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On the use of bend–twist coupling in full-scale composite marine propellers for improving hydrodynamic performance

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ABSTRACT

Marine propellers are designed to work for a particular operating condition. However, a propeller often requires to operate at different off-design conditions, when its hydrodynamic efficiency drops. In this paper, a comprehensive numerical study is presented on the use of bend–twist coupling of composite propeller blades for improving their hydrodynamic efficiency at off-design conditions. The analysis is carried out on a full-scale propeller of diameter 4.2 m, considering the complete viscous turbulent flow, as the loading and deformation of model propellers that have been typically studied in literature for this purpose cannot be extrapolated to a full-scale prototype propeller. The open water performance is estimated using the finite volume method employing the pressure based RANS equation for the steady, incompressible, turbulent flow. The deformation analysis is done using the finite element method based on the first order shear deformation theory for composite laminates. The fluid–structure interaction is incorporated in an iterative manner. The effect of laminate configurations on the maximum twist achieved in the blade is studied for four different composite materials. The numerical study reveals that, within the limits of material safety, the twist generated in the deformed propeller using commonly used composite materials is inadequate to create any noticeable change in the hydrodynamic efficiency. When the material failure is ignored, however, it is possible to generate sufficient deformation and twist that can cause appreciable improvement in the hydrodynamic performance.

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1. Introduction

A propeller is generally designed to operate for a particular velocity of advance and revolutions per minute, where it delivers the maximum hydrodynamic efficiency. In many situations, propellers are required to operate at off-design conditions, when its efficiency is compromised. For example, tugs and trawlers may or may not pull loads, ships may move in high sea conditions or a frigate may operate at a fast attack mode or a cruising speed. The angle of attack of the incoming flow to the propeller depends on the ratio of velocity of advance and its rotational speed. The pitch of the propeller blade is so designed that it receives flow at the optimum angle of attack. At off-design conditions, the angle of attack becomes sub-optimum and its hydrodynamic efficiency drops. The pitch can be altered in a controllable pitch propeller and it can remain efficient at different operating conditions (Das et al., 2012). It is well known that the metallic propellers (fixed pitch) are

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Nomenclature

A_{ij}	extensional stiffness matrix
a	length of plate
B_{ij}	coupling stiffness matrix
C	damping
Cp	pressure coefficient
$C\mu$	constant of $k\epsilon$ turbulence model
D	diameter of propeller
D_{ij}	bending stiffness matrix
E_i	Young's modulus along ith direction
F	force
G_{ij}	shear modulus
h	thickness of plate
J	advance ratio
k	kinetic energy of turbulence
K_t	coefficients of thrust
K_q	coefficients of torque
L	number of lamina in composite laminate
M_I	component of moment/twist per unit length
$[M]$	mass matrix
N_i	components of force resultants per unit length
$[N]$	shape function
n	revolution per second for propeller
P	pitch of propeller blade
p	pressure
$\bar{p}$	time averaged pressure
Q'	torque of propeller
Q	stiffness
$\bar{Q}$	stiffness for generally orthotropic condition
Q^e	element stiffness matrix
Q_g^e	element geometrical stiffness
$\mathbf{r}$	position vector
S_{Ui}	source term in transport equation
S	shear strength of composite lamina
T	thrust of propeller
t	thickness of propeller blade
U_i	ith component of velocity
$U\infty$	free-stream velocity
$\bar{U}$	time-averaged velocity vector
u_x, u_y, u_z	displacements
u'	fluctuating component of velocity
V	volume of element
v_f	volume fraction of fibre
$\hat{u}_z$	non-dimensionalised deflection
X_T	tensile strength in fibre direction for composite lamina
Y_T	tensile strength in normal to fibre direction for composite lamina
α	angle of attack
β	angle of resultant flow with propeller plane
ε	rate of dissipation of turbulent kinetic energy
$\varepsilon_i, \varepsilon_{ij}$	normal and shear strains
κ	curvature
θ	angle of orientation of fibre for composite
η	efficiency of propeller
μ	coefficient of viscosity
ϑ_{ij}	Poisson's ratio
Ω	rotational velocity vector
φ_i	rotational displacement in ith direction for plate
ψ	pitch angle
ρ	density of medium
σ_1, σ_2	normal stress in material direction in a composite lamina
σ_x, σ_y	normal stress in respective direction
τ_{12}	shear stress in material direction in a composite lamina
τ_{xy}	shear stress component

rigid enough to hold its shape under hydrodynamic loading and can only give the maximum efficiency for a particular operating condition. In layered fibre reinforced composite materials, however, the fibre orientations of the layers can be designed so as to generate bending–twisting coupling. This coupling can be used to get a twist of the propeller blade from the bending deformation under the hydrodynamic loading. The twist alters the pitch of the propeller and hence the angle of attack. This paper presents a comprehensive numerical study of the response of composite propellers at different operating conditions with a view to critically examine the effect of twisting of blades due to the bend–twist coupling on the hydrodynamic efficiency, and to explore if it can be used to improve the efficiency at off-design conditions.

The analysis of composite propellers to exploit the advantage of its flexibility and tailorability began towards the end of last century. Lin (1991) presented a numerical analysis of a three-dimensional (3-D) composite marine propeller using the commercial finite element method (FEM) software ABAQUS for the stress analysis and the PSF-2 code based on the vortex-lattice method (VLM) for computing the hydrodynamic loading. No effect of the deformation on the hydrodynamic loading was considered. The stresses and hydrodynamic performance were compared with those of a geometrically identical isotropic propeller. Lin and Lin (1996) presented a coupled 3-D FEM/VLM method for the hydroelastic analysis of metallic marine propellers, considering geometrical non-linearity for estimating the deformed shape of the propeller. Lee and Lin (2004) presented an optimum design of composite propeller blades for operating at design as well as off-design conditions, considering the effect of their deformation. The PSF-2 code was used for the fluid flow analysis and the FEM for deformation analysis. They used graphite-epoxy laminates composed of 0°, 45° and 90° plies and determined the optimum sequence of plies for maximising the twist of the blade, which in turn affects the torque requirement of the propeller. Their study, however, is made on a 0.305 m diameter model propeller. It ignores the viscosity and does not check for material failure. Extensive studies of composite propellers have been carried out by Young (2008). He used a panel based BEM method for the flow analysis, instead of the VLM used by his predecessors. The hydrodynamic pressure distribution due to rigid blade rotation is computed via the BEM, which is then applied as external normal surface traction for the FEM model to obtain the

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