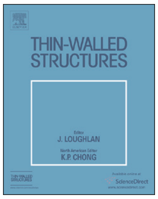
Thin-Walled Structures 95 (2015) 276–286

Contents lists available at ScienceDirect

Thin-Walled Structures

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



Frequency response of rectangular plate structures in contact with fluid subjected to harmonic point excitation force

Dae Seung Cho [a,*], Byung Hee Kim [b], Jin-Hyeong Kim [c], Nikola Vladimir [d], Tae Muk Choi [c]

[a] *Department of Naval Architecture and Ocean Engineering, Pusan National University, 63 beon-gil 2, Busandaehak-ro, Geumjeong-gu, Busan 609-735, Republic of Korea*
[b] *Samsung Heavy Industries Co. Ltd., Marine Research Institute, Geoje, Gyeongsangnam-do, Republic of Korea*
[c] *Createch Co. Ltd., Busan, Republic of Korea*
[d] *University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Zagreb, Croatia*

ARTICLE INFO

Article history:
Received 29 March 2015
Received in revised form
25 June 2015
Accepted 14 July 2015
Available online 24 July 2015

Keywords:
Forced vibration analysis
Harmonic excitation
Plate structures
Potential flow
Added mass
Assumed mode method
Mode superposition method

ABSTRACT

Numerical procedure for the forced vibration analysis of bottom and vertical rectangular plate structures in contact with fluid, subjected to internal point harmonic excitation force is developed. The procedure is based on the assumed mode method for free vibration calculation and mode superposition method for forced vibration analysis. Structural model covers Mindlin rectangular plates and stiffened panels. Lagrange's equation of motion is utilized to formulate the eigenvalue problem taking into account potential and kinetic energies of a plate and reinforcements, and fluid kinetic energy which is calculated according to potential flow theory, respectively. 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 and in-house code are verified with extensive numerical examples related to forced vibration of bare plates and stiffened panels in contact with different fluid domains. Comparisons of the results with those obtained by a general purpose finite element (FE) software confirmed high accuracy of the presented numerical procedure.

1. Introduction

Plates are widely used for structural members in all branches of engineering; aeronautical, civil, mechanical, naval, ocean, etc., and plate stiffening is often arranged to increase its loading capacity, prevent buckling or even to alter its natural frequency. It is generally known that plates and stiffened panels in contact with fluid behave differently from the same structures in the air due to the effect of added mass, which significantly decreases natural frequencies. Vibration analysis of plates in contact with fluid has been an issue for many years, and there are many papers dedicated to this interesting problem [1–3].

Literature overviews on dynamic analysis of bottom and vertical plate structures in contact with fluid can be found in [3–6]. Developed mathematical models can be classified into analytical ones [6–8], semi analytical models [9–11] and numerical models [12–14]. Nowadays, the finite element method (FEM) is probably the most advanced tool in practical engineering. Hence, it can be reliably applied in both free and forced vibration analysis of plates and stiffened panels in contact with fluid having arbitrary set of boundary conditions, but at the same time it may be rather time-consuming in model generation and calculation execution. In this sense, in the early design stage when different topologies of plate structures are considered, it is preferable to use some simplified method.

Most of references in this field are actually related to the hydroelastic vibration of circular plates. Hydroelastic analysis of a circular container bottom plate using the Galerkin method and taking into account sloshing effects is presented in [15]. Vibration of circular plates in contact with fluid considering infinite fluid domain is studied in [10,16–19], while references [4] and [5] deal with dynamic analysis of bottom and vertical rectangular plates, respectively. An analytical-Ritz method is applied and free surface waves are neglected [4,5]. 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 in [20]. In that paper the orthogonal polynomial functions, as admissible functions, were generated using the Gram–

---

* Corresponding author. Fax: +82 51 512 8836.
E-mail addresses: daecho@pusan.ac.kr (D. Seung Cho), bh48.kim@samsung.com (B. Hee Kim), mzfg@createch.co.kr (J.-H. Kim), nikola.vladimir@fsb.hr (N. Vladimir), taemuk@createch.co.kr (T. Muk Choi).

http://dx.doi.org/10.1016/j.tws.2015.07.013
0263-8231/© 2015 Elsevier Ltd. All rights reserved.

Schmidt process to approximate the wet dynamic displacements of the plates with a clamped–clamped–free–free boundary condition, and potential flow theory is used for fluid modelling. In above mentioned references the thin plate theory is adopted, and application of thick (Mindlin) plate theory in combination with Ritz method to the assessment of vertical rectangular plates on elastic foundations and in contact with fluid is recently presented in [21]. In that reference the structural displacement components are expressed by adopting a set of static Timoshenko beam functions where geometric boundary conditions are satisfied.

Furthermore, to the authors' knowledge there are only several studies dealing with the hydroelastic analysis of stiffened panels. Free vibration analyses of stiffened plates fully immersed and in contact with fluid, respectively, are done by transforming the structural part into orthotropic plate in [22]. The natural frequencies of vertical stiffened panels with thin plates and slender stiffeners in contact with water are reported in [23] and [24], and are obtained by using the energy method and expanding the velocity potential in water as a series of harmonic waves. Recently, a Rayleigh–Ritz based modal analysis of stiffened bottom plate in contact with 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 is presented [25].

The free structural response, considered in the above listed references, provides an insight into dynamic behaviour of wetted plate structures. However, it is often necessary, to check compliance of vibration amplitudes with the prescribed criteria, and therefore, forced vibration analysis has to be performed. The investigation presented in this paper is motivated by a practical engineering problem inherent to ships and offshore structures. Namely, in these structures there are different bare and stiffened tank bottoms and sides excited by main engine, propellers, pumps and other auxiliary machinery. Therefore, in the design process, forced vibration analysis of such local structural elements using some simplified tool is a prerogative. In this paper, numerical procedure for the natural vibration analysis of plate structures in contact with fluid presented in [3] is extended to analyse their frequency response under point excitation force. The solution is based on the assumed mode method for analysing natural vibration of plate structures and application of the mode superposition method for calculation of their forced response.

In the following section of this paper the considered coupled hydroelastic problem is explained in details and application of the assumed mode method in the free vibration analysis is outlined. Third section deals with hydrodynamic model where formulation of fluid kinetic energy for bottom and vertical plate structures is given. Fourth section outlines expressions for potential and kinetic energies of bare plates and stiffened panels. Mathematical model for forced vibration analysis of bottom and vertical plate structures in contact with fluid is based on application of the mode superposition method, as shown in fifth section. In the sixth and seventh sections extensive illustrative examples and concluding remarks, respectively, are given and accuracy and reliability of the developed numerical procedure is confirmed.

2. Problem statement—coupled hydroelastic vibration of plate structures

Vibration of bottom and vertical rectangular plates and stiffened panels in contact with an ideal and irrotational fluid, and having length *a* and width *b* is considered, Fig. 1. The considered plate structure part is assumed to be elastic, while the other parts of the rectangular domain are treated as rigid ones. Furthermore, the surface waves and hydrostatic pressure effects are neglected in this study. As explained in [4], the fluid–plate interaction system has two families of modes: the sloshing and the bulging ones. The sloshing modes are caused by the fluid free surface oscillation due to the rigid body motion of the tank (these modes can also be affected by the tank flexibility but are generally characteristic of a rigid tank). In this case, the amplitude of the free surface wave is dominant over that of the plate vibration, and when the sloshing modes are in resonance, the kinetic and potential vibration energies are mainly in the fluid. On the contrary, the bulging modes are related to the vibration of the flexible plate structures which moves the fluid. In such a case, the amplitude of the plate vibration is dominant over that of the free surface wave, and when the plate-dominated modes are in resonance, the potential vibration

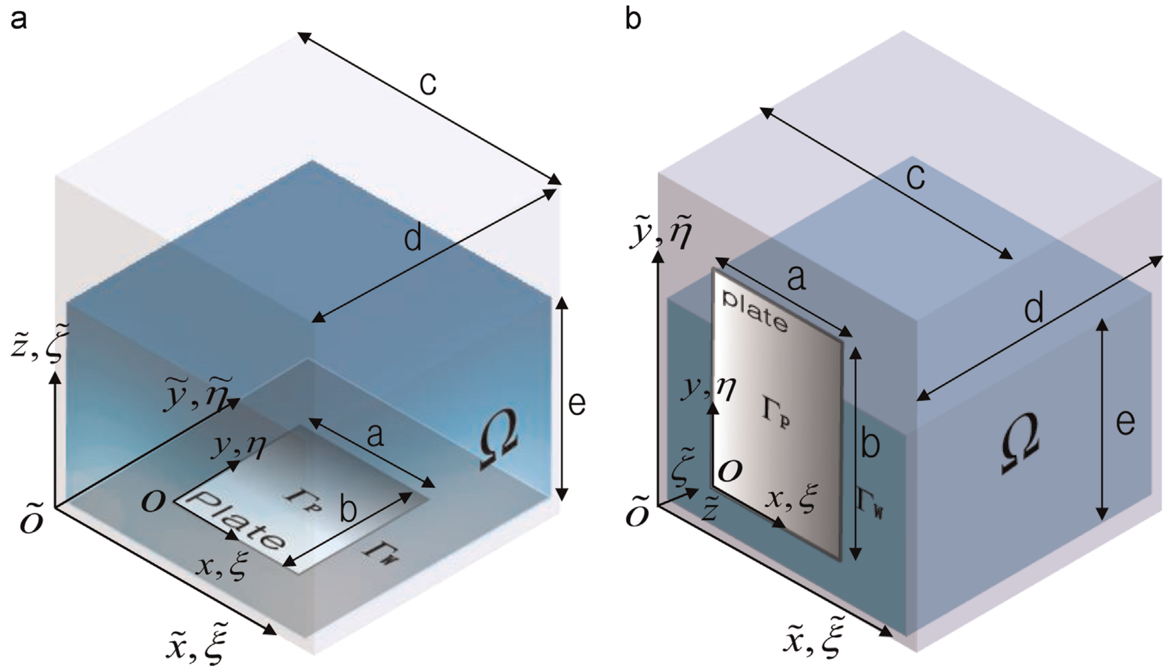


Fig. 1. Plate structure in contact with fluid; (a) bottom, and (b) vertical.