Fifth International Symposium on Marine Propulsors
smp'17, Espoo, Finland, June 2017

Development of a Numerical Model for the Hydrodynamic Performance Analysis of a Collective and Cyclic Pitch Propeller

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ABSTRACT

The collective and cyclic pitch propeller (CCPP) is a propulsion and manoeuvring system for Autonomous Underwater Vehicles (AUVs). Through control of the propeller's blade pitch the CCPP is capable of generating propulsion and manoeuvring forces in an effective and efficient manner at both high and low speeds. Recent studies identified the need for additional research into the CCPP's unsteady flow behaviour and force generation capabilities before the technology can become a usable propulsion and manoeuvring system for AUVs. The paper discusses the development of a unsteady Reynolds-averaged Navier-Stokes (RANS) based numerical model. The motion of a single propeller blade is simulated by applying a sliding mesh approach and periodic boundary conditions to investigate the CCPP's hydrodynamic performance. After initial assessment of the methodology through verification and validation, a first numerical study is set-up to investigate the effect of cyclic pitch variation at zero collective pitch and without forward velocity. The results established the capability of the CCPP to produce a manoeuvring force, which increases in magnitude as the pitch amplitude is increased. Additionally, the blade rake angle was proven to have an effect on both the orientation of the manoeuvring force and the magnitude of the generated thrust force.

Keywords

Autonomous underwater vehicles, collective pitch, cyclic pitch, numerical, hydrodynamic performance.

1 INTRODUCTION

Autonomous Underwater Vehicles (AUVs) have become a vital tool for the execution of underwater missions in many industries and fields of research, ranging from the recovery of lost objects over the inspection of off-shore structures to underwater surveillance missions (Alam et al 2014). The specific mission profiles have revealed the need for a vehicle design that combines efficient long-endurance travelling capabilities with effective manoeuvrability at low speeds (Chyba 2009). Traditional control surfaces, used for manoeuvring, become ineffective at low speeds, while specific low speed manoeuvring aids, such as thrusters, tend to decrease the long-endurance travelling efficiency of an AUV (Griffiths et al 2004, Wernli 2000). Different emerging technologies address the "efficiency vs. effectiveness" design issue, e.g. vectored thrusters (Cavallo et al 2004), buoyancy-based steering concepts (Thangavel et al 2015), and collective and cyclic pitch control combined with the traditional screw propulsion system. The application of collective and cyclic pitch control has showed great promise and is the topic of the current paper.

Propellers capable of collective and cyclic control are an evolution of the traditional fixed pitch propeller (FPP). Inspired by helicopter flight control, cyclic pitch capabilities are added to the existing pitch control abilities of the widely used controllable pitch propeller (CPP). Through collective and cyclic pitch both propulsion and manoeuvring forces can be generated by the propeller. A torpedo-shaped AUV equipped with a propeller capable of collective and cyclic pitch control can effectively generate manoeuvring forces in three directions (surge, pitch and yaw), while travelling efficiently over long distances. Despite the concept's inherent capabilities, the hydrodynamics and mechanics of the concept has yet to be fully understood to be a viable AUV propulsion and manoeuvring alternative.

Over the past five decades a wide range of patents and research papers were published on the concept of using collective and cyclic pitch control to manoeuvre marine vehicles. Patents included propeller designs for both traditional surface ships (Gadefelt 1965) and various types of underwater vehicles (Haselton 1963, Reich & Uhrich 1990, Silber et al 2015). Early experimental research showed the concept's ability to generate usable manoeuvring forces of any magnitude and direction at all speeds (Gabriel & Atlar 1998, Haselton & Rice 1966, Joosen et al 1963). Later work, in combination with numerical investigations, Chen et al (2009) and Murray et al (1994) further confirmed the abilities of collective and cyclic pitch control. More recently, experimental towing tank research on a propeller was conducted (Humphrey 2005, Niyomka et al 2013) and once again showed the potential of the concept (propeller shown in Figure 1). Nevertheless, the different research efforts identified significant hurdles needed to overcome before the technology becomes a usable propulsion and manoeuvring system for AUVs.

Recommendations were made by several of the researchers to expand the knowledge and understanding of the highly unsteady flow behaviour and phenomena involved in the application of collective and cyclic pitch control. One identified phenomenon requiring additional investigation is the observed shift between the orientation of the intended manoeuvring force and the resulting, generated manoeuvring force, as reported by Haselton & Rice (1966), Murray et al (1994) and, Niyomka et al (2013). As the force shift occurs the propeller will not be able to control the AUV's motion correctly, justifying the need for additional research into the unsteady behaviour. The current research aims to develop a numerical methodology to investigate the shift phenomenon, besides investigating the hydrodynamic propeller performance in general, using a numerical methodology. By developing a numerical methodology, and make use of its inherent advantages, the existing research efforts are complemented and extended.

The use of numerical methods has become common practice in marine propeller design and research, proving capable to accurately and efficiently evaluate propeller designs and predict propeller behaviour. The most commonly used approaches, in order of level of sophistication, are BEMT (Blade Element Momentum Theory), panel methods, RANS-based models (Reynolds Averaged Navier-Stokes) and, to a lesser extent, the use of LES / DES-simulations (Large Eddy Simulation / Detached Eddy Simulation). BEMT models are used to evaluate the thrust, torque and efficiency of a propeller in a computationally efficient manner in early design stages (Cairns et al 1998). Panel methods, based on potential flow theory (which is inviscid), are a widely used tool to predict and evaluate propeller performance at design conditions. However, the BEMT approach tends to fall apart at off-design conditions, i.e. when complex (unsteady) flow phenomena occur, despite the incorporation of correction models (Amini et al 2012, Benini 2004). Similarly, the more complex panel methods have proven to lack the ability to capture highly unsteady flows, effects of high propeller loading, and the occurrence of flow separation (Brizzolara et al 2008, Gaggero et al 2010). RANS-models on the other hand have been shown to be able to model highly unsteady flow phenomena, provide accurate predictions of (dynamic) stall behaviour, simulate cavitation occurrence and model scale effects (Brizzolara et al 2008, Krasilnikov et al 2009, Watanabe et al 2003). The application of LES / DES, resolving the large scale turbulence and modelling the smallest scales, is not considered further in this research due to the high computational costs involved.

Figure 1: CCPP by Humphrey (2005)

In this paper the development of an unsteady RANS-based numerical model is outlined. The paper focusses on the numerical investigation of the hydrodynamic performance of the collective and cyclic pitch propeller developed by Humphrey (2005), investigated by Niyomka et al (2013), and from now on referred to as the CCPP. The CCPP's working principle, behaviour, control and characteristics of the numerical methodology are discussed in detail. The paper aims to provide a first look into the developed numerical model's capabilities in simulating and evaluating the CCPP's hydrodynamic performance and flow behaviour. An initial numerical study evaluates the effect of the cyclic pitch at zero collective pitch and without forward velocity. The analysis involves examination of the generated propulsion force, assessment of the resulting manoeuvring force's magnitude and orientation, and evaluation of the force evolution over the azimuthal cycle. In doing so, the paper forms the basis for future numerical research to realize the objective of the CCPP becoming a viable propulsion and manoeuvring system for AUVs.

2 THE COLLECTIVE AND CYCLIC PITCH PROPELLER

2.1 CCPP Characterization

The working principle of the CCPP relies on the collective blade pitch angle to govern the direction and magnitude of the generated propulsion force, while cyclic blade pitch is responsible for the generated manoeuvring force(s). The CCPP allows the AUV to travel long distances efficiently by control of the collective pitch and offers effective manoeuvring at low speeds once arrived at the desired location of interest using its cyclic pitch capabilities.

The propulsion force is defined in the x-direction and the manoeuvring force consists of the vector sum of the forces in y- and z-directions, as defined in Figure 1. Through control and variation of the propeller blades' pitch over the azimuthal cycle, i.e. cyclic pitch, a force imbalance is generated over the cycle. The resulting imbalance causes a pitching / yawing moment, which changes the AUV's trajectory. Essential in the generation of usable manoeuvring forces / side-forces is the blade rake angle (β), i.e. the angle between the blades and propeller rotation plane, perpendicular to the rotational axis. Figure 2 visualises the force-imbalance resulting from the cyclic pitch variation and the applied blade rake angle.

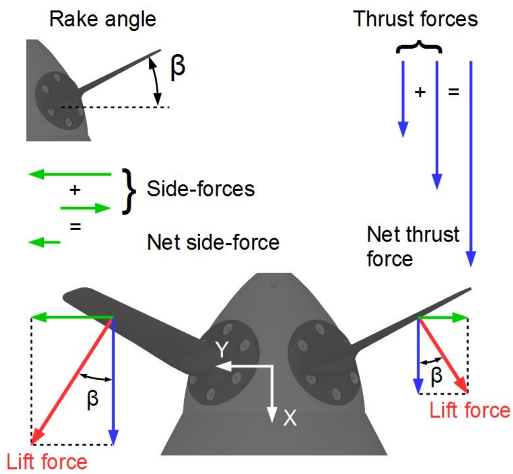

Figure 2: CCPP force break-down

The CCPP mechanism allows the pitch to vary over the cycle following a sinusoidal profile, to be discussed in more detail in the next sub-section. Table 1 and 2 provide an overview of the most relevant geometrical specifications and behavioural characteristics of the CCPP.

Table 1: CCPP behavioural characteristics

Rotation direction	–	Counter-clockwise
Rotation speed (max.)	n_{max}	600 $[rpm]$
Average rotation speed	n_{avg}	300 $[rpm]$
Collective pitch angle	Π_{coll}	± 29 [°]
Cyclic pitch angle	$\Pi_{cycl}^{U/D}$ / $\Pi_{cycl}^{R/L}$	± 20 [°]
Pitch angle range	Π_{min} - Π_{max}	-49 to $+49$ [°]

Table 2: CCPP geometry specifications

Number of blades	N	4
Blade section profile	–	NACA0012
Chord length (max.)	c_{max}	0.037 $[m]$
Blade span	s	0.118 $[m]$
Blade span profile	–	Tapered to $0.70c_{max}$
Rake angle	β	20 [°]
Diameter	D	0.305 $[m]$
Blade root radius	r	0.042 $[m]$
Blade area ratio	A/A_0	0.15 $[-]$
Pitch point	–	$0.25c$

2.2 Collective and Cyclic Pitch Control

Through control of the blades' collective and cyclic pitch the propeller is able to govern the forces and, more importantly, the resulting motions of the AUV. Understanding of the relation between the applied blade pitch and, the resulting force magnitude and direction is thus key in effective control of the AUV's motion.

Each individual propeller blade follows the same pitch profile as a result of the implemented mechanism. The resulting azimuthal pitch profile is prescribed by a goniometric function, defined in Equation (1), controlled by a single collective pitch parameter, two cyclic pitch parameters and the azimuthal blade position (ϕ_{azi}) (as defined in Figure 3 with Roman numerals indicating the azimuthal quadrants).

$$\begin{aligned}\Pi_{tot}(\phi_{azi}) = \Pi_{coll} \quad &+ \quad \Pi_{cycl}^{U/D} \cdot \sin(\phi_{azi} + 180^\circ) \\ &+ \quad \Pi_{cycl}^{R/L} \cdot \cos(\phi_{azi} + 180^\circ)\end{aligned} \tag{1}$$

The pitch angle is defined as the angle between the blade and the propeller rotation plane (yz-plane) with positive pitch defined as the leading-edge of the blade pointed moving towards the positive x-direction. Figure 4 defines the different pitch parameters for a two-dimensional blade section. The collective pitch parameter controls the mean around which the pitch angle oscillates, and the cyclic pitch parameters govern the magnitude of the pitch oscillation. Further illustration of the blade's pitch motion over the azimuthal cycle can be found in Figure 5. The resulting pitch oscillation can be considered both time-dependent and space-dependent. By combining both cyclic pitch parameters not only the magnitude of the oscillation is controlled, but the phase of the pitch profile is governed as well. The phase of the pitch profile is the main parameter controlling the orientation of the generated manoeuvring force, as will be explained further next.

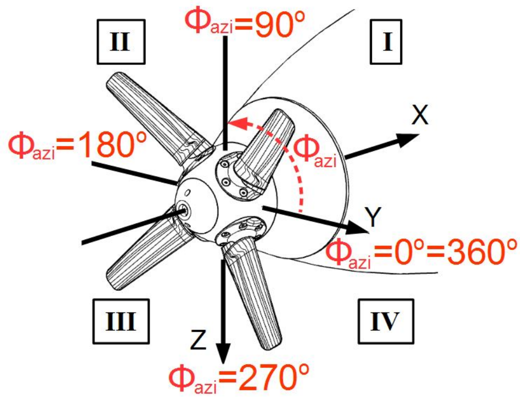

Figure 3: Definition azimuthal blade position

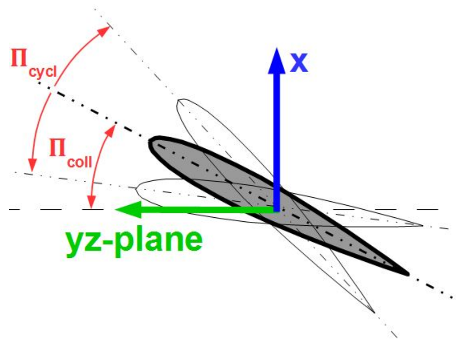

Figure 4: Definition of pitch parameters

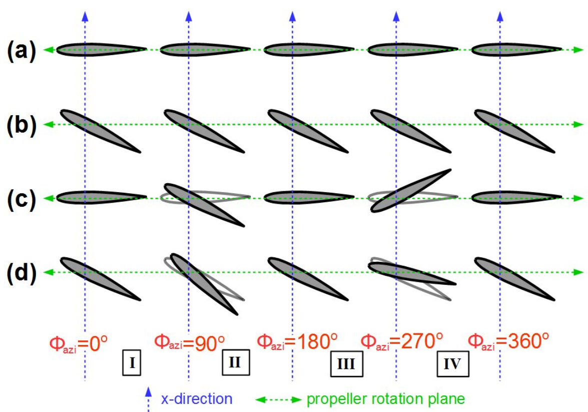

Figure 5: Blade pitch evolution over azimuthal blade positions: (a) no pitch, (b) collective only, (c) cyclic only and (d) collective and cyclic

The cyclic pitch parameters have the 'U/D' (Up / Down) and 'R/L' (Right / Left) indices because of the current assumption of the direct one-to-one relation between the applied pitch profile and the resulting manoeuvring force orientation / AUV motion. Table 3 and 4 relate the sign of the applied parameters to the presumed direction of the manoeuvring force and the resulting AUV motion. The current assumption is proven invalid in many cases, resulting in a (substantial) shift between the intended and the resulting orientation of the manoeuvring force, and requires extended investigation and evaluation.

Table 3: Assumed orientation of manoeuvring force(s)

$\Pi^{U/D}_{cycl}$ \ $\Pi^{R/L*}_{cycl}$	$-$	0	$+$
$+$	IV	z-axis $(+)$	III
0	y-axis $(+)$	Origin	y-axis $(-)$
$-$	I	z-axis $(-)$	II

Table 4: Assumed AUV motion

$\Pi^{U/D}_{cycl}$ \ $\Pi^{R/L}_{cycl}$	$-$	0	$+$
$+$	up-left	up	up-right
0	left	straight	right
$-$	down-left	down	down-right

2.3 Hydrodynamic Performance Definition

The hydrodynamic performance of the CCPP is defined as the efficient and controlled generation of a usable manoeuvring force. The research focusses on the orientation and magnitude of the generated manoeuvring force, as defined in Equation (2), to evaluate the CCPP's performance.

$$\begin{aligned} \vec{F_s} \quad &\rightarrow \quad F_s = \sqrt{F_y^2 + F_z^2} \\ &\rightarrow \quad \phi_s = f(\angle(F_y; F_z)) \end{aligned} \tag{2}$$

where $\vec{F_s}$ = resulting manoeuvring force / side-force; F_s = manoeuvring force magnitude; F_y / F_z = force magnitude in y/z-direction; and ϕ_s = manoeuvring force orientation.

3 NUMERICAL METHODOLOGY

3.1 Model Outline

The numerical model is developed using the commercial flow solver ANSYS FLUENT v16. Based on literature on numerical research into marine propellers (Brizzolara et al 2008, Dubbioso et al 2013) and other related topics, such as helicopter rotor systems (Choi et al 2007, Steijl et al 2006) and wind / tidal turbines (Holst et al 2015), a numerical methodology is developed, set-up and tested.

The flow over the CCPP blades is modelled using the unsteady RANS equations (URANS) with the k-ω SST transition turbulence model. The pressure-based solver uses a PISO-algorithm for the pressure-velocity coupling. Spatial discretisation of the gradients is least-squares cell-based, pressure discretisation is achieved using a second order method and, both momentum and turbulence parameters are discretised using second-order upwind schemes. For the time-discretisation a bounded second-order implicit dual-time stepping method is applied.

In the initial assessment of the CCPP, only one blade is numerically modelled to reduced the computational requirements. Taking advantage of the 90 degrees periodicity of the CCPP, the periodic boundary approach allows the single blade domain to implicitly represent the behaviour of the four-bladed system (see Figure 6). To achieve the motion of the CCPP and the propeller blade(s), the domain is divided into two zones: an inner zone to enable pitching of the blade and an outer zone to allow for rotation of the entire propeller. The motion strategy enables the use of a fixed grid approach, voiding the need for computationally expensive deforming meshes or re-meshing.

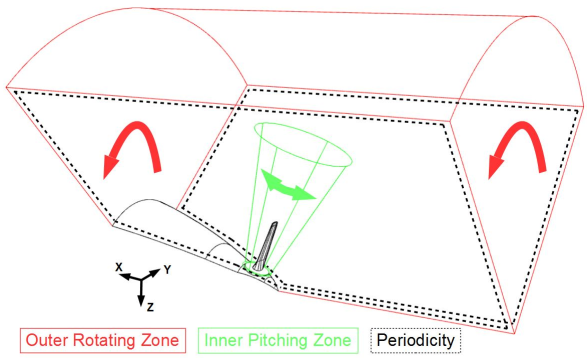

Figure 6: Numerical modelling strategy: periodic modelling and, separate rotational motion of AUV and pitching motion of the CCPP blade

The motion of the zones is specified through user-defined functions in ANSYS FLUENT. The solver only allows for the specification of one rotation around a single axis. Since the inner zone, i.e. the propeller blade, rotates both with the outer zone and around the blade's respective pitch axis, an additional step is needed. Using a quaternion-based algorithm both rotations are combined each time-step, recalculating the combined, new rotation axis and magnitude needed to ensure the correct blade motion.

3.2 Computational Domain

The periodic computational domain is further limited in size by not modelling the entire AUV. Figure 7 shows the domain dimensions and the different defined boundaries: inlet, outlet, top, sides, and CCPP / AUV.

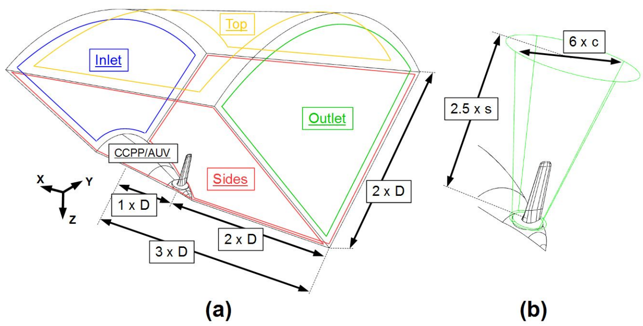

Figure 7: Computational domain specifications, (a) outer domain and (b) inner domain

The boundary conditions applied are: uniform velocity for the inlet, outflow for the outlet, symmetry for the top and no-slip wall for the CCPP. Interface boundary conditions are specified for the sides and the fluid domain interface. The sliding interface is defined to ensure communication between the domains and the rotational periodic interface on the sides enables the periodic set-up. Both interfaces are defined using the 'matching'-option to ensure proper interpolation between the non-conformal mesh surfaces.

3.3 Grid Generation

A multi-block structured hex grid of the flow domain is created using Pointwise. Some modifications to the CAD-geometry were necessary to facilitate easier meshing and the motion algorithm strategy. The modifications altered the root of the CCPP blades but are accepted to have no significant influence on the calculated direction and magnitude of the manoeuvring forces. A y+ of 1 with a boundary layer growth ratio below 1.2 in the near-wall mesh on the blade surface is ensured, while wall functions are applied over the AUV body. Figure 8 illustrates some of the important features of the numerical grid.

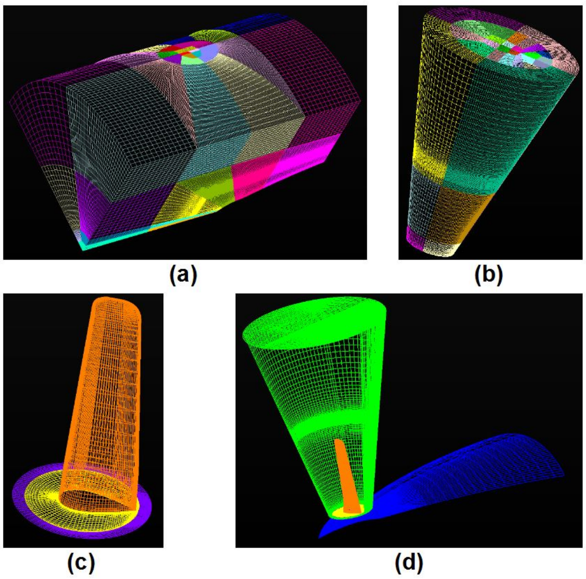

Figure 8: Grid visualisation: (a) outer zone, (b) inner zone, (c) CCPP blade and (d) CCPP and zone interface

3.4 Verification Study

To establish the dependency of the numerical solution on the applied methodology and discretisation, verification is carried out. The verification study aims to provide the numerical settings needed to achieve a converged solution in a computationally efficient manner.

Initial verification of the methodology was done based on the modelling of two-dimensional pitching hydrofoils, as reported by Dubois et al (2016). The study established the discretisation parameters for both space and time used in the current three-dimensional investigation. Spatial discretisation is based on the number of cells over the blade chord (86) and span (83), in addition to the number of cells over the radial distance around the blade within the inner domain (57). The spatial discretisation is extrapolated towards the entire flow domain similar to the two-dimensional procedure, resulting in a total domain cell count of five million cells. The dual-time stepping method is quantified by a continuity equation convergence tolerance of 10^{-4} for the inner iterations and 800 steps per azimuthal cycle for the outer, physical iterations.

An extended verification study, focusing on the evaluation and quantification of the influence of the numerical parameters on the three-dimensional methodology, will be undertaken in the future. The study includes an in-depth validation study, of which the first part is presented in the next sub-section, along with an uncertainty assessment.

3.5 Validation Study

Through an initial validation study the paper aims to provide insight into the current numerical model's ability to capture the flow behaviour and hydrodynamic forces involved in the operation of the CCPP. Through comparison of the numerical and experimental results the capability of the model to simulate the effect and performance of the CCPP under different operating conditions is investigated.

The experimental results for validation are taken from recent towing tank work at the Australian Maritime College. Three cases are selected, as shown in Table 5, spanning a range of applied operating conditions. Results of the validation, comparing the experimental and numerical manoeuvring force, are plotted in Figure 9.

Table 5: Validation study case parameters

	U $[m/s]$	n $[rpm]$	Π_{coll} [°]	Π_{cycl} [°]
Case A	0.0	400	0.0	20.0
Case B	1.2	300	0.0	10.0
Case C	1.2	300	15.0	10.0

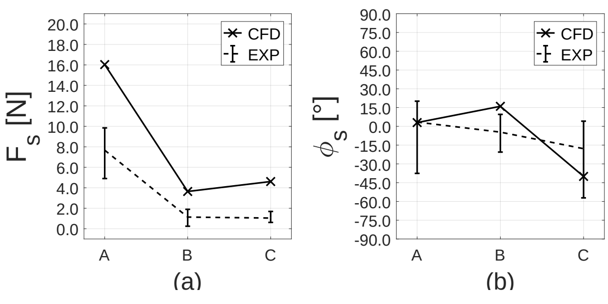

Figure 9: Validation study results for the manoeuvring force with (a) magnitude and (b) orientation

The numerical simulations over predict the manoeuvring force magnitude by a significant margin when compared to the experimental results. Despite the differences, the same trend among the three cases can be seen, with case A producing the highest manoeuvring force, and the force magnitude of case B and C almost equal at around 25% of case A's force magnitude.

The manoeuvring force orientation, expressed as the azimuthal direction of the force vector, shows a different and more erratic behaviour. The error range of the experimental results show a wide variation of the force's orientation and no clear trend can be established. The simulated force for case B appears to be orientated in the opposite direction as compared to the experimental direction. Clearly, no real conclusions can yet be established on the model's, and, in lesser extend, the experiment's capabilities of quantifying the azimuthal shift of the actual manoeuvring force.

Further validation (and verification) is currently being undertaken, which includes the investigation of a wider range of operating conditions and their effect on the manoeuvring force, as well as evaluation of both the experimental and numerical repeatability and uncertainty. Nevertheless the limitations established in the verification and validation study, an initial numerical investigation into the CCPP's hydrodynamic performance is performed.

4 HYDRODYNAMIC PERFORMANCE ANALYSIS

4.1 Study Outline

One of the main strengths of the CCPP is the generation of manoeuvring forces at low and even zero forward speeds. Therefore, the focus of the current numerical study is the effect of the cyclic pitch amplitude on the generated propulsion and manoeuvring force at zero collective pitch and without forward AUV velocity (no inflow in x-direction).

The current study evaluates four cyclic pitch amplitudes at a single operating condition; $\Pi_{cycl} = 0.0$, 5.0, 10.0, and 20.0 [°], with $\Pi_{coll} = 0.0$ [°] and $U = 0.0$ $[m/s]$ at $n = 400$ $[rpm]$. The zero cyclic pitch case provides a benchmark for the evaluation of the cyclic pitch amplitude influence on the generated forces.

The discussed results represent time-averaged values of five rotation cycles. Oscillatory convergence is monitored by analysing the convergence of average force values for each subsequent cycle until a 'stable' solution is reached. Stability is achieved when the averaged solution changes less than 5% over five consecutive cycles. All calculations are simulated with a time-step of 0.0001875 $[s]$, resulting in a total simulated flow time of 0.75 $[s]$.

4.2 Manoeuvring Force Magnitude

The magnitude of the generated manoeuvring force will determine the manoeuvring performance of the CCPP, and in turn of the AUV. Figure 10 shows the manoeuvring force magnitude as a function of the cyclic pitch amplitude.

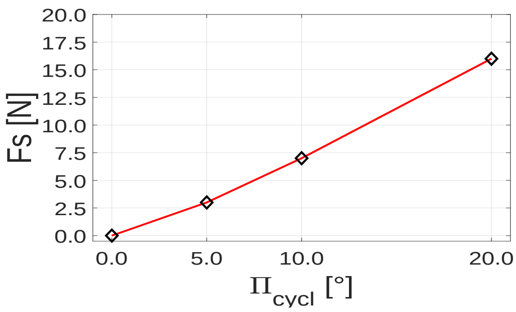

Figure 10: Manoeuvring force magnitude

As expected, no manoeuvring force is observed at zero cyclic pitch and the introduction of cyclic pitch results in a clear manoeuvring force. A linear relation exists between the applied cyclic pitch amplitude and the resulting manoeuvring force magnitude. The relative increase in force magnitude appears to become lower at larger cyclic pitch amplitudes. Further investigation is needed to find out if a further increase of the cyclic pitch amplitude might not result in a larger manoeuvring force.

4.3 Effective Manoeuvring Force

The effective manoeuvring force, i.e the component of the manoeuvring force in the intended direction is just important as the manoeuvring force magnitude, in terms of controlling the AUV. As concluded by previous research, a shift of the force away from the intended orientation tends to occur under certain conditions. Figure 11 plots the contribution of the intended and the perpendicular force component to the total manoeuvring force.

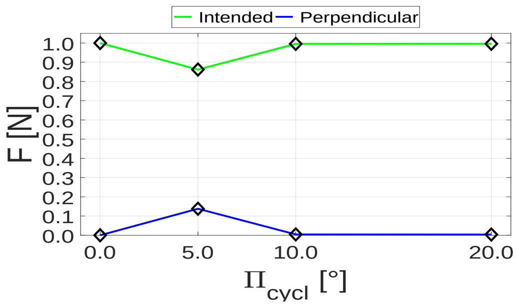

Figure 11: Manoeuvring force orientation

Since the generated force at zero cyclic pitch is near non-existing, the contributions of the intended and perpendicular force can be considered singularities. At $\Pi_{cycl} = 5$ [°], the perpendicular component significantly reduces the effectiveness of the manoeuvring force. An increased cyclic pitch amplitude reduces the contribution of the perpendicular, non-desired, force component to almost zero. Investigation of the azimuthal evolution of the forces should help to clarify the observed force behaviour.

4.4 Azimuthal Evolution of Manoeuvring Forces

The numerical methodology provides the ability of monitoring the force evolution over the azimuthal cycle. Closer investigation of the origins and behaviour of the generated forces can provide valuable insights into the hydrodynamic performance. Figure 12 visualises the azimuthal force evolution for all simulated cases (separately for the intended and perpendicular force component).

Evaluation of the intended force component evolution shows two important features, besides the larger peak values as the pitch amplitude is increased. First of all, asymmetry of the force evolution is observed between the first and second half of the azimuthal cycle. Secondly, a shift of the peak values occurs as the pitch amplitude becomes larger. Both the asymmetry and the shift are attributed to the blade rake angle. The rake angle counter-acts the applied pitch oscillation in the first half of the cycle, while enforcing the effects of the pitch oscillation in the second half. At larger pitch amplitudes the relative effect, i.e. the asymmetry, is smaller, indicating a certain threshold value to be overcome. The same threshold value is expected to be the cause of the observed behaviour of the effective manoeuvring force, as discussed in the previous section.

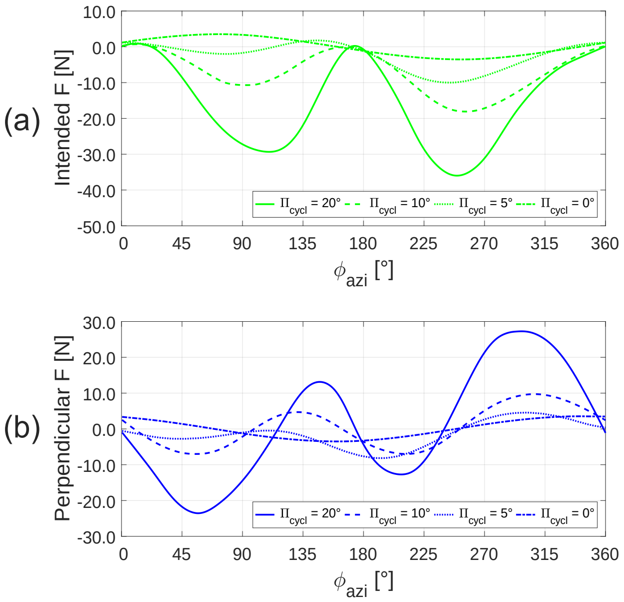

Figure 12: Azimuthal force evolution: (a) intended force component and (b) perpendicular force component

The perpendicular force component's evolution further confirms the observed force behaviour. A similar asymmetry can be seen in all cases. For the lowest cyclic pitch amplitude the asymmetry is less pronounced, resulting in a non-zero mean value of the perpendicular force component. At the higher pitch amplitude the force becomes point-symmetric and no longer has a non-zero mean, i.e. no actual force is generated. Apparently at $\Pi_{cycl} = 5$ [°], the effect of the blade rake, which clearly can be seen in the no cyclic pitch case, is not yet overcome. Future investigation will focus on quantifying the exact threshold value by simulating additional cyclic pitch amplitudes.

4.5 Propulsion Force

The zero collective pitch angle combined with zero forward speed is expected to not generate a propulsion force. Nevertheless, Figure 13 shows that a thrust force is generated at, and independent of, all cyclic pitch amplitudes.

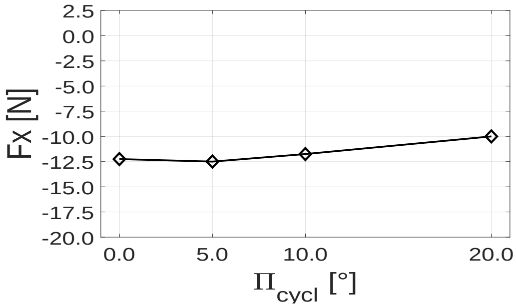

Figure 13: Forward thrust force

The generation of a thrust force is expected to be only controlled by the collective pitch angle, i.e. the angle around which the pitch oscillates. Based on the current numerical results it can be seen that another factor influences the forward thrust generation. As the current observations are made at zero cyclic pitch the origins of the behaviour are not pitch related but can be attributed to the blade rake angle. The results show that under the current conditions, a collective pitch angle should be introduced to overcome the rake effect and ensure no thrust force is generated.

5 CONCLUDING REMARKS

A numerical methodology has been developed to simulate and investigate the hydrodynamic performance of the CCPP. An URANS approach with transitional k-ω SST turbulence modelling is applied on a periodic domain, modelling a single propeller blade. Through a quaternion-based algorithm the rotational and pitching motion of the CCPP is described on a two zone fluid domain. The two zone approach allows for a fully block-structured grid without the need for computational expensive mesh deformation or re-meshing, with the two zones linked using a sliding interface. Initial verification and validation showed the potential of the numerical methodology, despite the clear need for additional work in both areas.

The numerical results showed the capability of the CCPP to generate an effective manoeuvring force by applying cyclic pitch at zero collective and a zero forward velocity. Furthermore, the research established the importance of the blade rake in the control of both the manoeuvring force's effectiveness / orientation, and the generated thrust force. The study should be extended with additional cyclic pitch amplitudes, both intermediate and larger amplitudes, in order to fully quantify the observed flow behaviour.

Further development of the numerical methodology is a main focus of future work. Included is the extended verification and validation study to be concluded by an uncertainty assessment, evaluation of the periodic assumption by modelling all four blades, analysis of the 'uniform' inflow condition, and investigation of the applied flow modelling procedure. Additionally, more experimental will be undertaken to generate new validation material and provide new insights into the CCPP's working principle.

After thorough assessment of the numerical methodology, the developed model can be used as a powerful research tool to analyse, and subsequently improve, the CCPP's hydrodynamic performance. Through extended numerical analysis of the CCPP, the research aims to generate knowledge on operational and design improvements aspiring to increase the CCPP's effectiveness and efficiency.

ACKNOWLEDGEMENTS

The authors would like to thank the Australian Maritime College and the University of Tasmania for the provided PhD-scholarship. Special thanks as well to the Ship Hydrodynamics centre, PhD-student Minh Tran, and the towing tank technicians for the experimental work and data.

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DISCUSSION

Question from Stefano Brizzolara

What is the relative amount of (maximum) side-force the propeller can develop when sailing in straight motion at full speed?

Author's closure

No numerical results are available yet on the relation between the max side-force and the forward propulsion force at full speed. Nevertheless, recent experimental work shows forward thrust values to be around 1.5 to 2 times larger than the generated manoeuvring force (maximum collective and cyclic pitch and travelling forward at 2 m/s). A side-note here should be that this concerns the total generated side-force magnitude and the effective side-force in the desired direction is thus even smaller. The fact of the matter is that this is one of most relevant problems in the current CCPP research. The relation will be the subject of closer investigation, both to better understand it and find solutions to improve the relation and make the side-force truly efficient and effective, both at low and especially as well at high forward velocities.

Question from Yin Lu Young

a) You could use the double stream-tube model (like the work by M. Benedict) to account for blade-to-blade presence.

b) It may be worth it to compare your results with the results of the work by S. Huyer on controllable pitch preswirl stators on undersea vehicles.

Author's closure

a) The work by M. Benedict was not know to us before, but we will certainly have a look at it and investigate the applicability of the results on the current research.

b) The work by S. Huyer is known to us and certainly has interesting features applicable as well to the current work. A more detailed comparison of the results and conclusions will indeed be interesting to use and compare the effectiveness of both manoeuvring solutions.

Question from Mike Krieg

It seems that an increase in rake angle would increase the effectiveness of manoeuvring at the expense of forward propulsion and that the optimal rake value will change depending on the mission. Have you considered a variable rake angle?

Author's closure

The current rake angle was determined based on a force prediction model by the designers, as a good compromise between the forward thrust and gain in manoeuvring force magnitude. The optimal angle will indeed be dependent on the mission, e.g. pure manoeuvring would benefit from an angle as close to 90 degrees as possible (similar to a Voith-Schneider system) and propulsion would be more effective at angles closer to 0 degrees. The option of changing the rake angle would thus certainly be interesting, although it would introduce an additional level of (mechanical) complexity. Further investigation of the effect of the rake angle will certainly be undertaken in the current research.