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Buoyancy coupling with structural deformation analysis of ship based on finite element method

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ABSTRACT

The hydrostatic balance of a ship floating on the water is the result of buoyancy coupling with structural deformation. As to the ship with a relatively flexible hull girder, this coupling phenomenon is very important for the accuracy of general design and structural analysis. However, the existing ship design methods could not solve this coupling problem accurately. Aiming at this problem, a new numerical method based on FEM, called Buoyancy Coupling with structural Deformation Analysis (BCDA), is presented in this paper to improve both efficiency and accuracy of ship design. In BCDA, the concept of buoyancy element is proposed to simulate element on hull wet surface. As to a buoyancy element, the buoyant force is regarded as properties of element rather than external load. The buoyant matrices for both quadrilateral and triangular elements are derived, and the structural stiffness matrix of buoyant element is corrected by buoyant matrix. Being different from the traditional FEM, constraints on translation freedom along vertical direction should not be added in BCDA. The generalized displacements for each node, which consist of displacements due to buoyancy change and structure elastic deformations, are obtained by solving the global equilibrium equations. The results of BCDA satisfy both structural mechanics equation and gravity-buoyancy balance equation. A 15,000 t launching barge is taken as example to verify the validity and accuracy of BCDA. With this example, it also proved that the coupling analysis of buoyancy and hull structural deformation is necessary for the general design and structural analysis of floating structure with relatively flexible hull.

1. Introduction

When a ship floats on the water, the hull bears gravity load and buoyant load. When hydrostatic balance is achieved, gravity and buoyant force satisfy the gravity-buoyancy balance equation

$$\begin{cases} Disp = G \\ LCB = LCG \\ TCB = TCG \end{cases} \tag{1}$$

where *Disp* is the displacement of hull, *G* is total weight, including hull light weight, cargo load, and water ballast load etc. *LCG*, *LCB*, *TCG* and *TCB* are longitudinal center of gravity, longitudinal center of buoyancy, transverse center of gravity, transverse center of buoyancy, respectively. In the traditional general design methods of ship and floating offshore structure, the hull is regarded as a rigid body, and the buoyancy of hull is determined by several variables. The most important three ones are mean draft, trim angle, and heeling angle. The buoyancy variables that satisfies the gravity-buoyancy balance equation are calculated by hydrostatics equations, iterative algorithm (Yu et al., 2010), or optimization method (Lu et al., 2007). Actually, the hull is not rigid, and elastic deformation will occur on hull structure under uneven weight and buoyant load distribution. The elastic deformation will influence the wet surface, which will further influence buoyancy of hull. As a result, the final hydrostatic balance of hull is the result of buoyancy coupling with structural deformation. In the traditional general design methods, the effect of structure elastic deformation on buoyant force distribution is ignored in the calculation of hydrostatics, buoyancy, stability and longitudinal strength etc. Meanwhile, in the traditional hull structural strength analysis methods, the hydrostatic load is computed on the premise of rigid hull, which means the effect of buoyancy coupling with structural deformation is also not considered.

As to the conventional transportation ship, the hull stiffness is relatively high, so the hull structure elastic deformation due to uneven load in static water is small, and the change of buoyant

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distribution caused by hull structure elastic deformation is also relatively small. For those ships, the effect of buoyancy coupling with structural deformation is not significant, so the design accuracy with the above simplified method is acceptable. However, as to the ship with small length-depth ratio, such as pontoon, launching barge, floating dock, and very large floating structure etc., the relative stiffness of hull girder is significantly lower than that of the conventional transportation ship, and the hull deformation of those ships is much greater than that of the conventional transportation ship under the action of similar load. This deformation has significant influence on the design water pressure, buoyant force distribution, longitudinal strength check, and water pressure load in structural strength analysis etc. If the coupling phenomenon is ignored for such a ship, usually the results of design and analysis will be conservative.

Finite Element Method (FEM) is the most reliable method used in analysis of hull structural strength and stiffness. There are mainly two kinds of Finite Element (FE) model used in hull structural deformation analysis, which are 1D FE model and 2D FE model. The 1D FE model simulates the hull girder with several Timoshenko beams, which takes deformation due to shear stress into account. 1D FE model is applied in the global analysis of hull girder, such as deformation analysis of pontoon in the process of assisting another ship to launch (Zhang et al., 2004). The 1D FE model is ease to apply and could obtain results with acceptable accuracy in the hull girder global deformation analysis. However, it could not be used in the hull structure local deformation analysis, such as transverse deformation, complex twist deformation, and deformation distribution in cross section of hull etc. 2D FE model simulates hull structure with shell, membrane, and beam element etc. 2D FE model is much accurate in hull structural deformation analysis, and it suits for both global deformation and local deformation analysis.

In the traditional hull structural static FEM, hydrostatic load is considered as external load, and should be calculated and applied to the FE model before FEM solving. There are various methods to calculate the hydrostatic load of a floating ship on the premise that hull elastic deformation is ignored. The simplest way is to calculate the hull buoyancy (mean draft, heel angle and trim angle) first, and then calculate the hydrostatic load according to principle of fluid pressure. Another method is to calculate the fluid pressure based on 3D hydrodynamic model, based on which both hydrostatic load and hydrodynamic load could be solved. Malenica and Derbanne (2014) use a linear quasi static hydro structure interaction model to analyze structural responses. In Malenica's method, the hydrodynamic and hydrostatic load are calculated by 3D hydrodynamic model, and translated into the FE model on the premise of perfect equilibrium. As the loads applied to the FE model is exactly balanced, there are zero reaction forces at the artificial supports. Such methods are important for evaluation of stress distribution of hull structure. However, the load applied to the FE model is calculated without consideration of hull structure elastic deformation, so those methods are not suitable for the problem of buoyancy coupling with hull structure elastic deformation analysis. In order to calculate the hull deformation accurately for a ship floating on the water, the coupling of buoyancy and structural deformation, which is a fluid-structure coupling problem in essence, should be properly taken into account.

In the existing literature, the methods for fluid-structure coupling analysis of a floating ship could be divided into two categories by whether taking hull elastic deformation into account. The first ones are based on the assumption that the hull is rigid, and the research objectives of those methods focus on the coupling of hull with wave, such as prediction of wave-induced ship motion response (Suresh et al., 2015) etc. The methods in the second category consider hull deformation in fluid-structure coupling analysis, and those methods are concerned with the motion of deformable hull structure through the sea water, which are called hydroelasticity (Bishop and Price, 1979). Hydroelasticity takes the hull structure and fluid as a whole system, the dynamic pressure of fluid is the external load of hull structure, and the magnitude of dynamic pressure depends on the displacement, velocity and acceleration of hull structural vibration. The hydroelasticity methods include frequency domain analysis (Senjanović et al., 2014a, 2014b; Malenica and Derbanne, 2014) and time domain analysis (Kim et al., 2013), and they are applied to ships with a natural vibration frequency close to the wave encounter frequency, such as container ship (Kim et al., 2013; Senjanović et al., 2014a, 2014b; Malenica and Derbanne, 2014), and very large floating structure (Cheng et al., 2015) etc.

Hydroelasticity is mainly used in the dynamic response analysis of a flexible structure coupling with fluid, taking the structural vibrations into account. Theoretically, hydroelasticity could solve the problem of buoyancy coupling with hull structure elastic deformation in still water, but it is not a classical way. First, the wet surface of hull is specified and keeps unchanged in the typical hydroelastic analysis. Actually, the wet surface is related to the hull structural deformation, and in most cases it could not be forecasted accurately before solving the fluid-structure coupling problem. Second, the hydrostatic load and structure weight is defined by means of restoring stiffness in the hydroelastic equations (Huang and Riggs, 2000, Senjanović et al., 2012). In spite of the fact that ship hydroelasticity has been a known issue for many years, there is still no unique solution for restoring stiffness (Senjanović et al., 2008). Determination of restoring stiffness is a quite complex problem, and two formulations are current today, which are the consistent stiffness with distributed or lumped masses, and the complete stiffness matrix (Malenica et. al., 2013). In the hull structure analysis, different kinds of loads are used to improve the convenience and accuracy, such as uniform force, gradient force and concentrated force etc. Both of the two restoring stiffness formulations do not support the above loads, certain simplification should be carried out. Besides, in the existing hydroelasticity methods, including the methods based on frequency domain or time domain, the hull structure model and the hydrodynamic model are two independent models. The dynamic water pressure load is translated from hydrodynamic model to structure model, and the structure motion is translated from structure model to hydrodynamic model in the solving process. The solving strategy of hydroelasticity might be feasible for the problem discussed in this paper, but obviously it is lack in both accuracy and efficiency. Generally, hydroelasticity is used to analysis the vibration response of hull structure under dynamic load, it needs a hydrostatic balance hull as the initial state, rather than calculate the hydrostatic balance.

In summary, the existing methods have not provided an accurate and efficient way to solving the coupling of buoyancy and structural deformation problem for a ship floating on the water. Aiming at this problem, a new method, which is called Buoyancy Coupling with structural deformation Analysis (BCDA), is proposed in this paper. In BCDA, the buoyant element is developed to simulate elements on hull wet surface. The buoyant force is regarded as the intrinsic properties of buoyant element in the form of buoyant matrix. The generalized displacements for each node, which consist of displacements due to buoyancy change as well as structure elastic deformation, are obtained by solving the global equilibrium equations. An iterative re-balance procedure is used to determine the wet surface, and a method to correct the buoyant matrix of buoyant element crossing the water plane is given.

This paper is organized as follows: The basic principle and procedure of BCDA is elaborated in Section 2, including gravity-buoyancy balance equation considering hull deformation, element