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Natural vibration analysis of rectangular bottom plate structures in contact with fluid

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ABSTRACT

A simple and effective procedure for the natural vibration analysis of rectangular bottom plate structures in contact with fluid is presented. Structural part of the coupled hydroelastic problem covers thin and thick rectangular plates and stiffened panels with different framing types. The eigenvalue problem is formulated using Lagrange's equation of motion and taking into account potential and kinetic energies of a plate structure and fluid kinetic energy, respectively. Natural frequencies and modes are obtained applying the assumed mode method using the characteristic polynomials of a Timoshenko beam. Potential flow theory assumptions are adopted for the fluid and the effect of free surface waves is ignored. From the boundary conditions for the fluid and structure the fluid velocity potential is derived and it is utilized for the calculation of added mass using the assumed modes. The developed theoretical model is verified with several numerical examples dealing with the natural vibration of bare plates and stiffened panels in contact with different fluid domains. A comparison of the results with those obtained by a general purpose FEA software showed very good agreement, especially for the lowest natural frequencies that are actually most relevant for the structural design from the viewpoint of vibration.

1. Introduction

Bare and stiffened plates are primary structural members of ships, offshore structures, submarines, etc., and it is very important to assess their vibration properties to avoid resonance with relevant excitation sources. It is generally known that plates and stiffened panels in contact with fluid behave differently from the same structures in the air. Namely, due to the effect of added mass, their natural frequencies in contact with fluid are significantly decreased which makes the vibration analysis rather complex. This challenging problem has been investigated for many years and the earliest works were done by Lamb (1921) and McLachlan (1932). Apart from the above mentioned applications, natural vibration analysis of plates/stiffened panels in contact with fluid is important in the context of vibration of rectangular container bottoms (Cheung and Zhou, 2000).

An extensive literature survey up to 1998 on the vibration analysis of vertical and bottom plates in contact with fluid has been presented by Zhou and Cheung (2000). Accordingly, analytical methods (Bauer, 1981; Soedel and Soedel, 1994), semi analytical ones (Amabili, 1996; Cheung et al., 1985; Shafiee et al., 2014) and numerical methods (Kerboua et al., 2008; Kwak, 1996; Marcus, 1978) are distinguished. Nowadays, the finite element method (FEM) represents an advanced and widespread numerical tool for different engineering applications and in combination with the boundary element method (BEM), can be successfully applied to the natural vibration analysis of plate structures in contact with fluid. However, due to the rather lengthy model preparation and numerical calculation at the preliminary design stage, it is useful to have some simplified method at hand. Semi-analytical approaches using classical approximate methods for plates and analytical methods for fluid arise as an alternative since the analytical ones are limited to very special and simple models.

Cheung and Zhou (2000) and Zhou and Cheung (2000) applied an analytical-Ritz method to analyse the dynamic characteristics of the fluid-structure interaction of vertical and horizontal rectangular plate, neglecting the free surface waves. A theoretical Rayleigh-Ritz dynamic model of the fuel assembly submerged in the coolant of research reactor, leading to free vibration analysis of a bundle of identical rectangular plates fully in contact with an ideal liquid is introduced by Jeong and Kang (2013). In that paper the orthogonal polynomial functions, as admissible ones, were generated by Gram–Schmidt

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Nomenclature

A	area of beam cross-section
A_k, B_k, C_k	coefficients of orthogonal polynomials
a	plate/panel length
a_{mn}, b_{mn}, c_{mn}	influence coefficients of orthogonal polynomials
b	plate/panel width
c	length of fluid domain
D	plate flexural rigidity
d	width of fluid domain
E	Young's modulus
e	depth of fluid domain
G	shear modulus
h	thickness of plate
I	moment of inertia of beam cross-section
J	mass moment of inertia of stiffener
$j=\sqrt{-1}$	imaginary unit
k	shear coefficient
K_T	non-dimensional translational stiffness
k_T	translational spring constants per unit length
K_R	non-dimensional rotational stiffness
k_R	rotational spring constants per unit length
L	beam length
M, N	number of orthogonal polynomials in x and y directions
m, n	indexes of orthogonal polynomials in x and y directions
n_x, n_y	number of stiffeners in x and y directions
p, q	indexes of trigonometrical series in $\tilde{x}$ and $\tilde{y}$directions
r	non-dimensional parameter for area moment of inertia
S	stiffness ratio
s	non-dimensional parameter for beam rigidity
T	kinetic energy
t	time
V	potential energy
W	transverse deflection amplitude
w	transverse deflection
x,y	coordinates of plate/panel
$\tilde{x},\tilde{y},\tilde{z}$	coordinates of fluid domain
$X(\tilde{x}),Y(\tilde{y}),Z(\tilde{z}),\dot{T}(t)$	assumed solutions of velocity potential in $\tilde{x},\tilde{y},\tilde{z}$ directions and time
$X_m(\xi),Y_n(\eta)$	orthogonal polynomials to represent transverse deflection in x and y directions
$[K]$	stiffness matrix
$[M]$	mass matrix
$\{q(t)\}$	generalized coordinates vector
$\alpha=a/b$	aspect ratio of plate/panel
$\beta=e/d$	depth to width ratio of fluid domain
Γ_P,Γ_W	plate and fluid area in bottom
$\tilde{\zeta}$	non-dimensional coordinate for fluid in z direction
$\eta,\tilde{\eta}$	non-dimensional coordinates of plate/panel and fluid in y direction
$\lambda=c/d$	length to width ratio of fluid domain
ν	Poisson's ratio
$\xi,\tilde{\xi}$	non-dimensional coordinates of plate/panel and fluid in x direction
ρ,ρ_W	densities of structure and fluid
ϕ	velocity potential
$\Psi_m(\xi),\Phi_n(\eta)$	orthogonal polynomials to represent rotational angles about x and y axes
ψ_x,ψ_y	rotational angles of plate cross-section about x and y axes
Ω	fluid domain
ω	angular frequency
∇	Hamilton differential operator

process to approximate the wet dynamic displacements with a clamped–clamped-free–free boundary condition, and potential flow theory is adopted for fluid modelling. Many references in this field actually deal with circular plates in contact with fluid. That is probably the result of their wide applicability for instance in petrochemical industry and relatively simpler mathematical formulation. Cheung and Zhou (2002) analysed the vibration of a circular container bottom plate using the Galerkin method and taking into account sloshing effects. In some references, for instance (Amabili, 1996; Amabili and Kwak, 1996; Espinosa and Gallego-Juarez, 1984; Kwak, 1997; Tariverdilo et al., 2013) hydroelastic vibration of circular plates in contact with infinite fluid is studied. In all above references, the thin plate (Kirchhoff) theory is applied, and to the authors' knowledge, there is a rather limited number of papers dealing with thick (Mindlin) plate theory which takes into account transverse shear effects and rotary inertia. Recently, Hosseini Hashemi et al. (2010) applied the Ritz method in the vibration analysis of thick vertical rectangular plates on elastic foundations in contact with fluid. They expressed three displacement components of the plate by adopting a set of static Timoshenko beam functions satisfying geometric boundary conditions. A fluid domain with finite depth and width, but infinite in length direction is considered, and the method of the separation of variables and the Fourier series expansion method are used for fluid modelling.

Moreover, to the authors' knowledge there are only several studies dealing with the dynamic analysis of stiffened panels in contact with fluid. Schaefer (1979) replaced the stiffened plate with an orthotropic plate and exploited the concept of an equivalent system to analyse natural vibration of stiffened plate with different edge constraints, fully immersed and in contact with water, respectively. The natural frequencies of vertical stiffened panels with thin plates and slender stiffeners in contact with water are analysed by Nishino et al. (1995) and Takeda and Niwa (2000), using the energy method and expanding the velocity potential in water as a series of harmonic waves. Recently, based on the Rayleigh–Ritz approach Li et al. (2011) presented theoretical modal analysis model for the stiffened bottom plate and finite fluid domain, neglecting the free surface waves and taking into account the effects of bending, transverse shear and rotary inertia in both the plate and stiffeners. Comparisons with FE and experimental results are presented and the mode reversal phenomenon is discussed.

Up to now, the assumed mode method using the characteristic polynomials of the Timoshenko beam (Chung et al., 1993) is successfully applied to the dry vibration analysis of rectangular plates and stiffened panels with arbitrary boundary conditions (Kim et al., 2012; Cho et al., 2013, 2014, 2015). This concept very similar the Rayleigh–Ritz method (Liew et al., 1995), but instead of minimizing the energy functional, it opts to apply Lagrange's equation of motion. Actually, different variants of Ritz method are used in plate vibration analysis for many years, very often with two dimensional polynomials (Liew et al., 1993) or static Timoshenko beam functions (Dawe and Roufaeil, 1980) for the longitudinal and transverse direction. Free vibration of Mindlin plates with arbitrary boundary conditions in lower and higher frequency domain are also successfully analysed by applying DSC-Ritz method (Hou et al., 2005; Lim et al., 2005). The idea to apply the assumed mode method to the wet vibration analysis of bottom plate systems originates from Kim et al. (2008).