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The dynamics of ship propulsion unit-large hull–water interactions

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ABSTRACT

This paper developed a generalised theory to model the dynamics of an integrated ship propulsion unit-large hull–water interaction system. The engine shaft unit, the hull structure are considered as two substructures and the water as a subdomain, of which the motions of each subsystem are governed by the fundamental laws in continuum mechanics, and on their interfaces, kinematical and dynamical conditions are satisfied. The integrated variational formulation is given, based on which the numerical equation is derived by using the mode summation approach. The shaft frequency and deformation factors are defined to study on its interactions with large hull and water in order to provide a mean for safety propulsion unit design in large ships. An example is given to illustrate the applications of the general theory presented in the paper. Some guidelines which are useful in preliminary design stage for dynamical designs of large ship hull – propulsion system are suggested.

1. Introduction

With fast development of ship sizes, dynamic interactions between ship hulls and engine propulsion systems have been playing more and more roles for safety operations of ships. For the type of small ships, the hull deformations excited by wave loads have no obvious effects on the operation of engine propulsion shaft systems. However, for large ships, especially with very big length, the deformation of ship may seriously change the mounting position of its propulsion shaft system, so that it could not normally work (Murawski, 2005; Shi, 2010; Shaft alignment, 2000). The statistical researches reported that about 52.9% ship operation fails during 1998–2004 were caused by engine propulsion system problems (Leontopoulos, 2006; The Swedish Club Highlights, 2005), of which some photos of broken parts of main propulsion system can be read in (Dymarski, 2009; Fonte and Freitas, 2009). Based on this practical situation as well as very strong requirements of worldwide ocean transportations, designers and scientists have to put much attention into dynamic interactions between ship hull and main engine system (Moctar and Junglewitz, 2005; Ogawa, 2011; Lu, 2010; Pouw, 2008; Li, 2009) in order to get the safety operations of large ships. Recently, a review paper (Yan et al. 2013) presents more details on the dynamic interactions between the propulsion system and large ship structures. The discussed problems involve the torsional vibration and its bearing arrangement (Murawski and Charchalis, 2015; Tang and Brennan, 2013; Roemen and Grevink, 2009), the robust global sliding model controls (Li et al., 2015a, 2015b; Li, 2013) and the modelling with simulations (Tian et al. 2014; Tu and Chen, 2014) of marine propulsion system. The methods used to deal with the problems are mainly by numerical analysis, such as finite element models and substructure approaches (Schulten, 2005; Jun et al., 1998) .

Ships move on the water, the integrated system is a fluid–structure interaction system (Newman, 1978), for which the water flows affect ship motions and its elastic deformation so that the deformation of the engine propulsion system mounted in/on the ships. Reversely, the motions of ships are also affecting water flows through wet interaction interfaces. Therefore, to predicate more accurate deformation of engine shaft and hull structure and more safely to arrange the engine system, investigations on an integrated water–hull–engine system interaction is necessary, for example, the reported marine structures–water interactions (Newman, 1979; Bishop and Price, 1979; Bishop et al. 1986; Morand and Ohayon, 1995; Xing et al., 2009; Deruieux, 2003), to cite but too more. Based on the developed fluid–structure interaction theory and computer code (Xing, 1995a, 1995b) which has been used to simulate many dynamic problems in marine engineering (Xing et al., 2006; Xiong et al., 2006a; Tan et al., 2006; Xiong et al., 2006b; Xiong and Xing, 2007; Xing et al., 2007a; Xing et al.,

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2007b; Xing, 2007, 2008; Xiong and Xing, 2008a; Xiong and Xing, 2008b), this paper intends to propose an integrated ship propulsion unit-large hull–water interaction model to reveal dynamic effects of water–hull interactions on large ship engine propulsion system.

2. Governing equations of integrated interaction system

Fig. 1 shows an integrated ship propulsion unit-large hull–water interaction system studied in this paper. This system consists of a flexible hull structure of mass density ρ_s, body force $\hat{F}_i$ and elastic tensor E_{ijkl} within a domain Ω_s of boundary $S = S_T \cup S_w \cup \Sigma$ with its unit normal vector ν_i, the sound speed of water c, body force $\hat{f}_i$ and mass density ρ_f in a domain Ω_f of boundary $\Gamma = \Gamma_f \cup \Gamma_w \cup \Gamma_p \cup \Sigma \cup \Gamma_\infty$ with a unit normal vector η_i and a ship propulsion unit Ω_p mounted on the hull by $\hat{I}$ journal bearings $B_I, (I = 1, 2, \cdots, \hat{I})$. Cartesian coordinate system $o - x_1x_2x_3$, where the gravitational acceleration g is along the negative direction of the coordinate axis $o - x_3$, is chosen as a reference frame to describe the dynamics of interaction system. A hull-Lagrange coordinate system $O - X_1X_2X_3$, of which the three coordinator vectors are parallel to the ones of the system $o - x_1x_2x_3$, is fixed at the mass centre $O(x_{10}, x_{20}, x_{30})$ of the ship hull. A propulsion unit-Lagrange coordinate system $\hat{o} - Y_1Y_2Y_3$ is fixed at a suitable point chosen by users, such as its centre of mass $\hat{o}(X_{10}, X_{20}, X_{30})$ of the central line of the propulsion shaft. The relationship between the hull-coordinate system $O - X_1X_2X_3$ and the system $\hat{o} - Y_1Y_2Y_3$ for the propulsion unit is defined by an orthogonal transformation matrix $\boldsymbol{\beta}$,of which the components $\beta_{ij} = \cos(Y_i, X_j)$, here (Y_i, X_j) denotes the angle between axis $\hat{o} - Y_i$ and $O - X_j$. The system may be excited by external dynamical forces $\hat{F}_i, \hat{T}_i, \hat{f}_i, \hat{p}$ ground acceleration $\hat{w}_i$. The Cartesian tensor notations (Fung, 1977) with subscripts i, j, k and l $(=1, 2, 3)$ obeying the summation convention are used in this paper. For example, u_i, v_i, w_i, e_{ij} and σ_{ij} represent the displacement, velocity, acceleration vectors, strain and stress tensors in solid, respectively, p denotes the pressure in fluid, $p_{tt} = \partial^2 p/\partial t^2$, $u_{i,j} = \partial u_i/\partial x_j$, $v_i = \dot{u}_i = u_{i,t} = \partial u_i/\partial t$, $w_i = \dot{v}_i = \ddot{u}_i = u_{i,tt} = \partial^2 u_i/\partial t^2$ and Kronecker delta δ_{ij}etc.

Here one or double dots over the parameters represent their derivatives with respect to time t.

As shown in Fig. 2, we consider the propulsion unit as a shaft system consisting of the propeller D_p, supporting bearings $B_I, (I = 1, 2, \cdots, \hat{I})$, engine crack box D_E and attached disks D_J, $(J = 1, 2, \cdots, \hat{J})$, to represent flying wheels, connectors. The shaft system $\hat{o} - Y_1Y_2Y_3$ is used to study the motion of this propulsion unit, which undergoes a translation and a rotation in/about axis $\hat{o} - Y_1$, two bending motions in the directions $\hat{o} - Y_2$ and $\hat{o} - Y_3$, respectively. We assume these motion components are governed by the classical beam, rod or shaft theory and their couplings are neglected. Therefore, the propulsion unit is represented by a shaft central line of mass density ρ per unit volume, extension stiffness ES and rotation stiffness GJ_1 for axis $\hat{o} - Y_1$ as well as two bending stiffness EJ_2 in the plane $Y_1\hat{o}Y_2$ and EJ_3 the plane $Y_1\hat{o}Y_3$, respectively. A typical disk D_J, $(J = 1, 2, \cdots, \hat{J})$, is fixed on the shaft line at point $(Y_{J1}, Y_{J2} = 0 = Y_{J3})$, which has concentrated mass M_J, inertial moment I_{J1} for rotation about $\hat{o} - Y_1$, inertial moment I_{J2} for bending in the plane $Y_1\hat{o}Y_2$ and I_{J3} for bending the plane $Y_1\hat{o}Y_3$.

We assume that the ship is in its stable equilibrium motion with a constant velocity on the water. The propulsion shaft unit has been mounted on the hull in a good alignment state (Shaft alignment, 2000; Leontopoulos, 2006). We are interested in the dynamic responses added on the equilibrium motion state of the system, which is caused by extra external forces, such as waves and earthquakes. Therefore, the coordinate system $o - x_1x_2x_3$ is considered as an inertial system in association with the ship constant velocity, which could be ignored. For a first instance to explore these complex dynamic interactions we consider the system is a linear system in which the hull motion is governed by linear elastic theory and the motion of the propulsion unit follows the beam/shaft theory as mentioned above. The water is compressible fluid with irrotational motions and a linear free surface wave condition. The dynamic pressure of the water satisfies a wave equation in the water domain. To derive the governing equations of the integrated interaction system, we have to model the dynamic interactions of the propulsion unit with the hull and the water through the bearings, engine crack box and the propeller, which is discussed and described by the corresponding equilibrium and geometrical relationships as follows.

2.1. Propulsion unit-ship hull–water interactions

2.1.1. Bearings

For a representative bearing B_I, of which the mass of moving parts is neglected, is fixed at a point $B_I(Y^B_{I1}, Y^B_{I2}, Y^B_{I3})$ in the hull and a point $A_I(Y^A_{I1}, Y^A_{I2} = 0 = Y^A_{I3})$ on the central line of the shaft. The coordinates of these two points in the hull system $O - X_1X_2X_3$ can be obtained from the following coordinate transformation

$$X^A_{Ii} = X_{i0} + \beta_{ji}Y^A_{Ij}, \quad X^B_{Ii} = X_{i0} + \beta_{ji}Y^B_{Ij}. \tag{1}$$

The interaction dynamic force components $\tilde{f}^A_{Ii}$ and $\tilde{f}^B_{Ii}$ at two ends of bearing B_I in the shaft coordinate system, between the shaft and the hull can be calculated by using the stiffness coefficient $k_{I\hat{i}}$ (Bernhard Bettig, http://www.me.mtu.edu/~mdrl) but neglecting its damping c_{Ii} shown in Fig. 2, i.e.

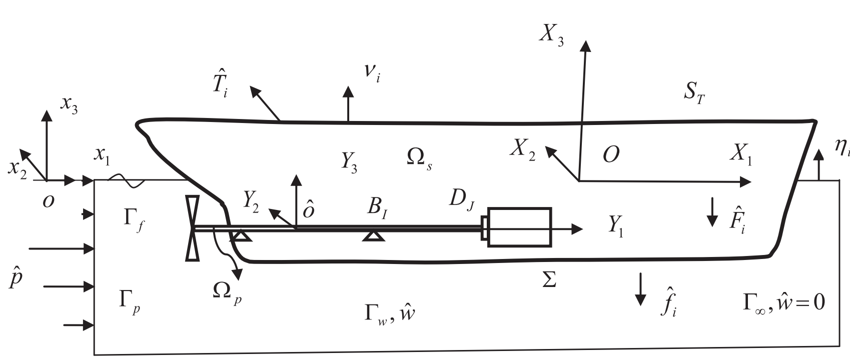

Fig. 1. The integrated ship propulsion unit-large hull–water interaction system.