Applied Acoustics 89 (2015) 128–140

Contents lists available at ScienceDirect

Applied Acoustics

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

Directionality of sound radiation from rectangular panels

Pattabhi R. Budarapu [a,*], T.S.S. Narayana [b], B. Rammohan [c], Timon Rabczuk [a,d]

[a] Institute of Structural Mechanics, Bauhaus University of Weimar, 99423 Weimar, Germany
[b] Assystem India Private Limited, Bangalore, India
[c] IFB Automotive Private Limited, Bangalore, India
[d] School of Civil, Environmental and Architectural Engineering, Korea University, Republic of Korea

ARTICLE INFO

Article history:
Received 31 December 2013
Received in revised form 17 August 2014
Accepted 5 September 2014

Keywords:
Receptance
Acoustic radiation
Directivity

ABSTRACT

In this paper, the directionality of sound radiated from a rectangular panel, attached with masses/springs, set in a baffle, is studied. The attachment of masses/springs is done based on the receptance method. The receptance method is used to generate new mode shapes and natural frequencies of the coupled system, in terms of the old mode shapes and natural frequencies. The Rayleigh integral is then used to compute the sound field. The point mass/spring locations are arbitrary, but chosen with the objective of attaining a unique directionality. The excitation frequency to a large degree decides the sound field variations. However, the size of the masses and the locations of the masses/springs do influence the new mode shapes and hence the sound field. The problem is more complex when the number of masses/springs are increased and/or their values are made different. The technique of receptance method is demonstrated through a steel plate with attached point masses in the first example. In the second and third examples, the present method is applied to estimate the sound field from a composite panel with attached springs and masses, respectively. The layup sequence of the composite panel considered in the examples corresponds to the multifunctional structure battery material system, used in the micro air vehicle (MAV) (Thomas and Qidwai, 2005). The demonstrated receptance method does give a reasonable estimate of the new modes.

1. Introduction

The rectangular plate is one of the most widely used structures in the industrial world. The sound radiation from vibrating unbaffled panels [2–4], baffled panels [4–9] and submerged panels [10–12] has been the subject of active research for many years. Particularly, the sound radiation from vibrating plates is a common problem in automobiles, airplanes, industrial machinery, buildings and electro-acoustical devices, to name a few. Understanding the sound radiation characteristics of these structures is important for the researchers to maintain the noise levels within the specified limits. Regular or periodic excitation forces are likely to be experienced by the plates when they form part of a structure. The driving force spectrum may be composed of a single frequency alone or of a large number of frequencies. There is usually little that can be done to change the nature of the driving forces. Therefore, researchers are studying various techniques related to acoustic radiation for making engineering systems quieter.

One of the methods is to arrange the design so that the forces act on a nodal line for the mode shape about to be excited. This method is useful when the applied forces act on a concentrated area only. Naghshineh et al. [13] proposed material tailoring of structures for designing structures that radiate sound inefficiently in light fluids. They solved the problem in two steps. In the first step, given a frequency and overall geometry of the structure, a surface velocity distribution for minimum radiation condition was found. In the second step, a distribution of Young's modulus and density distribution was found for the structure such that it exhibits the weak radiator velocity profile as one of its mode shapes. Wodtke and Lamancusa [14] discussed the use of damping layers in sound power minimization. They mainly concentrated on the minimization of sound power radiated from plates under broad band excitation by redistribution of unconstrained damping layers, by assuming the total radiated sound power is represented by the power radiated at structural resonances. Apart from the above methods, Jog [15] proposed the reduction of dynamic compliance. St Pierre and Koopmann [16] worked on the point mass attachments to the structures to control the sound. Sonti [9] studied the variation of the sound power from a baffled point-force-driven simply supported rectangular plate subjected to a line constraint,

* Corresponding author.
E-mail address: pattabhib@gmail.com (P.R. Budarapu).

http://dx.doi.org/10.1016/j.apacoust.2014.09.006
0003-682X/

as a function of the constraint angle. Sastry et al. [17] have studied the sound radiation from the baffled rectangular panels attached with point masses and Ramaiah et al. [18,19] have estimated the sound radiation from the baffled composite panels. Xuefeng and Li [20,21] tried to reduce the sound radiation from a plate by modifying the boundary conditions. Fahy [22] proposed the vibro-acoustic noise control based on the reciprocity principle. These methods are grouped as passive methods of noise attenuation and works well at high frequencies.

Complimentary to the above technique is active noise control, which covers the low frequency range. In active noise control, global control can be achieved for enclosed sound fields at low frequencies, by appropriate placement of sensors and actuators [23,24]. In contrast, global control in the unbounded domains, such as external radiation is still a challenge [25]. Sonti and Jones [26] have developed a curved piezo-actuator model for active vibration control of cylindrical shells. Guo and Pan [27] have demonstrated the active noise control in free field environments. It requires appreciable hardware and achieves reasonable broadband control when the microphones and speakers are optimally located in the sound field. In the free fields, exact cancellation of sound occurs only when the secondary source is a replica of the primary and placed at the same location, which cannot happen in practice.

In applications such as stealth in submarines and ships, one alternative might be to achieve the control over the directivity of the external radiated sound, rather than attenuating sound totally. Even in industrial applications it is useful to direct the sound away from the work place and make the environment acceptable. The main objective of the current work is to achieve a change in the directivity of a point driven rectangular plate set in a baffle by attaching point masses/springs to it. The strategy here involves deliberate changes in the mode shapes of the radiator in order to achieve the stated objective. The analysis of the coupled system i.e., determination of new resonances, modes and the response, is performed based on the receptance method [28–37]. The sound field is estimated through the Rayleigh integral [38,39]. The developed methodology has been applied to three different coupled systems as presented in the examples. In the first example, we demonstrate the receptance method through a steel plate attached with point masses. In the second and third examples, the methodology is applied to estimate the sound directivity from a composite panel with attached point springs and masses. The layup sequence of the composite panel considered in examples 2 and 3 corresponds to the multifunctional structure battery material system, used in the MAV [1].

The arrangement of the article is as follows: the receptance method is introduced in Section 1. Details of the receptance method are explained in Section 2. Section 3 explains the estimation of sound field using the Rayleigh integral. Numerical examples are presented in Section 4. In the first example, acoustic directivity of the plate-mass system is studied. The size(s), location(s) and the excitation frequencies are varied to arrive at a particular configuration where the directionality is significant. In the second example, directionality of the composite plate-spring system is studied. The third example is on estimating the acoustic directivity of a composite panel with five attached point masses along a line, at a particular orientation. Section 5 concludes the article.

2. The receptance method

The receptance method is well developed and a detailed description of the method can be found in [28–37]. With the receptance method, vibrational characteristics of a combined system can be estimated from the characteristics of the component systems. A feature of the receptance method is that the receptances of the component systems may be determined by any method that is sufficiently accurate. In this paper, the receptances are written in terms of the natural frequencies and modes, which can be obtained from any finite element programs or through the experiments. The advantage of the receptance method is that it is a pure analytical method and the new mode shapes and the natural frequencies of the combined system are determined in terms of the old mode shapes and natural frequencies.

Receptance is defined as the ratio of response at a certain point (location i) to the harmonic force or moment input at the same or different point (location j), as given below:

$$\alpha_{ij} = \frac{\text{Response of system } A \text{ at location } i}{\text{Harmonic force or moment input to system } A \text{ at location } j}. \quad (1)$$

The response may be either a line displacement or a rotation. The notation adopted in this paper is as follows: capital letters such as A, B, C refer to subsystems and the Greek letters α, β, γ will denote the receptances of the subsystems. The material coordinates of a point in domain Ω are denoted by $\mathbf{X}$, whose spatial coordinates are denoted by $\mathbf{x}$. 'M' indicates the external mass attached to the plate and m^a is the mass per unit area of the plate. Note that from the reciprocity theorem $\alpha_{ij} = \alpha_{ji}$ [22].

Consider two systems, a plate (system A) and mass(es)/spring(s) (system B), connected in the domain Ω at two points 1 and 2 respectively, shown in Fig. 1(a). Let the combined system be subjected to harmonic excitation and α's denote the receptance

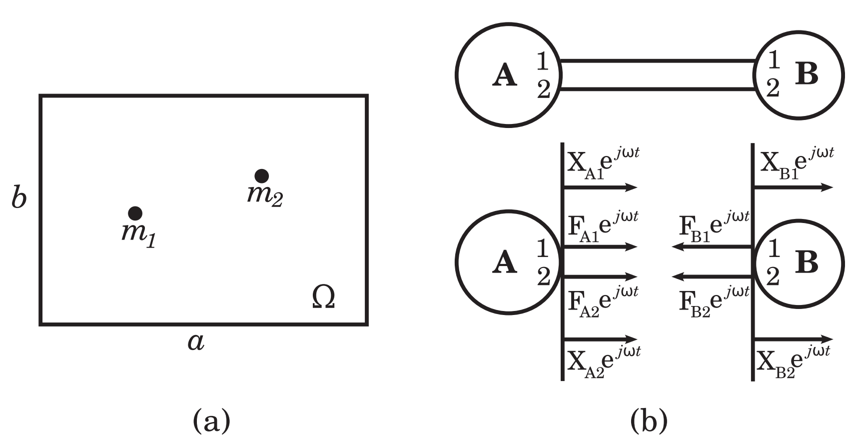

Fig. 1. Two systems connected at two points. (a) Two masses (system B) m_1 and m_2 connected at points 1 and 2 on a rectangular plate (system A). (b) Equilibrium displacements and force distribution on systems A and B, subjected to harmonic excitation.