Results in Physics 11 (2018) 188–200

Contents lists available at ScienceDirect

Results in Physics

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

# Sound-vibration behaviors of the thin orthotropic rectangular fluid–structure coupled system resting on varying elastic Winkler and Pasternak foundations

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ARTICLE INFO

*Keywords:*
Fluid-structure coupled system
Sound-vibration behaviors
Winkler and Pasternak foundations
Fourier series method
Rayleigh-Ritz method

ABSTRACT

This paper establishes a thin orthotropic rectangular fluid–structure coupled system which effectively studies the sound-vibration behaviors. The established coupled system is made up of an acoustic enclosure filled with air or water and a single orthotropic thin plate or parallel double plate on varying elastic Winkler and Pasternak foundations. Based on Fourier series method and classical plate theory (CPT), the admissible functions of the orthotropic plate and cavity could be represented as superposition of the periodic functions. All the unknown series coefficients are gained by the Rayleigh-Ritz method. On the premise of validating the great convergence and accuracy of the established analytical model, both the natural characteristics analysis and the forced response studies under the excitations of a unit monopole source or a unit simple harmonic force are carried out. The effect of various elastic foundations on the fluid–structure coupled system is mainly studied. In addition, some new discoveries have been listed, on the basis of varying orthotropic degrees, boundary constraints and acoustic medium, which could set up the benchmark for the following research.

## Introduction

The plate-cavity coupled system, as an abstract model of many engineering applications, has been an important subject of continued research. It is of great significance to reveal the coupled effect and mechanism between the acoustic cavity and flexible plate. However, there are few literatures of the plate-cavity coupled system resting on elastic foundations. In fact, as an analytical model closer to actual production, it is undoubtedly more valuable to study the coupled system on various elastic foundations, which can correctly predict the sound-vibration coupled characteristics and provide theoretical guidance for vibration reduction and noise control.

There are many literatures on the study of the plate-cavity coupled system. Tanaka et al. [1] derived explicitly the eigenpairs of the rectangular thin flexible plate coupled with an acoustic enclosure consisting of five rigid walls. Du et al. [2] presented a Fourier series method to analyze the sound-vibration behaviors of a three-dimensional acoustic enclosure coupled with a flexible rectangular plate under elastic boundary constraints. Wang et al. [3] tested the structural–acoustic coupled system consisting of an enclosure and a clamped panel which were different from those consisted of a simply supported one. Chen et al. [4] extended the Chebyshev polynomial series to study the sound-vibration characteristics of an enclosure with varying impedance walls which coupled with an elastic supported rectangular plate. Pirnat et al. [5] established a rectangular structural–acoustic coupled system to discuss the coupled behaviors by introducing the point sound source. And the analytical results matched very well with the experimental data. Shi et al. [6] analyzed the sound-vibration properties of an enclosure coupled with double plates. In this paper, some important parameters are discussed, such as the various supported constrains, acoustic medium, different impendence walls and the varying depths of enclosure. Jiao et al. [7] examined the sound-vibration coupling behaviors of the elastic supported plate coupled with a rectangular enclosure by introducing statistical method and the principle of hybrid determination. Xie et al. [8] investigated the sound-vibration properties of an irregular acoustic enclosure with varying impedance walls coupled with an elastic supported plate. It should be pointed out that the strong or weak coupled effects between the plate and different acoustic medium were studied in this paper. Jain et al. [9] built the sound-vibration coupled system composed of a rectangular enclosure and an elastic supported thin plate. Cui et al. [10] focused on the sound-vibration characteristics of a fully elastic plate backed by a

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https://doi.org/10.1016/j.rinp.2018.09.002
Received 28 May 2018; Received in revised form 10 August 2018; Accepted 1 September 2018
Available online 06 September 2018
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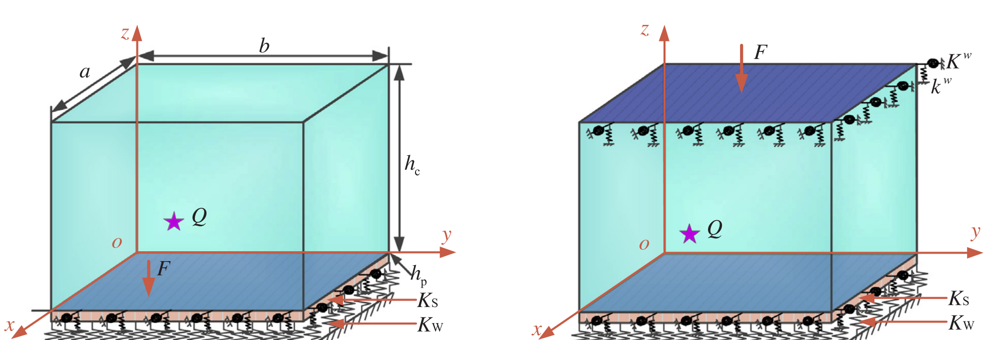
**Nomenclature**

| | |
|---|---|
| $h_p$, $h_c$ | thickness of the plate and cavity |
| $\omega_p$, $\omega_c$ | circular frequencies of the plate and cavity |
| $\rho_p$, $\rho_c$ | density of the plate and cavity |
| $c_0$ | sound velocity inside the cavity |
| $A$ | amplitude of the source |
| $k$ | wave number |
| $D_{ij}^r$ | standard bending rigidities |
| $E_x^r$, $E_y^r$ | modulus in $x$ and $y$ directions |
| $G_{xy}^r$ | shear modulus |
| $\mu_x^r$, $\mu_y^r$ | Poisson's ratios |
| $Z_q$ | complex acoustic impedance |
| $k^w$, $K^w$ | boundary springs |
| $K_W$, $K_S$ | linear and shear foundation parameters |
| $F$, $Q$ | point force and point sound source |
| $\boldsymbol{W}^{\Omega}$, $\boldsymbol{P}^{\Omega}$ | point force and point sound source |
| $\boldsymbol{W}^{\Omega}$, $\boldsymbol{P}_i^{S}$ | internal displacement and pressure vector |
| $\boldsymbol{A}_{mn}$, $\mathbf{B}_{mn}$, $\boldsymbol{C}_{m_1n_1l_1}$ | supplementary polynomials |
| $f_r$ | unknown Fourier vectors |
| $\delta_p$, $\delta_c$ | external load distribution function |
| $\boldsymbol{K}_{\text{plate}}$, $\boldsymbol{K}_{\text{cavity}}$ | 2D and 3D Dirac function |
| $\boldsymbol{M}_{\text{plate}}$, $\boldsymbol{M}_{\text{cavity}}$ | stiffness matrices of the plate and cavity |
| $\boldsymbol{C}_{\text{c - p}}$, $\boldsymbol{C}_{\text{p - c}}$ | mass matrices the plate and cavity |
| $\boldsymbol{Z}_{\text{cavity}}$ | coupled matrices |
| $\mathbf{F}$, $\mathbf{Q}$ | impedance matrix |
| Mc, Nc, Qc | truncation values of cavity |
| Mp, Np | truncation values of plate |

rectangular enclosure by applying the structural force on the elastic plate. Cui et al. [11] studied the efficient and accurate numerical method of sound-vibration coupled equation according to the smooth finite element analysis method based on edge for the structure and the gradient weighted finite element method for the sound field. We can easily discover that the above literature on the plate-cavity coupled system is mainly related to isotropic plate. Gradually, the studies on coupled system consisting of orthotropic plates, sandwich plates and laminated plates are also going deep. Sarigül et al. [12] analyzed the sound-vibration characteristics of the composite plate and enclosure coupled system by finite element analysis software. Then they [13] applied the analysis model on the sound-vibration coupled system, whose laminated plate can change the material parameter arbitrarily. Das et al. [14] solved the sound-vibration behaviors for the partly elastic composite laminated plate with a sound domain inside under the harmonic excitement. Dozio et al. [15] solved the sound-vibration problems for the coupled system which was made up of multilayered composite plates and an enclosure by applying a finite element formulation. Sadri et al. [16] investigated the sound-vibration coupled responses for a sandwich elastic plate-cavity coupling system filled with air. Larbi et al. [17] explored the effect of a viscoelastic layer of double-wall sandwich panels on the sound transmission by establishing an original finite element modeling. Shi et al. [18] deduced a theoretical solution for sound-vibration analysis of an orthotropic rectangular elastic plate coupled with a closed rectangular enclosure based on Spectro-Geometric Method (SGM). According to piecewise shear deformation theory, Li et al. [19] derived the sound-vibration characteristics for a rectangular composite sandwich plate under completely clamped boundary conditions in high temperature environments. And in our previous study, we also established a rectangular composite thin plate-cavity coupled system with uniform elastic supports [20] on the basis of CPT and a composite plate-cavity coupled system with uniform/non-uniform varying elastic supports [21] based on first-order shear deformation theory (FSDT) to predict the vibro-acoustic characteristics. The above study on the plate-cavity coupled system provides a good foundation for further research in the future.

However, it must be pointed out that all the above studies do not consider the influence of elastic foundations on the sound-vibration coupled system. It must be admitted that the study of plate resting on elastic foundations has been very thorough. Winkler foundations [22–25] are the theoretical models with only one linear parameter. With the in-depth analysis, the two parameters foundations are put forward timely which are closer to the analysis model than the Winker foundation. The Pasternak foundation is a typical representative among them and has been widely applied. Thai et al. [26] analyzed the vibration, buckling, and bending of the thick plate on the varying elastic Pasternak foundation based on a simple refined shear deformation theory. Based on a simple hyperbolic shear deformation theory, Nedri et al. [27] explored the vibration characteristics of laminated composite plate on the Pasternak-type foundations. Benahmed et al. [28] explored the vibration and bending analyses of functionally graded (FG) plate on the two-parameter Pasternak foundations. Dehghany et al. [29] examined an exact solution to analyze the vibration characteristics of rectangular plates with simply supports on the Pasternak foundations. Based on the generalized differential quadrature method and FSDT, Tornabene et al. [30–33] studied the vibration problems of the composite panels and shells on the Winkler-type foundation or Pasternak-type foundation. In addition, His team also studied in depth various mechanical properties of plate and shell structures with different theories [34–37]. According to the generalized Galerkin's method and extended Hamilton's principle, Pradhan et al. [38] investigated the vibration characteristics of a asymmetric three-layered beam on an elastic Pasternak-type foundation with the excitation of a pulsating axial load. Liu et al. [39] proposed the first known vibration characteristic of rectangular thick elastic supported plates on Pasternak-type foundations on the basis of the three dimensional theory. Parida et al. [40]




(a) Single-plate-cavity coupling system (b) Double-plate-cavity coupling system

**Fig. 1.** The coordinate system and geometry model of the single-plate-cavity and double-plate-cavity coupling system resting on Pasternak foundation.

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