Acoustic Modeling of Lightweight Structures: A Literature Review

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Abstract. This paper gives an overview of acoustic modeling for three kinds of typical lightweight structures including double-leaf plate system, stiffened single (or double) plate and porous material. Classical models are cited to provide framework of theoretical modeling for acoustic property of lightweight structures; important research advances derived by our research group and other authors are introduced to describe the current state of art for acoustic research. Finally, remaining problems and future research directions are concluded and prospected briefly.

1. Introduction

The content of this section will be organized in the way of explaining every important phrase in the topic of this paper, and it intends to help readers to know quickly about the subject and scope of this paper involved.

Figure 1. Acoustic behavior of sound wave striking a structural surface

Acoustic modeling: As a branch of physics, acoustic is an extensional subject including quite different contents across with other fields. In the present paper, we will mainly discuss the acoustic modeling of beam-plate structure and sound absorption of porous material. The total incident sound energy is divided into three parts (as shown in Fig.1) including scattering sound, absorbed energy and transmitted sound when a sound wave strikes a structural surface. Among them, how to predict scattered sound and transmitted sound is a problem involving vibroacoustic field. The contents of this paper are arranged as follows: The main body of this paper is constituted of three parts including double-leaf plate system, stiffened plate system and porous material, respectively.

2. Double-Leaf Plate Systems
As one of the most basic theories in acoustics, mass law tells that the transmission loss of double-leaf plate system can add 6 dB over one of single-leaf plate in ideal case, so double-leaf plates have been widely applied in industries due to their better sound insulation performance. In the earliest period, a few models have been proposed to explore the physical mechanism of sound transmission problems. Cremer [1] underlined the influence of critical frequency on sound transmission through single panel. Under the assumption of two identical walls, London introduced standing wave resonance and mass-air-mass resonance phenomenon of double-leaf structure using wave-based model [2]. These two kinds of resonances greatly reduce the sound insulation property of double-leaf plate system and make the problem more complex. Beside classic wave-based approach, transfer matrix method [3] were also employed to solve the problem of sound transmission through layered structures. However, all the above works are limited to structure in infinite fluid domain. If finite room backing panel system is considered [4], the model will consist of five coupling oscillators including ‘room-panel-cavity-panel-room’, and it is shown that modes of room play a significant effect especially at low frequency [5]. The double panel structure is really rather complicated because there exist many variables though it seems to be a simple problem at first glance. In fact, many sophisticated models have been developed with the consideration of different structural variables. For instance, Ng and Zheng [6] have extended sharp’s model [7] to predict sound transmission through double-leaf panel with corrugated core. Among series of parameters, the viscosity of air play a significant role when the gap is small especially. The results of Dijkstra [8] et al showed that the thin air layer could improve the sound transmission loss of the structure remarkably; Lee and Ih [9] stated that non-diffuse of test room is an important reason resulting in the discrepancies between theories and experiments. The concept of limited angle introduced by Beranek [10] can favorably evaluate the diffuse field sound transmission [11]. A more detailed discussion for the wave-based modeling of diffuse field sound transmission can refer to the review paper [12]; It may be a simplest way to improve the sound insulation of double panel by filling porous material (e.g. mineral wool) which has two kinds effect [13] including damping and fictive increase of volume in the cavity. Unfortunately, it is not an easy work to model the acoustic property of porous material, detailed discussion can be found in the following sections.

3. Stiffened Plate System
Stiffeners are used extensively in order to improve the static mechanical strength of plate-like structure, which make the original structure to be not uniform and homogeneous and bring the complexity of analyzing. In fact, the stiffeners not only influence the vibration behavior of structures directly, but also affect the radiated sound field especially in the case of double panel with structural links.

3.1. Overall dispose of periodic problem
Stiffened single panel has been widely used in aircraft and marine structures [14], while stiffened double plate is a typical structure used in building field [13] especially in Nordic countries. Mead [15] comprehensively reviewed the research developments for wave propagation in continuous periodic structure concentrating on the contributions of Southampton. Only space harmonic method and energy method can be used to analyze two-dimensional structure. Moreover, space harmonic method is suitable for predicting sound radiation since transverse displacement has been expressed as a series of sinusoidal travelling waves. Brunskog and Hammer have also given a comprehensive review [16] relevant to present work.

3.2. Overall dispose of stiffeners
A most straightforward way [17] is to equivalent the whole structure to be an orthotropic uniform plate if the bending wave length is greater than the stiffeners spacing. Lee and Kim [18] predicted the transmission loss of periodically stiffened plates just considering the equivalent tension and torsion stiffness of supports. If the geometry of stiffeners has been taken into account, the stiffeners are usually equivalent to be independent beams. In most cases, only normal force between beam and base panel are included in theoretical model for simplicity, but moment coupling should be embodied to
achieve more accurate results [19]. Moreover, more accurate beam theories such as Timoshenko theory has been used to model base panel or stiffeners to include the effect of shear motion. Note that the rigid coupling between base panel and stiffeners has been simplified in all the above models, because the practical connections may be much complex such as spot-weld or fixing through screws. To solve this problem, Arruda et al [20] introduced elastic points to approximate the coupling condition. Most stiffeners are placed parallelly or orthogonally on base panel, but Xu et al [21] found that the effect of orientation of stiffeners play an important role in composite structure system. Besides, most papers have ignored the eccentric effect of stiffeners, which means that the base panel and stiffeners are jointed along middle surface, but the stiffeners are set on the based panel along side surface actually. A more accurate theoretical model has been developed by several authors [22] with this eccentric effect taken into account.

4. Porous Material
When sound propagates in porous material, the inside space and matrix provide two paths, which leads to a complex problem. There exist many models [23] from different viewpoints, and three kinds of main models and existing problems are summarized in the following.

4.1. The rigid framed models
The basic assumption of the following rigid framed models is that the frame of material is motionless, and then the fluid inside porous material can be equivalent to be free fluid. This assumption is valid when the stiffness of matrix of porous material (e.g. metal foam) is much larger than the fluid inside [24] or porous material has been set on rigid wall [25].

The first conceptual model for porous media may be the Rayleigh model [26], which describes exact sound propagation in parallel circular capillaries, and many theories are evolved from the Rayleigh model. Later, viscous and thermal effect were assumed to be independent by Zwikker and Kosten [27], they found that such treatment was at least efficient for fluid motion in a cylindrical channel. Moreover, Stinson [28] revisited the validation of Zwikker and Kosten’s assumption and concluded that this approximation could be applicable for a broad range of tube radius from 10-3 cm to several centimeters.

Following the way of this analytical modeling, Lu et al [29] proposed a model to predict acoustic wave through various cell shapes by combining three kind of drag forces including parallel, perpendicular to propagation direction forces and drag force caused by joints, microstructural optimization [30] have been subsequently conducted based on this model.

4.2. The rigid framed models
If the elastic frame of porous material is taken into account, many wave types play significant roles due to the coupling between matrix and fluid inside the pores, which thus leads to a more complex problem. In this case, a more complete model Biot’s theory [31] was developed, which is the most popular model so far. In the context of Biot’s theory, both fluid and matrix are assumed to be continuum ignoring the microscopic level when wavelength is longer than volume element.

Detailed derivation process can be found in Atalla’s book [23]. Besides, the Biot’s theory can predict three kinds of waves propagating in porous material including two compressional waves and one transverse wave. Plona’s experiments [32] have supported the existence of two compressional waves. Based on Biot’s theory, other authors have developed new models (e.g. Atalla’s work [33]) by modifying the representation of stress-strain relation or other relation.

5. Conclusions
A number of theoretical methods for vibroacoustic property of three kinds of lightweight structures have been reviewed, which tries to present the whole frame work of acoustic modeling with recent advances also introduced. In general, there must emerge new problems with the development of other fields such as material production.

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