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Experimental Characterization of Collective and Cyclic Pitch Propulsion for Underwater Vehicle

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ABSTRACT

A new design of a propulsion device is a Collective and Cyclic Pitch Propeller, CCPP. The principle of the CCPP is similar to a helicopter main rotor. As such, the propeller operates as a combination between a propulsion device and a directional manipulator. It can generate side thrust to provide directional control, in addition to axial thrust variation, which can be generated on a normal controllable pitch propeller. The key component of the propeller is a swash plate, which allows the angle of the propeller blades to be cyclically controlled. This paper presents the performance of the CCPP. The performance of the propeller was assessed under various conditions to construct the relationships between the RPM, pitch angles of propeller blades and axial and side thrusts. The results were used to improve a simulation program of its operation and control system of an underwater vehicle .

Keywords

Cyclic pitch, Collective pitch, Controllable Propeller, Low speed manoeuvres, Experimental characterization

1 INTRODUCTION

This research work focuses on a propulsion system of an underwater vehicle and more particularly on Autonomous Underwater Vehicles (AUVs) for survey missions. The survey performance capabilities of these vehicles are usually assessed by their endurance and speed. The limited energy supply is a constraint on the survey performance.

A Remotely Operated Vehicle, ROV is usually assigned to do a mission, which requires a vehicle to operate at low speed, to keep station or to operate in a tight space. Multiple thrusters of an ROV consume more energy in order to provide any directional controls. The results of high-energy consumption and a high-resistance shape make an ROV need to have a power source nearby. An underwater vehicle with a single propulsion usually has sails/rudders to manoeuvre its orientation. However, in low speed operation, the control surfaces become ineffective. This issue is usually found on the underwater vehicle on a mission to take samples in a tight space or on a mission that requires keeping its position during sampling.

A solution for an underwater vehicle with a single propulsion system to have good low speed manoeuvrability is to have a new type of a propulsion system, which can generate thrust in various directions. The new type of a propulsion system investigated here is a Cyclic and Collective Pitch Propeller, CCPP. The principle of a mechanical design of the new type of a propulsion system is adapted from the mechanism of a main helicopter rotor. Lindahl (1965, p. 90) invented the cyclic and collective pitch propeller for the marine industry. It provided steering forces to a ship. For the underwater industry, Haselton, W.G. Wilson, and Rice (1966) proposed a new submarine propulsion with two cyclic and collective pitch propeller at the fore and aft ends of a submarine. With this configuration, the submarine was expected to be capable of manoeuvring in all six degrees of freedom. The Tandem Propulsion System concept was not extensively developed at the time due to mechanical complexity and control issues, (Benjamin et al. 2008). Benjamin (2008) did a renewed design of the TPS concept with an advanced control system, electric

motors, and electric actuations. In Japan, Nagashima, Taguchi, Ishimatsu, and Mizokami (2002) developed a propulsion system called a variable vector propeller for a compact underwater vehicle using radio control helicopter elements.

The CCPP in this research was developed by Humphrey (2005). The mechanical design is outlined in Figure 1

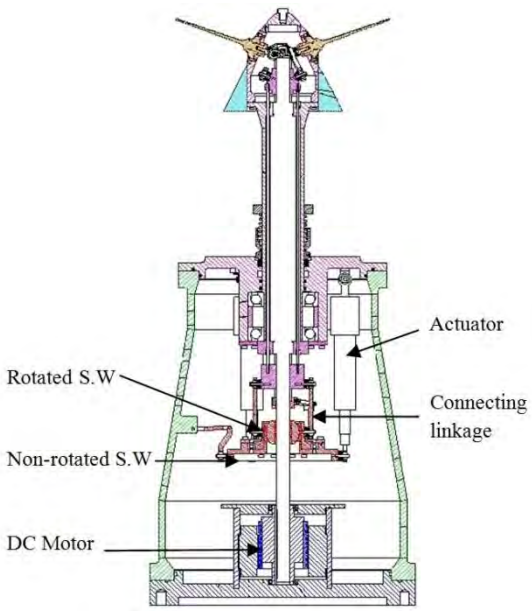

Figure 1: A cross section drawing of the Cyclic and Collective Pitch Propeller

1.1 How the Cyclic and Collective Pitch Propeller works

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.

The swash plate assembly consists of two parts: the non-rotating and the rotating swash plates as shown in Figure 1. 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 on 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.

1.2 Propeller Characteristics

Used here CCPP had four blades. The blade section was a NACA 0012. The thickness and chord length constantly decrease towards the tip. The pitch distribution progressively increases towards the tip because the blades had no twisted The rake angle of the blades was 20 deg. The blades do not have skew or twist. The diameter of the propeller was 0.305 m. The propeller turns counterclockwise direction.

The specification of the CCPP is given in Table 1 in the appendix.

1.3 Applications of the Cyclic and Collective Pitch Propeller to the underwater industry

The CCPP can generate thrust in the longitudinal and lateral directions. The propeller is designed for a streamlined shaped underwater vehicle in order to produce high manoeuvrability at low speed.It is postulated that an underwater vehicle propelled by a single CCPP can provide three degrees of freedom (surge, pitch and yaw). In addition, if a vehicle installed two CCPP at both fore and aft end, the vehicle could be capable to manoeuvre in six degrees of freedom.

The information about the performance of the CCPP is required for the development of the design and control system of the propeller. In addition, the development of the simulation program of an underwater vehicle is based on this information and control system. The desired data to acquire are the resistance of the vehicle, the magnitudes of thrust, torque , and thrust directions at various pitch settings and advance coefficients. The details of input variables are in the experimental section.

1.4 Definitions of pitch setting parameters

The pitch angle at any particular angular position of the propeller plane can be expressed by Equation 1.

Equation 1 was developed to estimate the instantaneous angles of each propeller blade at any pitch setting. It is that the change of the angle of the propeller blades is sinusoidal for a cyclic pitch setting since it is controlled by the swash plate. The equation is presented as follows.

$$\alpha_{(i,\varphi)} = \alpha_{Col(i)} + \alpha_{U/D(i)} \sin(\varphi + 180) + \alpha_{R/L(i)} \cos(\varphi + 180) \quad (1)$$

Where subscript i (1, 2, 3 and 4) is the blade number. subscript φ (0 to 360 deg) is the location of the propeller blade.

$\alpha_{(i,\varphi)}$ is the total pitch angle of each blade.

$\alpha_{Col(i)}$ is the assigned collective pitch angle of a particular blade ($\alpha_{Col(i)}$=–29 deg to +29 deg).

Two parameters for controlling cyclic pitch are as follows;

$\alpha_{U/D(i)}$ is the maximum up/down cyclic pitch angle of a particular blade ($\alpha_{U/D(i)}$=–20 deg to +20 deg).

$\alpha_{R/L(i)}$ is the maximum right/left cyclic pitch angle of a particular blade ($\alpha_{R/L(i)}$=–20 deg to +20 deg).

The cyclic variables, $\alpha_{R/L(i)}$, $\alpha_{U/D(i)}$ are explained in following examples.

A blade has a minimum pitch angle at the top position ,φ= 90 deg when $\alpha_{U/D(i)}$ is positive and $\alpha_{R/L(i)}$ is zero. The maximum pitch angle is in the bottom position, φ= 270 deg.

A blade has a maximum pitch angle at the port position, φ= 180 deg when $\alpha_{U/D(i)}$ equals to zero and $\alpha_{R/L(i)}$ is positive. The minimum is in the starboard position, φ= 0 deg.

In addition, positive collective produces forward thrust.

For ease of development of the control system, the pitch angle parameters were converted into percentage number. For instance, a collective pitch angle was set to +100% which is equal to +29 deg. In addition, a up/down cyclic pitch angle, $\alpha_{U/D(i)}$ was set to -50% which is equal to -10 deg.

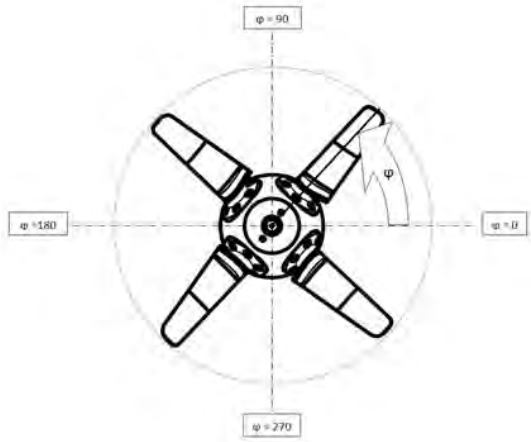

Figure 2: Rotation of the CCPP

1.5 Dimensions of the underwater vehicle with the reference frame

The vehicle has dimension 2.34 m in length and 0.406 m in diameter. The total wetted area is 2.55 m^3 . In the experiment, the axis system X, Y, Z is the body-fixed coordinate system. The surge motion of the vehicle is on the X axis. Positive X is when the vehicle moves forwards. The sway motion in the Y direction and positive Y is on the starboard side. The heave motion is in the Z direction and the Z is positive downwards as presented in Figure 3.

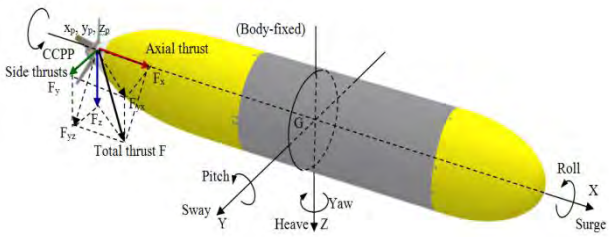

Figure 3: The reference frame

2 METHODS & EXPERIMENT

The performance of the CCPP was assessed by conducting a captive test. The captive test was selected because it is a simple test and it can assess the performance of the propeller in various desired conditions. The experiment was divided into three sections. The first section was for a collective pitch setting only. The second section was for a combination of a collective pitch, a cyclic pitch (up/down) and a cyclic pitch (right/ left). The third section was a resistance test of the underwater vehicle. The range of each input variable is present in Table 2 in the appendix. The collective pitch values for each advance coefficient are shown in Table 3 in the appendix.

2.1 Measurement devices

The experiment used two force balances. The first one was a small 6-DOF force transducer and the second one was a big 6-DOF force balance.

The small six-DOF force transducer directly measured propeller thrust and torque. The small force transducer was calibrated over a range of 0 to 5 kg of thrust and 0 to 1.25 kg-m.

The big force balance measured the resistance of and the thrust on the vehicle. The resistance data were turned off by analysing separate experiments, in order to acquire the thrust and torque data. The uncertainty of the performance data from the big force balance was contributed to the difference of the testing condition between measuring resistance and measuring thrust and torque. The big force balance was calibrated over a range of 0 to 7 kg. The calibrations of both devices were checked after the completion of the experiments to confirm the repeatability of the data.

The speed of the propeller shaft was measured by three Hall Effect sensors, which were attached to the main motor. The speed of the vehicle was taken as the speed of the carriage. The speed of the carriage was varied according to the desired advance coefficients.

2.2 Experimental Setup

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 big force balance was attached onto the carriage. The underwater vehicle was connected to the big force balance by two steel pipes. The two steel pipes were covered with the airfoil shaped fairing in order to prevent unsteady flow forwards to the propeller. The small force transducer was attached between the middle vehicle body and the CCPP as shown in Figure 5. 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 Figure 4 and Figure 5.

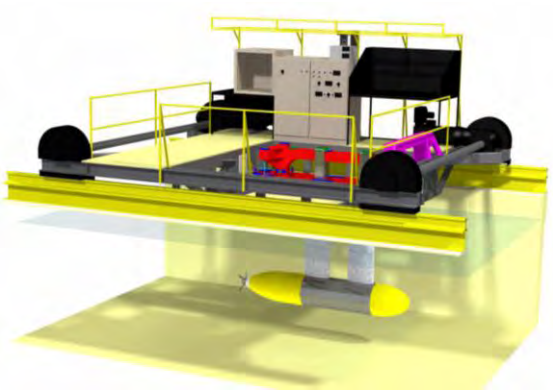

Figure 4: Setup Configuration of the experiment in 3D

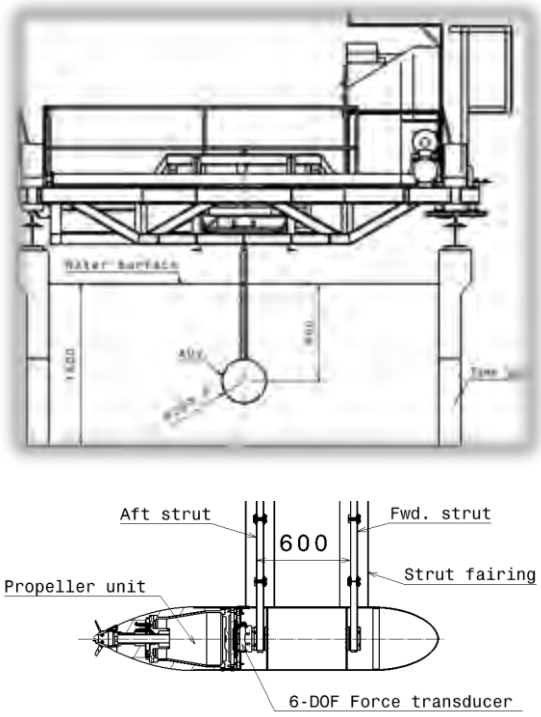

Figure 5: Set up Configuration in front view and in a cross section view

2.3 Experiment procedure

2.3.1 Propulsion tests

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.

2.3.2 Resistance tests

The speed of the carriage was set to desired values. The propeller blade was set to be in line with the water flow. At the beginning of each test run, the data of no-load conditions of each measurement device were recorded. The carriage was accelerated to the set 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.

2.4 Data acquisition and analysis

Sample rates were set to 100 Hz for the small force and to 2000 Hz for the big force balance. The data from each measurement device was averaged at the end of recording and then it was subtracted from the no-load condition.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 The results of the propulsion tests

3.1.1 Collective pitch tests

The thrust and torque coefficients of the CCPP are presented as a function of the advance coefficient in Figure 6 and 7 for a positive collective pitch setting and a forward speed. In condition of a negative collective pitch setting and a forward speed, Figure 8, and 9 present thrust and torque coefficients respectively. The pitch angle setting was in percentage number as explained in section 1.4. The propeller with a positive collective pitch produces a lower thrust in comparison with the negative pitch because the direction of the drag of the propeller blades is opposite to the direction of the thrust with a positive collective pitch setting. In contrast, the measured thrust with a negative pitch setting was not only the pure generated force from the propeller but it also included the drag of the propeller blades. The torque of positive collective pitch settings was larger than the torque of negative pitch settings. The maximum torque occurred at +100%, -100% collective pitch angle (+29 deg, -29deg). The maximum torque was approximately 2.1 N.m (0.214 kg.m). The efficiency of the propeller for positive pitch is presented in Figure 10. The efficiency plot was generated from the experimental data up to the highest advance coefficient of 0.8. Therefore, the highest efficiency of the 100% collective pitch cannot be certain. The maximum efficiency of positive pitch settings is approximately 70 % on the 60 % collective pitch angle (17.4 deg.) at about advance coefficient of 0.6. The performance of the cyclic and collective pitch propeller was similar to a conventional controllable pitch propeller. The performance of a controllable pitch propeller can be seen in a typical controllable pitch propeller characteristic curve (Carlton, 2007). Pitch angle needs to be matched to required loads and advance coefficients in order to maximise efficiency. This is the same method as the one which is used to optimise a fixed pitch propeller.

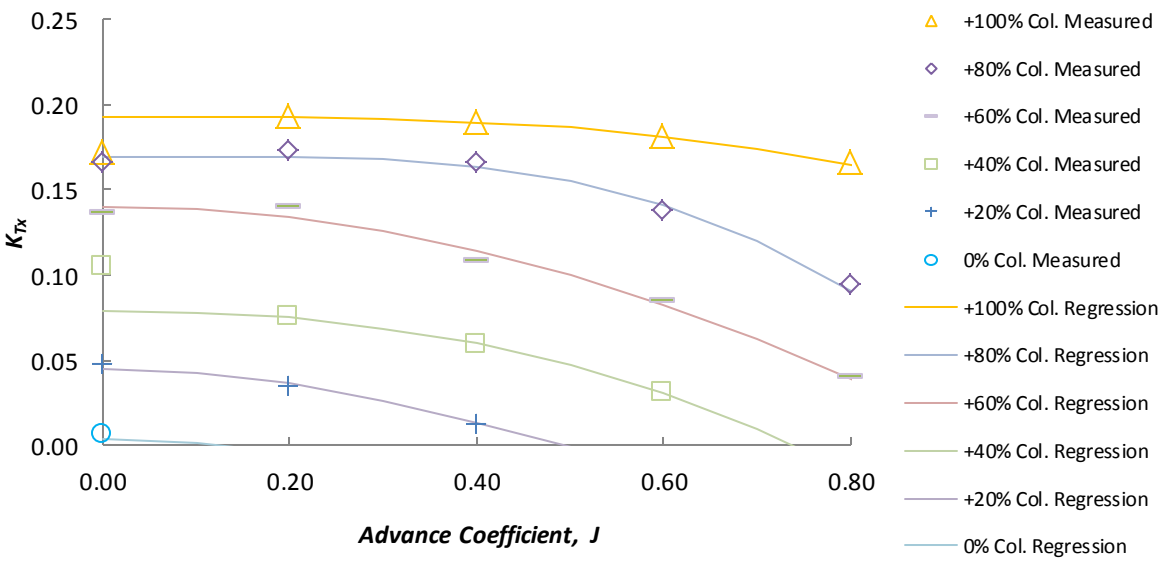

Figure 6: Thrust coefficient, K_T vs. Advance coefficient, J for positive collective pitch setting

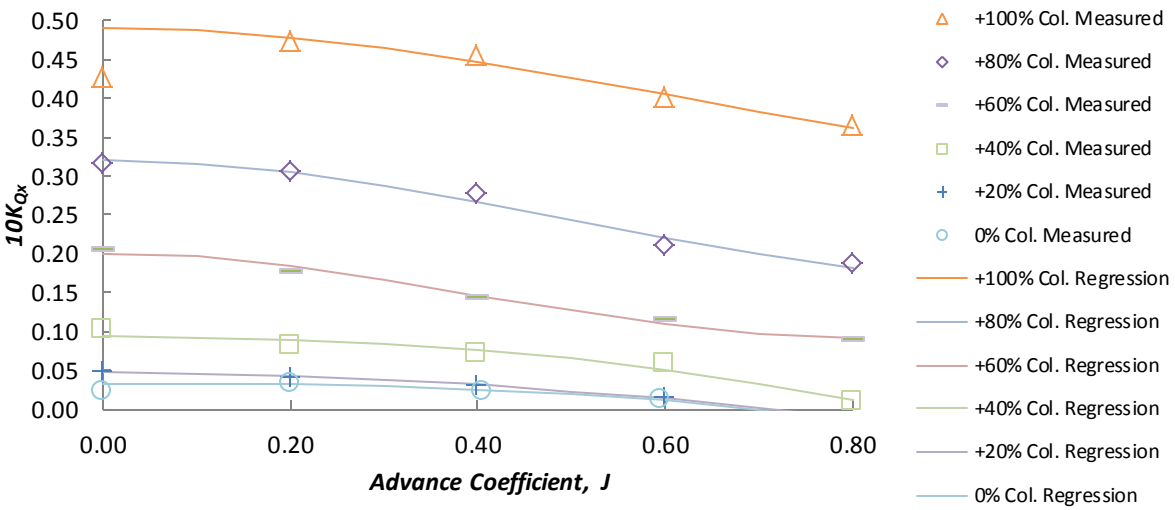

Figure 7: Torque coefficient, K_Q vs. Advance coefficient, J for positive collective pitch setting

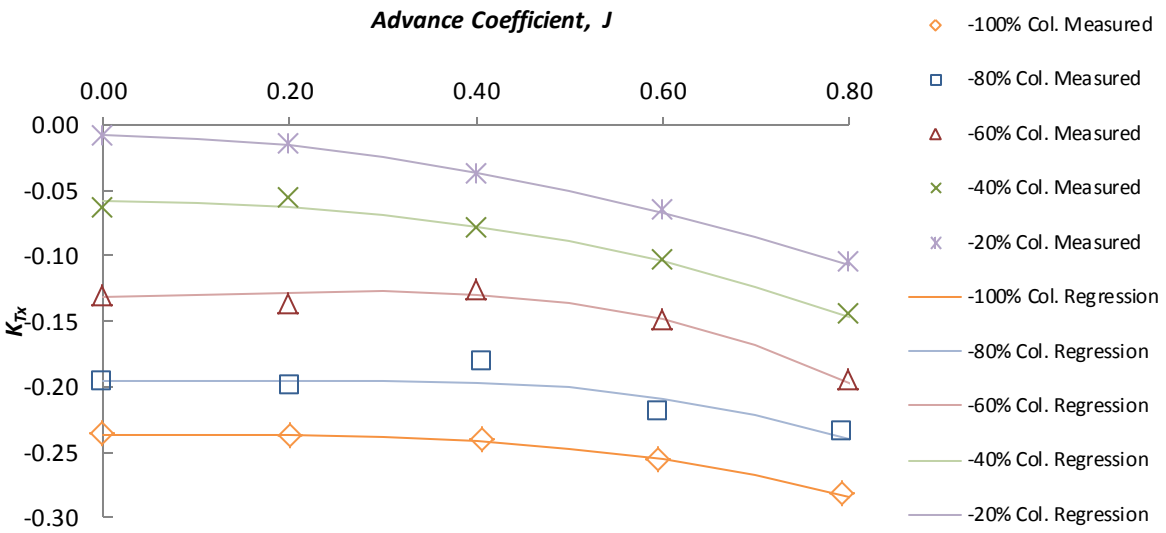

Figure 8: Thrust coefficient, K_T vs. Advance coefficient, J for negative collective pitch setting

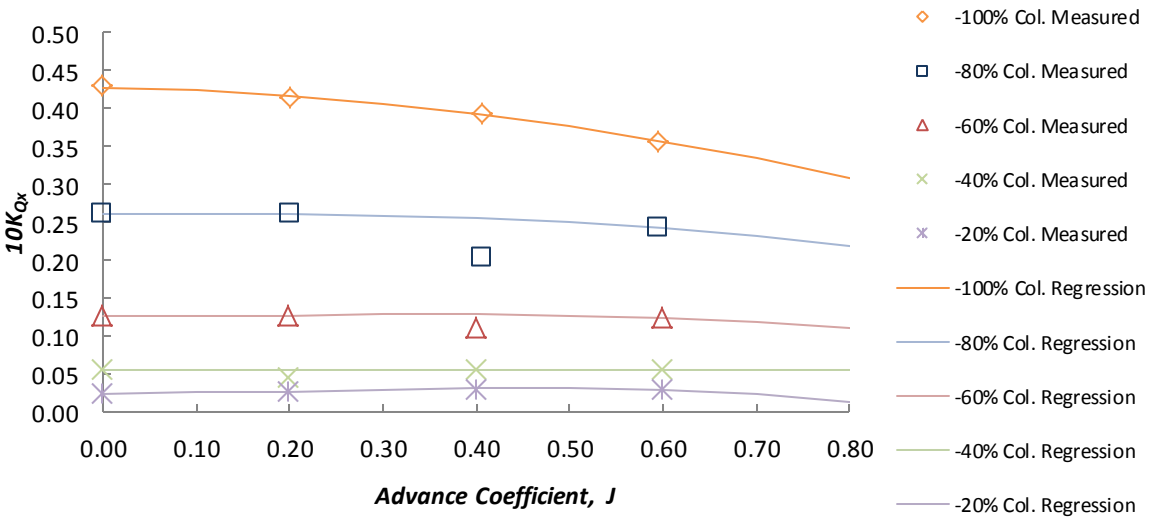

Figure 9: Torque coefficient, K_Q vs. Advance coefficient, J for negative collective pitch setting

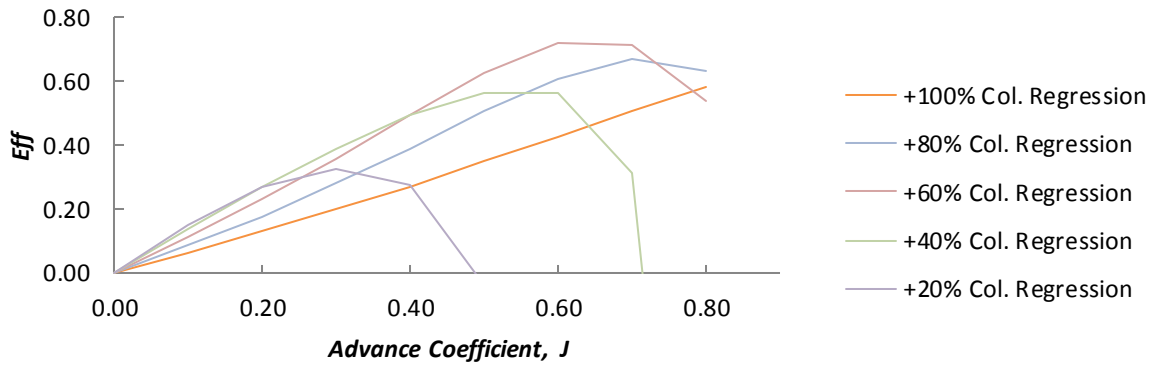

Figure 10: Efficiency vs. Advance coefficient for positive collective pitch setting

3.1.2 Combination of Collective and Cyclic pitch tests

All experimental data presented in the Figure 11, 12,13 and 14 were conducted in an advance coefficient of 0.2. Each pitch setting is distinct from each other by the types and colours of rectangles. For instance, in Figure 11, a black rectangle is for a +80% right/left pitch angle setting. A Square Dot, a Long Dash Dot Dot and a Double Square Dot are +80%, +40%, and 0% collective pitch angle setting, respectively. Figure 11 and 12 present the magnitude and the direction of the transverse forces in various combinations of pitch angle settings. The figures show that the propeller with a positive right/left and a negative right/left cyclic pitch setting generates a force in port side and starboard side, respectively. When the collective pitch setting was increased, the magnitude of the transverse forces also increased. There was an evidence that the direction of the generated transverse force rotated when the collective pitch setting was increased.

A collective pitch setting and a right/left cyclic pitch setting were fixed to a positive value and then an up/down cyclic pitch setting was varied. The direction of the transverse force turned in a clockwise direction as decreasing the amplitude of the up/down cyclic pitch setting from +100% to 0% (20 deg to 0 deg) or -100% to 0%.

Regarding to directional control, if a collective pitch setting is not zero, a pure right/left force was able to generate by combining an up/down cyclic pitch setting and a right/left cyclic pitch setting. For instance, the propeller with a +80% collective pitch setting and -80% right/left cyclic pitch setting, it can produce a pure right force by adding +80%.

Figure 13 presents a magnitude and a direction of the transverse forces of the propeller when a positive up/down pitch setting was fixed at +80% (16 deg). The propeller generated a force in a port direction when the right/left cyclic pitch setting was positive. In contrast, the propeller generated a force in starboard direction when the right/left cyclic pitch setting was negative.

Figure 14 presents a magnitude and a direction of the transverse forces of the propeller when a positive up/down pitch setting was fixed at -80% (-16 deg). The propeller generated a force in a starboard direction when the right/left cyclic pitch setting was negative.

A collective pitch setting and an up/down cyclic pitch setting were fixed and then a right/left cyclic pitch setting was varied. The direction of the transverse force turned in a counter-clockwise direction as decreasing the right/left cyclic pitch setting from +100% to 0% (20 deg to 0 deg). However, as the right/left cyclic pitch setting decreasing from 0% to -100% , the transverse force turned in clockwise direction.

The advance coefficient also influenced the magnitude and direction of the transverse force as shown in Figure 15. The direction of transverses force rotates in clockwise direction.

The maximum torque occurred at a combination of +100% collective, +100% up/down and +100% right/left cyclic pitch setting. The torque was approximately 2.7 N.m (0.275 kg.m). The data of torque will be used to design an anti-roll device to an underwater vehicle.

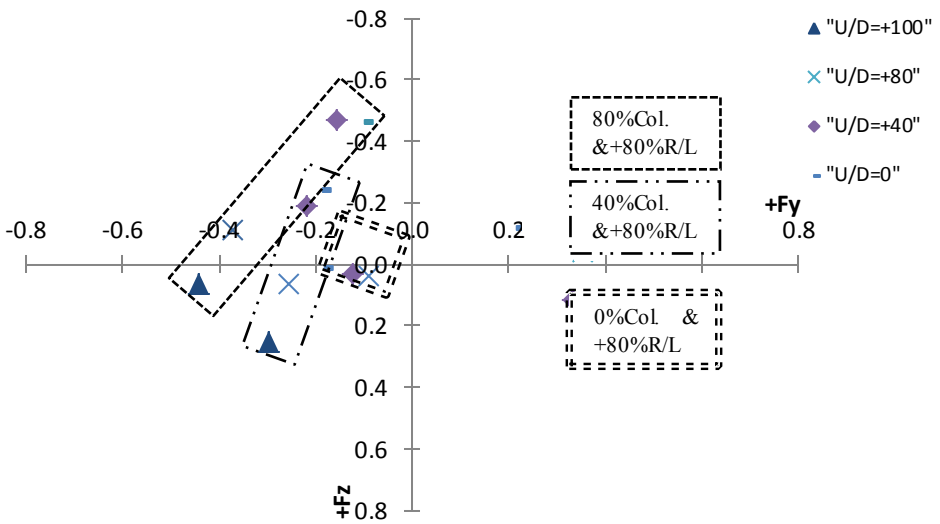

Figure11: Magnitude and direction of transverse forces acting on the small 6-DOF force transducer with various up/down pitches on a constant pitch of +80%, +40%, 0% Col, and +80% right/left.

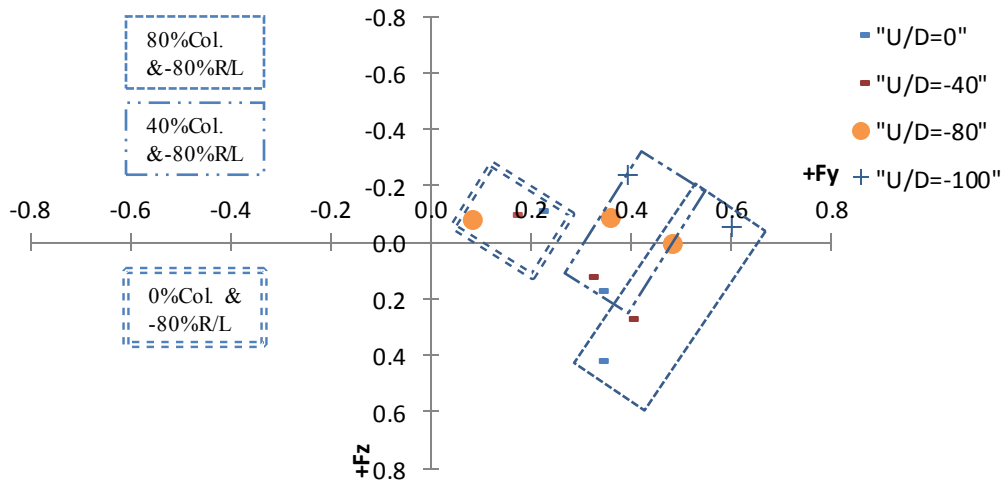

Figure12: Magnitude and direction of transverse forces acting on the small 6-DOF force transducer with various up/down pitches on a constant pitch of +80%, +40%, 0% Col, and -80% right/left.

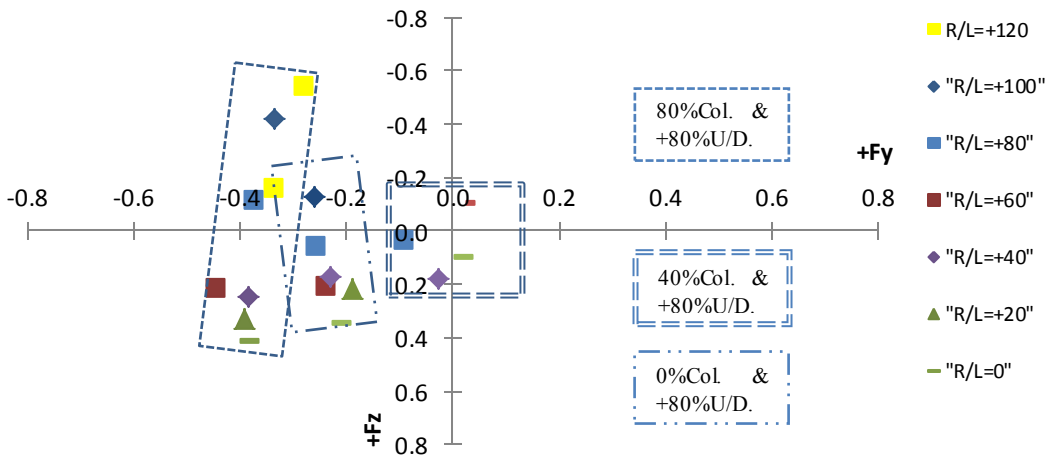

Figure13: Magnitude and direction of forces acting on the small 6-DOF force transducer with various right/left pitches on a constant pitch of +80%, +40%, +0% Col, and +80% up/down.

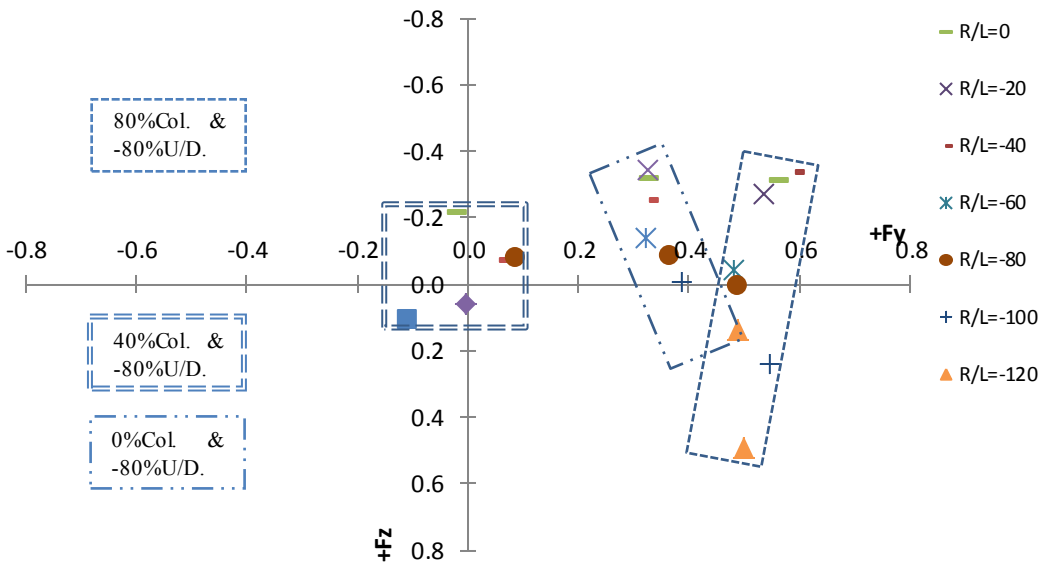

Figure14: Magnitude and direction of transverse forces acting on the small 6-DOF force transducer with various right/left pitches on a constant pitch of +80%, +40%, 0% Col, and -80%up/down.

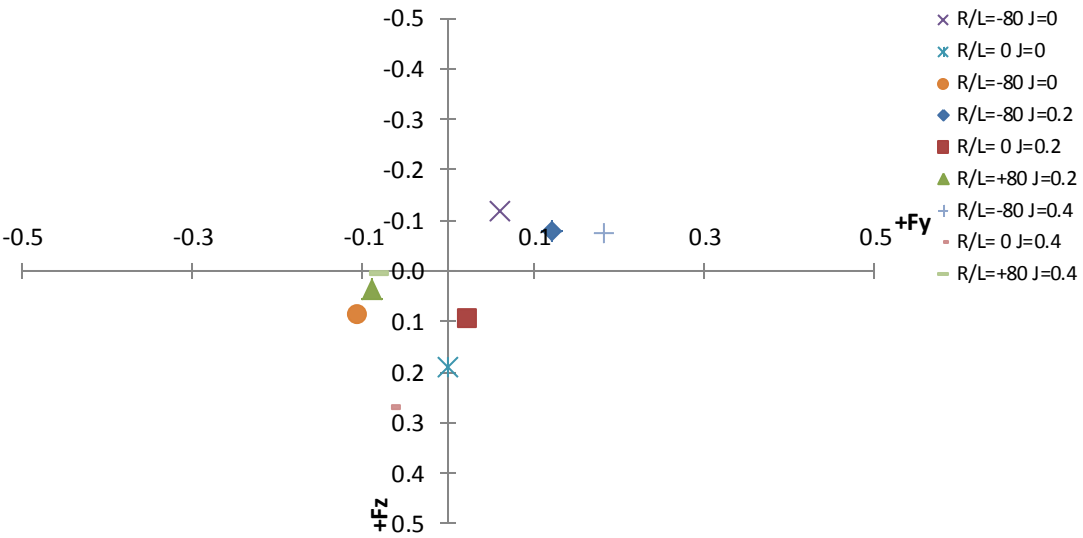

Figure15: Magnitude and direction of transverse forces acting on the small 6-DOF force transducer A combination of pitch with various right/left pitches on a constant pitch of 0% Col, and +80%up/down.

3.2 The results of the resistance tests

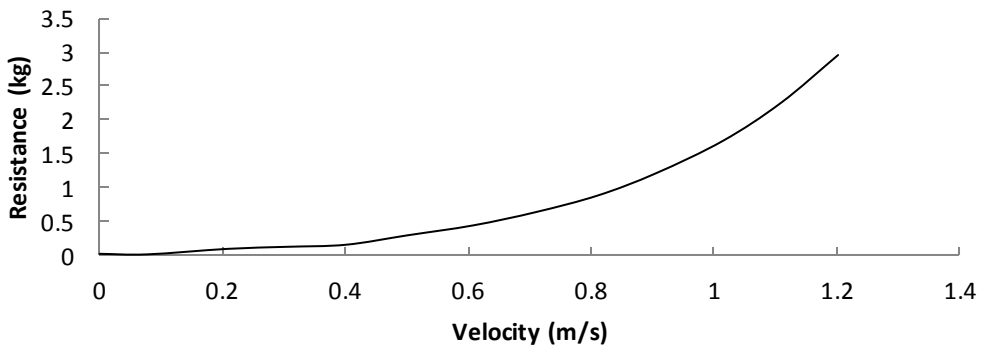

Figure16: Resistance of the tested underwater vehicle

The big force balance measured the total resistance including the testing underwater vehicle and the airfoil shaped struts . The resistance of the airfoil shaped struts subtracted from the total resistance is the resistance of the underwater vehicle as presented in Figure 16

4 CONCLUSION

The cyclic and collective pitch propeller with a collective pitch setting performs was similar to a conventional controllable pitch propeller. The propeller with a positive collective pitch setting pushed an underwater vehicle forward. The propeller with a negative collective pitch setting pulled the vehicle backward.

The cyclic and collective pitch propeller with a positive right/left cyclic pitch setting generated force in port direction. The propeller with a negative right/left cyclic pitch setting generated force in the starboard direction. In addition, the propeller with a positive up/down cyclic pitch setting produced force in a downward direction.

Increasing collective pitch will also increase the magnitude of transverse forces. However, the combination of cyclic pitch must be adjusted to compensate changing of the direction of the transverse forces.

The advance coefficient also affected the magnitude and direction of the transverse force. The direction of the transverse force rotated in a clockwise direction as increasing the advance coefficient.

An underwater vehicle should be designed to prevent roll motion because of the torque generated from the propeller.

The manual control of the direction of transverse forces is too complicated because a combination of pitch setting is not intuitive. Therefore, the cyclic and collective pitch propeller requires the development of a control system to automatically correct the combination of pitch.

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Appendixes

Table 1: Specifications of the CCPP,

Overall Length:	838mm
Propeller	305mm
Overall Diameter:	400mm

Propeller Area	0.15
Blade Rake Angle:	20°
Blade Angle:	±29° collective pitch, ±20°
Number of Blades:	4
Main Motor	1.1HP (800W)
Propeller Speed	500 RPM
Main Motor	48VDC
Control Voltage:	±12VDC
Control Options:	TCP/IP, USB, PCI 6036E

Table 2: Input variables and their ranges

	INPUT VARIABLS			
	Collective Pitch, %	Cyclic Pitch (up/down), %	Cyclic Pitch (left/right), %	Advance Coefficient
Ranges	+100 to -100	+100 to -100	+100 to -100	0 to 0.8
Interval	20	20	20	0.2

Table 3: The collective pitch values for each advance ratio value

Collective Pitch (%)
-100
-80
-60
-40
-20
0
20
40
60
80
100