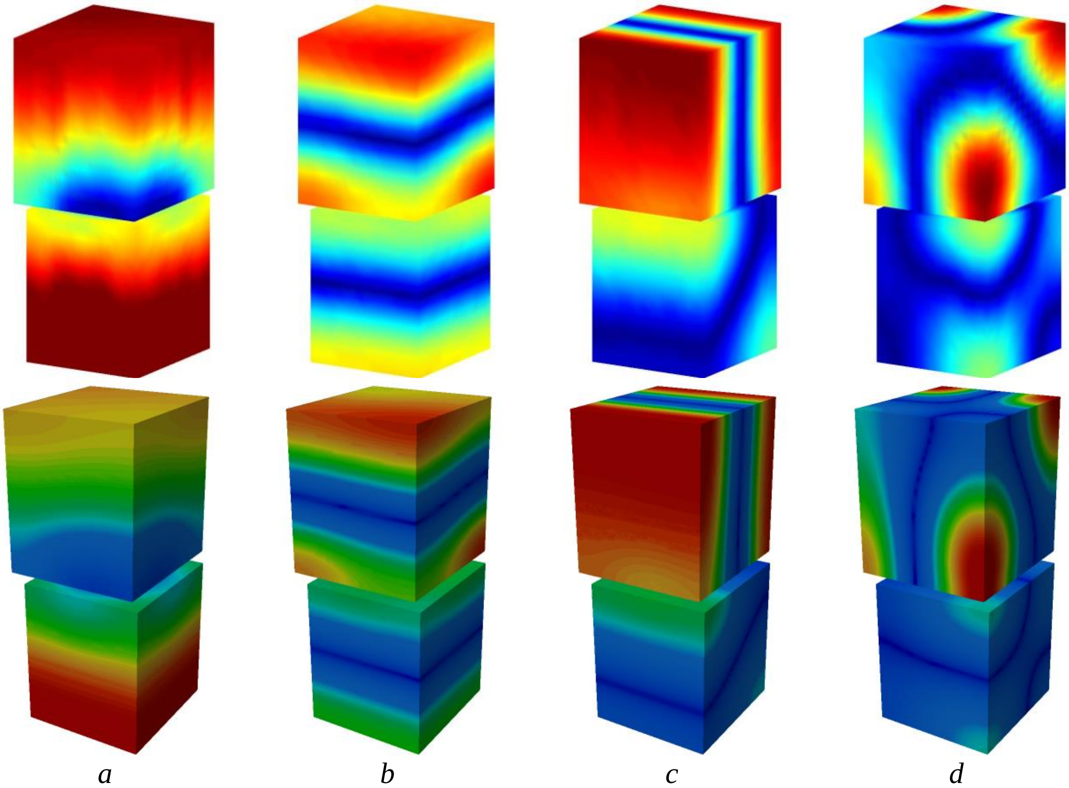


Figure 3 Comparison of the mode shapes of coupled cavities (upper plot: current, lower plot: FEM; a: 1st order; b: 2nd order; c: 3rd order; d: 10th order)

The challenging task for the coupling problem is the pressure continuity of the two sides of aperture. In Figure 4, the sound pressure of the two side of the aperture are plotted. From Figure 4, it could be seen that no interrupt occurs in the modal and the pressure match each other with well continuity.

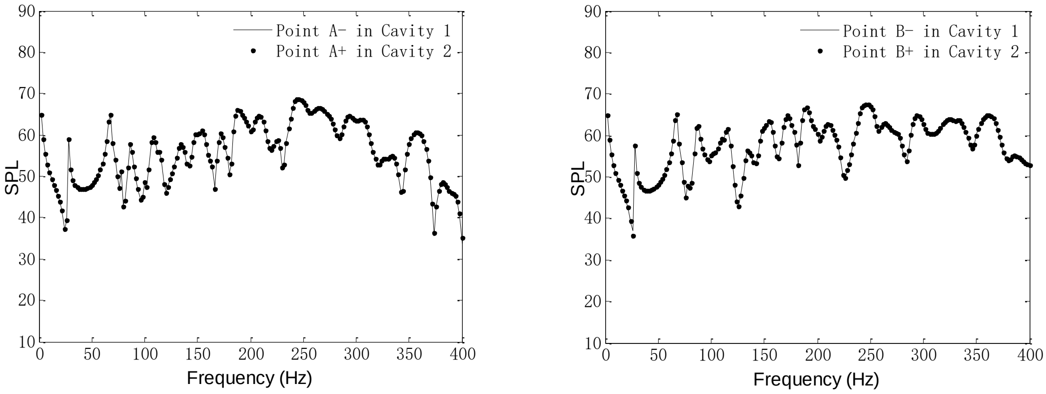


Figure 4 Validation of the pressure continuity at two sides of the aperture (a: Points A- and A+; b: Points B- and B+)

4. CONCLUSIONS

In this paper, an equivalent virtual panel treatment is proposed to study the vibroacoustic system with apertures. The present method is capable of handling mixed separation comprising both structural and acoustic components, allowing sound transmission both structurally and acoustically. The theoretical formulation is validated against the results obtained by FEM. Through numerical examples, the capability and flexibility of the proposed treatment are demonstrated. Based on the current formulation, parametric studies can also be conducted to provide guidance when designing such acoustic systems.

5. ACKNOWLEDGEMENTS

This project is supported by National Natural Science Foundation of China (Grant No. 51805341), Natural Science Foundation of Jiangsu Province (Grant No. BK20180843) and China Postdoctoral Science Foundation (Grand No. 2018M632361).

6. REFERENCES

1. Gomperts M C, Kihlman T. *"The sound transmission loss of circular and slit-shaped apertures in walls"*. Acta Acustica united with Acustica, 1967, 18(3): 144-150.
2. Mechel F P. *"The acoustic sealing of holes and slits in walls"*. Journal of sound and vibration, 1986, 111(2): 297-336.
3. Sgard F, Nelisse H, Atalla N. *"On the modeling of the diffuse field sound transmission loss of finite thickness apertures"*. The Journal of the Acoustical Society of America, 2007, 122(1): 302-313.
4. Trompette N, Barbry J L, Sgard F, et al. *"Sound transmission loss of rectangular and slit-shaped apertures: Experimental results and correlation with a modal model"*. The Journal of the Acoustical Society of America, 2009, 125(1): 31-41.
5. Dowell E H, Gorman G F, Smith D A. *"Acoustoelasticity: general theory, acoustic natural modes and forced response to sinusoidal excitation, including comparisons with experiment"*. Journal of Sound and vibration, 1977, 52(4): 519-542.
6. Ouellet D, Guyader J L, Nicolas J. *"Sound field in a rectangular cavity in the presence of a thin, flexible obstacle by the integral equation method"*. The Journal of the Acoustical Society of America, 1991, 89(5): 2131-2139.
7. Beslin O, Guyader J L. *"The use of an "ectoplasm" to predict free vibrations of plates with cut-outs"*. Journal of sound and vibration, 1996, 191(5): 935-954.
8. Beslin O, Guyader J L. *"The use of "ectoplasm" to predict radiation and transmission loss of a holed plate in a cavity"*. Journal of sound and vibration, 1997, 200(4): 441-465.
9. Poblet-Puig J, Rodríguez-Ferran A. *"Modal-based prediction of sound transmission through slits and openings between rooms"*. Journal of Sound and Vibration, 2013, 332(5): 1265-1287.
10. Yu X, Cheng L, Guyader J L. *"On the modeling of sound transmission through a mixed separation of flexible structure with an aperture"*. The Journal of the Acoustical Society of America, 2014, 135(5): 2785-2796.
11. Yu X, Cheng L, Guyader J L. *"Vibroacoustic modeling of cascade panels system involving apertures and micro-perforated elements"*. 20th International Congress on Sound and Vibration. 2013.
12. Yu X, Cheng L, Guyader J L. *"Modeling vibroacoustic systems involving cascade open cavities and micro-perforated panels"*. The Journal of the Acoustical Society of America, 2014, 136(2): 659-670.
13. Wang G, Li W L, Du J, et al. *"Prediction of break-out sound from a rectangular cavity via an elastically mounted panel"*. Journal of the Acoustical Society of America, 2016, 139(2): 684-692.