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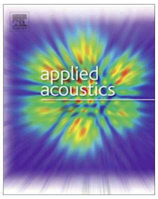

Study of sound transmission through single- and double-walled plates with absorbing material: Experimental and analytical investigation

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ABSTRACT

In this work, the authors study sound transmission through single- and double-walled thin rectangular plates of finite extent, theoretically and experimentally. For this purpose, statistical energy analysis (SEA) is developed to predict the sound transmission loss of the plates. The essential SEA parameters, modal density and loss factors, are calculated and expressions for the sound transmission loss based on the SEA method are presented for both single- and double-walled plates. In order to validate the analytical results obtained for the transmission loss, an experimental setup was constructed including two reverberant chambers and a plate structure. The plate was placed between two rooms and the rooms were made in such a way that the sound waves propagate from the source room to the receiving room only through the rectangular panel. The sound transmission losses evaluated from the SEA models are compared with the experimental results which show good agreement. Three experimental methods were used to measure the transmission loss: The transmission suite method, a sound intensity method with a direct approach and a sound intensity method with an indirect approach. It is shown that the sound intensity method with a direct approach is more accurate than the other methods. This latter method could predict the critical frequency of the plate with only 0.5% error, whereas the other two methods had an error of more than 5%. The effects of using absorbing materials with single-walled plates were investigated experimentally and the effects of filling the cavity of double-walled plates with absorbing materials were also studied analytically. It was found that filling the cavity of the double-walled plate with lightweight absorbing material such as fiberglass increases the sound transmission loss at the critical frequency from 39 dB to a value slightly more than 53 dB. Also about 45 dB improvement in noise reduction is achieved in comparison to a similar single-walled plate.

1. Introduction

Thin rectangular plates have a wide variety of engineering applications in various industries. They are used in architectural structures, bridges, naval structures, machine parts and also aerospace structures such as tail surfaces, flaps and fins of aircraft. Extensive studies in the area of the acoustic behavior of thin plates have been carried out in the last few decades. This is mainly because achieving a suitable acoustical condition has become the main goal of designers and engineers specially in structures subjected to noise such as automotive and aircraft or in places with specific acoustical standards such as concert halls.

The control of noise is of particular importance in occupied spaces in buildings, hotels, offices and residences, where noise annoyance is caused by sound transmitted between rooms through the wall structures and from heating, ventilation and air-conditioning mechanical rooms [1,2]. Various innovative approaches have been proposed by researchers for sound attenuation and insulation of plate structures. Sound transmission loss has been used in numerous studies as a criterion for noise reduction and is defined as the ratio of the incident sound energy relative to the transmitted sound energy expressed in decibels [1]. These studies can be categorized into two groups; one based on finite plate models, whereas the other is based on infinite plate models.

Trochidis and Kalaroutis [3] studied sound transmission through double partitions. They presented a simple model of two infinite parallel thin plates containing sound absorbing materials between them. Chonan and Kugo [4] obtained an exact solution for the sound transmission loss of two-layered infinite plates based on two-dimensional elasticity theory. Steel [5] analyzed sound transmission at joints between plates in framed structures such

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as rooms that are constructed using partitions. Osipov, Mees and Vermeir [6] investigated the airborne sound transmission of single partitions in the low frequency range of 20 Hz – 250 Hz. Liu, Cai and Lam [7] studied sound transmission and reflection of an infinite plate immersed in fluids. They showed that attaching a coating layer of thickness 0.1 m on the incident side can decrease the sound reflection by about 6 dB above a frequency of 10 kHz. Campolina et al. [8] examined the effect of porous material lined with an isotropic plate on the sound transmission of a single-walled plate using the transfer matrix method. They also carried out several experiments to measure the transmission loss and placed a plate between a reverberant room and an anechoic room. They measured the transmitted sound power by intensimetry and deduced the incident sound power from measuring the sound pressure level and assuming a diffuse sound field inside the reverberant room. Zhou, Bhaskar and Zhang [9] optimized sound transmission through a double-walled plate by minimizing its weight and maximizing the transmission loss. All of these studies are based on infinite models and almost all of them used the wave propagation approach in order to compute the transmission loss. Pellicier and Trompette [10] published a review paper about models based on the wave approach for calculating transmission loss in infinite partitions.

The wave approach used in predicting sound transmission through infinite plates does not consider the effects of boundary conditions in theoretical calculations. An approach which is suggested for finite models of plate structures with defined boundary condition is the statistical energy analysis (SEA) method. The SEA method was developed by Maidanik [11], Lyon [12] and Crocker and Price [13]. In the SEA method, a system is modeled as several subsystems. Each subsystem may receive input power by an external source. The input powers flow from one subsystem to other subsystems and can be dissipated because of the damping in each subsystem. Therefore, the effect of dissipation in sound transmission can also be taken into account in the SEA method.

Jean and Roland [14] presented a simple SEA method to predict the sound insulation between dwellings. Hynna, Klinge and Vuoksinen [15] used the SEA method for predictions of structure-borne sound transmission in large welded ship structures. Craik, Steel and Evans [16] also studied the influence of resonant modes in the low frequency range while using the SEA method for structure-borne sound transmission. Osipov and Vermeir [17] investigated the effect of elastic layers at junctions on airborne and structure-borne sound transmission in buildings. Hopkins [18] presented measured data for the validation of SEA evaluations of sound transmission through masonry cavity wall constructions. Craik and Smith [19,20] investigated airborne and structure-borne sound transmission through double leaf lightweight partitions. They examined different SEA models based on the details of construction and categorized them as SEA models of a double wall with no structural connections, with structural coupling at a few point connections and with structural coupling as a line connection. They found out that the performance of each model is dependent on the frequency range and the construction details. In this paper, no structural coupling is assumed for the double-walled plate. Therefore, the first SEA model was used. Zhou and Crocker [21] analyzed sound transmission through honeycomb sandwich panels. They developed a closed form solution for the modal density of sandwich plates which is one of the important and essential parameters that is involved in the SEA modeling. Reynders et al. [22] presented a stochastic method, consisting of finite element method (FEM) and SEA method. They showed that this hybrid approach is suited for the mid-frequency analysis of sound transmission through a wall between two rooms. Although the FEM approach is useful for predicting the sound transmission between rooms in the low- and mid-frequency range, it becomes unmanageable at high frequencies, in which the number of finite elements becomes very large. However, it can be used in estimating the modal density and other modal parameters needed in plate and cylindrical shell structures [23,24].

Besides the wave approach and the SEA method, other methods such as transfer matrix methods [25] and FEM numerical methods [26] have also been used in order to investigate the sound transmission through plate structures.

Experimental techniques have also been developed to measure the sound transmission loss of structures. Wang, Crocker and Raju [27] measured the transmission loss of an aluminum cylinder using the sound intensity technique and the transmission suite method. Chen et al. [28] used the sound intensity method in order to measure damping components of plates. Connelly and Hodgson [29] studied the sound transmission of vegetated roofs experimentally using the sound intensity method. Oliazadeh, Farshidianfar and Crocker [30] recently studied the sound transmission through a cylindrical shell with absorbing material using both the transmission suite and sound intensity methods. They compared the experimental results with those obtained by the SEA theory. Luo, Sun and Wen studied the influence of the boundary conditions on the modal parameters of thin cylindrical shell [31]. Composite cylindrical shells are being increasingly used as aircraft cabins instead of metal ones. Florence, Renji and Subramanian have now extended studies on cylindrical shells to those made of honeycomb sandwich composite [32].

In the present work, a finite model for sound transmission through a panel is considered. Therefore, the SEA theory is used in order to find the sound transmission loss of a thin single-walled rectangular plate and the theory is developed for a double-walled plate. The analytical expression is obtained and presented for each of the single- and double-walled plates. The transmission loss is also measured using three experimental methods, the transmission suite method, the sound intensity method with a direct approach and the sound intensity method with an indirect approach. The effectiveness of each method is discussed by comparing the analytical and experimental results. Then the effects of applying absorbing material in the design of single- and double-walled plate structures are examined completely.

2. Theoretical Model

Consider a rectangular plate with length l_x and width l_y in the x and y directions, respectively and thickness $h \ll l_x$ and l_y lying in the $x-y$ plane, as shown in Fig. 1. The plate material is assumed to be isotropic, homogeneous and elastic with Poisson ratio $\nu, invacuo$ bulk mass density ρ, and $invacuo$ Young's modulus of elasticity E. It is assumed that the plate has uniform thickness and undergoes small displacements. The partial differential equation of motion of a plate can be obtained by employing equilibrium equations of forces and moments for a section of the plate and using Hooke's law to find their constitutive elations [33].

$$D\left(\frac{\partial^4 w}{\partial x^4}+2\frac{\partial^4 w}{\partial x^2 \partial y^2}+\frac{\partial^4 w}{\partial y^4}\right)+\rho h\frac{\partial^2 w}{\partial t^2}=0, \tag{1}$$

where $w(x,y,t)$ is the transverse displacement of the neutral plane of the plate and D is the flexural rigidity of the plate which is defined by

$$D=\frac{Eh^3}{12(1-\nu^2)}. \tag{2}$$