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Theory and applications of coupled fluid-structure interactions of ships in waves and ocean acoustic environment*

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Abstract: Wave induced motions and structural distortions, and machinery or propeller excited vibrations and acoustic radiations of a ship are two kinds of important fluid-structure interaction problems. The branch of ship science that describes the coupled wave induced dynamic behavior of fluid-structure interaction system is referred to as hydroelasticity. During the past three decades the development of three-dimensional hydroelasticity theories and applications gained great progress. Recently the 3-D hydroelasticity theory was further extended to account for the fluid compressibility and the effect of the ocean acoustic environment with finite water depth. A three-dimensional sono-elasticity theory was then produced. In this paper, the 3-D hydroelasticity theory and the 3-D sono-elasticity theory of ships are briefly described. To illustrate the applicability and feasibility of these theories and the corresponding numerical approaches, several examples are presented including the predictions of wave loads, rigid-body and flexible-body responses, springing and fatigue behaviors, machinery or propeller excited coupled structural vibrations and acoustic radiations, as well as design optimizations for improving safety and acoustic behaviors of ships.

Key words: hydroelasticity, sono-elasticity, wave load, structural strength, springing, vibration, acoustic radiation

Introduction

A ship structure continually flexes in a seaway. The loading acting on it actually is neither static nor quasi-static. Hence there continuously exists dynamic interaction between the hull responses and the actions of the surrounding fluid, the so called fluid-structure interaction. To catalog the fluid-structure interaction problems of ships according to the excitation sources, the first kind relate to the fluid action (surface waves, slamming, wet deck impacting, sloshing, vortices disturbance, under-water explosion and acoustic waves etc.) induced steady-state, transient and random motions and structural dynamic responses, as well as the scattered surface wave or acoustic waves, the second kind are the non-fluid action (for example, the on-board machinery and propeller excitations) induced structural vibrations and acoustic radiations. According to different fluid wave properties involved in these two kinds of comprehensive fluid-structure interaction problems, the fluid surrounding the structure can be treated as the incompressible medium or the compressible medium in the analyses.

When the focus of observation is on the dynamic responses of ships and local structures induced by steady-state or transient-state surface gravity-wave excitations, the change of the fluid density is very small and the influence of the fluid compressibility on the hydrodynamic forces acting on ship structure may be neglected. The reason is that the acoustic wave lengths in the frequency region same as the gravity-wave frequencies are much longer than the characteristic dimensions and the motion-distortion amplitudes of a ship. The theory developed up to now to investigate this kind of fluid-structure interaction problems is referred to as the hydroelasticity theory.

Provided the focus of observation is on the structural responses excited by the under-water explosion shock wave or the incident acoustic wave etc., or on the acoustic radiations produced by structural vibrations, the fluid compressibility must be considered in the analyses. For different situations of intense or weak compressive waves involved in the fluid-structure interaction problems, the theoretical expressions are different. When only the weak compressive wave, i.e.

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the acoustic wave is concerned the theory describing this kind of fluid-structure interaction problems is called the sono-elasticity theory.

The research of these two kinds of fluid-structure interaction problems closely related to various engineering applications, including the improvement of motion performance and serviceability, insurance of structural safety, control of vibration and noise, enhancement of underwater acoustic stealthy of a ship etc..

In the late 1970s, the 2-D hydroelsticity theory of ships was established as a new branch of ship science[1]. The concept and basic principle to embody the structure and the surrounding fluid as a coupled entirety was further employed and extended in the establishment of the general linear 3-D hydroelasticity theory for an arbitrary shaped flexible marine structure travelling with a forward speed in a seaway in the middle of 1980s[2-4]. Since then, great progress has been achieved in the development and application of 3-D hydroelasticity theories[5]. These include the more rigorous methods of frequency-domain linear analysis accounting for the forward speed effect and the steady flow effect[6], the time-domain linear 3-D theory[5], the non-linear 3-D theory and the numerical methods for a floating structure travelling in rough seas with large motions[7-9], experimental techniques of 3-D flexible ship models[5,10], the hydroelasticity-based design and safety assessment[5] etc.. When a floating structure is placed near islands and reefs, the complicated geographic environment including the varied seabed topography and the inhomogeneous wave statistics may greatly influence its hydroelastic responses. This was also investigated[11,12].

During the last decade, the 3-D hydroelasticity theory[2-4] was extended to include the effect of fluid compressibility by replacing the Green's function for incompressible fluid with that for uniformly distributed ideal compressible fluid in semi-infinite domain[13]. This enables the acoustic responses and radiations of ship structures to be predicted with the free surface and the forward speed effects being included[14]. Later on it was further incorporated with the Green's function of the Pekeris ocean hydro-acoustic waveguide model[15] to produce an approach for prediction of ship acoustics in shallow sea. The seabed condition is then represented by a penetrable boundary of prescribed density and sound speed. A 3-D sono-elasticity theory of ships in shallow sea hydro-acoustic environment was then created together with the corresponding numerical methods[16,17]. This has provided an efficient new approach to predict both the machinery excited structural vibrations and the radiated noise in the near or far field surrounding the ship in shallow or deep sea.

Based on the 3-D hydroelasticity theory, the software 3-D Hydroelastic Analysis of Floating and Translating Structures[18] (THAFTS) and the acoustic module THAFTS-Acoustic[19] with a user friendly interface for pre-processing and post-processing were developed by China Ship Science Research Center. Since 1980s, THAFTS has been validated by model tests and full scale measurements and improved based on feedback from engineering applications.

In this paper, the 3-D hydroelasticity theory and the 3-D sono-elasticity theory of ships are briefly described. Several examples are presented to illustrate the applicatins of the theories and numerical approaches in the predictions of wave loads, rigid-body and flexible-body responses, springing and fatigue behaviors, machinery excited structural vibrations and acoustic radiations, propeller-shaft-hull coupled vibrations and acoustic radiations and also in design optimizations for improving safety and acoustic behaviors of ships and other marine structures.

1. Brief description of the 3D hydroelasticity and sono-elasticity theories of ships

1.1 *The 3-D Hydroelasticity theories of ships and other floating structures*

1.1.1 The linear theory[2-4]

The hydroelastic and sono-elastic behaviors of a ship are observed in an equilibrium coordinate system $Oxyz$, with x-axis pointing from stern to bow, x-y plane on the undisturbed water surface, z-axis pointing upwards and passing through the equilibrium position of the gravity center of the ship. By introducing the principal coordinates $q_r(t)(r=1,2,\cdots,m)$, the displacement $\boldsymbol{u}=(u,v,w)$ of the structure is expressed as the aggregation of the principal modes $\boldsymbol{u}_r=(u_r,v_r,w_r)(r=1,2,\cdots,m)$ of the structure in vacuum:

$$\boldsymbol{u}=\sum_{r=1}^{m}\boldsymbol{u}_r q_r(t) \tag{1}$$

The generalized equations of motion may be represented in terms of q_r in the matrix form

$$[a+A]\{\ddot{q}\}+[b+B]\{\dot{q}\}+[c+C]\{q\}=\{\Xi^{(1)}(t)\} \tag{2}$$

where $[a]$, $[b]$ and $[c]$ are matrices of generalized modal intertial, modal damping and modal stiffness of the dry structure. $\{q\}$ and $\{\Xi^{(1)}\}$ are the principal coordinate vector and the first-order (linear) generalized wave exciting force vector respectively. $[A]$, $[B]$ and $[C]$ are the matrices of generalized hydrodynamic inertia, damping and restoring coefficients respectively. $\{\Xi^{(1)}\}$, $[A]$ and $[B]$ are defined by the integrals of