Journal of Sound and Vibration 419 (2018) 352–366

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Acoustic modeling and eigenanalysis of coupled rooms with a transparent coupling aperture of variable size

Shuangxia Shi [a], Guoyong Jin [b, *], Bin Xiao [a], Zhigang Liu [b]

[a] School of Energy and Power Engineering, Northeast Electric Power University, Jilin, 132012, PR China
[b] College of Power and Energy Engineering, Harbin Engineering University, Harbin, 150001, PR China

ARTICLE INFO

Article history:
Received 17 June 2017
Received in revised form 10 November 2017
Accepted 10 January 2018

Keywords:
Coupled rooms
Coupling aperture
Eigenmodes
Energy principle

ABSTRACT

This paper is concerned with the modeling and acoustic eigenanalysis of coupled spaces with a coupling aperture of variable size. A modeling method for this problem is developed based on the energy principle in combination with a 3D modified Fourier cosine series approach. Under this theoretical framework, the energy exchange property and acoustically transparent characteristics of the opening are taken into account via the inflow and outflow sound powers through the opening without any assumptions. The sound pressure in the subrooms is constructed in the form of the three-dimensional modified Fourier series with several auxiliary functions introduced to ensure the uniform convergence of the solution over the entire solution domain. The accuracy of the natural frequencies and mode shapes of three exemplary coupled rooms systems is verified against numerical data obtained by finite element method, with good agreement achieved. The present method offers a unified procedure for a variety of cases because the modification of any parameter from one case to another, such as the size and location of the coupling aperture, is as simple as modifying the material properties, requiring no changes to the solution procedures.

1. Introduction

In the study of acoustic cavities, it is well known that the acoustic openings have a great influence on the acoustic characteristics of closed cavities. In the studies of the effects of openings on the acoustic cavities, two classes of problems are involved, i.e., open cavities and coupled spaces, which are both of engineering interest and fundamental importance in acoustics. The investigation of the modal characteristic of an acoustic cavity having opening boundary conditions could provide a theoretical basis for the acoustic design or noise prediction of sound fields in acoustic-related engineering applications, such as office spaces, ship cabins, concert halls, etc.

The open cavity, which is composed of two regions coupled by the openings, is a typical model of a radiated noise structure in engineering. The noise in the interior acoustic space is usually radiated into the exterior free field through acoustically transparent openings. To control the radiated noise level, various numerical methods [1–4] and analytical models [5–9] are utilized to determine the acoustic quantities of interest in the open cavity. FEM is the tool routinely used for most acoustic studies [2]. Perfectly Matched Layer (PML) [3]absorbing boundary conditions are adopted to compute the acoustic resonances

* Corresponding author.
E-mail address: guoyongjin@hrbeu.edu.cn (G. Jin).

https://doi.org/10.1016/j.jsv.2018.01.024

in three-dimensional open cavities with more general boundaries. The air aperture in the three-dimensional open cavity has been theoretically considered as an equivalent structural component with small thickness [7]. However, this treatment neglected the physical properties of the opening. To simulate the energy exchange property and acoustically transparent characteristics of the opening, Jin and Shi [9] proposed a modeling method for predicting the acoustic responses of a 3D rectangular opened enclosure with general wall impedance that has a rectangular opening of variable size.

Coupled spaces, composed of two or more spaces that are connected through acoustically transparent openings, have long been of interest in architectural acoustics. In practice, many typical configurations consisting of subrooms that are coupled together through acoustic openings are representatives of coupled spaces, such as churches with several naves and chapels, ship cabins, and office spaces. A prerequisite for performing acoustic design for the coupled spaces is knowledge of the related acoustic characteristics. Thus, an increasing number of researchers are focused on understanding the acoustic characteristics and physical mechanisms of coupled spaces [10–22].

Until now, several methods applied to determine the acoustics of coupled spaces have been presented, such as the diffusion model [10–14], statistical acoustic method [15,16], geometrical acoustic method [17,18], and modal expansion method [19–22]. Both the geometrical acoustic method and statistical acoustic method are suitable for the large spaces and high frequency range. For ship cabins or building rooms, it is more reliable and favorably to utilize the wave acoustics method to calculate the acoustic field distribution at relatively low frequencies. The modal expansion method based on wave acoustics could describe the acoustic phenomenon of the coupled spaces overall, but it is difficult to implement. Meissner [21,22] investigated the acoustical properties of coupled rooms using the modal expansion method based on a numerical technique and determined the acoustic energy density distribution and sound intensity vector field inside coupled spaces.

In this paper, the energy principle in combination with a 3D modified Fourier cosine series proposed for the acoustic analysis of a 3D rectangular opened cavity [9] will be extended to the acoustical coupling and eigenanalysis of coupled spaces with a coupling aperture of variable size. To illustrate the energy exchange property and acoustically transparent characteristic of the opening, the effects of the coupling aperture between subrooms is taken into account via the difference between the inflow and outflow sound powers of the opening. The sound pressures in the subrooms are represented by the modified Fourier series consisting of a standard 3D cosine series and an auxiliary function introduced to ensure the convergence rate of the solution inside the coupled spaces including the opening boundary. To prove the application range of the current modeling method, the natural frequencies and mode shapes for three exemplary coupled room systems are calculated via the current modeling method. The accuracy of the natural frequencies and mode shapes of three exemplary coupled room systems is verified by numerical data obtained via the finite element method. The influences of the size and location of the coupling aperture between subrooms are investigated through a unified procedure offered by the current method.

2. Theoretical formulations

2.1. Description ofthe model

The configuration of the coupled rooms and the associated coordinate system under investigation are shown in Fig. 1. The coupling system is composed of two rectangular cavities (cavity 1 and cavity 2) and a coupling opening. The length, width, and height of the ith ($i = 1$ or 2) rectangular cavity are, respectively, represented by Lxi, Lyi and Lzi. The rectangular coupling aperture connecting the two subrooms that transports sound energy between the two subrooms has variable position and size. The boundary conditions of the walls of the coupled rooms are assumed to be acoustically rigid.

The sound pressure p_1 and p_2 inside cavity 1 and cavity 2 are expressed by classical wave equations

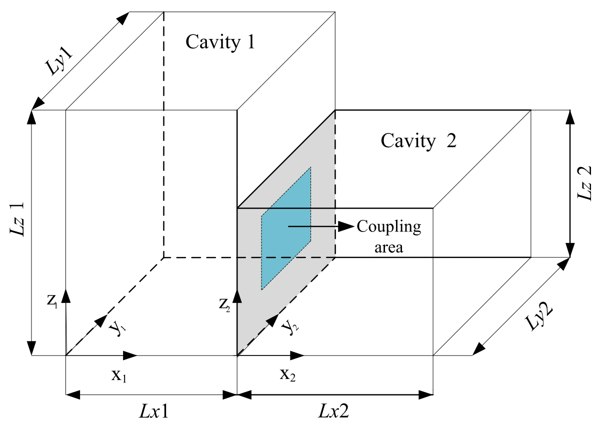

Fig. 1. L-shaped coupled rooms with a rectangular coupling aperture.