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Coupled longitudinal–transverse dynamics of a marine propulsion shafting under primary and internal resonances

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ABSTRACT

In this study, the longitudinal primary resonance of a marine propulsion shafting is investigated with special consideration of the internal resonance between the longitudinal and transverse directions (the first longitudinal natural frequency is approximately equal to the sum of the first transverse forward and backward frequencies). A coupled longitudinal–transverse dynamic model is established by using the extended Hamilton's principle and discretized by Galerkin method. First, the multiple scales method to solve these discretized equations is used, and then, the steady-state response and its stability are analyzed. Our results show that the first transverse forward and backward modes could be excited if the longitudinal excitation load is larger than the critical load, even though there is no excitation in the transverse direction. A saturation phenomenon is observed with the longitudinal motion and the extra energy is transferred to the transverse modes. The energy distribution ratio between the forward and backward modes is inversely proportional to their frequency ratio. The effects of damping ratio and frequency detuning parameters on the critical load are discussed. Results obtained by using the perturbation method are validated by numerical simulations.

1. Introduction

Propulsion shafting is an important unit of marine components. Dynamic analyses of propulsion shafts are essential for marine design engineers. The propulsion shaft system could be considered to be a typical rotor-bearing system. Early dynamic studies on rotating shafts focused on linear vibrations, including the prediction of natural frequencies and calculation of unbalance responses [1–3]. For some structures, a linear dynamic analysis model may be sufficient when the vibrations are not very large. However, the linear theory is not valid if the oscillation amplitudes are large. Therefore, the nonlinear model must be considered in such conditions. Most often, the nonlinearity is geometric because of the nonlinear relation between strains and displacements. The propeller (which may weigh up to a few tens of tons) is very large in propulsion shafts, and has inescapable eccentricity due to machining accuracy or wear and tear. Therefore, it suffers from a huge unbalance excitation when it rotates. At the same time, it also suffers from a very large fluid pulse pressure in the longitudinal direction. Hence, the vibration amplitudes of the propulsion shaft are very large and the nonlinear coupling

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Table 1
The ranges of natural frequency for most propulsion shafts.

The first lateral natural frequency		The second lateral natural frequency		The first longitude natural frequency	The second longitude natural frequency
Forward whirl	Backward whirl	Forward whirl	Backward whirl		
7–20 Hz	4–17 Hz	13–37 Hz	10–34 Hz	10–35 Hz	20–100 Hz

between transverse deflection and longitudinal deflection is easy. Therefore, it is important to study the nonlinear dynamic response of propulsion shafts.

In longitudinal vibration of the propulsion shaft, the excitation source is the fluctuation thrust that results from a nonuniform and unsteady flow. Therefore, abundant frequency components occur in the frequency spectrum of thrust. However, the rotational frequency and the blade frequency (which is equal to rotational frequency times blade numbers) dominate the frequency spectrum of thrust. In most of the large ships, the rotational speed is not more than 300 rev/min. Therefore, the rotational frequency lies between 0 and 5 Hz and the blade frequency lies between 0 and 35 Hz for a seven blades propeller. The ranges of the lateral and longitudinal natural frequencies for most large propulsion shafts, according to our experience and reference [4], are as shown in Table 1.

As can be seen in Table 1, many nonlinear phenomena may occur, such as primary resonances, combined resonances, and internal resonances. It is possible that the blade frequency is equal to the first longitudinal natural frequency. Then the longitudinal primary resonance may occur under blade frequency excitation. The lateral primary resonance may also happen. At the same time, internal resonances may occur between longitudinal and lateral modes. For example, the frequency of the first longitudinal mode may be approximately equal to the sum of the first lateral forward and backward frequencies. The frequency of the first longitudinal mode may be approximately equal to twice the frequency of the first lateral forward mode or to twice the frequency of the second lateral forward mode. Also, the frequency of the second longitudinal mode may be approximately equal to the sum of the first lateral forward and the second lateral forward frequencies and so on. Hence, the longitudinal and lateral modes may interact with each other due to internal resonances.

Recently, the number of studies related to nonlinear coupling vibration between the transverse and longitudinal deflections of the beams or shafts is quite large. Lacarbonara [5] has described this topic in detail. These studies could be categorized mainly into two classes.

In the first class, both longitudinal and transverse displacements are considered, and coupled partial differential equations of motion are obtained first. Then these equations are reduced into one integro-partial differential equation, using a kind of assumption on the longitudinal displacement such as neglecting the longitudinal inertia [6]. This assumption gives the longitudinal displacement as a function of the transverse one. One integro-partial differential equation is obtained by substituting this function into the transverse equations [7]. Most of the studies could be grouped into this class. For example, Lacarbonara and Yabuno [8] discussed accurate mechanical models of elastic beams undergoing large in-plane motions with consideration of coupling between longitudinal and transverse deflections. Then they transformed the couple partial differential equations into two models. One based on the inextensible assumption and the other based on the extensible assumption. Dwivedy and Kar [9–12] examined nonlinear dynamics of a slender beam carrying a lumped mass. These analyses included principal parametric resonances, combination resonances and internal resonances. Emam and Nayfeh analyzed internal resonances of a buckled beam [13]. The foregoing analyses relate to the plane beam structures. For rotating shafts, there are also some studies. Khadem and coworkers made outstanding achievements about nonlinear rotating shafts. They discussed primary and parametric resonances of an asymmetrical rotating shaft with stretching nonlinearity [14] and primary resonances of a nonlinear in-extensional rotating shaft [15]. They also investigated two-mode combination resonances of a simply supported rotating shaft by the method of harmonic balance [16]. Hosseini and coworkers also did lots of work in this field. They analyzed free vibrations of a rotating shaft with nonlinear curvature and inertia [17]. They investigated primary resonances of a rotating shaft with stretching nonlinearity [18]. Furthermore, they studied the dynamic stability and bifurcations of a nonlinear in-extensional rotating shaft with internal damping [19].

In the second class, both longitudinal and transverse displacements are considered and the coupled partial differential equations of motion are obtained. But in this class the two coupled equations are solved together with no addition assumptions. For example, Saghafi et al. [20] studied the nonlinear tuning of nano/microresonators, and they established a nonlinear model that governed the transverse and longitudinal dynamics of multilayer microbeams. Ghayesh and coworkers [21–23] studied coupled longitudinal–transverse dynamics of an axially moving beam while both longitudinal and transverse displacements were taken into account and solved together. Moeenfard and Awtar [24] studied free vibrations of a beam with a tip mass considering the coupling of longitudinal and transverse deflections. Pesheck et al. [25] investigated nonlinear normal modes of a beam with consideration of the nonlinear coupling between transverse and axial deflections. Arvin and Bakhtiari-Nejad [26] investigated free vibrations of coupled longitudinal–transverse rotating beams with or without internal resonances. They [27] also studied nonlinear modal interactions in rotating composite Timoshenko beams and considered the nonlinear coupling of transverse, shear and longitudinal motions. Han and Benaroya [28,29] investigated free vibrations and forced responses for a compliant tower by the finite difference approach. Stoykov and Ribeiro [30]