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Longitudinal vibration and unsteady thrust transmission of the rim driven thruster induced by ingested turbulence

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ABSTRACT

The longitudinal vibration characteristics of the rim driven thruster (RDT) induced by the ingested turbulence are numerically studied and compared with that of the traditional shaft driven propeller (SDP). The pressure spectrum acted on the blade surface is first computed using the correlation method based on strip theory and the statistical characteristics of isotropic turbulence. Appling the computed pressure spectrum as excitation, the random vibration response of the whole immersed thruster is obtained using the mode superposition method. The differences between the vibration responses, especially the longitudinal unsteady thrust transmission characteristics, of the two kinds of propulsors that have the same blade geometry are discussed. Computational results show that though RDT has lower hydrodynamic damping in the lower order bending modes, its resonant amplification on the unsteady thrust is still lower that of SDP for the lower modal force induced by the poor coincidence between the modal shape and space distribution of excitation. A potential merit of traditional SDP is that it has better attenuation effect on the unsteady thrust in the frequency band between the first and second bending modes of the propeller blade.

1. Introduction

The fluctuating forces at propulsor are an important cause of sound radiation from a submarine in the low frequency range (Ross, 1987). These unsteady forces consist of periodic force components and broadband force components (Abbas et al., 2015; Blake, 1986; Homicz and George, 1974). The periodic force components often occur at multiples of the blade passage frequency and are considered to the result from the unsteady pressure distribution on the propeller blades (Brooks, 1980; Homicz and George, 1974; Jessup and Stuart, 1990). The broadband force components often distribute from several to several hundred hertz, with some ‘hump’ around the first and second blade rate frequencies (Blake, 1986; Jiang et al., 1991; Sevik, 1970). Among which, the low frequency broadband forces are mainly due to the interaction of the inflow turbulence with the propeller blades. The turbulence is generated by the boundary layer of hull and all the appendages upstream of the propeller, superposed on the ambient free-stream turbulence.

When the unsteady thrust is transmitted to the hull via the shaft for its high stiffness (Merz et al., 2009; Wei and Wang, 2013), significant sound radiation will occur for the hull vibration. In order to minimize the sound radiation caused by the propeller forces, many controlling measures can be taken on the shaft system. For example, a hydraulic vibration attenuation device known as a resonance changer was implemented in the shafting system (Dylejkoa et al., 2007; Goodwin, 1960). The force transmission can be altered by adjusting the dynamic parameters of the hydraulic device. An Active magnetic control device has been proposed to reduce the oscillatory axial shaft vibrations in ship shaft transmission systems (Lewis and Allaire, 1989). The result showed that good control effect can be achieved for the periodic excitations. In addition to the controlling measures on the shaft, some earlier research (Brooks, 1980; Jessup and Stuart, 1990) indicated that the blade vibration itself may reduce the periodic propeller force with frequency higher than the propeller's fundamental resonance frequency. These behaviors may be important when pursuing more effective controlling measure on the unsteady thrust induced by the propulsor.

Compared with the traditional shaft driven propeller (SDP), the electric rim driven thruster (RDT) is a relatively new marine propulsor that has been developed in recent years. It uses a permanent magnet rotor built into a rim around the propeller (Abu Sharkh et al., 2001). The permanent magnetic rotor is embedded in a rim around the tips of the blade as shown in Fig. 1(a). The motor stator is mounted in the duct. The RDT has shown lots of advantages compared with the SDP, such as less energy loss due to the vanish of gap between blade and duct, more flexible installation due to the modular design and more

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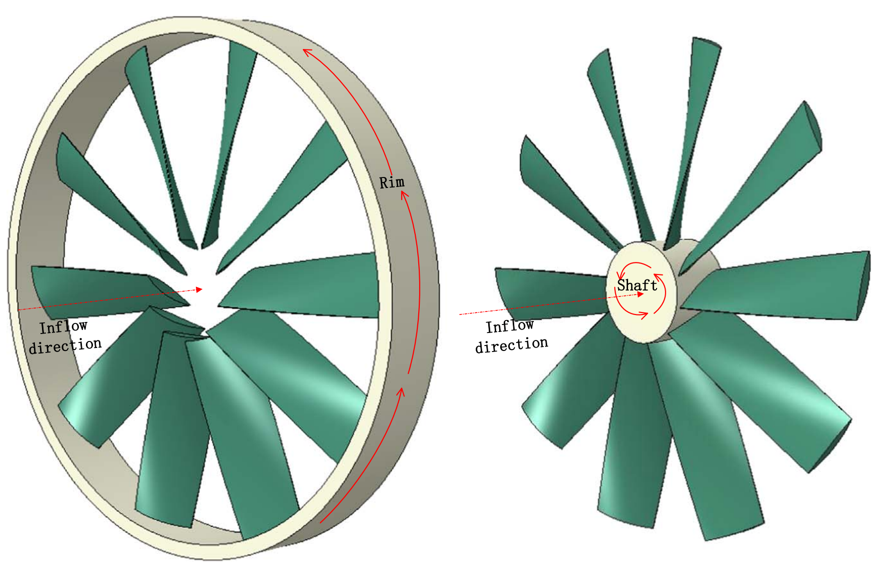
Nomenclature

$F_{ij}^{\alpha\beta}(t,\tau)$	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_∞	mean inflow velocity for the propeller
U_0	mean inflow velocity for a specified blade strip
$\tilde{u}$	velocity fluctuation in the turbulent inflow
C	chord length of blade strip
R	radius of propeller
w	width of flat plate (beam)
L_3	span of flat plate (beam)
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 γth 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
$q(\omega)$	an intermediate variable
$\overline{q}_i$,$\overline{f}_i$	the generalized coordinate and generalized load associated with the ith mode
ω_i,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 longitudinal shafting 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 in the physical and modal coordinate
$\overline{H}_j(\omega)$	complex frequency response function of structure.
ρ_p, ρ_0	the density of propeller material and water
E_p	the elastic modulus of propeller material
k_s	the combined longitudinal stiffness of the thrust bearing and foundation
η_t, η_h, η_m	the total, hydrodynamic and mechanical loss factors
$\overline{l}_i(\overline{\Omega})$	modal oscillatory lift coefficient
$L_i^p(\overline{r})$	chord-wise lift distribution function
$V_i(\overline{r},\omega)$	the Fourier component of vertical velocity on the blade surface
$V_i(\omega)$	modal velocity for the ith mode
$\overline{U}_0^e$	equivalent mean inflow velocity



(a) (b)

Fig. 1. (a) The rim driven thruster (RDT); (b) The traditional shaft driven propeller (SDP).

prompt steering (Hughes et al., 2000; Song et al., 2015). But as a candidate propulsor for future submarine, its vibration and acoustic characteristics have seldom been studied, which is essential for the stealth capability of submarine. As can be seen in Fig. 1, there is great difference between the blade configuration of RDT and traditional SDP. The difference in the structure inevitably changes the dynamic characteristics of the rotors. Therefore, how does the blade configuration influences the unsteady thrust transmission of the propulsors is worth studying. In this paper, the multimodal vibration response, especially the longitudinal unsteady thrust transmission of the RDT caused by the ingested turbulence inducing broadband excitation is numerically investigated. Meanwhile, the vibration response a SDP with the same