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Development and optimization of dual-mode propellers for renewable energy

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ABSTRACT

Propeller as both propulsion and turbine device has been used for many marine vehicle renewable energy applications, especially for sailing boats and yachts. However, dual-mode propellers in these applications were mainly selected from off-the-shelf with little or no hydrodynamic performance optimization coupling propulsion and energy generation efficiency on the same rotor. To address this issue and provide some scientific evidence and data for the design of the towed propeller shaft alternator, a dual-mode rotor series, as an example, in terms of a balanced propulsion and energy generation were evaluated and optimized. Previous experimental data for these rotors was used for code validation, to ensure a reliable and accurate prediction of the effects of pitch and solidity on performance. The results obtained indicate that the optimized fixed pitch propeller could perform as propulsion and tidal/current turbine with a balanced efficiency in both modes for low speed ships, especially for yachts. The balanced relatively high power productivity and propulsive performance are achievable for low speed ships anchored in a current or a regular sail boat for which a propeller is used as a towed turbine.

1. Introduction

A healthy and sustainable electricity supply is the core competency of the economy and prosperity of a nation. Power source sustainability and emission reduction require renewable energy gradually replace the fossil fuel energy sources. In a recent independent expert panel report on the Australian national electricity supply for the Australian Government led by the Australian Chief Scientist Finkel [8], it indicates that the electricity supply in Australia is the largest single source of emissions and therefore it would be the main target for emission control. It also indicated that by 2030, renewable energy sources will contribute 42% electricity supply in Australia. With the increase of renewable energy in the grid, the reliability of power supply becomes an issue due to the energy generated from wind and solar. As tidal energy is dependent on the motion of the earth and moon, it is more predictable and reliable than the wind and solar sources. Among the renewable energy sources, tidal has also the lowest environmental impact [7].

There are a number of recently studies on tidal turbine performance improvement and optimization. Allmark et al. [2] developed a parametrisation scheme to define cyclic variations of generated torque for tidal stream turbine to response to severe loading mechanisms. Nan at al. [28] suggested a contra-rotating small hydro-turbine design method to increase the power generating efficiency by investigating the internal flow condition numerically and experimentally. To increase the power generation efficiency, Gu at al. [11] designed a pitch-control system using rack and pinion gear set to provide an pitch angle envelope of 0–180°. In their work, a tidal current velocity preview (CVP) method was developed to adjust the pitch angle for the optimum power generation efficiency. Ahn at al. [1] prototyped a turbine and performed power generation optimization using two-phase simulation model consisting of a turbine unit and two reservoir models. Examples of tidal turbine related technologies, in addition, include the converging nozzles [17] and micro hydro turbine [18].

The concept of using the same propeller-rotor to perform both propulsion and energy generation is not new. In fact propeller as both propulsion and turbine device has been used in some marine

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Nomenclature

A	Area of rotor disk, $A = \pi R^2$, m^2
A_o	Area of blades, m^2
AoA	Angle of attack, ° or *rad*
NAB	Nickel-Aluminium-Bronze
$c_{0.7R}$	Blade chord length at $r = 0.7R$, m
D	Propeller-rotor diameter, m
n	Propeller-rotor shaft speed, revolution per second, rps
N	Propeller-rotor shaft speed, revolution per minute, RPM
R	Propeller-rotor radius, m
V_a	Propeller-rotor shaft or ship advance speed, m/s
J	Advance coefficient, $J = \frac{V_a}{nD}$
U.S.	Upper side of blade sectional profile
L.S.	Lower side of blade sectional profile
L.E.	The leading edge of a blade section
T.E.	The trailing edge of a blade section
ρ	Fluid density, kg/m^3
T	Propeller shaft thrust, N
K_T	Propeller shaft thrust coefficient, $K_T = \frac{T}{\rho n^2 D^4}$
Q	Propeller shaft torque, $N \cdot m$
K_Q	Propeller shaft torque coefficient, $K_Q = \frac{Q}{\rho n^2 D^5}$
p	Blade pitch, m
p_D	Blade pitch diameter ratio
$p_{D_{0.7R}}$	Blade pitch diameter ratio at $r = 0.7R$
EAR	Propeller expanded area ratio or rotor disk solidity $EAR = \frac{A_o}{A}$
Z	Number of blades
h_D	Hub diameter to rotor diameter ratio
α_p	Geometric angle of blade section, Rad or deg
α'_v	Resultant angle of inflow velocity with added induced velocity, Rad or deg
α_o	Angle of zero lift of blade section, Rad or deg
α_e	Effective angle of attack of blade section, Rad or deg
V_{prop}	Propeller-rotor relative speed to fluid, m/s
μ	Fluid dynamic viscosity, $N \cdot s/\mathrm{m}^2$
ν	Fluid kinetic viscosity, μ/ρ, m^2/s
$V_{resultant}$	$=\sqrt{(0.7R\omega)^2 + V_{in}^2}$, Resultant velocity at $r = 0.7R$, m/s
V_a	Inflow velocity $V_{prop} = -V_a$, m/s
V'_a	Inflow velocity with added induced velocity, m/s
V_t	Induced tangential velocity at the rotor disk plane, m/s
V_x	Induced axial velocity at blade section, m/s
TSR	Tip speed ratio $TSR = \frac{2\pi nR}{V_{in}} = \frac{\pi}{J}$
R_n	Reynolds number, $Rn = \frac{VL}{\nu} = \frac{\sqrt{(0.7R\omega)^2 + V_a^2}\, c_{0.7R}}{\nu}$
Q	Shaft torque, $N \cdot m$
T	Thrust or drag on shaft, N
C_t	Rotor thrust/drag coefficient, $C_t = \frac{T}{\frac{1}{2}\rho V_a^2} = \frac{8K_t}{\pi J^2}$
C_{pow}	Rotor power coefficient, $C_{pow} = \frac{P}{\frac{1}{2}\rho V_a^3 A} = \frac{16K_q}{J^3}$

installations, for example, for sailing boats and yachts. However, propellers used in these applications are often selected from off-the-shelf propellers with little or no hydrodynamic performance optimization coupling both propulsion and energy generation efficiency on the same rotor. Reports on of this kind of development in the technical literature, have not been found by the authors and appeared to be rare.

In this study, a series of bi-directional propellers yet performing as turbines to generate renewable energy were prototyped, designed and optimized, for a compromised and coupled optimum power generating efficiency and propulsive efficiency.

This study then investigated the hydrodynamic feasibility of a series of dual-mode rotors in terms of propulsion efficiency and power coefficient. In the design and optimization, a panel method code Propella was enhanced and used as a tool to produce the required predictions and to establish a performance database. The following is the brief review of the developments on the panel methods for both propeller and tidal turbine.

Panel methods, are called the boundary element methods, or boundary integral methods (BEM in short as well). Lifting surface and panel methods have been widely used in research and development of aircraft wings, hydrofoils and both aerial and marine propellers. Zero thickness propeller blade simulated and computed by lifting surface theory in the computational fluid dynamics (CFD) field has a history of over 60 years. The use of the surface panel method for a simple body surface mesh can be traced back to the early 1960s. Hess and Vararezo [13] made the first panel method computation for propellers in literature. To deal with complete aircraft geometry, panel method codes, PMARC (Panel Method Ames Research Center) developed by Katz [16] and VSAERO by Maskew [27] are the early examples of panel methods for aircraft wings and propellers. On the other hand, panel methods have also been used for marine propeller research development and early examples among those are publications by Greeley and Kerwin [10] and Hoshino [14], just to name a few. A time domain unsteady panel method code OSFBEM (oscillating foil boundary element method) was developed by Liu for oscillating propulsors of both chordwise and spanwise flexibility to simulate propulsion of marine animals [19].

For wind or tidal turbine research and development, various computational methods have been extensively established and widely used. A comprehensive review of these methods and their merits and limitations, for example, was given by Nicholls-Lee et al. [29]. Among these methods, the panel methods, in the most advanced and complicated method group, have both high computing efficiency and prediction accuracy as an engineering tool for turbine simulation and design optimization. While probably the blade element methods (BEM) are the most widely used as preliminary simulation tools for wind and tidal turbines, much fewer penal methods could be found for turbine in literature. To the authors knowledge, these few panel methods for turbine simulation and prediction include a 2D panel method by Drela et al. mentioned in Ref. [29], a 3D time domain panel method for wind turbine by Hampsey [12], a rudder-propeller interaction panel code by Turnock [6] and a design based simulation work by Greco et al. [9].

Panel methods have been also used for oscillating foil turbines. Liu [22] developed an innovative tidal turbine by utilizing the wing-in-ground effect to maximize the renewable energy generation efficiency and minimize the requirement kick-in speed.