Applied Acoustics 76 (2014) 431–444

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Vibro-acoustic behaviors of an elastically restrained double-panel structure with an acoustic cavity of arbitrary boundary impedance

S.X. Shi, G.Y. Jin *, Z.G. Liu

College of Power and Energy Engineering, Harbin Engineering University, Harbin 150001, PR China

ARTICLE INFO

Article history:
Received 18 February 2013
Received in revised form 9 August 2013
Accepted 4 September 2013
Available online 11 October 2013

Keywords:
Double-panel structure
Vibroacoustics
Sound transmission
Structural–acoustic coupling

ABSTRACT

An analytical study on the vibro-acoustic behaviors of a double-panel structure with an acoustic cavity is presented. Unlike the existing studies, a structural–acoustic coupling model of an elastically restrained double-panel structure with an acoustic cavity having arbitrary impedance on sidewalls around the cavity is developed in which the two dimensional (2D) and three dimensional (3D) modified Fourier series are used to represent the displacement of the panels and the sound pressure inside the cavity, respectively. The unknown expansions coefficients are treated as the generalized coordinates and the Rayleigh–Ritz method is employed to determine displacement and sound pressure solutions based on the energy expressions for the coupled structural–acoustic system. The effectiveness and accuracy of the present model is validated by numerical example and comparison with finite element method (FEM) and existing analytical method, with good agreement achieved. The influence of key parameters on the vibro-acoustic behaviors and sound transmission of the double-panel structure is investigated, including: cavity thickness, boundary conditions, sidewall impedance, and the acoustic medium in the cavity.

1. Introduction

The double-panel structures have found increasingly wide applications in modern buildings, transportation systems, vehicles, aircraft fuselage shells, and window glazing, etc., due to their superior sound insulation properties over single-panel configurations. In the past several decades, a huge amount of research efforts [1–21] have been devoted to the sound transmission through a double-panel partition, aiming to provide fundamental insights into the physical understanding of the sound transmission properties and energy transmission mechanism, so that an effective guidance for system design and noise control can be derived.

In the existing investigations on double-panel partition, considerable efforts have been devoted to infinitely large partitions [1–9]. Beranek and Work [1] and London [2] investigated sound transmission through infinitely double-panel structures for normally incident waves. The theoretical results of their model are found to be in good agreement with their experiment results, whereas the model is too simple to gain physical understanding of the sound transmission of the coupled system. The latter mainly investigated sound transmission through two identical panels. Lin and Garrelick [3] presented a theoretical model to investigate the sound transmission properties of periodically frame stiffened double-panel structures with the assumption of infinite periodicity. Yairi et al. [4] studied the sound radiation from a double-leaf elastic plate with a point force excitation, and discussed the effect of an interior panel on the structure-borne sound radiation. Wang et al. [7] presented a theoretical modeling of sound transmission loss (STL) through infinite periodically stiffened, double-leaf lightweight partitions using the space harmonic method. Antonio et al. [8] investigated the influence of panel thickness and air cavity on the sound reduction across double-paneled structures. Pellicier and Trompette [9] gave an excellent review of existing analytical methods based on the wave approach to compute sound transmission loss across double-panel partitions.

Double-panel partitions of finite extent are extensively used in real-world applications. Research work on finite double-panel structures is of great significance in engineering applications [10–28]. Therefore, recent efforts have been more focused on sound transmission and active control of double-panel partitions of finite extent [12–28]. Langer and Antes [12] applied a general Finite Element/Boundary Element (FE/BE) coupling methodology based on the principle of virtual works to calculate the sound transmission of double-leaf windows. Sgard et al. [13] and Panneton and Atalla [14] utilized finite element method to predict sound transmission loss across finite-sized, double-panel sound barrier with poroelastic materials. Carneal and Fuller [16] presented an analytical and experimental investigations into sound transmission through simply supported double-panel structures. Chazot

* Corresponding author. Tel.: +86 451 82569468; fax: +86 451 82518264.
E-mail address: guoyongjin@hrbeu.edu.cn (G.Y. Jin).

0003-682X/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apacoust.2013.09.008

and Guyader [17] developed a patch-mobility method to predict the transmission loss of double panels. Cheng et al. [18] investigated the energy transmission problem in a mechanically linked double-wall structure coupled to an acoustic enclosure. On the basis, Li and Cheng [19] studied the rotational effect of mechanical links on energy transmission. Xin et al. [20–22] proposed an analytical model to study the vibro-acoustic behaviors and sound transmission of clamped and simply supported finite double-panel structures with enclosed air cavity by using the modal function and velocity potential method. The accuracy and effectiveness of their predicted results were checked against experiment data with good agreement achieved.

For finitely bounded constructions, the influence of boundary conditions and additional factors in relation to the finiteness of the structure on sound transmission is no longer negligible, promoting the search of effective and accurate modeling means [14]. However, in the existing studies there exist two main limitations: (a) double panels are only subjected to uniform and classical boundary conditions, i.e., the simply supported or clamped cases, and (b) the sidewalls around the cavity are assumed to be ideal boundary conditions, i.e., acoustically rigid. Since the boundary conditions of panel structures and enclosed acoustic cavity can significantly affect the modal properties of double panels and acoustic properties of cavity, a valuable insight into the vibro-acoustic behavior and its sensitivity to change any of the system parameters of boundary conditions is worthy of further research and investigation. Moreover, the development of a robust and sophisticated method which is capable of simplifying solution algorithms and universally dealing with various boundary conditions will be of great interest to both researchers and application engineers. To the authors' best knowledge, the influence of the aforementioned two important system parameters, i.e., the structural and cavity boundary conditions on the vibro-acoustic behaviors of double-panel structures has not been addressed theoretically.

Motivated by overcoming the aforementioned limitations with the existing models and providing insight into the vibro-acoustic behavior and its sensitivity to change any of the system parameters of boundary conditions, this paper develops an general structural–acoustic coupling model of an elastically restrained double-panel structure with an acoustic cavity having arbitrary impedance on sidewalls around the cavity in which the two dimensional (2D) and three dimensional (3D) modified Fourier series are used to represent the displacement of the plate and the sound pressure inside the cavity, respectively. Mathematically, elastic restraints represent a general form of boundary conditions from which all the classical boundary conditions can be readily obtained by simply setting the spring stiffness to either zero or infinity. The displacement and sound pressure solutions are obtained using the Rayleigh–Ritz procedure based on the energy expressions for the coupled system. The effectiveness and accuracy of the present model is validated by numerical example and comparison with finite element method (FEM) and existing analytical method, with good agreement achieved. The influence of key parameters on the vibro-acoustic behaviors of the double-panel structure is studied, including: cavity thickness, boundary conditions, sidewall impedance, and the acoustic medium in the cavity.

2. Theoretical formulations

2.1. Description of the coupled system and boundary conditions

The structure under investigation, which comprises two panels and an enclosed acoustic cavity, is shown in Fig. 1. The incident panel and the radiating panel are, respectively, coupled with the upper and bottom surfaces of the acoustic cavity. The two panels

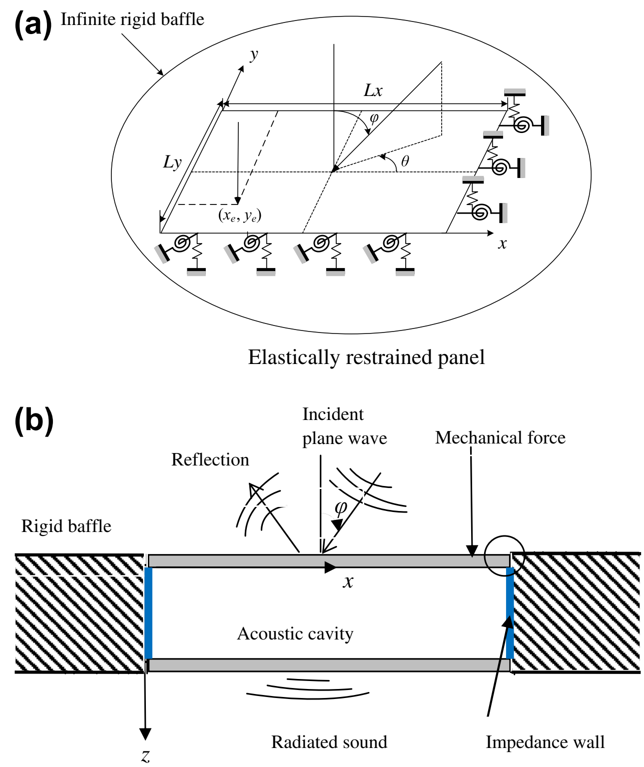

Fig. 1. Schematic of sound transmission through an elastically restrained double-panel structure with an acoustic cavity of arbitrary impedance wall: (a) elastically restrained panel and (b) baffled double-panel partition.

are homogenous and isotropic. The dimensions of the two panels are identical. The coupled structure is mounted on an infinite acoustic rigid baffle. The incident panel is excited by an obliquely uniform plane sound wave with incident elevation angle φ and azimuth angle θ. The vibration of the incident panel due to the incident plane wave induces alterations in the pressure field in the enclosed acoustic cavity, which causes the vibration of the radiating panel, and the consequent sound radiation into the air.

The acoustic pressure $p(r_s, t)$ inside the enclosed acoustic cavity is expressed by the classical wave equation:

$$\nabla^2 p(r_s,t) - \frac{1}{c_0^2}\frac{\partial^2 p(r_s,t)}{\partial t^2} = 0, \tag{1}$$

and the acoustic boundary conditions for the cavity are:

$$\frac{\partial p(r_s,t)}{\partial n} = \begin{cases} -\rho_0 \frac{\partial^2 w_1(r_1,t)}{\partial t^2} & \text{on incident panel}, \\ -\rho_0 \frac{\partial^2 w_2(r_2,t)}{\partial t^2} & \text{on radiating panel}, \\ -j\frac{\rho_0 c_0}{Z} kp & \text{on impedance surface}, \end{cases} \tag{2}$$

where $p(r_s, t)$, $w_1(r_1, t)$ and $w_2(r_2, t)$ are, respectively, the acoustic pressure inside the cavity, the flexible displacement of the incident panel and the flexible displacement of the radiating panel; r_1, r_2 and r_s denote the position vectors of the flexible plates and the acoustic cavity; ρ_0 and c_0 are, respectively, the equilibrium fluid density and the sound velocity in the acoustic medium; k, n, and Z denote the wave number in the acoustic medium, the normal direction towards the outside, and the acoustic impedance of the impedance surface. It can be known that for an acoustic rigid wall the impedance will be selected as infinity to ensure zero particle velocity at the surface. Conversely, once the impedance becomes extremely small, this surface can be treated as a pressure released wall.

The flexible displacements of the two panels are governed by