Applied Ocean Research 51 (2015) 1–13

Contents lists available at ScienceDirect

Applied Ocean Research

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

Time domain prediction of hydroelasticity of floating bodies

Fuat Kara

Cranfield University, MK43 0AL, UK

ARTICLE INFO

Article history:
Received 8 July 2014
Received in revised form 28 January 2015
Accepted 7 February 2015
Available online 9 March 2015

Keywords:
Hydroelasticity
Time domain
Transient free-surface wave Green function
Boundary integral equation method
Euler–Bernoulli beam
Neumman–Kelvin approximation

ABSTRACT

The numerical predictions of the hydroelasticity of floating bodies with and without forward speed are presented using a direct time domain approximation. Boundary-Integral Equation Method (BIEM) with three-dimensional transient free surface Green function and Neumman–Kelvin approximation is used for the solution of the hydrodynamic part and solved as impulsive velocity potential whilst Euler–Bernoulli beam approach is used for the structural analysis with analytically defined modeshapes. The hydrodynamic and structural parts are then fully coupled through modal analysis for the solution of the hydroelastic problem. A stiff structure is then studied assuming that contributions of rigid body modes are much bigger than elastic modes. A rectangular barge with zero speed and Wigley hull form with forward speed are used for the numerical analyses and the comparisons of the present Istanbul Technical University (ITU)-WAVE numerical results for response amplitude operator, bending moment, shear force, etc. show satisfactory agreement with existing experimental results.

1. Introduction

The motion due to the fluid-structure interaction of the floating bodies with or without forward speed on the sea can be categorized as rigid body and elastic (or flexural) motions. If the pressure field around floating body is affected significantly due to rigid body motions only, the hydrodynamics and structural analyses (which include the complete both diffraction and radiation fields due to rigid body motion only) are coupled weakly and performed separately. The weakly coupling of hydrodynamic and structural analyses implies that the floating bodies under consideration are stiff and the frequencies due to first order wave loads are much smaller than the eigenfrequencies of elastic deflections. Furthermore, the structural stiffness is much higher than the hydrodynamic restoring which means that elastic motion is considered to be an insignificant contribution to the hydrodynamic loading. The weakly coupling also means that the decoupled hydrodynamic analysis can be performed in either frequency or time domain where the effect of free surface included [3,4,12,17].

If the structural deformation affects the radiation field significantly, the structure and hydrodynamic analyses are fully coupled and includes hydroelasticity. Hydroelastic analysis implies that the frequencies due to the first order wave loads fall into eigenfrequencies of the elastic deflections which results in steady state global elastic vibration known as springing and decrease the fatigue life of the floating bodies [12,17,33]. Hydroelastic analysis is substantially important for larger and high-speed floating bodies. The natural frequency of the larger structures falls into frequency range of the incident wave frequency whilst in the case of high-speed structures the increased encounter frequency in which floating body response to waves approaches the frequency range of the hull-girder vibrations. In this case, the elastic inertia, stiffness, and damping coefficients are predicted from a structural analysis and added to the mass, stiffness, and damping matrices in the equation of motion. This implies that the frequency or time domain analysis includes the radiation effects due to structural modes in the case of hydroelastic analysis.

A set of modeshapes can be used to define the elastic deflections of the structures accurately for the structural analysis in air while this is not the case for floating bodies as the pressure field around the floating body changes due to radiation field which results from elastic motion. The change of pressure field affects the modeshapes which cannot be determined in advance. In this case the hydroelastic motion of the floating body can be represented by the superposition of the modeshapes. The structural deflection of the floating body can be presented by free undamped wet modes of the hull by the dry modes of the same structure in air [3] (in which the different vibration characteristics are taken into account including torsional and vertical vibrations of floating bodies), or the orthogonal modes of a uniform beam [9], or the orthogonal polynomials [33] although the polynomials do not satisfy free-free boundary conditions at both ends. Structural deflections and rigid body displacements are all represented by the boundary conditions of the same form. It is common to represent all of these possible motions by generalized modes. Each mode may have a physical interpretation, like a rigid body mode and a wet or dry beam mode,

E-mail address: f.kara@cranfield.ac.uk

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http://dx.doi.org/10.1016/j.apor.2015.02.001

or it may not, like a Legendre or Fourier mode. It is expected that the selected modeshapes would represent both rigid and elastic motions of floating bodies accurately and as the number of modes increase, the contribution from the higher modes decreases (since the natural frequencies in these modes are very high compared to incident wave frequencies and as a result there would not be interactions between them).

The solution of the hydrodynamic and hydroelastic problems can be obtained using frequency [3,4] or time domain approaches [17,19,20,29,30,38] as mentioned above. The body surface considered as an ensemble of two-dimensional transverse sections in strip theory and the hydrodynamic forces are obtained by integrating these sections longitudinally. However, the strip theories [18,23,36] give inaccurate results especially at high Froude numbers for the low frequency, high forward speed, complex body shapes, global loads predictions, and end effects (e.g. bow and stern). The necessity for the accurate prediction of the end effects and others has given rise to the use of three-dimensional approaches which uses quadrilateral or triangular panel rather than strips to model three-dimensional arbitrary floating body shapes.

In the context of linear theory, in both two- and three-dimension there are two popular kinds of formulations that can be used for the solution of the hydrodynamic problem. These are Green's function formulations [12,22,26,27] or Rankine type source distribution [2,21,31]. The former satisfies the free surface boundary condition and condition at infinity automatically, and only the body surface needs to be taken into account for discretization, while in the latter source and dipole singularities are distributed on both the body surface and a portion of the free surface in order to satisfy the radiation condition or condition at infinity numerically. The main disadvantage of the Rankine type source distribution is the stability problem for the numerical implementation, since the radiation condition or condition at infinity is not satisfied exactly or automatically. The requirement of the discretization of some portion of the free surface increases the computational time substantially in the case of especially three-dimensional analysis. The time domain and frequency domain numerical results are related by Fourier Transform in the context of linear analysis. It appears that in both time domain and frequency domain it is an advantage to use the Green's function approach for computational and practical purposes. As the extension of the time domain approach to more general cases, such as non-constant forward speed case, large amplitude body motion, water on deck, unsteady manoeuvres of the body surface, nonlinear cable forces, etc., is much easier than the frequency domain approach.

The structural part of the hydroelastic analysis can be modelled using one-dimensional beam elements [3,6,40,41] (e.g. Euler–Bernoulli, Timoshenko, Vlasov beams), two-dimensional plate elements [17] (Kirchhoff or Mindlin plates), and three-dimensional shell elements [21] to obtain the elastic resultants (e.g. principal modes, natural frequencies, bending moments, twisting moments, shear force, etc.) by the use of Finite Element Methods (FEM) for the prediction of elastic resultant numerically including eigenvalues and eigenvectors. The interface boundary conditions due to interaction between deformable structure and fluid motion can be obtained [3,4,33,37] extending Newman's [32] unified theory results for hydroelastic analysis.

In the present paper, Euler–Bernoulli beam theory (in which the modeshapes and its derivatives are obtained analytically) is used to model the elastic behaviour of the floating structures whilst fluid boundaries described by the use of Boundary Integral Equation Methods (BIEM) with Neumann–Kelvin linearization. The exact initial boundary value problem is then linearized using the free stream as a basis flow and replaced by the boundary integral equation applying Green theorem over three-dimensional transient free surface Green function [12–17]. The resultant boundary integral equation is discretized using quadrilateral elements over which the value of the potential is assumed to be constant and solved using the trapezoidal rule to integrate the memory part of the transient free surface Green function in time. The free surface and body boundary conditions are linearized on the discretized collocation points over each quadrilateral element to obtain algebraic equation. The accuracy of the present hydroelastic method is assessed by comparing the results with the available experimental data [1,28].

2. Linearized initial-boundary value problem

A right-handed coordinate system is used to define the fluid action and a Cartesian coordinate system $\vec{x} = (x, y, z)$ is fixed to the body which is used for the solution of the linearized problem in the time domain Fig. 1. Positive x-direction is towards the bow, positive z-direction points upwards, and the $z = 0$ plane (or xy plane) is coincident with calm water. The body is translating through an incident wave field with velocity U_0 while it undergoes oscillatory motion about its mean body position. The origin of the body-fixed coordinate system $\vec{x} = (x, y, z)$ is located at the centre of the xy plane. The solution domain consists of the fluid bounded by the free surface $S_f(t)$, the body surface $S_b(t)$, and the boundary surface at infinity S_∞ Fig. 1 [12].

The following assumptions are taken into account in order to solve the physical problem. If the fluid is unbounded (except for the submerged portion of the body on the free surface), ideal (inviscid and incompressible), and its flow is irrotational (no fluid separation and lifting effect), the principle of mass conservation dictates the total disturbance velocity potential $\Phi(\vec{x}, t)$. This velocity potential is harmonic in the fluid domain and is governed by Laplace equation everywhere in the fluid domain as $\nabla^2\Phi(\vec{x}, t) = 0$ and the disturbance flow velocity field $\vec{V}(\vec{x}, t)$ may then be described as the gradient of the potential $\Phi(\vec{x}, t)$ (e.g. $\vec{V}(\vec{x}, t) = \nabla\Phi(\vec{x}, t)$).

In the present paper, it is assumed that the fluid disturbances due to steady forward motion and unsteady oscillations of the floating body are small and may be separated into individual parts for the linearized problem. In addition to the separation of the fluid disturbance into steady and unsteady part, the free surface boundary condition, body boundary condition, and Bernoulli's equation may be linearized. In the steady problem, the body starts its motion at rest and then suddenly takes a constant velocity U_0 parallel to free surface. After some oscillation all transients are allowed to decay to zero for the steady problem which gives rise to the calculation of the steady resistance, sinkage force, and trim moment [12,14]. Then the unsteady problem [12,13], which consists of radiation and diffraction analyses, is solved, when the body is in its equilibrium position. Because of the small disturbance of the fluid, the total velocity potential produced by the presence of the floating body in the fluid domain may be separated into three different parts Eq. (1)

$$\Phi(\vec{x}, t) = \varphi_{\text{basis}}(\vec{x}) + \varphi_{\text{steady}}(\vec{x}) + \varphi_I(\vec{x}, t) + \varphi_S(\vec{x}, t) + \sum_{k=1}^{K}\varphi_k(\vec{x}, t) \tag{1}$$

where $K = 1, 2, 3, \ldots$ is the degree of freedom of the fluid-structure interaction system which is greater than the number of rigid body motion. The steady problem is the combination of $\varphi_{\text{basis}}(\vec{x})$ and $\varphi_{\text{steady}}(\vec{x})$ potentials due to the steady translation of the floating body at forward speed U_0. The incident potential $\varphi_I(\vec{x}, t)$ is produced when the steadily translating floating body meets with an incident wave field. If the incident wave is reflected by the floating body, the resultant potential is the scattering potential $\varphi_S(\vec{x}, t)$ and comprises the diffraction potential. The solution of the incident wave potential and diffraction potential is called