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On the fluid structure interaction of a marine cycloidal propeller

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ABSTRACT

Marine cycloidal propulsion system is efficient in maneuvering ships like tugs, ferries, etc. It is capable of vectoring thrust in all direction in a horizontal plane. When used in pair, the system enables a vessel to perform maneuvers like moving sideways, perform rotation about a point, i.e. turning diameter of its own length, etc. In this system, the propeller blades have to change their angle of attack at different angular position of the disc. Due to this reason, the inflow velocity vector to propeller blades changes continuously. The propeller blade oscillates about a vertical axis passing through its body and at the same time rotates about a point. Superposed on these motions is the dynamics of the ship on which the propulsion system is installed. This results in a formidable and challenging hydrodynamics problem. Each of the propeller blade sections could be considered as an aerofoil operating in combined heave and pitch oscillation mode. Due to the constantly varying inflow velocity, the hydrodynamic flow is unsteady. The unsteady hydrodynamic flow is simulated by incorporating the effect of shed vortices at different time instant behind the trailing edge. Due to the kinematics of the problem, the blade is subjected to higher structural deformation and vibration load. The structural deformation and vibration when coupled with the hydrodynamic loading add another level of complexity to the problem. In this paper, the variation of hydrodynamic load on the propeller blade due to steady and unsteady flow is compared. We also model the structural dynamics of the blade and study its effect on the hydrodynamic loading. Finally, we couple the structural dynamics with hydrodynamics loading and study its influence on the propeller blade for different operating regimes.

1. Introduction

In marine cycloidal propulsion system, the propulsion and maneuvering units are combined together as a single unit. Therefore, no separate rudder is required to maneuver the ship. Marine Cycloidal Propellers (MCP) is fitted in pairs. Each unit consists of five to six blades. The location of the two propellers depends upon the type of ship. In ferries, the propellers may be fitted one forward and one aft, which would allow the vessel to move sideways or to turn within a circle of its own length. In a pusher tug, they may be fitted side by side at the stern, whereas in a tractor tug, the propellers may be fitted side by side at the bow. MCP has larger swept area. This makes the rotational speed of MCP about 75% less than the speed of the normal conventional propeller of comparable size and power [17]. The other benefit is reduced thrust loading which delays cavitation inception. The blades of MCP are arranged vertically on the periphery of a rotating disc. Therefore, the inflow velocity remains same throughout the length of the blade. Therefore, no twist is required on blades, unlike the conventional marine screw propellers. However, the inflow velocity to the blades changes at the different angular position of the disc. This makes the flow unsteady. The angle of attack of the blade has to be changed continuously, due to the continuous variation in the inflow velocity. Therefore, the thrust generated by each blade varies with time. Due to this reason, the load variations on each one of the cycloidal propeller blades is high. This variation increases during maneuvering when the vessel has motions in different degrees of freedom. This time varying load can lead to vibration and fatigue failure of the propeller blade and its components. The varying inflow velocity vector also gives an opportunity to optimize the hydrodynamic performance of the propeller blade. The operating variables are very high for marine cycloidal propeller. It is difficult to achieve the above objectives by carrying out experiments. A huge number of experiments will be required for this purpose. To achieve the above objectives a good fluid structure coupled model for the cycloidal propeller system is required. Such a model will be helpful in the design and development of this propulsion system. The arrangement of a typical cycloidal propeller on a ship is shown in Fig. 1.

Allan and Molyneux [1], presented the hydrodynamic performance of three different combinations of hull shape, appendages

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Nomenclature

A	Exposed area of blade (m^2)
C_D	Coefficient of drag
C_L	Coefficient of lift
C_M	Coefficient of moment
C_P	Coefficient of pressure
c	Chord length of blade (m)
D	Drag force (kN)
d	Depth from free surface to the propeller surface (m)
$d\Gamma$	Change in shed vortices
g	Acceleration due to gravity (m/s^2)
k	Reduced frequency
L	Lift force (kN)
N	Number of panels
$N.F$	Normal chord force on blade (kN)
n	RPS of propeller
$\vec{P}$	Distance vector from blade stock to midpoint of panels
P_A	Atmospheric pressure (101.325 kN/m^2)
P_V	Vapour pressure (1.704 kN/m^2)
Q	Hydrodynamic torque (kN m)
$q(s)$	Source strength per unit length (m/s^{-1})
R	Radius of the propeller disk (m)
r, θ	Polar coordinates of the field point
s	Length of panel (m)
V_A	Advance velocity of ship (m/s)
V_R	Onset flow to the blade (m/s)
x, y	Field point
α	Angle of attack to the blade (deg)
$\gamma(s)$	Vortex strength per unit length (m/s^{-1})
ξ	Angle of line joining the vortex shed point and panel
θ	Angular position of disc (deg)
λ	Advance coefficient of ship
μ	Load coefficient of propeller
ρ_w	Density of sea water (1025 kg/m^{-3})
σ	Angle of line joining the stock point and panel
ϕ_B	Potential due to the pitching motion of blade
ϕ_s	Potential due to the source
ϕ_v	Potential due to the vortices
ϕ_Γ	Potential due to shed vortices
ϕ_∞	Potential due to the uniform onset flow
ψ	Inflow angle to the blade (deg)
Ω	Cavitation number
ω_f	Pitching rate of propeller blade (rad/s)
ω_p	Rotational speed of propeller (rad/s)

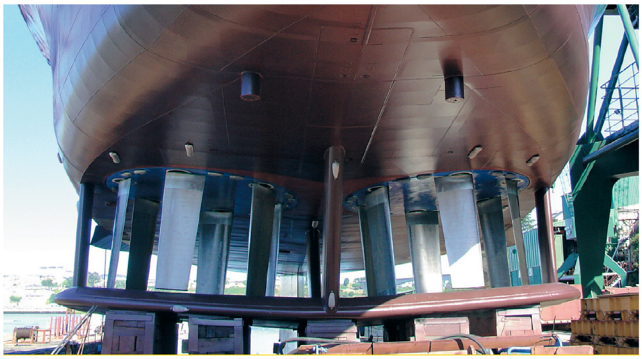

Fig. 1. Typical set up of MCP on a ship.

and propulsion system, and discussed the effectiveness of alternative design solutions for escort tugs with specified steering force requirements. They found there is no significant difference between the hydrodynamic forces of the combined hull and propulsion systems tested for the three tug concepts tested as part of the project. The specified steering force (for example, 150 t) can be achieved by all of the concepts, provided that the hull is designed to provide the appropriate level of stability. Barrett et al. [2] experimentally computed the force and power on robotic fish. They demonstrated that the power required to propel an actively swimming, streamlined, fish-like body is significantly smaller than the power needed to tow the body straight and rigid at the same speed. The unsteady motion of a body offers possibilities for more efficient propulsion as compared to conventional steady propellers. It has been shown that unsteady motion of airfoils result in higher lift coefficient and produce propulsive thrust very efficiently. Haberman and Harley [7] used Taniguchi method to compute the performance characteristics of vertical axis propellers having cycloidal blade motion and semi-elliptic blades. Taniguchi method is based on the assumption that only the induced velocities due to the trailing vortex in the direction of propeller advance contributes to the thrust and torque of the propeller. The vortex remains constant over the length of blade. The value of the induced velocity is obtained from momentum considerations with modifications based on experimental performance of a six-bladed vertical axis propeller. It is found that the thrust and torque of each blade and the maximum efficiency of the propeller decreases with increase in number of blades of same dimensions.

Jurgens and Heinke [10] studied the cavitation behaviour of heavily loaded Voith Schneider Propeller (VSP) blades under bollard pull condition. Experiments were carried out with different profile shapes of the VSP blades. A new blade profile (P9659) was developed using a numerical optimisation strategy based on CFD calculation. The blade profile showed improved cavitation behaviour. Jurgens and Palm [11] studied the influence of the Voith Schneider Propeller (VSP) on stern slamming conditions, the roll damping capabilities and the impact of air ventilation. Investigations were carried out using experiments and computational fluid dynamics and compared with the results of azimuth thrusters. It is found that the VSP has a reduced impact of pressure loads due to stern slamming. The VSP uses positively the slamming behaviour of a vessel because of its vertical rotating axis. Additionally the VSP can be used to reduce the roll motion of a vessel. When used in this configuration it is called as Voith Roll Stabilization System. The VSP provides effective functionality for roll damping besides propulsion and steering. Palm et al. [12] compared the ventilation characteristics of azimuth thrusters with Voith Schneider propeller. Experiments were carried out and results supported with CFD numerical simulation. They found that the cycloidal propeller is less prone to ventilation than the azimuth thrusters.

Sfakiotakis et al. [13] presented the fish swimming types and specific swimming modes. The study is made on the propulsor and the type of movements (oscillatory or undulatory) employed for thrust generation. The locomotion by angelfish is similar to rowing action consisting of two phases, the power and recovery stroke. In power stroke, the fins move perpendicular to the body at a high attack angle and with a velocity greater than the overall swimming speed. During recovery stroke, the fins are feathered to reduce resistance and brought forward. In MCP also, the blades are making the power and recovery stroke as the blades moves backward and forward respectively. In angel fish locomotion no thrust is generated in recovery stroke but in MCP a nominal thrust is generated. Stefan et al. [14] carried out a study to demonstrate the capability of a cycloidal propeller to use unsteady dynamic lift for operation. The investigation was carried out at Reynolds numbers ($Re = 10^3$) based on the chord length. The thrust production and energy extraction