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# On the heuristic based electronic control of marine cycloidal propeller

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ABSTRACT

The design and feasibility of electronically controlled Marine Cycloidal Propeller (MCP) by implementing heuristic-based approach is demonstrated. Adding closed-loop control enhances performance. This is shown by simulation. The chances of improving efficiency are more in electronically controlled MCP, as pitch angle of each blade can be independently controlled. Multiple configurations of MCP can be anchored within the same model without changing hardware. Simulations are used to finalize the technical specifications of the system. Experimental results demonstrate the acceptable trajectory generation (using online feedback) and synchronizations of all instruments.

## 1. Introduction

The idea of using a rotating plate with a few vertically mounted vanes rotating about their self-axes originated many years ago without proper mathematical calculations. Some examples are "Feathering propellers" [1] and "Paragon Propeller" (Durtnall) [1]. Kirsten [1] derived the first mathematical model of compound motion of cycloidal propeller. It was then proposed as Kirsten-Boeing (hereafter KB) propeller. In KB propeller, the trajectory of a blade is similar to the motion of a bird's wing [1]. Schneider [2] suggested at about the same time, a new design of cycloidal propeller. This design was thereafter known as Voith-Schneider (hereafter VS) propeller. Later, additional research was performed to investigate the performance of the cycloidal propeller by Nakonechny [3], Haberman and Harley [4], Ficken and Dickerson [5], Bose and Lai [6]. The measured quantities such as hydrodynamic thrust, hydrodynamic torque, side force and propulsive efficiency were represented as the function of the advance coefficient, blade pitch angle and eccentricity ratio. Sinusoidal and modified cycloidal motions of the blade were introduced to investigate the optimum motion pattern. It was concluded that the cycloidal propeller might be less efficient than screw propeller, but it could develop higher forces during maneuvering, backing, crabbing and crash stop conditions. Sparenberg and Degraaf [7], numerically computed the efficiency of one bladed (untwisted) cycloidal propeller having trochoidal motion($\lambda > 1$). The pitching motion of the blade was optimized by neglecting the influence of other blades. The outputs of mathematical analysis were bound and free vorticity, thrust, velocity potential, kinetic energy, normal velocity and angle of incidence. In Marine Cycloidal Propeller (hereafter MCP), the magnitude and direction of thrust are developed due to controlled pitching motion of the blades. So far, in most of the design of the cycloidal propeller in literature, the control mechanism of each blade consists of a precise and robust mechanical gear arrangement. Each one of the blades is interlinked to a steering centre. The pitching motion of the blade is dependent on the location of the steering centre. Each blade moves in a predefined pattern depending on the gear configuration, which in turn depends on the steering centre.

In aerodynamic application, the cycloidal propeller has been used in the form of a cyclorotor. Kim et al. [8] examined the effect of different parameters namely number of blades, rotor radius, eccentricity and rotating speed on the performance characteristics of the cycloidal propeller. Along with that, the aerodynamic characteristic was evaluated by CFD analysis of cycloidal propeller having the control rod mechanism to control the flapping of blades. The outcome of the investigation was that the thrust and power were proportional to the square and cubic power of rotational speed. Nozaki et al. [9] performed experiments to evaluate the generation of thrust and consumption of power by a cycloidal propeller. The cycloidal propeller was installed on an airship model. Pitch angles were mechanically controlled. A fairing with NACA 0024 shaped blade was connected with each driving arm and winglets were incorporated with wings to improve its efficiency. They found that the rate of increment of thrust was higher at high rotational speed. Jurgens et al. [10–12] investigated Voith-Schneider propeller experimentally and computationally for dynamic positioning applications. The performance of VSP was compared with contra-rotating z-drives and azimuth thrusters. The enhancement in efficiency was obtained by optimizing the blade profile. However, the new profile of blade had a higher mass. Endplates were equipped with VSP blades to reduce the development of tip vortex and minimize noise and

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## Nomenclature

| | |
|---|---|
| $\begin{Bmatrix}S\\P\end{Bmatrix}$ | Starboard or port propeller |
| $a$ | Chord Length of blade (m) |
| $C_D$ | Coefficient of Drag |
| $CF$ | Centrifugal force (N) |
| $CG$ | Centre of gravity of blade aerofoil section |
| $C_L$ | Coefficient of lift |
| $C_M$ | Coefficient of moment |
| $CP$ | Centre of pressure |
| CCW | Counterclockwise direction |
| CW | Clockwise direction |
| $d_{i\|b}$ | Inner diameter of the bearing used for blade in experiment (m) |
| $d_{o\|b}$ | Outer diameter of the bearing used for blade in experiment (m) |
| $dt$ | Time step (s) |
| $D$ | Diameter of disc (m) |
| $D_{i\|d}$ | Inner diameter of the bearing used for disc in experiment (m) |
| $D_{o\|d}$ | Outer diameter of the bearing used for disc in experiment (m) |
| $e$ | Eccentricity ratio |
| $e_1$ | The distance of eccentricity point along Y-axis from disc centre in disc co-ordinate system (m) |
| $e_2$ | The distance of eccentricity point along X-axis from disc centre in disc co-ordinate system (m) |
| $f_C$ | Control frequency (Hz) |
| $f_S$ | Simulated frequency (Hz) |
| $F_{D\begin{Bmatrix}S\\P\end{Bmatrix}}$ | Drag force on propeller blade (N) |
| $F_{x\begin{Bmatrix}S\\P\end{Bmatrix}}$ | Component of thrust on the disc along the X-axis in disc co-ordinate system (N) |
| $F_{y\begin{Bmatrix}S\\P\end{Bmatrix}}$ | Component of thrust on the disc along the Y-axis in disc co-ordinate system (N) |
| $G$ | Torsional modulus of rigidity of solid steel shaft |
| $I_b$ | Mass moment of inertia of the blade about z-axis (kg-m$^2$) |
| $I_d$ | Mass moment of inertia of the disc about the z-axis (kg-m$^2$) |
| $K_D$ | Derivative gain of the blade controller |
| $K_{I1}$ | Integral gain of the blade controller due to blade pitch angle |
| $K_{I2}$ | Integral gain of the blade controller due to blade orbit angle |
| $K_P$ | Proportional gain of the blade controller |
| $L_{\begin{Bmatrix}S\\P\end{Bmatrix}}$ | Lift force on blade (N) |
| $M_B$ | Mass of the propeller blade (kg) |
| $M_D$ | Mass of the propeller disc with all accessories including blade and machinery (kg) |
| $N_B$ | Rotational speed of propeller blade (rpm) |
| $N_{D\begin{Bmatrix}S\\P\end{Bmatrix}}$ | Rotational speed of propeller disc (rpm) |
| $O$ | Centre of propeller disc |
| $P$ | Steering centre |
| $Q_{\begin{Bmatrix}S\\P\end{Bmatrix}}$ | Hydrodynamic torque on propeller disc (N-m) |
| $r$ | Radius of the propeller blade shaft (m) |
| $r_b$ | Average radius of propeller blade bearing (m) |
| $R$ | Radius of propeller disc (m) |
| $R_d$ | Average radius of propeller disc bearing (m) |
| $R_{TS}$ | Resistance force on ship (N) |
| $Rn$ | Reynolds number of propeller disc |
| $SP$ | Stock position of the blade |
| $t$ | Time (s) |
| $t_{cycle}$ | Time required for one complete rotation of the disc (s) |
| $t_{delay}$ | Initial delay period (s) |
| $t_1$ | Time required for 1$^{st}$ half movement of the blade (s) |
| $t_2$ | Time required for 2$^{nd}$ half movement of the blade (s) |
| $T_{x\begin{Bmatrix}S\\P\end{Bmatrix}}$ | Thrust acting on the blade stock along the X-axis of disc co-ordinate system (N) |
| $T_{y\begin{Bmatrix}S\\P\end{Bmatrix}}$ | Thrust acting on the blade stock along the Y-axis of disc co-ordinate system (N) |
| $V_O$ | velocity of ship (m/s) |
| $V_R$ | Resultant inflow velocity on blade (m/s) |
| $V_{T\begin{Bmatrix}S\\P\end{Bmatrix}}$ | Tangential velocity of propeller disc (m/s) |
| $v_x$ | X component of velocity of ship (m/s) |
| $v_y$ | Y component of velocity of ship (m/s) |
| $z_i$ | Index pulse signal of the encoder connected to blade motor |
| $Z$ | Number of propeller blades |
| $\alpha_{\begin{Bmatrix}S\\P\end{Bmatrix}}$ | Angle of attack of blade (deg) |
| $\beta_{\begin{Bmatrix}S\\P\end{Bmatrix}}$ | Index pulse signal of the encoder connected with propeller disc motor |
| $\theta_{\begin{Bmatrix}S\\P\end{Bmatrix}}$ | Blade orbit angle (deg) |
| $\dot{\theta}_{\begin{Bmatrix}S\\P\end{Bmatrix}}$ | Angular velocity of propeller disc (rad/sec) |
| $\delta_{\begin{Bmatrix}S\\P\end{Bmatrix}}$ | Pitch angle of propeller blade (deg) |
| $\dot{\delta}_{\begin{Bmatrix}S\\P\end{Bmatrix}}$ | Angular velocity of propeller blade (rad/sec) |
| $\ddot{\delta}_{\begin{Bmatrix}S\\P\end{Bmatrix}}$ | Angular acceleration of propeller blade (rad/sec$^2$) |
| $\delta_{Error}$ | Error in pitch angle for a propeller blade (deg) |
| $\delta_{step}$ | Step angle of blade stepper motor (deg) |
| $\lambda$ | Advance coefficient of propeller disc |
| $\Delta t$ | Time difference between the two consecutive achievable angles (s) |
| $\tau_{\begin{Bmatrix}S\\P\end{Bmatrix}}$ | Torque on the stock of a single blade (N-m) |
| $\tau_{BF\begin{Bmatrix}S\\P\end{Bmatrix}}$ | Torque due to bearing friction on propeller blade (N-m) |
| $\Gamma_{BF\begin{Bmatrix}S\\P\end{Bmatrix}}$ | Torque due to bearing friction on propeller disc (N-m) |
| $\tau_{CG\begin{Bmatrix}S\\P\end{Bmatrix}}$ | Torque on blade due to centrifugal force (N-m) |
| $\Gamma_{CG\begin{Bmatrix}S\\P\end{Bmatrix}}$ | Torque on propeller disc due to centrifugal force (N-m) |
| $\tau_{ENCD\begin{Bmatrix}S\\P\end{Bmatrix}}$ | Torque of encoder mounted on motor connected to the blade (N-m) |
| $\Gamma_{ENCD\begin{Bmatrix}S\\P\end{Bmatrix}}$ | Torque of encoder mounted on motor connected with propeller disc (N-m) |
| $\tau_{EMF\begin{Bmatrix}S\\P\end{Bmatrix}}$ | Electromagnetic torque of motor connected to the blade (N-m) |
| $\Gamma_{EMF\begin{Bmatrix}S\\P\end{Bmatrix}}$ | Electromagnetic torque of motor connected with propeller disc (N-m) |
| $\Gamma_{FF\begin{Bmatrix}S\\P\end{Bmatrix}}$ | Torque due to fluid friction on the propeller disc (N-m) |
| $\tau_{LD\begin{Bmatrix}S\\P\end{Bmatrix}}$ | Torque on single blade due to hydrodynamic Lift and Drag force (N-m) |
| $\tau_{stiffness\begin{Bmatrix}S\\P\end{Bmatrix}}$ | Torque due to the stiffness of blade shaft (N-m) |