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Experimental and analytical modal studies of vibrating rectangular plates in contact with a bounded fluid

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ABSTRACT

The free vibration response of a thin rectangular plate in contact with fluid is experimentally studied by Acoustic and Modal tests. To this purpose, a series of experiments are done on rectangular plates contacting fluid, with different dimensions and materials, wherein the plate is connected on one side of a heavy solid container by certain number of bolts, where are situated near to each other on the boundaries of the plate to make clamped support. In Acoustic test, the plate in contact with an inviscid fluid is stimulated by a hammer and the produced sound from free vibration of the plate is sampled by microphone. Thereafter by transforming of sound pressure signal to frequency domain, the natural frequencies of the plate are acquired in different spectrum. To verify the method, some Modal tests are performed and also an analysis is done via Rayleigh-Ritz method. Comparing results of experiments and theory shows good agreement between them. Finally by considering frequency response function, natural frequency of the plate is extracted in different height of the fluid and effects of some parameters on the natural frequencies such as fluid height and dimensions of the plate are studied.

1. Introduction

Wide uses of plates in industry as well as interesting geometry which may cover almost the entire two-dimensional problems, are caused many attempts to solve the static and dynamic problems of this structural element. Over the years, many theories are developed to solve such problems which simultaneously simplified solution procedures and made more precise results. One of the most important problems is investigation of effects of fluid on vibration analysis of structures which arises in nuclear and marine industries. To this aim, the vibration analysis is carried out to determine natural frequencies and mode shapes of plates contacting fluid in order to predicting probably damages and improving design of these structures. In the analysis, the natural frequencies and mode shapes can be calculated using two ways including theoretical and experimental methods. Experimental vibration analyses of plates are also performed in some procedures such as acoustic and modal tests which are interested by many authors. Robinson and Palmer (1990) presented modal analysis of a flat horizontal plate floating on liquid, for low-frequency and amplitude oscillations. They examined the normal modes and the particular case of a plate constrained to have zero slope at its edges and obtained the transfer function of a point-driven floating plate. Kwak (1996) concerned with the virtual mass effect on the natural frequencies and mode shapes of rectangular plates due to the presence of the water on one side of the plate. In this paper, the added virtual mass incremental factors for rectangular plates are obtained using the Rayleigh-Ritz method combined with the Green function method. Haddara and Cao (1996) investigated the dynamic response of flat horizontal plates vibrating in air and under water experimentally and analytically and derived an approximate expression for the evaluation of the modal added masses for rectangular plates. Amabili and Kwak (1996) dealt with the analytical and numerical approaches are used to estimate the natural frequencies of circular plates in contact with a liquid on one side and placed into the hole of an infinite rigid wall. Zhou and Cheung (2000) studied the vibratory characteristics of a rectangular plate in contact with water on one side using the Rayleigh-Ritz approach to derive the eigenfrequency equation of the system via the variational principle of energy. Liang et al. (2001) based on empirical added mass formulation, presented a simple procedure to determine the vibration frequencies and mode shapes of submerged cantilevered plates. Yadykin et al. (2003) presented a numerical study of the fundamental properties of the added mass of a plane flexible plate which is clamped at one edge and free at the other edges and oscillating in a fluid. A theoretical study presented on the hydroelastic vibration of two identical rectangular plates coupled with a bounded fluid by Jeong et al. (2004). They observed two transverse vibration

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modes, in-phase and out-of-phase, in the symmetric fluid-coupled structure in terms of a finite Fourier series. Ergin and Uğurlu (2003) investigated modal characteristics, such as natural frequencies and mode shapes, of cantilevered plates, partially in contact with a fluid. Zhou and Liu (2007) studied the three-dimensional vibratory characteristics of flexible rectangular tanks partially filled with liquid by using a combination of the Rayleigh–Ritz method and the Galerkin method. Hosseini-Hashemi et al. (2009) investigated acoustic radiation of rectangular Mindlin plates in different combinations of classical boundary conditions using a set of exact close-form sound pressure equations.

Khorshidi (2010) focused on the hydrostatic vibration analysis of a rectangular plate in partial contact with a bounded fluid in bottom and vertical directions and calculated the natural frequencies of the plate coupled with sloshing fluid modes using the Rayleigh-Ritz method. Khorshidi and Farhadi (2013) studied hydrostatic vibration analysis of a laminated composite rectangular plate partially contacting with a bounded fluid and examined effect of different parameters including boundary conditions, aspect ratio, thickness ratio, fiber orientation, material properties of the laminas and dimensions of the tank on the plate natural frequencies. Hosseini-Hashemi et al. (2012) presented the free vibration analysis of a horizontal moderately thick rectangular plate based on the Mindlin plate theory (MPT), either immersed in fluid or floating on its free surface. Kwak and Yang (2013) examined the free flexural vibration of a cantilevered plate partially submerged in a fluid. They expressed the virtual mass matrix which reflects the effect of the fluid on the natural vibration characteristics in analytical form in terms of the Mathieu functions and then combined it with the dynamic model of a thin rectangular plate obtained by using the Rayleigh–Ritz method. Askari et al. (2013) developed a theoretical method to investigate free vibrations of circular plates immersed in fluids as a semi-analytical procedure and presented a series of experimental tests to validate the model. Hashemi et al. (2013) proposed an analytical method to determine the dynamic response of 3-D rectangular fluid containers with four flexible walls, subjected to seismic ground motion by applying Rayleigh–Ritz method using the vibration modes of flexible plates. Carra et al. (2013) experimentally studied the linear and geometrically nonlinear (large amplitude) vibration response of a thin plate in contact with water on one or both sides considering different filling levels. Khorshidi (2011) conducted an investigation on the acoustic radiation of rectangular Mindlin plates in different combinations of classical boundary conditions. As it has been shown in this paper, the radiation field of a vibrating plate with a specified distribution of velocity on the surface can be computed using the Rayleigh integral approach and the acoustic pressure distribution of the radiator also obtained analytically in its far field. Recently many authors (Cho et al., 2016; Liao and Ma, 2016; Ivanov et al., 2016) inquired into the multiple aspects of the problem at hand which shows the necessity of the problem.

The present study deals experimentally with the vibration analysis response of thin plates in contact with fluid via acoustic method. In each test, a rectangular flat plate with different geometrical and material properties in conjunction with a solid fluid filled steel container is involved. The plate is bolted on one side of container such that the boundary conditions of plate are estimated as clamped. After installation the signal transfer device, the plate is stimulated by hammer and developed signals are used to obtain vibration characteristics of the system. To the knowledge of authors, vibration analysis of plates in contact with fluid by acoustic test is done for the first time. Furthermore, the vibrational responses, i.e., the natural frequencies are computed by using the modal test and also Rayleigh-Ritz method to verify proposed analysis. Some rather interesting results such as effect of aspect ratio, fluid height ratio and material properties on natural frequency of the plates have been obtained, as the reader will see in what follows.

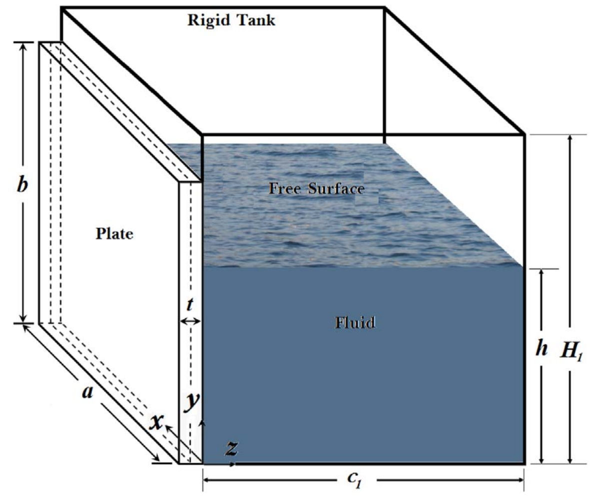

Fig. 1. A schematic of rectangular plate in contact with fluid dimensions and coordinate systems.

2. Mathematical model

In this section some theoretical equations regarding interaction of fluid dynamics on the plate vibration are presented. Consider an isotropic, homogeneous rectangular plate with length a, width b, thickness h, Young modulus E, Poisson's ratio ν and density ρ_p which make up one of the vertical walls of a container partially filled of fluid and other walls are assumed to be rigid. The container is filled with an ideal and irrotational fluid with density ρ_f in a rectangular domain with width c_1, depth b_1, and a length equal to the length of the plate a. A rectangular Cartesian coordinate system (o, x, y, z) is used to describe the motion of the fluid and the free vibration of the plate such that the neutral middle surface of the plate includes the x and y axes, as shown in Fig. 1.

2.1. Structural model

With the assumptions that plate is thin and has small deformation, according to the classical plate theory, the displacement components are assumed to be given by:

$$u(x, y, z, t) = -z\frac{\partial w_0(x, y, t)}{\partial x} \tag{1}$$

$$v(x, y, z, t) = -z\frac{\partial w_0(x, y, t)}{\partial y} \tag{2}$$

$$w(x, y, z, t) = w_0(x, y, t) \tag{3}$$

where $w_0(x, y, t)$ represents the transverse displacement of the middle surface and $\partial w_0/\partial x$ and $\partial w_0/\partial y$ are the cross section rotations of the transverse normal sections of the plate due to bending about the x and y axes respectively.

The elastic strain energy of the plate due to bending of the plate is given by (Cho et al., 2015):

$$U_p = \frac{1}{2}\int_0^a\int_0^b\int_{-h/2}^{h/2}(\sigma_x\varepsilon_x + \sigma_y\varepsilon_y + \tau_{xy}\gamma_{xy})dzdydx \tag{4}$$

where σ_x, σ_y and $\tau_{ij}\,(i, j = x, y, z)$ are normal stress components in x and y directions and shear stress in ij plane respectively. Total kinetic energy of the rectangular plate is given by:

$$T_p = \frac{1}{2}\rho_p h\int_0^a\int_0^b(\dot{u}^2 + \dot{v}^2 + \dot{w}^2)dydx \tag{5}$$

where over dot represents derivative with respect to time.