Performance Evaluation of an Underwater Vehicle Equipped with a Collective and Cyclic Pitch Propeller

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Abstract: This paper presents modelling and simulation of an underwater vehicle equipped with a collective and cyclic propeller (CCPP). A CCPP has been applied in helicopters and it generates both axial and side thrusts that move a helicopter in all directions. If axial and side thrusts of the CCPP are controlled as desired it is possible to apply the CCPP to an underwater vehicle. A new CCPP has been designed and fabricated for a torpedo shaped underwater vehicle. Captive experiments were conducted to quantify the performance of the CCPP. The paper reports recent development of an underwater vehicle equipped with the CCPP including design and fabrication of the experimental facility, conduct of experiments, modeling, performance of the CCPP and simulation of the vehicle propelled by the CCPP.

Keywords: Underwater vehicle, modelling, simulation and collective and cyclic pitch propeller

1. INTRODUCTION

Underwater vehicles have been designed for subsea exploration and missions over many years. They have various types and are equipped with different types of propulsion and control system. They have a wide range of shapes. The torpedo shaped (streamlined) ROVs/AUVs are often equipped with a propeller and several control planes and rudders at bow and stern, while the non-torpedo shaped ROVs/AUVs are equipped with a number of thrusters.

A typical streamlined ROV/AUV has a propeller installed at the stern and four control planes as in Fig. 1(a) or eight control planes as in Fig. 1(b). In some cases there are tunnel thrusters to improve AUV manoeuvrability (Evans, 2003).

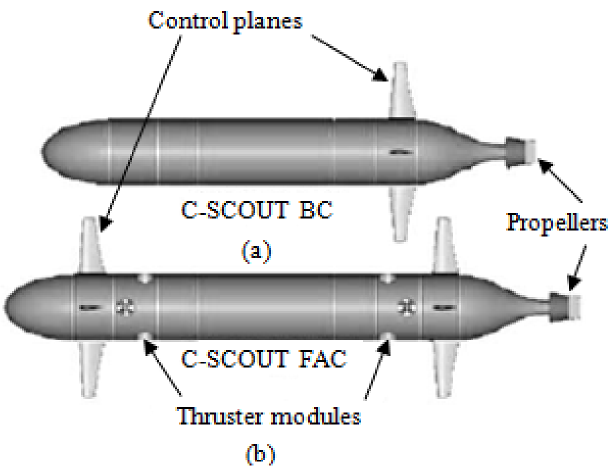

Fig. 1 A typical conventional propulsion system for a streamlined ROV/AUV (Perrault, 2002 and Evans, 2003).

The main feature of a conventional propeller for a ROV/AUV is that the propeller generates only axial thrust (drag). Thus the ROV/AUV is allowed to move forward and backward only. In order to move the ROV/AUV up and down and turn side-to-side several control planes are required.

A helicopter propeller motivates an idea of application of a CCPP into a ROV/AUV. A helicopter propeller is a collective and cyclic pitch propeller with four blades as in Fig. 2. The collective pitch control of the blades is to allow the helicopter to lift up or down while the cyclic pitch control of the blades of a helicopter rotor is important to allow the helicopter to fly forward, backward or side-to-side and maintain stability of the helicopter (Humphrey, Bose and Williams, 2005).

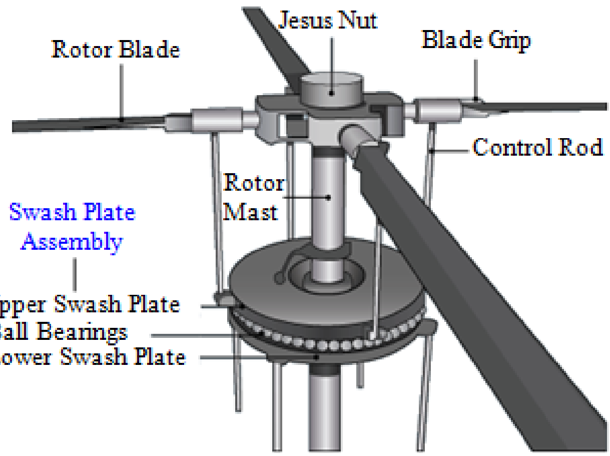

Fig. 2 A helicopter propeller with four blades and rotor (Brain and Harris, 2013).

When a CCPP is applied to a ROV/AUV, it should be modified such that it is installed horizontally in a ROV/AUV. Axial and side thrusts of the CCPP are used to steer the ROV/AUV in all directions as shown in Fig. 3. An important idea of utilising the CCPP is to control the vector total thrust as desired by the propeller shaft speed (rpm), collective pitch and cyclic pitch angles.

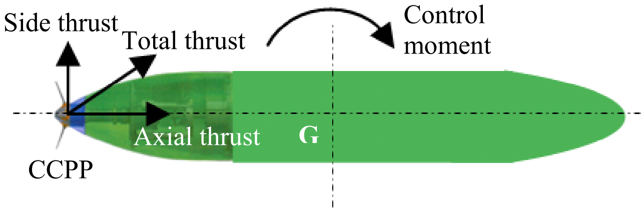

Fig. 3 Conceptual axial and side thrusts of a CCPP for steering a ROV/AUV in all directions.

The CCPP was originally designed and fabricated by Humphrey (2005) at the Memorial University of Newfoundland. It was moved to the Australian Maritime College (AMC)/University of Tasmania (UTAS) in 2008, and has been installed in a ROV/AUV body for further investigation of its performance.

The paper aims at describing the CCPP, a ROV/AUV equipped the CCPP and experiments; modelling the CCPP and ROV/AU; analysing the performance of the ROV/AUV equipped the CCPP based on theoretical and experimental data; and simulating the ROV/AUV to evaluate the mathematical model and the performance of the CCPP.

2. DESCRIPTION OF ROV/AUV EQUIPPED WITH CCPP

2.1 Collective and Cyclic Pitch Propeller (CCPP)

A CCPP was originally designed for the test ROV/AUV named C-SCOUT (see Fig. 1). Four blades of the CCPP are controlled by a connecting linkage, actuators and swash plate as shown in Fig. 4.

The mechanism of the CCPP allows the angle of each propeller blade to be positioned while the propeller shaft is turning. The operator can simultaneously change the angles of all blades to a particular angle, similarly to a controllable-pitch propeller, CPP. In addition, the angles of each propeller blade can be positioned periodically. An important mechanism component of the CCPP is a swash plate. It provides the adjustment of the angle of the propeller blades while the propeller shaft is rotating (Niyomka *et al.*, 2013).

The swash plate assembly consists of two parts: the non-rotating and the rotating swash plates as shown in Fig. 4. The rotating swash plate rotates with the propeller shaft. The connecting linkages allow the rotating swash plate to change the pitch of the propeller blades. The three linear actuators manipulate a movement and orientation of the non-rotating swash plate. The operator can control the cyclic and collective pitch via the linear actuators. For instance, setting a collective pitch can be achieved by command to all actuators to move in the same direction and distance. The non-rotating and the rotating swash plates are connected with a spherical swash plate bearing between the two plates. The bearing allows the rotated swash plate to spin around the non-rotating swash plate. Furthermore, the propeller was designed to have a rake angle in order to generate side thrusts. A brushless dc motor drives the propeller. The propeller has two main controllers, one controls the propeller motor speed and the other controls the blade angles (Niyomka *et al.*, 2013).

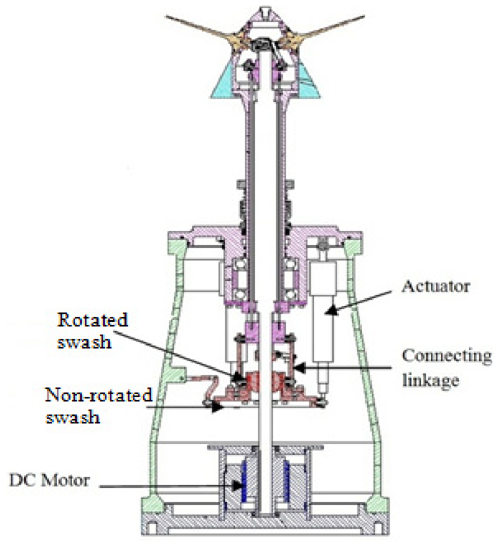

Fig. 4 Cross section drawing of the CCPP

2.2 Underwater Vehicle Equipped with the CCPP

As soon as the CCPP was designed and fabricated at the Memorial University of Newfoundland, it was tested by submerging in a small test tank. It required further tests to quantify its performance in order for it to be used in a ROV/AUV. After it was moved to the AMC a ROV/AUV body, hanging mechanism and force balance mechanism were designed and fabricated as shown in Fig. 5. The main particulars of the ROV/AUV equipped with the CCPP are given in Table 1.

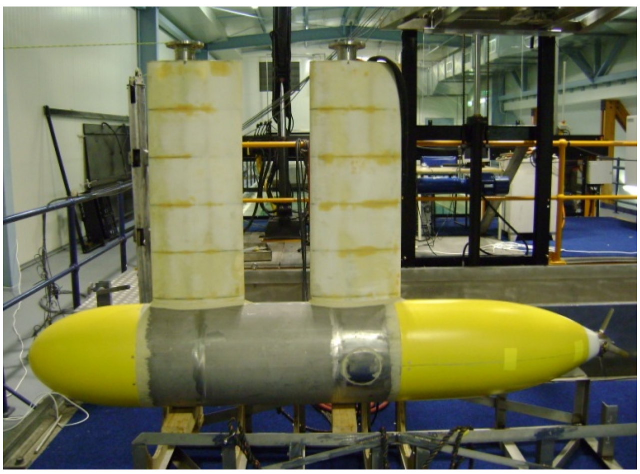

Fig. 5 ROV/AUV with CCPP and force and moment balance mechanism.

Table 1 Main particulars of the ROV/AUV with a CCPP

Length [L]	2.335 m
Diameter [D]	0.4052 m
Volume [V]	0.016 m^3
Mass [m]	126.409 kg
Surface area [A]	2.55 m^2
Type of propeller	CCPP (x_p=L/2; y_p=0; z_p = 0)

2.3 Configuration of Experimental Equipment

In order to set up experimental facility the ROV/AUV equipped with the CCPP was attached to a force balance through two faired struts as shown in Fig. 6 and Fig. 7.

The experiment was conducted at the Towing Tank facility of Australian Maritime College (AMC). The dimension of the tank is 100 m length, 3.55 m width and 1.5 m depth. The towing carriage speed has the maximum speed of 4.6 m/s.

The force balance was attached onto the carriage. The underwater vehicle was connected to a big force balance by two steel pipes. The two steel pipes were covered with the aerofoil shaped fairing in order to prevent unsteady flow forwards to the propeller. A small internal force transducer was attached between the middle vehicle body and the CCPP as shown in Fig. 7. The small force transducer was installed in a housing to prevent any damage from water ingress. The centre of the underwater vehicle was 0.9 m below the water surface. The layout of the experimental setup is shown in Fig. 6 and Fig. 7 (Niyomka *et al.*, 2013).

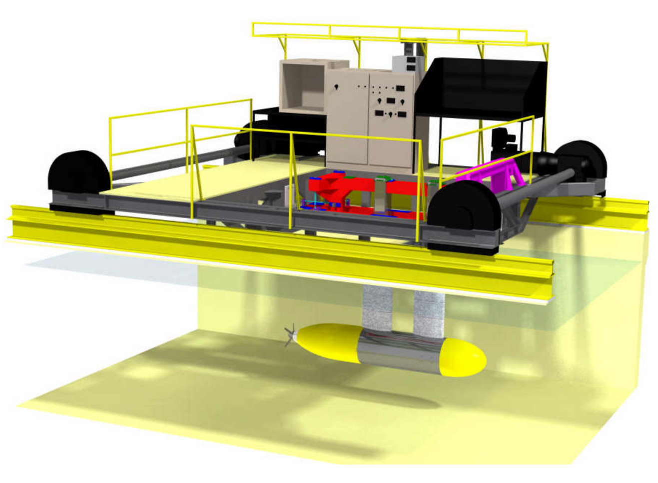

Fig 6 3D arrangement of experimental facility.

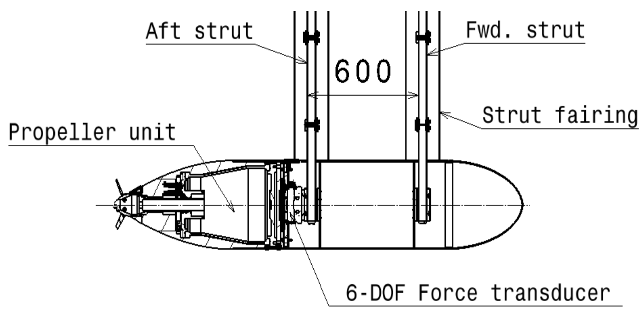

Fig. 7 Set-up configuration in a cross section view.

The propulsion test was divided into two parts. In the first part, the pitch setting of the CCPP was varied collectively at each test run. In the second part, the pitch setting of the CCPP was a combination of collective pitch and cyclic pitch.

The performance of the CCPP was assessed at various advanced coefficients. The advanced coefficient was varied by changing the vehicle speed (the flow velocity in the Towing Tank) and the RPM of the propeller shaft.

Each condition was established by setting the speed of the carriage and propeller RPM to achieve a desired advance coefficient. The propeller pitch was set to the desired parameter. At the beginning of each test run, the data of no-load conditions of each measurement device were recorded. After that the speed of the propeller shaft was ramped up to a desired RPM. Then the carriage was accelerated to the desired speed. When the speed of the carriage was constant, the measurement devices began recording for 80 seconds. After each run, there was a break for 10 minutes to let the water settle down.

The forces acting at the force transducers, the vehicle speed and the RPM of the propeller shaft were measured and recorded by a data logging and control program.

3. MODELLING OF ROV/AUV WITH CCPP

The underwater vehicle equipped with the CCPP requires a mathematical model with full hydrodynamic coefficients for analysing its performance. This section is to describe the development of the mathematical model for the ROV/AUV.

4.1 Reference Frames

Two reference frames as shown in Fig. 8 are used to describe kinematics and kinetics of the UV with the CCPP.

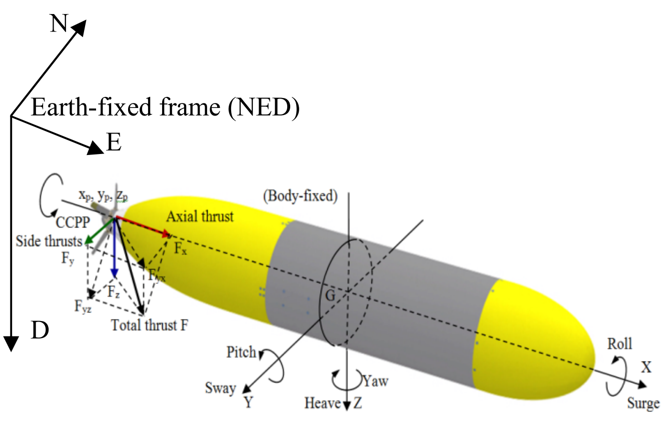

Fig. 8 Reference frames and the ROV/AUV with a CCPP.

Fig. 8 shows forces and moments generated by the CCPP. To control the ROV/AUV is to control the total thrust F in a desired direction.

4.2 Kinamatic and Kinetic Equations of the ROV/AUV Equipped with a CCPP

By referring to Fig. 8 the 6-DOF kinematic equations in the NED (north-east-down) reference frame in the vector form are (Fossen, 1991, 1994, 2002, Ross, 2008, Nguyen, 2012),

$$\dot{\boldsymbol{\eta}} = \mathbf{J}_{\Theta}(\boldsymbol{\eta})\mathbf{v}, \tag{1}$$

where

$$\mathbf{J}_{\Theta}(\boldsymbol{\eta}) = \begin{bmatrix} \mathbf{R}_b^n(\boldsymbol{\Theta}) & \mathbf{0}_{3\times3} \\ \mathbf{0}_{3\times3} & \mathbf{T}_{\Theta}(\boldsymbol{\Theta}) \end{bmatrix}, \tag{2}$$

with $\boldsymbol{\eta} \in \mathbb{R}^3 \times S^3$ and $\mathbf{v} \in \mathbb{R}^3$, $\mathbf{v} = [u \quad v \quad w \quad p \quad q \quad r]^T$ and

$$\mathbf{J}_{\Theta}(\boldsymbol{\eta}) = \begin{bmatrix} c\psi c\theta & -s\psi c\varphi + c\psi s\theta s\varphi & s\psi s\varphi + c\psi c\varphi s\theta & 0 & 0 & 0 \\ s\psi c\theta & c\psi c\varphi + s\varphi s\theta s\psi & -c\psi s\varphi + s\theta s\psi c\varphi & 0 & 0 & 0 \\ -s\theta & c\theta s\varphi & c\theta c\varphi & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & s\varphi t\theta & c\varphi t\theta \\ 0 & 0 & 0 & 0 & c\varphi & -s\varphi \\ 0 & 0 & 0 & 0 & s\varphi / c\theta & c\varphi / c\theta \end{bmatrix}. \tag{3}$$

In order to derive the differential equations governing the kinematics and dynamics of the vehicle of which inputs and outputs are shown Fig. 9, it is assumed that:

- the origin of the body-fixed reference frame is at the centre of gravity;
- the vehicle is symmetric about both the longitudinal axis x and lateral axis y;
- the vehicle is symmetric about the mid-plane;
- the vehicle is neutrally buoyant and the mass distribution of the vehicle is homogeneous throughout the vehicle;
- the ROV/AUV is compatible with the C-SCOUT model (Perrault, 2002, Evans, 2003).

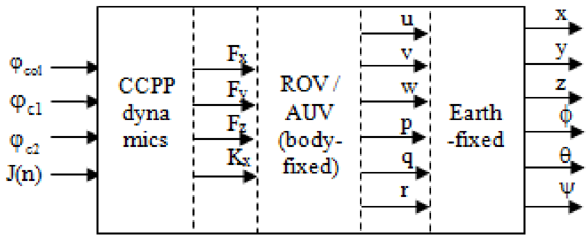

Fig. 9 Inputs and outputs of the ROV/AUV with CCPP.

Six kinetic equations (Fossen, 1991, 2002, 2011) are

$$\mathbf{M}\dot{\mathbf{v}} + \mathbf{C}(\mathbf{v}) + \mathbf{D}(\mathbf{v})\mathbf{v} + \mathbf{g} = \boldsymbol{\tau}, \tag{4}$$

where $\mathbf{v} = [u \quad v \quad w \quad p \quad q \quad r]^T$, $\mathbf{M} = \mathbf{M}_{RB} + \mathbf{M}_A$ is the inertial matrix, $\mathbf{C}(\mathbf{v})$ is the Coriolis and centrifugal matrix, $\mathbf{D}(\mathbf{v})$ is the damping matrix, $\mathbf{g}$ is the buoyancy and hydrostatic vector and $\boldsymbol{\tau}$ is the input vector.

Based on the assumption that the ROV/AUV has xz-, xy- and yz-planes of symmetry, i.e. $x_g = 0$, $y_g = 0$ and $z_g = 0$, $\mathbf{M}$ is (Perrault, 2002 and Evans, 2003):

$$\mathbf{M} = \begin{bmatrix} m_{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & m_{22} & 0 & 0 & 0 & 0 \\ 0 & 0 & m_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & m_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & m_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & m_{66} \end{bmatrix}, \tag{5}$$

where $m_{11} = m - X_{\dot{u}}$; $m_{22} = m - Y_{\dot{v}}$, $m_{33} = m - Z_{\dot{w}}$; $m_{33} = m - Z_{\dot{w}}$; $m_{44} = I_x - K_{\dot{p}}$; $m_{55} = I_y - M_{\dot{q}}$ and $m_{66} = I_z - N_{\dot{r}}$.

The Coriolis, centrifugal and gravitional matrix is

$$\mathbf{h}(\mathbf{v}) = \mathbf{C}(\mathbf{v})\mathbf{v} + \mathbf{D}(\mathbf{v})\mathbf{v} + \mathbf{g}, \tag{6}$$

Thus, Eq (4) is rewritten as (Evans, 2003)

$$\dot{\mathbf{v}} = \mathbf{M}^{-1}[\boldsymbol{\tau} - \mathbf{h}(\mathbf{v})]. \tag{7}$$

The input vector including forces and moments generated by the CCPP is given by

$$\boldsymbol{\tau} = [X_P \quad Y_P \quad Z_P \quad K_P \quad M_P \quad N_P]^T, \tag{8}$$

or

$$\boldsymbol{\tau} = [F_x \quad F_y \quad F_z \quad K_x \quad x_p F_y \quad x_p F_z]^T, \tag{9}$$

where F_i (i = x, y, z) and K_x are functions of φ_{col}, φ_{c1}, φ_{c2} and J. Note that φ_{col} is the collective pitch angle, φ_{c1} is the right-left cyclic pitch angle, φ_{c2} is the up-down cyclic pitch angle, and J, the advance coefficient that is given by

$$J = \frac{v}{nD}, \tag{10}$$

where v is the vehicle velocity (or water velocity in the captive experiment using the towing tank or circulating water channel), D is the diameter of the CCPP and n is the shaft speed in rps.

4.3 Control of the CCPP

After the CCPP was designed and fabricated it was controlled by a Smart Card BL2000 and Dynamic C control program in order to do premelinary testing. The Dynamic C control program did not allow the user to collect data for analysis. Therefore it was required to develop measurement and control electronics.

The control system for the CCPP has been developed as follows:

Stage 1: The controller included an embedded computer SmartCat BL2000 and Dynamic C control program as shown in Fig. 10.

Stage 2: For captive experiments using the towing tank and circulating water channel, the propeller was controlled by LabVIEW control programs and a National Instruments DAQ card. These LabVIEW control programs were used to investigate the performance of the CCPP. A functional block diagram of the control programs is shown in Fig. 11.

Stage 3: In the future the current ROV will be developed further to a free running model ROV/AUV with the CCPP, onboard sensors and control electronics.

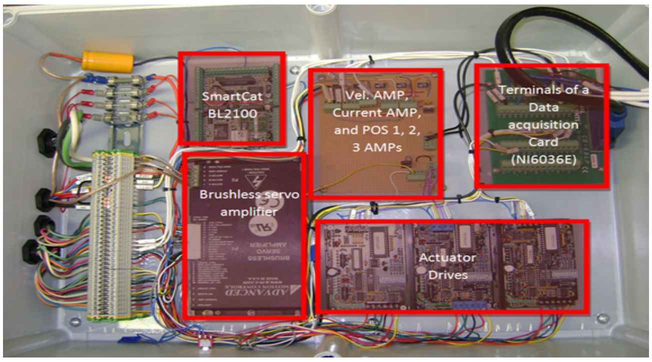

Fig. 10 Control electronics for the CCPP.

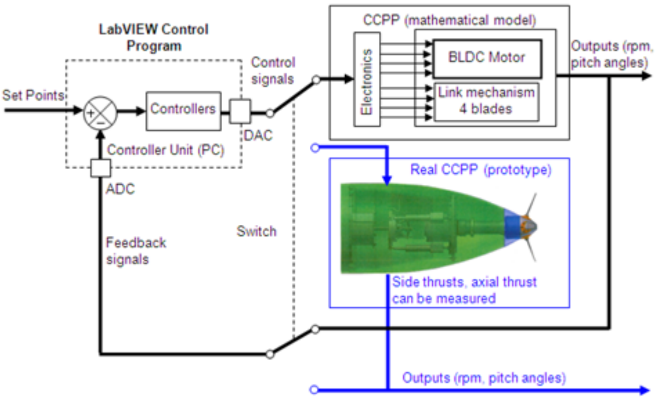

Fig. 11 Functional block diagram of the CCPP.

4. PERFORMANCE OF CCPP

In order to investigate the performance of the CCPP, the experiments conducted using the AMC Towing Tank and Circulating Water Channel are collective pitch tests; combined collective cyclic pitch tests and resistance tests.

The measured data were averaged at the end of each test run. From the experimental results, the thrust, the torque and the thrust direction at various conditions were formed in polynomial formulae as follows.

$$F_i = \sum_{n=1}^{N} C_n (J)^{(s_n)} \left(\frac{\varphi_{col}}{100}\right)^{(t_n)} \left(\frac{\varphi_{cyl1}}{100}\right)^{(u_n)} \left(\frac{\varphi_{cyl2}}{100}\right)^{(w_n)}, \quad (11)$$

where C_n = the nth coefficient of the polynomial;
i = force directions (x, y and z);
n = order of polynomial terms;
N = number of polynomial terms;
s_n = power of advance coefficient;
t_n = power of collective pitch terms;
u_n = power of cyclic pitch terms (up/down);
w_n = power of cyclic pitch terms (left/right); and
J = the advance coefficient that is a function of shaft speed (rps) as in Eq (10).

It should be noted that the torque generated by the CCPP, K_x is calculated by (11) with different number of coefficients.

With the Eq. (11), the propulsion forces can be acquired at various conditions. However Eq. (11) cannot be completed by using only data from the experiment. A performance prediction program was required to predict the performance of the CCPP in other conditions which were not in the experiment. The prediction program was verified by the existing experimental results.

The prediction program was based on the Blade Element Momentum Theory. The lifting and drag coefficients for the propeller blade at each radius were modified by taking account for dynamic stall behaviour of the oscillating blade. The dynamic stall behaviour was modelled by Leishman (1989) and the model was used in the prediction program. However the Leishman-Beddoes model was modified by Sheng *et al.* (2008) for the low Mach numbers as the CCPP operating at a low Mach number.

The inputs and outputs of a theoretical model of the CCPP dynamics are shown Fig. 9. The pitch angle $\alpha_{(i,\varphi)}$ of each blade is given by (Niyomka *et al.*, 2011, 2013)

$$\alpha_{(i,\varphi)} = \varphi_{col(i)} + \varphi_{cyl1(i)} \sin(\omega t + \pi) + \varphi_{cyl2(i)} \cos(\omega t + \pi), \quad (12)$$

where i (= 1 to 4) is the ith blade of the CCPP, ω is the shaft velocity (rad/s) and collective and cyclic pitch angles are $\varphi_{col(i)}$ = –29° to +29° (or –100% to +100%), $\varphi_{cyl1(i)}$ = –20° to +20° (or –100% to +100%), and $\varphi_{cyl2(i)}$ = –20° to +20° (or –100% to +100%).

F_x, F_y, F_z and K_x are predicted by applying the Blade Element Momentum Theory (Leishman, 1989, Benini, 2004).

5. SIMULATION STUDY

Numerical simulation study has been done for the following scenarios:

- Open-loop system with main manoeuvres (turning circles (right and left), horizontal zigzag, vertical zigzag) for validating the mathematical model of the CCPP, the mathematical model of the ROV/AUV and verifying the ROV/AUV performance; and
- Closed-loop control scenarios for underwater missions.

The simulation study has shown it is possible to control a ROV/AUV forward and backward, turn left and right and diving and surfacing by only one CCPP. A representative simulation result is presented in this paper due to limited space. Fig. 12 shows simulated horizontal turning circles for a speed of 250 rpm, collective pitch angle = 80% (forward), cyclic pitch angle (up/down) = 0 and left/right cyclic pitch angle = 50% (right turning) and –50% (left tuning).

Fig. 13 shows the pitch angles, thrusts and torque generated by the CCPP for two horizontal turning manoeuvres. It can be seen that from Fig. 13 the turning moment is mainly generated by F_y while F_z and K_x are relatively small.

6. CONCLUSIONS

The paper has described the design of CCPP, design of the ROV/AUV equipped with the CCPP and a series of experiments to investigate the performance of the CCPP. The paper has developed a theoretical mathematical model of the CCPP to predict thrust and torque generated by the CCPP and a mathematical model of the ROV/AUV equipped with the CCPP. The paper presented some simulated results to validate the theoretical model of the ROV/AUV and CCPP. The simulation study has shown that it is possible to use a CCPP for omni-directional control of an underwater vehicle.

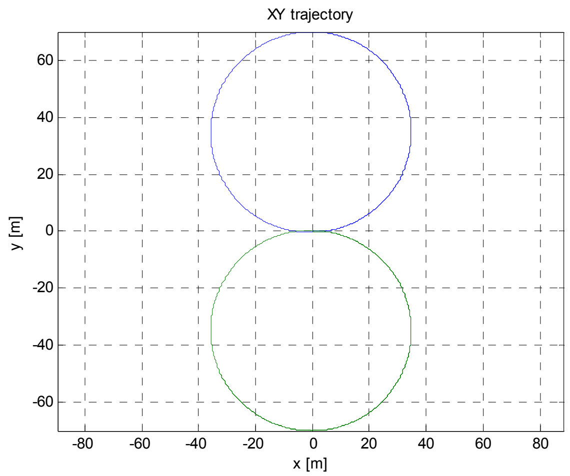

Fig. 12 XY trajectory of the ROV/AUV with n = 250 rpm, collective pitch = 90%, cyclic (U/D) = 0 and cyclic (L/R) = 50% and –50%.

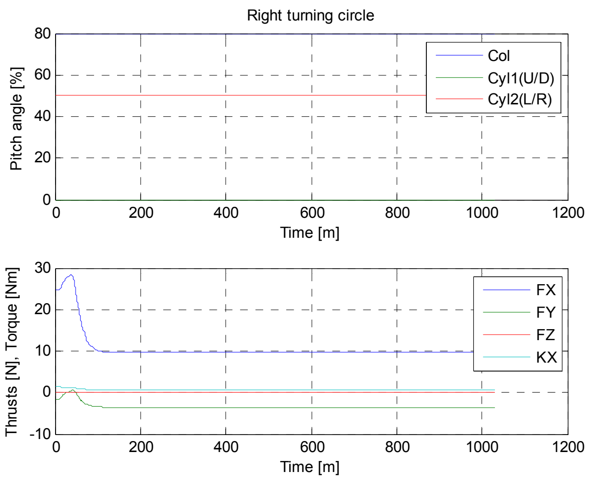

Fig. 13 Right tuning circle.

In order to further investigate the performance of the CCPP and the ROV/AUV equipped with the CCPP, it is necessary to conduct more experiments so that the experimental performance can be compared with the theoretical performance by numerical simulation. To estimate full hydrodynamic coefficients more effective modelling methods such as the CFD modelling method and/or optimal estimation method are recommended. A free running ROV/AUV model equipped with the CCPP will be developed.

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