Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Ocean Engineering 33 (2006) 439–457
OCEAN ENGINEERING
www.elsevier.com/locate/oceaneng

Review of hydroelasticity theories for global response of marine structures ☆

Xu-jun Chen[a,b,c,*], You-sheng Wu[b], Wei-cheng Cui[b], J. Juncher Jensen[c]

[a] *Engineering Institute of Engineering Corps, PLA University of Science and Technology, Nanjing 210007, China*
[b] *China Ship Scientific Research Center, Wuxi 214082, China*
[c] *Department of Mechanical Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark*

Received 1 February 2004; accepted 3 April 2004
Available online 19 August 2005

Abstract

Existing hydroelastic theories are reviewed. The theories are classified into different types: two-dimensional linear theory, two-dimensional nonlinear theory, three-dimensional linear theory and three-dimensional nonlinear theory. Applications to analysis of very large floating structures (VLFS) are reviewed and discussed in details. Special emphasis is placed on papers from China and Japan (in native languages) as these papers are not generally publicly known in the rest of the world.

Keywords: Ocean engineering; Hydroelasticity; Nonlinear of the fluid; Nonlinear of the structure; VLFS

1. Introduction

By definition, hydroelasticity of marine structures is the branch of science concerned with the motion and distortion of deformable bodies responding to environmental excitations in the sea. Hydroelasticity is concerned with phenomena involving interaction between inertial, hydrodynamic and elastic forces (Heller and Abramson, 1959). Earlier comprehensive reviews may be found in Jensen and Madsen (1977) and Wu (1987).

☆ The project was jointly supported by the National Natural Science Foundation of China (Grant No.50039010, 50309018) and the Danish Rectors' Conference.
* Corresponding author. Tel.: +86 25 8487 3355; fax: +86 25 8487 3355.
E-mail address: xjchen@sjtu.edu.cn (X.-j. Chen).

0029-8018/$ - see front matter
doi:10.1016/j.oceaneng.2004.04.010

More recent progress of hydroelasticity may be found in Wu (1994), Suo and Guo (1996) and Kashiwagi (2000). Hydroelasticity theories for local elements like panels and decks have recently been reviewed by Faltinsen (2000). Hydroelasticity theories for global responses of marine structures are reviewed in the present paper including a special section on VLFS.

2. Two-dimensional linear theories

The strip theories, well developed for sea-keeping problems from the late 1950s to the early 1970s (Korvin-Kroukovsky and Jacobs, 1957; Salvesen et al., 1970), provide an efficient tool for calculating the hydrodynamic forces acting on a flexible ship's hull and formed the essential preliminary step in the establishment of two-dimensional hydroelasticity theories for symmetric and antisymmetric responses of hulls (Betts et al., 1977; Bishop and Price, 1977, 1979).

Briefly, the existing two-dimensional theories treat the hull as a non-uniform Timoshenko beam. They express the structural responses to wave excitation as a summation of distortions in the principal modes of the beam in vacuum, represent the hydrodynamic forces acting on the hull by means of a suitable strip theory, and solve the whole fluid–structure interaction problem through the generalized equation of motion given in the form

$$(\boldsymbol{A}+\boldsymbol{a})\ddot{p}+(\boldsymbol{B}+\boldsymbol{b})\dot{p}+(\boldsymbol{C}+\boldsymbol{c})\boldsymbol{p}=\boldsymbol{E} \tag{1}$$

In this equation, $\boldsymbol{p}$ is the principal coordinate vector; $\boldsymbol{a}$, $\boldsymbol{b}$ and $\boldsymbol{c}$ are the generalized mass, damping and stiffness matrices of the dry hull respectively; $\boldsymbol{A}$, $\boldsymbol{B}$ and $\boldsymbol{C}$ are the generalized hydrodynamic inertia, damping and restoring matrices respectively; $\boldsymbol{E}$ is the generalized wave exciting force vector. This equation is only valid in the frequency domain for a ship sailing in regular waves. Its solution for the principal coordinates in conjunction with the modal superposition theorem provides the dynamic displacements, the bending moments and the shearing forces, etc., at any section in the structure.

Based on certain simplifying assumptions, Bishop et al. (1978) and Belik et al. (1980) extended this frequency domain analysis to allow for the time simulation of the responses of a flexible ship's hull travelling in irregular head seaway with the inclusion of contributions from slamming. The corresponding principal coordinates may be calculated in the form

$$\boldsymbol{p}(t)=\sum_j \sqrt{2S(\omega_{ej})\Delta\omega_{ej}}\boldsymbol{H}(\omega_{ej})\boldsymbol{E}(\omega_{ej})\mathrm{e}^{\mathrm{i}(\omega_{ej}+\varepsilon_j)}+\int_0^t \boldsymbol{h}(\tau)\boldsymbol{F}(t-\tau)\mathrm{d}\tau \tag{2}$$

where $S(\omega_{ej})$ is the wave spectrum as function of the encounter wave frequency ω_{ej}; $\boldsymbol{H}$ the receptance matrix of Eq. (1); $\boldsymbol{E}(\omega_{ej})$ the magnitude of the generalized wave exciting force due to a regular wave with unit amplitude; ε_j the randomly distributed phase angle; $\boldsymbol{h}$ the impulse response matrix, being the Fourier transform of $\boldsymbol{H}$. The generalized force $\boldsymbol{F}$ models the impact slamming force and the momentum slamming force.

This approach has been extensively applied to prediction of the wave- and slamming-induced structural response of frigates with good correlation with measured results from full-scale trials (Clarke, 1986). Based on this theory, Dong et al. (1989) and Dong and Lin (1992) predicted the wave-excited vibration and bending moments of a full-form ship with shallow draught and showed reasonably good agreement with the experimental results from a segmented model test. Aksu et al. (1991a) investigated the dynamic behavior of a product carrier in ballast condition in waves. Bishop et al. (1991) studied the mechanism of the loss of the oil/bulk/ore carrier Derbyshire and examined similar evidence found from six sister ships. By calculation and test, Lin (1995) verified the existence of wave-induced springing vibration of a large oil tanker. Zhong et al. (1995) developed a method for calculating resonant frequency of wave-induced ship hull vibrations of a large ship. Based on the hydroelasticity theory of ships (Bishop and Price, 1979), Zhong and Zhao (1998) studied the effects of wavelength and forward speed on the natural frequency and wave-induced responses.

The underlying theory was also extended to account for antisymmetric wave-induced responses for sway, yaw, roll, coupled twisting and lateral bending (Bishop et al., 1980). Price and Temarel (1982), Pedersen (1983) and Wang et al. (1999) analyzed the horizontal bending and torsion responses of a container carrier taking into account warping deformations. Pedersen (1983) derived consistent discontinuity relations between open and closed hull section and showed that such relations are needed to get an accurate calculation of the natural frequencies. Asymmetric structures such as an aircraft carrier or a heeled ship was considered by Conceicao et al. (1984).

The above-mentioned two-dimensional theories retain all the aspects of strip theories, including the neglecting of hydrodynamic disturbances in the longitudinal direction. Wu et al. (1991b) proposed a general slender body hydroelasticity theory by extending Newman's unified theory (Newman, 1978; Newman, 1986) to admit distortions of the ship's hull. Owing to the better prediction by the unified theory of the sectional hydrodynamic force distribution along the ship's length over the whole wave frequency region, this slender body theory might provide better evaluation of structural dynamic responses. Wang et al. (1991b) and Che et al. (1992, 1994) presented an improved hydroelasticity theory for predicting hydroelastic behavior of very large floating structures (VLFS) and small water-plane area twin-hull (SWATH) ships in ocean waves. Here a new strip method is developed for evaluating the hydrodynamic interaction between the main immersed structural members by a decomposition concept of cross-section in-plane distortion, while a conventional finite element method is applied to the dynamic analysis of the three-dimensional dry structure. Since a three-dimensional finite element model of the structure is used, the method allows direct computation of three-dimensional structural response, such as individual member forces and stresses.

Based on a modal approach and generalization of the high-speed strip theory of Faltinsen and Zhao (1991), Hermundstad et al. (1999) presented a linear hydroelastic analysis of high-speed vessels. Hydrodynamic interaction between the hulls of a catamaran is properly accounted for by utilizing symmetry. It is demonstrated how an integral theorem can be utilized to find the hydrodynamic force for general mode shapes.

Cho and Kim (1998, 2000) investigated the interaction of monochromatic incident waves with a horizontal porous flexible membrane in the context of a two-dimensional linear hydroelastic theory.

Bereznitski (2001) showed by calculations that hydroelasticity plays an important role in the slamming problem. It was found that the ratio between the impact duration and the period of the first mode of vibration of a dry structure is the key factor in taking the decision when the solution of the structural response should include hydroelastic effects.

Liu et al. (2001) carried out experiments in a two-dimensional water flume to measure the elastic deformation and mooring force of a large-scale floating structure under regular waves. The main purpose of their study was to investigate the effect of hydroelastic response on the mooring force by changing the thickness and the length of model structures.

For monohull ships, Jensen and Mansour (2002, 2003) developed a procedure for estimating the effect of impulsive loads like slamming and green water on deck on the wave-induced bending moment by a semi-analytical approach. The results are given in closed-form expressions and the required input information for the procedure is restricted to the main ship dimensions: Length, breadth, draught, block coefficient and bow flare coefficient together with speed and heading.

3. Two-dimensional nonlinear theories

When a ship is experiencing relatively large motion in moderate seas, its hull may sustain nonlinear dynamic response. Many researchers have investigated these nonlinear effects. The studies may be broadly classified into two approaches. The first approach is characterized by treating the rigid body motion problem and the structural response problem separately. The second approach treats the structure and the surrounding fluid as a coupled entity. This closely resembles a hydroelasticity analysis.

Most works, though accounting for slamming actions, retain in their expressions of the nonlinear sectional hydrodynamic forces linear terms, which are derived basically from a linear strip theory suitable only for small and oscillatory motions with the sectional hydrodynamic coefficients treated as frequency dependent. However, during a slam, the motion is neither small nor oscillatory. The difficulty in including nonlinear effects in stochastic response analysis in the time domain lies in a proper determination of the sectional hydrodynamic forces that is motion history and local draught dependent. Consequently, new methods for stochastic predictions of ship nonlinear structural responses in moderate irregular seas continue to receive much attention.

Jensen and Pedersen (1979) developed a nonlinear quadratic strip theory formulated in the frequency domain for predicting wave loads and ship responses in moderate seas. It is based on a perturbation procedure in which the linear terms are identical to those of the classical linear strip theories, while the quadratic terms arise due to non-linearity of the exciting waves, the non-vertical sides of the ship, and the nonlinear hydrodynamic forces. This quadratic theory was extended to a hydroelastic approach by Jensen and Pedersen (1981), Jensen and Dogliani (1996) in order to provide a more accurate prediction of springing responses due to continuous wave excitations.

A generalized strip theory representation was introduced by Gu et al. (1988, 1989), in which the linear radiation solution is expressed by a time convolution and the nonlinear hydrodynamic actions due to the instantaneous draught and the time variation rate of the sectional added mass are included.

Söding (1982) proposed an alternative approach, which avoids both the time-consuming convolution integral and frequency dependent coefficients and hence allows for the arbitrary heave motion of the structure by introducing a high order differential relation between the relative velocity and the corresponding hydrodynamic force. Wang (1992), Wu et al. (1994), Xia and Wang (1997) applied this relation to formulate a hydroelasticity theory, which takes into account the nonlinear hydrodynamic actions due to the bow flare effect. This theory was applied to the S175 containership and other ships in irregular waves. The results showed agreement with existing experimental results. Xu et al. (1997) estimated the probability of the dynamic buckling of the ship taking into account both slamming and wave excitation. Xia et al. (1998) presented a nonlinear time domain strip theory for vertical wave loads and ship responses. The theory is generalized from a rigorous linear time domain strip theory representation. The hydrodynamic memory effect due to the free surface is approximated by a higher order differential equation. On the basis of this time domain strip theory, an efficient nonlinear hydroelastic method for wave- and slamming-induced vertical motions and structural responses of ships is developed, where the structure is represented as a Timoshenko beam. Numerical calculations are presented for the S175 containership. The agreement between predictions and experiments was rather good.

Song et al. (1994) extended the linear frequency domain strip theory to a nonlinear two-dimensional hydroelasticity representation by the following modifications. Firstly, the nonlinear terms due to the bow flare effect and the instantaneous draught are introduced. Secondly, in regular waves, the nonlinear motion of the ship and the corresponding hydrodynamic force are decomposed into their Fourier components, so that the frequency domain strip theory can be retained for each frequency component. Thirdly, in irregular waves the frequency domain strip theory is still employed in time domain analysis with the frequency dependent hydrodynamic coefficients being determined step by step at the frequency defined by the zero-crossing period of the wave elevation.

4. Three-dimensional linear theories

To overcome the limitations imposed by two-dimensional hydroelasticity theories, and to make it possible to examine the behavior of non-beam like flexible structures, a general three-dimensional linear hydroelasticity theory was developed (Wu, 1984; Price and Wu, 1985; Bishop et al., 1986). A linear finite element approach is used to describe the dynamic behavior of any three-dimensional dry structure in vacuum. The fluid actions associated with the distorting wet structure are determined from a three-dimensional theory of potential flow around the flexible floating structure in a seaway.

The generalized equation of motion has a form similar to that given in Eq. (1) but the coefficients in the equation are calculated differently. On the assumption of ideal fluid and irrotational flow, the generalized hydrodynamic inertia, damping and restoring matrices,

$\boldsymbol{A}$, $\boldsymbol{B}$ and $\boldsymbol{C}$ together with the generalized wave exciting force $\boldsymbol{E}$ are defined by integrals of the solutions of the potential flow over the wetted surface. The strengths of the singularities are solved by employing the interface boundary condition over the wetted surface. In this connection, Xia and Wu (1993) presented a general form of the interface boundary condition of the fluid–structure interactions, which takes into account the strain tensor field of the body surface. When the strain tensor field equals zero, the form is simplified to the Timman–Newman relation for a rigid body. In case no tangential external forces act on the wetted surface of the flexible structure, it is reduced to the generalized Timman–Newman relation for a flexible body (Wu, 1984; Price and Wu, 1985). For a slender body, the form becomes the body boundary condition of the strip theory.

This three-dimensional hydroelasticity theory has been applied to a wide range of fluid–structure interaction problems. This range includes arbitrarily shaped flexible structures excited by random waves, the slamming of flexible structures travelling in head or oblique seaways and the transient loading caused by an explosion. In all cases, the three-dimensional hydroelasticity theory has proved its versatility to describe the physics of the fluid–structure interaction process in terms of rigid-body and distortion responses, external loading and internal stresses.

Price et al. (1985), Fu et al. (1987), Lundgren et al. (1988), Wu and Du (1990), Aksu et al. (1991a), Kean et al. (1991), Ergin et al. (1992), Louarn et al. (1997), Wang et al. (2001), Phan and Temarel (2002), Li et al. (2002) and Fu et al. (2003) have applied this theory to different kinds of floating structures. Price and Wu (1989) modified the theory to allow for fluid viscous damping effects based on a Morison type approximation for viscous drag forces. Aksu (1993) extended the theory to time domain simulation of the behavior of slamming in irregular head and oblique waves. Comparison of responses derived from two- and three-dimensional hydroelasticity theories for a slender structure experiencing slamming in head waves showed good agreement (Aksu et al., 1991b).

A complete frequency domain analysis method for linear three-dimensional hydroelastic responses of floating structures moving in a seaway is presented by Du (1996). The method allows all the terms appearing in the general linear hydroelasticity theory, proposed by Wu (1984), Price and Wu (1985) to be retained in the numerical analysis. Thus, a more rigorous and complete analysis of the hydroelastic behavior may be carried out in the frequency domain for a travelling structure with no severe restrictions on its slenderness and forward speed.

Wang (1996); Wang and Wu (1998) used the Price–Wu condition at the interface between a flexible marine structure and a surrounding fluid flow to obtain a solution for the three-dimensional potential flow in the time domain around a flexible structure travelling in waves expressed as a boundary integral equation. The Green function, which satisfied the linearised free surface condition for the time dependent problem, was employed. A hydroelastic analysis in time domain to predict the loads, motions and structural responses of ships at a steady forward speed in a seaway was formulated.

Based on the semi-moment shell theory and the three-dimensional fluid boundary element method, Zhang et al. (1996) used the technique of the dry model to establish a three-dimensional model for fluid–structure interaction for ships vibrating in water. Similarly, Suo and Guo (1996) extended an existing three-dimensional hydroelasticity theory to bodies moving forward and rotating in water. Applications of the theory to marine propeller blades are illustrated.

Liu and Sakai (2000, 2002) developed a time domain numerical method for analysing the hydroelastic response of flexible floating structures to waves. The boundary element method is used to evaluate the fluid motion and the finite element method to analyze the elastic deformation of the structure. The dynamic wave–structure interaction is simulated by prescribing the conditions on a wave generation boundary for each time step and by satisfying the continuity of the pressure and the displacement on the fluid–structure interface. The numerical results are compared with experimental results. Further, the development of a solitary wave under a flexible floating structure is observed both in numerical analyses and experiments.

5. Three-dimensional nonlinear theories

Wu et al. (1997) firstly presented a three-dimensional nonlinear hydroelasticity theory. The expressions of the generalized second-order hydrodynamic forces are formulated by Wu et al. (1997), and the nonlinear equations of motion in frequency domain and in time domain are presented as

$$\sum_{k=1}^{m}[(a_{rk}+A_{rk})\ddot{p}_k(t)+(b_{rk}+B_{rk})\dot{p}_k(t)+(c_{rk}+C_{rk}+\Delta C_{rk}+Cm_{rk})p_k(t)]$$
$$=E_r^{(1)}(t)+Z_r^{(2)}(t)+Z_r^{(0)}+Q_r+J_{r0} \tag{3}$$

and

$$\sum_{k=1}^{m}\Bigg[(a_{rk}+\tilde{A}_{rk})\ddot{p}_k(t)+(b_{rk}+\tilde{B}_{rk})\dot{p}_k(t)+(c_{rk}+\tilde{C}_{rk}+\tilde{C}'_{rk})p_k(t)$$
$$+\int_0^t K_{rk}(t-\tau)p_k(t)\mathrm{d}\tau\Bigg]=E_r^{(1)}(t)+Z_r^{(2)}(t)+\Delta_r(t)+Z_r^{(0)}+Q_r \tag{4}$$

where $r=1,2,\ldots,m$.

In Eqs. (3) and (4), a_{rk} b_{rk}, and c_{rk} are elements of the generalized mass matrix $\boldsymbol{a}$, the generalized damping matrix $\boldsymbol{b}$ and the generalized stiffness matrix $\boldsymbol{c}$ of the structure; A_{rk} and B_{rk} are the elements of the generalized hydrodynamic inertia matrix $\boldsymbol{A}$ and the generalized hydrodynamic damping matrix $\boldsymbol{B}$, respectively; C_{rk} and ΔC_{rk} are the elements of the generalized restoring matrix $\boldsymbol{C}$ and $\boldsymbol{\Delta C}$ respectively; Cm_{rk} is the elements of the generalized restoring matrix of the mooring system; p_k is the component of the principal coordinate vector $\boldsymbol{p}$; $E_r^{(1)}$ and $Z_r^{(2)}$ are components of the generalized first-order and second-order hydrodynamic forces respectively; $Z_r^{(0)}$, Q_r and J_{r0} are the components of the generalized steady-state forces; $\tilde{A}_{rk}$, $\tilde{B}_{rk}$, $\tilde{C}_{rk}$ and $\tilde{C}'_{rk}$ are the time domain hydrodynamic coefficients; K_{rk} is the retardation function. The expressions for the coefficients and functions can be found in Wu et al. (1997).

Based on the theory of Wu et al. (1997), a second-order nonlinear hydroelastic analysis method and associated numerical results of a moored floating body are presented by Chen (2001) and Chen et al. (2002a,b, 2003d,e). The predicted principal coordinates of the second-order sum and difference frequency components of a moored rectangular box-like beam platform indicate that resonance may occur in waves of every direction. The second-order forces have a great effect on the responses of the floating structure.

6. Nonlinear structural characteristics

The importance of hydroelasticity of large floating ocean structures (VLFS) has come into focus in recent years. A pontoon type VLFS is often simplified as a thin plate (Ohkusu and Namba, 1996, 1998; Ertekin and Kim, 1999). Published results (Ohkusu and Namba, 1996, 1998; Ertekin and Kim, 1999) showed that the maximum vertical displacements of a VLFS can be larger than 1 m. These deflections are of the same order of magnitude as the plate thickness and if the incident waves come from different directions, the wavelengths are so small that the membrane forces in the plate should be considered, Chen et al. (2003b).

A hydroelastic analysis considering nonlinear characteristics of the structure is introduced by Chen (2003) and Chen, et al. (2003a,c). The hydroelastic equations for a floating plate with large deflections is

$$(\boldsymbol{a} + \boldsymbol{A})\ddot{p}(t) + (\boldsymbol{c} + \boldsymbol{C})\boldsymbol{p}(t) = \boldsymbol{E}(t) + \boldsymbol{f}(t), \tag{5}$$

where $\boldsymbol{f}(t)$ is the generalized nonlinear force vector induced by the nonlinear characteristics of the large deflections of the plate. A numerical procedure is developed based on the von Karman plate theory. The nonlinear hydroelastic behavior of a model of a VLFS in multidirectional waves is predicted. The results show that when account is made for the membrane effect in short-crested sea in the calculation of the vertical displacements and bending moments, the membrane forces can increase the longitudinal stresses by 30% and should therefore be considered in a design procedure.

Nonlinear hydroelastic analysis theories considering both the nonlinear characteristics of the fluid and the characteristics of the structure are established by Chen (2003) in the frequency and time domain. A solution procedure is introduced, but no numerical results are presented.

7. Example of application: hydroelasticity of very large floating structures

The types of VLFS discussed are usually pontoon type and semi-submersible type. From a dynamic point of view, the VLFS is different from conventional floating structures. The stiffness is relatively small and its behavior on the water surface is similar to that of an elastic thin plate. As the incident wavelength is relatively very short, it is often difficult to maintain a good accuracy of the numerical simulation of motions.

Hydroelasticity is important for VLFS and therefore the application of hydroelasticity theories in the analysis of VLFS are reviewed in details in this section. A few of the papers are the same as in the preceding sections but now the focus is on the application.

Experimental studies in this area are very scarce and there are only a few papers, e.g. Yago (1995), Yago and Endo (1996a, b), Yamashita et al. (1997), Ohta et al. (1998), Wang (2001) and Chen et al. (2003).

The double composite singularity distribution method was proposed by Wu et al. (1991a) for the hydroelastic analysis of a structure with both port-starboard and fore-aft symmetries, and it was employed to check the conceptual design of a kind of very large floating airport of a length form 500 m (five modules) to 1600 m (16 modules) or larger (Wang et al., 1991b; Du and Ertekin, 1991; Ertekin et al., 1993; Riggs and Ertekin, 1993; Wang, 2001).

Wang et al. (1991b) presented an improved hydroelasticity theory for predicting the hydroelastic behavior of VLFS in ocean waves. In this theory, a new strip method is developed for evaluating the hydrodynamic interaction between the main immersed structural members by a decomposition concept of cross-section in-plane distortion, while a conventional finite element method is applied to dynamic analysis of the three-dimensional dry structure.

Wu et al. (1995) applied an eigenfunction expansion matching method to two-dimensional hydrodynamic analyses of VLFS, and Nagata et al. (1997a, b) and Ohmatsu (1997) expanded this method to three-dimensional analyses.

Often, the mode expansion method is applied to analyze the responses of a VLFS, e.g. Tsubogo (1998), Seto and Ochi (1998), Kashiwagi (1998b), Maeda et al. (1996, 1997), Nagata et al. (1997a, b), Takaki and Gu (1996), Zhu et al. (1997), Kagemoto et al. (1996), Wang et al. (2001), Sun et al. (2002), Li et al. (2002) and Jin (2003).

There are different techniques for calculating the hydrodynamic forces for a given prescribed mode. Newman et al. (1996), Price et al. (1996), Ma and Hirayama (1997) presented a method based on the boundary element method (BEM). Maeda et al. (1995); Yago (1995); Takaki and Gu (1996) developed calculation techniques based on the pressure distribution method, which is essentially the same as the BEM except for an assumption of zero draught. In these calculation methods, the surface of a floating structure is divided into element panels. The unknown pressure on a panel is assumed to be constant in most papers, but this necessitates a large number of panels for high accuracy in the range of short waves. Yasuzawa et al. (1997), Hamamoto et al. (1997) used a linear element, and Hamamoto et al. (1998) adopted the eight-point quadratic element. However, the problem of large computation time for very short waves is not resolved. Newman et al. (1996) and Kashiwagi (1998b) developed an efficient means of calculation by introducing a B-spline accuracy with a relatively small number of unknowns.

Wang et al. (1997) introduced two techniques in the three-dimensional hydroelasticity theory to increase the computational efficiency for the determination of the dynamic response. One technique is related to the convergence of the Green function and its derivatives, through the introduction of a criterion used to truncate the influence of the Green function and its derivatives. The other involves the use of an iterative sparse solver for the linear system of equations. The basic idea behind the application of these two techniques is that a source makes a very small contribution to the potential at a point ‘far away' from the source point. By employing these two techniques in the hydroelastic analysis of a VLFS, the CPU time and required storage are considerably reduced.

Many modes must be taken into consideration in the mode expansion method, but some of them do not contribute to the solution. To avoid this, direct methods have been studied, solving the equations of elastic motion and pressure distribution simultaneously. Yago and Endo (1996b), Yasuzawa et al. (1997) and Hamamoto et al. (1997) developed a direct method in which the pressure distribution is calculated by means of the boundary element method and the elastic motion is solved by a finite element method. Kashiwagi (1998b,c) proposed another direct method using the B-spline function for representing both the pressure and the elastic deflections. Ohkusu and Namba (1998) showed a different approach to the direct technique. An elastic thin plate is assumed to be a part of the water surface but with different physical characteristics than those of the free surface of the water. Hermans (1998) proposed a unified integral equation for the deflection only, by eliminating the pressure using the elastic equation of motion. Kim and Ertekin (1998) developed a new direct method using the eigenfunction expansion matching method.

An eigenfunction expansion method based on a new orthogonal inner product is proposed by Sahoo et al. (2000) for the study of the hydroelastic response of mat-type VLFS in head seas. However, their main emphasis is on the effect of edge conditions and they assume that the plate is of a semi-infinite length. Sun et al. (2002) use the same eigenfunction expansion method for studying the hydroelastic response of an elastic plate of finite length in surface waves. It is found that the finite length effect is important.

Based on linear potential theory, Shin et al. (2000) studied the hydroelastic responses of the VLFS. A theoretical method is developed to analyze the hydroelastic responses using the pressure distribution method and the modal expansions of the structural motion. The singularities are distributed over the structure of a zero draught plate on the free surface and hydrodynamic pressures are evaluated. The integral equation is formulated by the Green function in case of finite water depth. The deflections of the structure are approximated by a modal expansion in terms of natural mode functions of free–free beams.

Bai et al. (2001) developed a numerical method for analysing the hydroelastic response of a floating runway located inside a harbour. Numerical implementation is made by use of the localized finite element method. The fluid domain is divided into domains. The solution in the outer domain is used to provide a numerical radiation condition for the inner domain.

Yan (2003) and Yan et al. (2003a) studied different deflection functions to analyze the hydroelastic response of VLFS. Yan et al. (2003b) combined the plate Green function and the fluid Green function in an analysis of the hydroelastic response of VLFS. The plate Green function is a new one proposed by the authors and it satisfies all boundary conditions for free–free rectangular plates on elastic foundations. The results are compared with experimental data. It is shown that the method proposed in this paper is efficient and accurate.

For the semi-submersible type of VLFS, knowledge of the hydrodynamic interaction between many columns is essential. The number of columns of VLFS may be more than one thousand, so that an efficient calculation method is required. Ma and Hirayama (1997) applied a boundary element method to this problem, but a large amount of computer time is required for an actual VLFS. Iijima et al. (1997) and Kashiwagi (1998a) proposed a practical method for obtaining the hydrodynamic interaction by means of hierarchical interaction theory for a large number of columns, which drastically shortens the computer time needed.

Wang et al. (1991a), Ertekin and Riggs et al. (1993) and Riggs and Ertekin (1991) described a simplified analysis procedure based on three-dimensional hydroelasticity, which can be used to determine the motions and internal forces of a multi-module VLFS. Each module is considered rigid, and hence all deformations occur in the module connectors. The maximum extreme connector forces for hinged modules are often a result of horizontal bending induced by oblique waves.

Ray theory has been applied by Hermans (2000). An exact integral differential equation for the deflection of a VLFS in deep water is derived. The equation was solved numerically by means of a boundary element method and a mode expansion. The formulation was used to derive the boundary condition for applying the ray method to short-wave diffraction (Hermans 2001, 2003). The influence of water depth on the hydroelastic response is studied by Andrianov and Hermans (2003). Recently, Takagi et al. (2003) used the ray theory to estimate the wave drift force and moment acting on a VLFS of arbitrary geometry.

Tsubogo (2001) presented an advanced boundary element method to analyze floating elastic plates subject to a train of plane waves. This method is based on Ertekin and Kim (1999), where a matching boundary integral equation method is applied using linear long-crested waves and a thin plate theory with the free edge conditions of the plate discretized by the finite difference method (FDM). In Tsubogo (2001), a Fourier series expansion is used instead of FDM.

Song et al. (2002a) found that the linear level I Green–Naghdi theory (Ertekin and Kim, 1999) gives nearly the same results as linear wave theory for finite water depth. Song et al. (2002) used the beam-on-elastic-foundation model to analyze the hydroelastic response of mat-like VLFS. Maeda et al. (2002), Ikoma et al. (2002) proposed an air supported type of VLFS and examined the hydroelastic behavior of the structures in not only head sea conditions but also oblique sea conditions.

Most studies on VLFS are restricted to linear problems in the frequency domain. However, Watanabe and Utsunomiya (1996), Kim and Webster (1996), Yeung and Kim (1998) and Endo (2000) calculated the time domain phenomenon when an aircraft lands and takes off from VLFS. Ohmatsu and Ohta (1998) presented a time domain superposition method for simulating the behavior of VLFS in irregular waves. Masuda et al. (1998) carried out numerical simulations concerning the elastic deformation and mooring force of a VLFS on Tsunami waves. Endo and Yoshida (1998) showed another time domain simulation method, based on Cummins' concept of impulse response functions.

Hydrodynamic problems concerned with VLFS can usually be treated as linear problems because the scale is very large compared with the amplitude of the incident waves. A local problem such as impact load around the end should, however, be treated as a nonlinear problem. The slamming phenomenon around the end of VLFS was studied experimentally and analytically by Yoshimoto et al. (1996). Faltinsen (1996) estimated local stress due to bottom slamming on a VLFS and compared these estimates with experimental results.

Maeda et al. (1997) and Ikoma et al. (1998) calculated the second-order wave loads acting on VLFS. They used a thin plate hydrodynamic theory, and the VLFS was simplified to a floating flexible plate.

VLFS are of an extremely large size of several kilometres in length. Thus, the water depth at one end of the platform may be different from that at the other end. Sun et al. (2003a) investigated the impact of the variable depth on the hydroelastic responses of a VLFS. For simplicity, an ascending plane slope is taken to simulate the varying bottom although the method is capable of treating a bottom of arbitrary variation. A thin plate theory is used to model the mat-like VLFS. The FDM is used to solve the boundary value problem. The results for the zero inclination slopes are compared with experimental data and an analytical method for validation of the present numerical method. The effects of the inclination of the slope on reflection and transmission coefficients and plate deflections are investigated thoroughly. Furthermore, they analyzed the hydroelastic response of VLFS over variable bottom in waves (Sun et al., 2003b).

8. Comments and conclusions

An overview of hydroelasticity of marine structures is given. Several of the theories (e.g. two-dimensional linear theory and three-dimensional linear theory in the frequency domain) are very mature, but others, such as three-dimensional nonlinear theory and the hydroelasticity considering nonlinear structural behavior are still being developed.

Frequency domain methods are discussed and used in many of the theories dealing with linear and nonlinear responses. Time domain methods are only suitable for fully nonlinear problems. Development of effective nonlinear hydroelastic theories in the time domain should be the main target in near future.

References

Aksu, S., 1993. Steady state and transient responses of flexible ship structures traveling in irregular seaway, PhD Thesis, University of Southampton.

Aksu, S., Bishop, R.E.D., Price, W.G., Temarel, P., 1991a. On the behavior of a product carrier in ballast traveling in a seaway. Transactions of the Royal Institution of Naval Architects 133, 45–59.

Aksu, S., Price, W.G., Temarel, P., 1991b. A comparison of two-dimensional and three-dimensional hydroelasticity theories including the effect of slamming. Proceedings of the Institute of Mechanical Engineering Part C-Journal of Mechanical Engineering Science 205 (1), 3–15.

Andrianov, A.J., Hermans, A.J., 2003. The influence of water depth on the hydroelastic response of a very large floating platform. Marine Structures 16 (5), 355–371.

Bai, K.J., Yoo, B.S., Kim, J.W., 2001. A localized finite-element analysis of a floating runway in a harbor. Marine Structures 14 (1–2), 89–102.

Belik, O., Bishop, R.E.D., Price, W.D., 1980. On the slamming response of ships to regular head waves. Transactions of the Royal Institution of Naval Architects 122, 325–337.

Bereznitski, A., 2001. Slamming: the role of hydroelasticity. International Shipbuilding Progress 48 (454), 333–351.

Betts, C.V., Bishop, R.E.D., Price, W.G., 1977. The symmetric generalised fluid forces applied to a ship in a seaway. Transactions of the Royal Institution of Naval Architects 199, 265–278.

Bishop, R.E.D., Price, W.G., 1977. The generalised antisymmetric fluid forces applied to a ship in a seaway. International Shipbuilding Progress 24, 3–14.

Bishop, R.E.D., Price, W.G., 1979. Hydroelasticity of Ships. Cambridge University Press, London, UK.

Bishop, R.E.D., Price, W.G., Tam, P.K.Y., 1978. On the dynamics of slamming. Transactions of the Royal Institution of Naval Architects 120, 259–280.

Bishop, R.E.D., Price, W.G., Temarel, P., 1980. Antisymmetric vibration of ship hulls. Transactions of the Royal Institution of Naval Architects 122, 197–208.

Bishop, R.E.D., Price, W.G., Wu, Y., 1986. A general linear hydroelasticity theory of floating structures moving in a seaway. Philosophical Transactions of Royal Society, London, A316.

Bishop, R.E.D., Price, W.G., Temarel, P., 1991. A theory on the loss of the MV Derbyshire. Transactions of the Royal Institution of Naval Architects 133, 389–453.

Che, X.L., Riggs, H.R., Ertekin, R.C., Wu, Y.S., Wang, M.L., 1992. Two-Dimensional Analysis of Prying Response of Twin-Hull Floating Structures Proceedings of 2nd International Offshore and Polar Engineering Conference -ISOPE 1992.

Che, X.L., Riggs, H.R., Ertekin, R.C., 1994. Composite 2D/3D hydroelastic-analysis method for floating structures. Journal of Engineering Mechanics 120 (7), 1499–1518.

Chen, X.J., 2001. Second Order Hydroelasticity Analyses for Marine Structures PhD Thesis, China Ship Scientific Research Center, Wuxi, China, (in Chinese).

Chen, X.J., 2003. Nonlinear Hydroelastic Analysis of Very Large Floating Structures, Report of Shanghai Jiao Tong University, Shanghai, China, (in Chinese).

Chen, X.J., Wu, Y.S., Cui, W.C., Shen, Q., 2002a. Second order nonlinear hydroelastic analyses of floating bodies—theory. Journal of Ship Mechanics 6 (4), 33–44.

Chen, X.J., Wu, Y.S., Cui, W.C., Sun, L.Z., 2002b. Second order nonlinear hydroelastic analyses of floating bodies—frequency characteristics of the principal coordinates of a moored floating body. Journal of Ship Mechanics 6 (5), 44–57 (in Chinese).

Chen, G.J., Yang, J.M., Zhang, C.Y., 2003. Hydroelastic model test of very large floating structures. The Ocean Engineering 21 (3), 1–5 (In Chinese).

Chen, X.J., Cui, W.C., Jensen, J.J., Tang, X.F., 2003a. Second order nonlinear hydroelastic analyses of floating bodies—the primary considering of nonlinear structure. Journal of Ship Mechanics 7 (5), 81–90 (in Chinese).

Chen, X.J., Cui, W.C., Song, H., Tang, X.F., 2003b. Numerical solution of the membrane forces for a free-free floating plate with large deflection. China Ocean Engineering 17 (2), 163–176.

Chen, X.J., Jensen, J.J., Cui, W.C., Fu, S.X., 2003c. Hydroelasticity of a floating plate in multidirectional waves. Ocean Engineering 30 (15), 1997–2017.

Chen, X.J., Wu, Y.S., Cui, W.C., Tang, X.F., 2003d. Nonlinear hydroelastic analysis of a moored floating body. Ocean Engineering 30 (8), 965–1003.

Chen, X.J., Wu, Y.S., Cui, W.C., Chen, Y.H., 2003e. Second order nonlinear hydroelastic analyses of floating bodies—the effect of the second-order forces to the time responses of the vibration. Journal of Ship Mechanics 7 (2), 11–23 (in Chinese).

Cho, I.H., Kim, M.H., 1998. Interactions of a horizontal flexible membrane with oblique incident waves. Journal of Fluid Mechanics 367, 139–161.

Cho, I.H., Kim, M.H., 2000. Interactions of horizontal porous flexible membrane with waves. Journal of Waterway, Port, Coastal and Ocean Engineering 126 (5), 245–253.

Clarke, J.D., 1986. Wave loading in warships. In: Smith, C.S., Clarke, J.D. (Eds.), Advances in Marine Structures. Elsevier Applied Science Publishers, pp. 1–25.

Conceicao, C.A.L., Price, W.G., Temarel, P., 1984. The influence of heel on the hydrodynamic coefficients of ship-like sections and a trawler form. International Ship Building Progress 31, 56–66.

Dong, Y.Q., Lin, W.X., 1992. Hydroelasticity and wave loads for full form ship with shallow draft. Journal of Ship Research.

Dong, Y.Q., Lin, W.X., Zhu, J.G., 1989. A study on wave-excited vibration of shallow draft full form ship. Shipbuilding of China1, 76–83.

Du, S.X., 1996. A complete frequency domain analysis method of linear three-dimensional hydroelastic responses of floating structure travelling in waves, PhD. Thesis, China Ship Scientific Research Center, Wuxi, China.

Du, S.X., Ertekin, R.C., 1991. Dynamic Response Analysis of a Flexibly Joined Multi-Module Very Large Floating Structure Proceedings of Conference of Institute of Electrical and Electronics Engineers (IEEE) Ocean (OCEANS'91), Honolulu, Hawaii, USA, 91 1991.

Endo, H., 2000. Behavior of a VLFS and an airplane during takeoff/landing run in wave condition. Marine Structures 13 (4–5), 477–491.

Endo, H., Yoshida, K., 1998. Timoshenko Equation of Vibration for Plate-Like Floating Structures Proceedings of 2nd International Conference on Hydroelasticity in Marine Technology 1998 pp. 255–264.

Ergin, A., Price, W.G., Randall, R., Temeral, P., 1992. Dynamic characteristics of a submerged, flexible cylinder vibrating in infinite water depths. Journal of Ship Research 36, 154–167.

Ertekin, R.C., Kim, J.W., 1999. Hydroelastic response of floating mat-type structure in oblique, shallow-water waves. Journal of Ship Research 43 (4), 241–254.

Ertekin, R.C., Riggs, H.R., Che, X.L., Du, S.X., 1993. Efficient methods for hydroelastic analysis of very large floating structures. Journal of Ship Research 37 (1), 58–76.

Faltinsen, O.M., 1996. Bottom Slamming on a Floating Airport Proceedings of Second International Workshop on Very Large Floating Structures 1996 pp. 97–106.

Faltinsen, O.M., 2000. Hydroelastic slamming. Journal of Marine Science and Technology 5 (2), 49–65.

Faltinsen, O.M., Zhao, R., 1991. Numerical predictions of ship motions at high forward speed. Philosophical transactions of the Royal Society of London, Series A 334, 241–252.

Fu, Y.N., Price, W.G., Temarel, P., 1987. The 'dry and wet' towage of a jack-up in regular and irregular waves. Transactions of the Royal Institution of Naval Architects 129, 149–159.

Fu, S.X., Fan, J., Chen, X.J., Cui, W.C., 2003. Analysis Method for the Mooring System for a Flexible Floating Body, Proc. of Deep Water Mooring System-Concepts, Design, Analysis, and Materials Proceedings of Deep Water Mooring System-Concepts, Design, Analysis, and Materials, Offshore Technology Research Center(OTRC) and Coasts,Oceans,Ports and Rivers Institute (COPRI) of ASCE, October 2–3, 2003, Houston, Texas, USA, 2003 2003 pp.142–151.

Gu, M.X., Wu, Y.S., Xia, J.Z., 1988. Time domain analysis of non-linear hydroelastic response of ships. Selected Papers of the Chinese Society of Naval Architecture and Marine Engineering3, 125–134.

Gu, M.X., Wu, Y.S., Xia, J.Z., 1989. Time Domain Analysis of Non-Linear Hydroelastic Response of Ships Proceedings of 4th International Symposium on Practical Design of Ships and Other Floating Structures (PRADS), Varna, Bulgaria 1989.

Hamamoto, T., Suzuki, A., Fujita, K., 1997. Hybrid dynamic analysis of large tension leg floating structures using plate elements. Proceedings of 7th International Offshore and Polar Engineering Conference ISOPE 1, 285–292.

Hamamoto, T., Suzuki, A., Tsujioka, N., Fujita, K., 1998. 3D BEM–FEM hybrid hydroelastic analysis of module linked large floating structures subjected to regular waves. Proceedings of 8th International Offshore and Polar Engineering Conference ISOPE 44 (450), 321–339.

Heller, S.R., Abramson, H.N., Hydroelasticity:, A., 1959. Hydroelasticity: a new naval science. Journal of America Society of Naval Engineers 71 (2), 205–209.

Hermans, A.J., 1998. A boundary element method to describe the excitation of waves in a very large floating flexible platform. Proceedings of 2nd ICHMT, 69–76.

Hermans, A.J., 2000. A boundary element method for the interaction of free-surface waves with a very large floating flexible platform. Journal of Fluids and Structures 14, 943–956.

Hermans, A.J., 2001. A geometrical-optics approach for the deflection of a floating flexible platform. Applied Ocean Research 23 (5), 269–276.

Hermans, A.J., 2003. The ray method for the deflection of a floating flexible platform in short waves. Journal of Fluids and Structures 17, 593–602.

Hermundstad, O.A., Aarsns, J.V., Moan, T., 1999. Linear hydroelastic analysis of high-speed catamarans and monohulls. Journal of Ship Research 43 (1), 48–63.

Iijima, K., Yoshida, K., Suzuki, H., 1997. Hydrodynamic and hydroelastic analyses of very large floating structures in waves. Proceedings of 4th OMAE 6, 139–145.

Ikoma, T., Maeda, H., Masuda, K., Rheem, C.K., 1998. Hydroelastic response of pontoon type very large floating offshore structures (The 4th report, Estimation method of slowly varying wave drift force and fender reaction force). Journal of the Society of Naval Architects of Japan 184, 291–296.

Ikoma, T., Masuda, K., Maeda, H., Rheem, C.K., 2002. Hydroelastic behavior of air-supported flexible floating structures. Proc. of the International Conference on Offshore Mechanics and Arctic Engineering—OMAE 2, 745–752.

Jensen, J.J., Dogliani, M., 1996. Wave-induced ship hull vibrations in stochastic seaways. Marine Structures 9 (3), 353–387.

Jensen, J.J., Mansour, A.E., 2002. Estimation of the long-term wave-induced bending moment in ships using closed-form expressions. Transactions of the Royal Institution of Naval Architects 144, 41–45.

Jensen, J.J., Mansour, A.E., 2003. Estimation of the effect of green water and bow flare slamming on the wave-induced vertical bending moment using closed-form expressions. In: Eatock, T. (Ed.), Proceedings of 3rd International Conference on Hydroelasticity in Marine Technology. The Oxford University, Oxford, pp. 155–161.

Jensen, J.J., Pedersen, P.T., 1979. Wave-induced bending moments in ships—a quadratic theory. Transactions of the Royal Institution of Naval Architects 121, 151–165.

Jensen, J.J., Pedersen, P.T., 1981. Bending moments and shear forces in ships sailing in irregular waves. Journal of Ship Research 24 (4), 243–251.

Jensen, J.J., Madsen, N.F., 1977. A review of ship hull vibration. Shock and Vibration Digest 9 (4), 13–22 (See also No. 5, pp. 25–38, No. 6, pp. 19–27, No. 7, pp. 13–28).

Jin, J.Z., 2003. On frequency domain approaches to the hydroelastic responses of mat-type VLFS in waves, MSc. thesis, Shanghai Jiao Tong University, Shanghai, China, (in Chinese).

Kagemoto, H., Fujino, M., Zhu, T., 1996. On the estimation method of hydrodynamic forces acting on a huge floating. Journal of the Society of Naval Architects of Japan 179, 173–182.

Kashiwagi, M., 1998. A hierarchical interaction theory for wave forces on a large number of elementary bodies of a semi-sub type VLFS. Proceedings of 14th Ocean Engineering Symposium, 425–431.

Kashiwagi, M., 1998. A B-spline Galerkin scheme for calculating hydroelastic response of a very large floating structure in waves. Journal of the Society of Naval Architects of Japan 184, 373–381.

Kashiwagi, M., 1998. A B-spline Galerkin scheme for calculating the hydroelastic response of a very large floating structure in waves. Journal of Marine Science and Technology 2 (1), 37–49.

Kashiwagi, M., 2000. Research on hydroelastic responses of VLFS: recent progress and future work. International Journal of Offshore and Polar Engineering 10 (2), 81–90.

Kean, A.J., Temarel, P., Wu, X.J., Wu, Y.S., 1991. Hydroelasticity of non-beamlike ships in waves The Dynamics of Ships. The Royal Soc., London p. 153.

Kim, J.W., Ertekin, R.C., 1998. An eigenfunction-expansion method for predicting hydroelastic behavior of a shallow-draft VLFS. Proceeding of 2nd ICHMT, 47–60.

Kim, J.W., Webster, W.C., 1996. The Drag of An Airplane Taking Off from a Floating Runway Proceedings of 2nd International Workship on VLFS (VLFS'96), Hayama, Japan 1996 pp. 235–241.

Korvin-Kroukovsky, V.B., Jacobs, W.R., 1957. Pitching and heaving motions of a ship in regular waves. Transactions of The Society of Naval Architects and Marine Engineers (SNAME) 65, 590–632.

Lin, J.R., 1995. Wave excited vibration of large ships. Ship Engineering2, 4–9 (in Chinese).

Liu, X.D., Sakai, S., 2000. Nonlinear analysis on the interaction of waves and flexible floating structure. Proceedings of 10th International Offshore and Polar Engineering Conference—ISOPE, 101–108.

Liu, X.D., Sakai, S., 2002. Time domain analysis on the dynamic response of a flexible floating structure to waves. Journal of Engineering Mechanics 128 (1), 48–56.

Liu, X.D., Sakai, S., Makino, S., Hanai, K., Sasamoto, M., 2001. Tsunami-induced mooring force on a flexible floating structure. Proceedings of 11th ISOPE 1, 241–247 (Jun 17–22).

Li, R.P., Shu, Z., Wang, Z.J., 2002. A Study on the Hydroelastic Behavior of Box-Typed Very Large Floating Structure in Waves Proceedings of the Third Conference for New Ship and Marine Technology, May 21–23, 2002, Kobe,Japan 2002 pp. 41–48.

Louarn, F., Price, W.G., Temarel, P., 1997. Dynamic behavior of a fast sailing monohull in waves. Proceedings of 7th International Offshore and Polar Engineering Conference—ISOPE, 712–720.

Lundgren, J., Price, W.G., Wu, Y.S., 1988. A Hydroelastic Investigation into the Behavior of a Floating 'dry' Dock in Waves Spring Meeting of Royal Institution of Naval Architects, London 1988.

Ma, N., Hirayama, T., 1997. Hydroelastic responses of two types of very large floating structure. Proceedings of 16th of the International Conference on Offshore Mechanics and Arctic Engineering—OMAE 6, 211–218.

Maeda, H., Masuda, K., Miyajima, D., Ikoma, T., 1995. Hydroelastic responses of pontoon type very large floating offshore structure. Journal of the Society of Naval Architects of Japan 178, 203–212.

Maeda, H., Masuda, K., Ikoma, T., 1996. Hydroelastic responses of pontoon type very large floating offshore structure. Proceedings of 15th of the International Conference on Offshore Mechanics and Arctic Engineering—OMAE (18–20 June, Florence, Italy).

Maeda, H., Masuda, K., Ikoma, T., 1997. Hydroelastic response of pontoon type very large floating offshore structures (The 3rd report), The effects of 2nd-order wave loads. Journal of the Society of Naval Architects of Japan 182, 319–328.

Maeda, H., Ikoma, T., Masuda, K., Rheem, C.K., 2002. Hydroelastic behaviors of large aircushion supported elastic floating structures in regular waves. Oceans Conference Record (IEEE), Ocean's 2002 Conference and Exhibition 3, 1792–1799.

Masuda, K., Miyazaki, T., Takamura, H., 1998. Study on estimation method for motions and mooring tensions of moored floating structure in offshore area under tsunami. Proceedings of 14th Ocean Engineering Symposium, 161–166.

Nagata, S., Yoshida, H., Fujita, T., Isshiki, H., 1997. The analysis of the wave-induced responses of an elastic floating plate. Proceedings of 16th of the International Conference on Offshore Mechanics and Arctic Engineering—OMAE 6, 163–169.

Nagata, S., Yoshida, H., Isshiki, H., Ohkawa, Y., 1997. Motions of a very large elastic plate in waves. Journal of the Society of Naval Architects of Japan 182, 285–294.

Newman, J.N., 1978. The theory of ship motions. Advances in Applied Mechanics 18, 221–285.

Newman, J.N., 1986. Marine Hydrodynamics. The Massachusetts Institute of Technology (MIT) Press, Cambridge, MA.

Newman, J.N., Maniar, H.D., Lee, C.H., 1996. Analysis of Wave Effects for Very Large Floating Structures VLFS'96 1996 pp. 135–142 (Hayama, Japan).

Ohkusu, M., Namba, Y., 1996. Analysis of hydroelastic behaviour of a large floating platform of thin plate configuration in waves VLFS'96 1996 pp. 143–148 (Hayama, Japan).

Ohkusu, M., Namba, Y., 1998. Hydroelastic behavior of floating artificial islands. Journal of the Society of Naval Architects of Japan 183.

Ohmatsu, S., 1997. Numerical calculation of hydroelastic responses of pontoon type VLFS. Journal of the Society of Naval Architects of Japan 182, 329–340.

Ohmatsu, S., Ohta, M., 1998. Time Domain Analysis of Hydroelastic Behavior of VLFS in Waves Proceedings of 14th Ocean Engineering Symposium 1998 pp. 483–486.

Ohta, M., Ikegami, K., Yamaguchi, Y., 1998. Experimental study on elastic behavior of a huge floating structure in waves. Transactions of The West-Japan Society of Naval Architects95, 99–108.

Pedersen, P.T., 1983. A beam model of torsional-bending response of ship hulls. Transactions of the Royal Institution of Naval Architects 125, 171–182.

Phan, T.S., Temarel, P., 2002. Hydroelastic responses of pontoon and semi-submersible types of very large floating structure in regular head waves. Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering—OMAE 2, 753–763.

Price, W.G., Temarel, P., 1982. The influence of hull flexibility in the anti-symmetric dynamic behaviour of ships in waves. International Shipbuilding Progress 29.

Price, W.G., Wu, Y.S., 1985. Structural Responses of a SWATH of Multi-Hulled Vessel Traveling in Waves International Conference on SWATH Ships and Advanced Multi-hulled Vessels. Royal Institution of Naval Architects, London.

Price, W.G., Wu, Y.S., 1989. The influence of non-linear fluid forces in the time domain responses of flexible SWATH ships excited by a seaway. Proceedings of 8th of the International Conference on Offshore Mechanics and Arctic Engineering—OMAE 2, 125–135.

Price, W.G., Temarel, P., Wu, Y.S., 1985. Structural Responses of a SWATH or Multi-Hull Vessel Traveling in Waves International Conference on SWATH Ships and Advanced Multi-hulled Vessels. Royal Institution of Naval Architects, London.

Price, W.G., Salas-Inzunza, M., Temarel, P., 1996. Behavior of Large Type Structures in Waves VLFS'96 1996 pp. 173–182.

Riggs, H.R., Ertekin, R.C., 1991. Approximate methods for dynamic response of multi-module floating structures VLFS'91, Honolulu, Hawaii, USA 1991.

Riggs, H.R., Ertekin, R.C., 1993. Approximate methods for dynamic response of multi-module floating structures. Marine Structures 6 (2 and 3), 117–141.

Sahoo, T., Yip, T.L., Chwang, A.T., 2000. On the interaction of surface wave with a semi-infinite elastic plate. Proceedings of 10th International Offshore and Polar Engineering Conference—ISOPE, Seattle, USA 3, 584–589 (May 28–June 2).

Salvesen, N., Tuck, E.O., Faltinsen, O., 1970. Ship motions and sea loads. Transactions of SNAME 78, 250–287.

Seto, H., Ochi, M., 1998. A Hybrid Element Approach to Hydroelastic Behavior of a Very Large Floating Structure in Regular Waves Proceedings of 2nd ICHMT 1998 pp. 185–193 (Fukuoka, Japan).

Shin, H., Lee, H.Y., Yang, Y.S., Shin, H.S., Park, I.K., 2000. Proceedings of 10th International Offshore and Polar Engineering Conference—ISOPE, Seattle, USA, 78–85 (May 28–June 2,).

Söding, H., 1982. Leckstabilität in Seagang, Report 429 of the Institut für Schiffbau, Hamburg.

Song, J.Z., Ren, H.L., Dai, Y.S., 1994. Hydroelastic Analysis of Non-linear Wave-Induced Loads of Ship Hull, Shipbuilding of China.

Song, H., Cui, W.C., Liu, Y.Z., 2002. Comparison of linear level I Green-Naghdi theory with linear wave theory for prediction of hydroelastic responses of VLFS. China Ocean Engineering 16 (3), 283–300.

Song, H., Peng, X.N., Sun, H., Cui, W.C., Liu, Y.Z., 2002. On beam-on-elastic-foundation model for the hydroelastic response analysis of mat-like VLFS. Journal of Ship Mechanics 6 (6).

Sun, H., Song, H., Cui, W.C., Liu, Y.Z., 2002. On the interaction of surface waves with an elastic plate of finite length in head seas. China Ocean Engineering 16 (1), 21–32.

Sun, H., Cui, W.C., Liu, Y.Z., Liao, S.J., 2003. Hydroelastic response analysis of mat-like VLFS over a plane slope in head seas. China Ocean Engineering 17 (3), 315–326.

Sun, H., Cui, W.C., Wu, Y.S., 2003. Hydroelastic Response Analysis of VLFS Over Variable Bottom in Waves Proceedings of the 3rd International Conference on Hydroelasticity in Marine Technology, Oxford, United Kingdom, 15–17 September 2003 2003 pp. 281–288.

Suo, Z.Q., Guo, R.X., 1996. Hydroelasticity of rotating bodies—theory and application. Marine Structures 9 (6), 631–646.

Takagi, K., Yano, W., Nagayasu, M., 2003. Wave drift force and moment acting on a very large floating structure of arbitrary geometry. International Journal of Offshore and Polar Engineering 13 (3), 198–204.

Takaki, M., Gu, X., 1996. Motions of a floating elastic plate in waves. Journal of the Society of Naval Architects of Japan 180, 331–339.

Tsubogo, T., 1998. A basic investigation on deflection wave propagation and strength of very large floating structures (3rd report). Journal of the Society of Naval Architects of Japan 182, 381–390 (in Japanese).

Tsubogo, T., 2001. The motion of an elastic disk floating on shallow water in waves. Proceedings of 11th International Offshore and Polar Engineering Conference—ISOPE 1, 229–233. Jun 17–22.

Wang, Z.H., 1992, Non-Linear Two-Dimensional Hydroelastic Analysis of Ships, MSc. Thesis, China Ship Scientific Research Center, (in Chinese).

Wang, D.Y., 1996. Three Dimensions Hydroelastic Analysis of Ships in Time Domain, PhD. Thesis, China Ship Scientific Research Center, Wuxi, China, (in Chinese).

Wang, Z.J., 2001. Study on Hydroelastic Response of Box-Type Very Large Floating Structures, PhD. Thesis, Shanghai Jiao Tong University, Shanghai, China, (in Chinese).

Wang, D.Y., Wu, Y.S., 1998. Three dimensional hydroelastic analysis in time domain with application to an elastic ship model. Journal of Hydrodynamics 10 (4), 54–61.

Wang, D.Y., Riggs, H.R., Ertekin, R.C., 1991a. Three-dimensional hydroelastic response of a very large floating structure. International Journal of Offshore and Polar Engineering 1 (4), 307–316.

Wang, M.L., Du, S.X., Ertekin, R.C., 1991b. Hydroelastic Response and Fatigue Analysis of a Multi-Module Very Large Floating Structure International Symposium on Fatigue and Fracture in Steel and Concrete Structures, Madras, India 1991 pp. 1277–1291.

Wang, S.Q., Ertekin, R.C., Riggs, H.R., 1997. Computationally efficient techniques in the hydroelasticity analysis of very large floating structures. Computers and Structures 62 (4), 603–610.

Wang, Z.H., Wu, W.W., Xu, M., Xi, Y.N., 1999. Hydroelasticity analysis of horizontal bend-torsion coupled responses of ships in waves. Shipbuilding of China 40 (2), 42–47 (in Chinese).

Wang, Z.J., Li, R.P., Shu, Z., 2001. A study on hydroelastic response of box-type very large floating structures. China Ocean Engineering 15 (3), 345–354.

Watanabe, E., Utsunomiya, T., 1996. Transient Response Analysis of a VLFS at Airplane Landing VLFS'96 1996 pp. 243–247 (Hayama, Japan).

Wu, Y.S., 1984. Hydroelasticity of Floating Bodies, PhD. Thesis, Brunel University, UK.

Wu, Y.S., 1994. Numerical and Experimental Hydroelasticity of Marine Structures—a Review International Conference on Hydrodynamics, 30th October-3rd November 1994, Wuxi China 1994 pp. 30–41.

Wu, Y.S., Du, S.X., 1990. Directly analysis method of marine structures—Random analysis theory and its application of three-dimensional hydroelasticity. Ship Behavior Research4 (in Chinese).

Wu, Y.S., 1987. Review of Hydroelasticiy Festschrift of Mr. Xin Yixin Died for 30 Years. China Ship Building Academy, China pp. 24–47 (in Chinese).

Wu, Y.S., Wang, D.Y., Riggs, H.R., Ertekin, R.C., 1991a. Composite singularity distribution method with application to hydroelasticity, VLFS'91, Honolulu, Hawaii, USA. Marine Structures 6 (2–3), 143–163.

Wu, Y.S., Xia, J.Z., Du, S.X., 1991b. Two Engineering Approaches to Hydroelastic Analysis of Slender Ships Dynamics of Marine Vehicles and Structures in Waves. Elsevier Science Publishers, Amsterdam pp. 157–165.

Wu, Y.S., Xia, J.Z., Wang, Z.H., Liu, Y.Z., 1994. Journal of Hydrodynamics, Series A (in Chinese).

Wu, C., Watanabe, E., Utsunomiya, T., 1995. An eigenfunction expansion matching method for analyzing the wave-induced responses of an elastic floating plate. Applied Ocean Research 17, 301–310.

Wu, Y.S., Maeda, H., Kinoshita, T., 1997. The second order hydrodynamic actions on a flexible body. Journal of Institute of Industrial Science, University of Tokyo 49 (4), 8–19.

Xia, J.Z., Wang, Z.H., 1997. Time domain hydroelasticity theory of ships responding to waves. Journal of Ship Research 41 (4), 286–300.

Xia, J.Z., Wu, Y.S., 1993. A general form of the interface boundary condition of the fluid-structure interactions. Ship Behavior Research4 (in Chinese).

Xia, J.Z., Wang, Z.H., Jensen, J.J., 1998. Non-linear wave loads and ship responses by a time-domain strip theory. Marine Structures 11 (3), 101–123.

Xu, X.D., Zhang, X.C., Wu, Y.S., 1997. Dynamic buckling induced by ship slamming. Journal of Ship Mechanics 1 (2), 39–42 (in Chinese).

Yago, K., 1995. Forced oscillation test of flexible floating structure and hydrodynamic pressure. Proceedings of 13th Ocean Engineering Symposium, 313–320.

Yago, K., Endo, H., 1996. On the hydroelastic response of box-shaped floating structure with shallow draft (Tank test with large scale mode). Journal of the Society of Naval Architects of Japan 180, 341–352 (in Japanese).

Yago, K., Endo, H., 1996. Model Experiment and Numerical Calculation of the Hydroelastic Behavior of Mat-Like VLFS VLFS'96 1996 pp. 209–214.

Yamashita, S., Itoh, A., Kabaya, T., 1997. An experimental investigation to wave loads on a mat-like floating structure in waves with short length. Proceedings of 16th of the International Conference on Offshore Mechanics and Arctic Engineering—OMAE 6, 241–248.

Yan, H.M., 2003. Hydroelastic Analysis of Very Large Floating Structures Using Plate Green Function Method, MSc. Thesis, Shanghai Jiao Tong University, Shanghai, China, (in Chinese).

Yan, H.M., Cui, W.C., Liu, Y.Z., 2003. A new deflection function for the problem of a rectangular plate on elastic foundation with four free edges. Journal of Ship Mechanics 7 (2), 61–70 (in Chinese).

Yan, H.M., Cui, W.C., Liu, Y.Z., 2003. Hydroelastic analysis of very large floating structures using plate Green functions. China Ocean Engineering 17 (2), 151–162.

Yasuzawa, Y., Kagawa, K., Kawano, D., Kitabayashi, K., 1997. Dynamic Response of a Large Flexible Floating Structure in Regular Waves Proceedings of 16th of the International Conference on Offshore Mechanics and Arctic Engineering—OMAE, Part IV 1997 pp. 187–194 (Yokoham, Japan).

Yeung, R.W., Kim, J.W., 1998. Structural drag and deformation of a moving load on a floating plate. Proceedings of 2nd ICHMT, 77–88 (Fukuoka, Japan).

Yoshimoto, H., Hoshino, K., Ohmatsu, S., Ikebuchi, T., 1996. Estimation of Slamming Load Acting on VLFS VLFS'96 1996 pp. 197–114.

Zhang, S.X., Yang, Y.Q., Wu, X.H., 1996. The theoretical analysis and experimental study on ship's hydroelasticity. Journal of Hydrodynamics 11 (1), 65–72 (in Chinese).

Zhong, T.Y., Zhao, D.Y., 1998. Study of calculation of natural frequency and response of shiphull vibration in waves. Journal of Dalian University of Technology 38 (4), 445–449 (in Chinese).

Zhong, T.Y., Lin, Z., Zhao, D.Y., 1995. Calculation method of resonant frequency on wave-induced shiphull vibration. Journal of Dalian University of Technology 35 (2), 212–215 (in Chinese).

Zhu, T., Kagemoto, H., Fujino, M., 1997. On the estimation method of hydrodynamic forces acting on a huge floating structure (2nd report). Journal of the Society of Naval Architects of Japan 182, 273–283 (in Japanese).