Journal of Fluids and Structures 68 (2017) 264–278

Contents lists available at ScienceDirect

Journal of Fluids and Structures

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

Longitudinal vibration of marine propeller-shafting system induced by inflow turbulence

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ARTICLE INFO

Keywords:
Marine propeller
Shafting
Inflow turbulence
Vibration
Unsteady thrust transmission

ABSTRACT

The multi-modal vibration characteristics of a ten-bladed marine propeller and its shafting system induced by the inflow turbulence are numerically investigated. Firstly, the distributed pressure on the propeller face is computed by the correlation method according to the statistical characteristics of isotropic turbulence. Next, the mapped unsteady pressure is applied on the blades and the associated random vibration responses of the immersed elastic propeller and its shafting system are computed by using the modal superposition method. Finally, vibration characteristics of the propeller and its unsteady thrust transmitted to the foundation are analyzed with different dynamic parameters of the system. The results show that amplification of the unsteady thrust associated with the low-order bending modes of the propeller blades cannot be neglected, especially when the frequency of the first bending mode approaches that of the longitudinal vibration mode of the shafting system. The propeller with 'soft' blades suffers higher excitation intensity at its first natural frequency but the corresponding modal hydrodynamic damping may be enhanced.

1. Introduction

The fluctuating forces of a marine propeller is an important source of underwater sound in the low frequency range for a submarine (Ross, 1987). These unsteady forces are composed of periodic components and broadband components (Blake, 1986; Homicz and George, 1974), which result from the rotation of the propeller in a nonuniform and nonstationary wake. The narrowband periodic force components usually occur at frequencies proportional to the shaft speed and the number of blades (Massaro and Graham, 2015; Tompson, 1976) as a result of the nonuniform inflow induced by such appendages as the fins or rudders. The broadband force components are usually distributed on a frequency span of several hundred hertz with some 'hump' at the first and second blade rate frequencies (Jiang et al., 1991; Sevik, 1970), resulting from the interaction between the unsteady inflow turbulence and the propeller blades (Blake and Maga, 1975b). The inflow turbulence, which is superposed on the ambient free-stream turbulence, is generated in the hull boundary layer and the boundary layers of all the appendages in the upstream of the propeller (Abbas et al., 2015; Anderson et al., 2014).

The unsteady thrust of a propeller, especially the longitudinal component, will induce significant underwater sound radiation when it is transmitted to the hull via the shafting system (Merz et al., 2009; Wei and Wang, 2013). In order to reduce sound radiation, some measures have been proposed to impede the transmission of unsteady forces, for example, a hydraulic device known as the resonance changer (Goodwin, 1960). Detailed theoretical analysis and optimization were given in (Dylejkoa et al., 2007; Merz

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http://dx.doi.org/10.1016/j.jfluidstructs.2016.11.002
Received 1 April 2016; Received in revised form 5 October 2016; Accepted 2 November 2016
0889-9746/

Nomenclature

Symbol	Description
$F_{ij}^{\alpha\beta}(t,\tau)$	hydrodynamic force related to the fluid velocity fluctuations
$H_{ik}^{\alpha\gamma}(\omega)$	hydrodynamic frequency response function
$l_i^{\alpha}(t)$	hydrodynamic force acting on the αth element at time t in the direction i
$\Phi_{ij}^{\alpha\beta}(\tau)$	correlation function of unsteady forces between $l_i^{\alpha}(t)$ and $l_j^{\beta}(t)$
$\Psi_{ij}^{\alpha\beta}(\omega)$	frequency spectrum of the force fluctuations
$R_{km}^{\gamma\delta}(\tau)$	correlation function between velocity fluctuation of fluid particles
$G_{km}^{\gamma\delta}(\omega)$	frequency spectrum of fluid velocity fluctuations
k_1,k_3	wave number in the direction of 1 (chord) and 3 (span)
k_a	acoustic wave number
k_i	wave number related to the ith mode of cantilever plate
U_∞	inflow velocity for the propeller
U_0	mean inflow velocity relative to a specified blade strip
$\tilde{u}$	velocity fluctuation in the turbulent inflow
C	chord length of blade strip
R	radius of the analyzed propeller
Ω	rotational speed of propeller
$\overline{\Omega}$	reduced frequency
Δp	pressure difference between the upper and lower surfaces of blade strip
Λ	integral length scale of turbulence
$\tilde{\alpha}^{\gamma}$	unsteady angle of attack of the γth strip of blade
ϕ^{γ}	mean flow angle of γ^{th} strip of blade
$r(\tau)$	instantaneous instance between fluid particles corresponding to different strips
M_s, K_s, C_s	the mass, stiffness and damping matrix of the structure
M_f, K_f, C_f	the coefficient matrix related to the fluid
S_{fs}	the coupling item related to the fluid and structure
$F_f(\omega)$	external loads exerted on the structure
$P_a(\omega)$	external pressure exerted on the fluids
$\delta(\omega)$	nodal displacement vector
$p(\omega)$	nodal pressure vector
$\tilde{q}(\omega)$	an intermediate variable
$\overline{q}_i$,$\overline{f}_i$	the generalized coordinate and generalized load associated the ith mode
ω_i and ϕ_i^N	the mode frequency and vector associated with the ith mode
f_s,f_{bi},f_t	the natural frequencies corresponding to the shaft vibration, blade bending and torsional vibration respectively
$S_{NM}^{F}(\omega)$,$S_{ij}^{\overline{f}}(\omega)$	force spectrum matrix in the physical and modal coordinate
$S_{NM}^{\delta}(\omega)$,$S_{ij}^{\overline{q}}(\omega)$	response spectrum matrix related to the physical and modal coordinate
$\overline{H}_j(\omega)$	complex frequency response function of structure
ρ_p, ρ_0	the density of the propeller material and water
E_p	the elastic modulus of the propeller material
k_s	the combined longitudinal stiffness of the thrust bearing and foundation
η_T, η_H, η_i	the total, hydrodynamic and mechanical loss factors
$\bar{l}_i(\overline{\Omega})$	modal oscillatory lift coefficient

et al., 2010) to evaluate performance of this kind of device. It is shown that force transmission can be altered by adjusting dynamic parameters of the resonance changer. Active control devices were also proposed to reduce the oscillatory axial shaft vibrations in ship shafting systems (Lewis and Allaire, 1989). Although there have been many investigations on the vibration and noise in shafting systems induced by unsteady propeller forces, few are focused on the vibration of marine propellers. In these researches, the propeller is often regarded as a rigid body in analyzing the unsteady transmitted thrust. This hypothesis is questionable as some early work indicated that the elasticity of blades can reduce the periodic propeller forces over a large frequency range, especially above the propeller's fundamental resonance frequency (Brooks, 1980; He et al., 2012; Jessup and Stuart, 1990). In modern submarine industry, the first natural frequency of a propeller blade can be lowered to several tens of hertz (Young, 2008). Therefore, once a propeller is subjected to broadband excitation distributed on its blades, elastic vibrations in the propeller and its shafting system is inevitable. In the early researches, only the periodic loading (induced by nonuniform wake) was considered and described

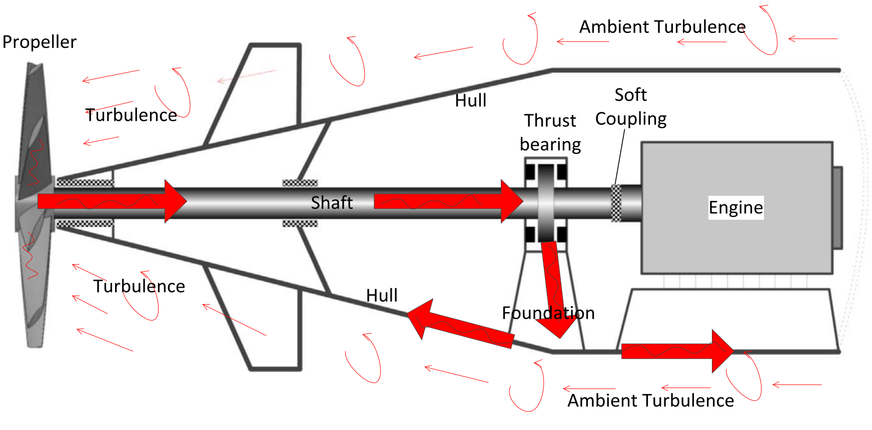

Fig. 1. The hull vibration induced by the unsteady longitudinal propeller thrust.