Ocean Engineering 136 (2017) 272–282

Contents lists available at ScienceDirect

Ocean Engineering

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

Numerical modeling and experimental analysis on coupled torsional-longitudinal vibrations of a ship's propeller shaft

Qianwen Huang[a,b], Xinping Yan[a,c,*], Yikun Wang[b], Cong Zhang[a], Zhihua Wang[a]

[a] Reliability Engineering Institute, School of Energy and Power Engineering, Wuhan University of Technology, Wuhan 430063, China
[b] Faculty of Engineering and the Environment, University of Southampton, Southampton SO17 1BJ, UK
[c] National Engineering Research Center for Water Transport Safety, Wuhan University of Technology, Wuhan 430063, China

ARTICLE INFO

Keywords:
Coupled torsional-longitudinal vibrations
Propeller shaft
Lumped-mass method
Numerical calculation
Experiments

ABSTRACT

A simplified lumped-mass model was established using ordinary differential equations, focusing on the coupled torsional-longitudinal vibrations of a ship's propeller shaft. The numerical simulation based on the presented algorithm was then developed and the dynamic behavior was investigated. A theoretical solution setup with simple model was solved to demonstrate the accuracy of the proposed lumped-mass model. Based on this model, the coupled natural frequencies and the maximum acceleration of each direction were determined. Experimental tests were conducted to validate the applicability of the numerical model, over a range of rotational speeds and loading conditions. It is found that the natural frequencies are unaffected while the maximum acceleration are increased with the rotational speed as well as the loading. Natural frequencies representing other directions are induced by the coupling effect, and enhance the dynamical response. The ultimate response in the direction without excitation is enlarged because of the coupling effect. An appropriate coupling stiffness coefficient value has been proposed based on the discussion on modeling and experimental results.

1. Introduction

An appropriate assessment of the dynamic behavior of a ship's propeller shaft is essential to enable the optional power delivery to the propeller and to minimize vibrations. Reliability of the propeller shaft is closely related to the ship's safety and navigation at sea. Excessive vibrations in torsional, longitudinal and transverse modes and their coupled vibration forms are undesirable and can cause numerous failures during the shaft operation (Murawski, 2004). Specifically, torsional vibration is normally induced by the pulsing torque of the engine, various propeller outputs and the torsional elasticity of power transmission system (Murawski, 2014; Han et al., 2015). Longitudinal vibration, attributed to unsteady propeller thrust, increases the relative motion between fixed and rotating parts, and hence induces the wear damage of thrust bearings (Zhang et al., 2014). Transverse vibration is attributed to the imbalance of the rotating part of the shaft system and the periodic motion of alternating bending deformation due to the non-uniform flow field that a propeller is operating in (Warikoo and Haddara, 1992).

During actual navigation, ships usually subject to waves, wind and other exciting forces in different forms. All these excitations will lead to vibration responses in the loading direction. As a result, coupled vibration responses may be excited in different directions simultaneously (Qin et al., 2012). Moreover, the cyclic motion in the main engine and the non-uniformity of propeller working area will induce complex exciting forces/moments (Jun et al., 1998). It needs to be pointed out that coupled vibrations will stimulate structural vibrations of the engine and its accessories, and also increase the noise level. The piston rod assembly may become eccentric due to the large movement of the shaft in the longitudinal direction. The longitudinal vibration caused by the torsional angle tends to lead to severe transmission problems and harmful in-cylinder pressure. In consequence, these will lead to fatigue, fracture and tribological issues partially on the shaft and even overall shaft failures. Ultimately the reliability of the ship will be significantly reduced (Li et al., 2015a, 2015b).

According to the machinery fault claims report by Swedish ship insurance company, the number of accidents caused by mechanical failure has increased significantly (Navigational claims brochure, 2014). Among them, the failure rate occurred in propeller shaft accounted for the proportion of mechanical fault increased from 11.3% during 1998–2004 to 17.7% during 2005–2013, and the number of failures increased from 63 times growth for 117 times

* Corresponding author at: Reliability Engineering Institute, School of Energy and Power Engineering, Wuhan University of Technology, Wuhan 430063, China.
E-mail address: xpyan@whut.edu.cn (X. Yan).

http://dx.doi.org/10.1016/j.oceaneng.2017.03.017
Received 26 July 2016; Received in revised form 11 January 2017; Accepted 12 March 2017

Table 1
Machinery claims, Swedish Club, 1998–2015 (Navigational claims brochure, 2014).

Claims type	Failure number (1998–2004)	Failure number (2005–2013)
Main engine	232	370
Steering gear	66	55
Aux. engine	120	185
Boilers	65	59
Propulsion	63	174
Other	12	139
Total	558	982

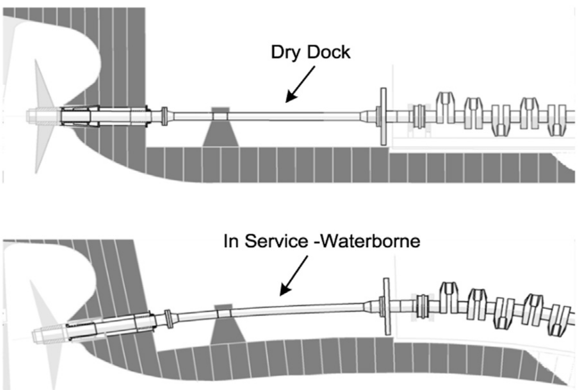

Fig. 1. The propeller shaft in dry dock and service (Chris, 2011).

(Table 1). These failure accidents for propulsion shaft affect the safety of the ships and causes property damage. Moreover, the wave-include ship vibration may cause hull deformation on the ship structures, as well as the shaft. It is reported that the loading conditions had serious effects on the ship's propeller shaft (Chris, 2011). Fig. 1 shows the comparison of shaft at dry dock and during service. It can be seen that the propeller shaft deflects due to the loadings, which will cause the vibration response unlike that of the free vibration. In order to investigate the effect of hull deformation on shaft vibration, it is necessary to study the shaft vibration in service loadings.

In addition to vibration control techniques reducing the bearing and shaft misalignment, investigations have mainly focused on the theoretical and practical methods that guide and support the prediction of the shaft dynamics. Therefore, the minimization of vibration intensity of propeller shaft has received much research attention. Early investigations only considered the shaft system and employed simple models, such as transfer matrix method (Huang and Horng, 1999) to analyze the independent vibration of various directions of the shaft. Although these models are fundamental to describe problems in shaft vibration, they are not sufficient to describe the interaction of coupled shaft vibration. Recently, investigations were conducted with more complicated models, such as system matrix method (Wu et al., 1995), mode synthesis method (Rao et al., 2003) and finite element method (Huang et al., 2016). Meanwhile, experiments concerning shaft dynamics and vibration control have also been carried out (Xiang et al., 2012).

The previous shaft vibration research focuses on independent torsional, longitudinal and transverse vibrations, without interaction between them. It makes the research results different from the actual measurements (Dai et al., 1989). As a matter of fact, the basic mechanism for coupled vibration is that deformation coupled with angle at every point on the shaft generates a response not only in the disturbance direction but also in other directions (Kim, 2000). Multi directional coupled vibrations of a propeller shaft, as well as shaft-hull coupled vibrations, is an emerging topic in the field of ship vibration research over the past decades (Paul, 2005). However, due to the complexity of the shaft dynamics, problems still exist regarding solving the shaft system accurately (Zhang and Rustighi, 2012). Currently there is only a limited amount of research in the public literature focusing on the coupled torsional-longitudinal vibrations of propeller shafts. Early work by Tsuda in 1969 (Tsuda, 1969) proposed a model applying matrix technique to analyze the coupled vibrations. Jeon et al. Jeon and Tsuda (1974) reported a practical technique to calculate the forced coupling vibrations with damping, which could estimate the vibration amplitudes, phase angles and frequencies. Kempner et al. Kempner and Nesterova (1974) proposed an approximate structural simulator to calculate the coupled torsional-longitudinal vibrations of a propeller shaft. Parsons (Parsons, 1983) studied the coupling effect caused by the propeller's torsional-longitudinal vibrations. Jang et al. Jang et al. (2004) derived the stiffness matrix numerically by using the finite element method and the influence coefficient method, followed by predictions of the coupled torsional-longitudinal vibrations. However, the disadvantage of the previous analytical and numerical analysis is that they are not flexible enough to deal with vibrations possessing complicated coupling stiffness, damping coefficient and rotational speeds simultaneously. Meanwhile, external excitation including torque and longitudinal forces with different amplitudes and frequencies are not taken into account in previous research. These models contains a serious error caused by the estimation of the stiffness and other mechanical characteristics. Additionally, the dynamics of coupled vibrations is not fully understood. Hence, the most suitable method should be able to predict dynamical performance with above influence factors and be convenient to be applied in theoretical analysis.

In view of this, a new numerical model is thus proposed in this paper in the exploration of a ship's propeller shaft, to investigate the coupled torsional and longitudinal vibrations the involved dynamics. In order to develop a practicable tool for predicting coupled dynamical performances of ship propeller shaft, it is crucial to investigate the coupling stiffness, damping coefficient, rotational speeds and loading conditions. In this study, a simplified lumped-mass model of the coupled torsional-longitudinal vibrations of a ship's propeller shaft has been developed with the aforementioned impact factors. Theoretical solution was obtained to validate the proposed lumped-mass model. A feasibility study of the natural frequency and maximum amplitude in the case of coupled vibrations due to the variation of rotational speed and loading condition was presented. Finally, experimental tests with various cases were conducted and compared to the numerical modeling results followed by discussion on the appropriate coupling stiffness coefficient value.

2. Methodology

2.1. The theoretical basis

The ship propeller shaft is equivalent to a cantilever beam with fixed end (the main engine) and free end (the propeller), and can be modelled as an Euler beam with a mass payload, where its mass center does not need be coincident with the centerline of the beam, as shown in Fig. 2 (Hassan and Mehrdaad, 2006). A longitudinal contraction of

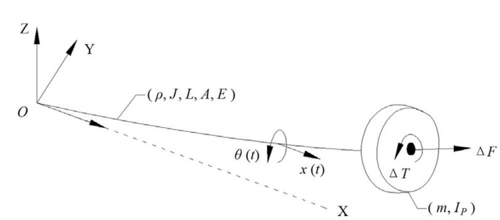

Fig. 2. Schematic of the beam with a mass payload. (here, ρ, J, L, A and E denotes the density, the moment of inertia, the length, the cross-sectional area, and the Young's modulus, respectively. m and I denotes the mass and the second axial moment of are. And $\theta(t)$ and $x(t)$ denotes the torsional angle and longitudinal deformation).