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UNDERWATER HELICOPTERS: IDENTIFYING THE MERITS OF COLLECTIVE AND CYCLIC PITCH CONTROL IN AUV PROPULSION AND MANOEUVRING

A Dubois, **Z Q Leong**, **H D Nguyen**, and **J R Binns**, Australian Maritime College – University of Tasmania, Australia

SUMMARY

Autonomous Underwater Vehicles (AUVs) are required to travel efficiently over long distances and operate effectively at low speeds. In the paper, five merits of collective and cyclic pitch control, a concept found in helicopter flight control, to achieve effective and efficient AUV propulsion and manoeuvring are identified through a literature review, in combination with the presentation of results of recent research by the authors. The first merits show the CCPP's ability to improve the overall vehicle manoeuvrability and enable effective low speed operation. Furthermore, the concept is demonstrated to effectively address unsteady wake effects. The last merits are the potential of resistance reduction and the optimisation of both space and power utilisation through the combination (and potential elimination) of other systems. Combined, the merits justify further research and development of collective and cyclic pitch control as a viable system for AUV propulsion and manoeuvring.

NOMENCLATURE

AUV	Autonomous Underwater Vehicle
BEMT	Blade Element Momentum Theory
CPP	Controllable Pitch Propeller
CCPP	Collective and Cyclic Pitch Propeller
FPP	Fixed Pitch Propeller
MUV	Manned Underwater Vehicle
RANS	Reynolds-Averaged Navier Stokes
UUV	Unmanned Underwater Vehicle

1. INTRODUCTION

Exploration of the unknown has compelled humanity since the beginning of time. From the voyages of the great explorers Christopher Columbus and Marco Polo (Encyclopædia Britannica, n.d.), over the deep space exploration missions of the Voyager-missions, to the renewed interest in travel to the Moon and Mars (The History Channel, n.d.), humans keep displaying a desire to discover. Closer to home, however, remains a largely undiscovered world, hidden beneath the waves of vast oceans covering more than two-thirds of the earth's surface (Graham *et al.*, 2000). Manned attempts at underwater exploration date back as early as Leonardo da Vinci (National Geographic, 2015). The high risks and dangers involved in manned underwater missions sparked the development of a wide variety of unmanned underwater vehicles (UUVs), replacing manned underwater vehicles (MUVs). Furthermore, the Autonomous Underwater Vehicle (AUV) was developed, a vehicle capable of performing a programmed, pre-determined mission without the need for additional human interaction.

Interest and research into AUVs started gaining momentum in the 1970s as reported by Alam *et al.* (2014). AUV designs and builds appeared in a wide range of shapes, sizes and propulsion types (Button *et al.*, 2009) as a result of the diversity in deployment purposes (Chyba, 2009). Today, AUVs are deployed for tasks ranging from the recovery of lost objects, over the inspection of submerged structures to underwater surveillance missions. The specific mission profiles of commercial AUVs require a combination of efficient, long-range travelling capabilities with effective operation at low speeds (Wernli, 2000). The combined requirement emphasises clearly the importance of efficient energy storage and utilisation in AUV development and operation (Griffiths *et al.*, 2004). Traditionally, AUV manoeuvring is conducted using control surfaces but these tend to lose their effectiveness at low speeds, because of the relation between the flow velocity over a surface and the magnitude of the generated lift force. Low speed manoeuvring aids, on the other side, such as side- or podded-thrusters, reduce the long-range travelling efficiency, and thus, a design issue arises. Potential solutions to address the design issue have been proposed. Technologies using the vehicle's buoyancy to generate steering forces (Thangavel *et al.*, 2015; Ullah *et al.*, 2015) and vectored thrust generation devices (Cavallo *et al.*, 2004; Le Page & Holappa, 2000) exist to solve the apparent design problem. However, the aforementioned technologies often lack in manoeuvring effectiveness or propulsive efficiency and can be mechanically to complex. An alternative solution to the aforementioned design issue is found in the use of collective and cyclic pitch control to propel and manoeuvre an AUV efficiently and effectively at both low and high speeds.

In this paper, a literature review aimed at the identification of the merits of collective and cyclic control in AUV propulsion and manoeuvring is presented. After a detailed discussion of the origins of collective and cyclic pitch control in marine propulsion and manoeuvring, a general overview of patents and research history on the concept is provided. The discussed work is then used to identify, scrutinise, and justify five concrete merits of the concept, i.e. improved overall manoeuvring, low speed manoeuvrability, addressing of unsteady wake effects, resistance reduction, and optimised space and power utilisation. The merit identification enables clear differentiation of the concept from other propulsion and manoeuvring systems, without direct comparison (as this is often not yet possible). Finally, an overview is provided of the results of a recently completed PhD research project into a specific implementation of a collective and cyclic pitch propeller concept. As such, the paper provides an update on the state of affairs regarding research into the collective and cyclic pitch propeller control for AUV propulsion and manoeuvring. Additionally, the authors aim to spark renewed and continued interest in the topic, all aimed at the realisation and development of the concept as a viable system for AUV propulsion and manoeuvring.

2. ORIGINS OF COLLECTIVE AND CYCLIC PITCH CONTROL IN MARINE PROPULSION AND MANOEUVRING

The fundamental idea behind screw-based marine propulsion is simple and robust. A finite number of foils or blades attached to a shaft rotate behind the hull of a marine vehicle, thereby generating forces over the blades, resulting in propulsion of the vehicle. Despite the simple working principle, the screw-based propeller has undergone some major evolutions and improvements since its inception (Carlton, 2012).

One of the most important propeller characteristics undergoing constant scrutiny is the blade pitch angle, and more importantly, its influence on the propulsive performance. The introduction of added control over the pitch angle, defined as the angle between a blade section reference line (most often the chord line) and the propeller plane, provides an important new performance control parameter. In essence, the pitch angle governs the effective angle of attack of each blade and thus the magnitude of the generated forces over the blades, in turn controlling the generated thrust and thus the propeller's effectiveness and efficiency. Through adjustment of the pitch angle, the propeller's loading, and consequently, the propulsive performance can be manipulated directly.

The most common maritime propeller is the fixed pitch propeller (FPP). The geometry and pitch angle of a FPP is, as the name states, fixed and results in simple and robust mechanics. The level of thrust generation of a FPP can only be controlled through its rotational velocity. Unfortunately, the lack of control makes the FPP highly susceptible to cavitation inception and, consequently, vibrations and erosion of the propeller when operating at off-design conditions. All the aforementioned effects will negatively affect the propeller's efficiency, resulting in higher fuel consumption and noise production throughout the vessel.

Added control over the generated thrust was made possible by the development of the controllable pitch propeller (CPP). A CPP allows the propeller load to be efficiently changed by adjusting the pitch of the propeller blades depending on the operational conditions. The pitch of all the CPP blades is controlled in a collective manner, i.e. all blades pitch an equal amount simultaneously. An additional benefit of the CPP is its ability to reverse the propeller pitch, thereby adding rapid manoeuvring capabilities, such as braking and reversing, to the propulsion system. Additionally, the possibility to feather the propeller blades exists reducing the propeller resistance at zero rotation. Despite the added mechanical complexity and costs involved, the CPP has gained a large market share over the last decades, especially in the passenger ship / ferry, tug, and trawling markets, due to the outlined advantages.

Further control of the propeller blade pitch can be achieved with the implementation of cyclic pitch capabilities. Cyclic pitch control allows the pitch of each individual blade to be adjusted (periodically) over the azimuthal cycle. The concept of cyclic pitch control finds its origins in helicopter flight control. Governing the cyclic pitch was identified as being key in realising flight control by A. Crocco, and later the B. Yur'ev and J.C. Ellehammer (Leishman, 2000). The introduction of cyclic pitch control allowed to solve the problem originating from the asymmetric loading between the advancing and retreating side of the helicopter rotor blades. By adjusting the pitch of the rotor blades over the rotational cycle, force symmetry, and consequently flight stability, is ensured.

Taking the helicopter technology under water, turns the symmetry problem around. Marine propellers apply cyclic pitch control to generate asymmetric forces over the azimuthal cycle to generate manoeuvring forces. In essence, a manoeuvring force or side-force is induced by a force imbalance as a result of force asymmetry over the rotational cycle, achieved through cyclic adjustment of the blade pitch. An AUV equipped with a single propeller capable collective and cyclic pitch control will be able to efficiently and effectively operate in three degrees of freedom: surge, pitch and yaw, at both zero and forward speeds. Additionally, the possibility exists to operate multiple propellers, e.g. front and aft, allowing the vehicle to manoeuvre in all six degrees of freedom and perform advanced manoeuvres.

3. PATENTS AND RESEARCH HISTORY

3.1 PATENT HISTORY

Since the 1960s, a number of patents on the concept of collective and cyclic pitch control as an alternative for the propulsion and manoeuvring of marine vehicles were issued. Unfortunately, and perhaps surprisingly, none of the filed patents resulted in the development of a commercial application. Nevertheless, the investigation of the patents is considered a useful and worthwhile avenue to identify the merits of the concept.

The first patents appeared in Sweden. Gadefelt (1965) patented a ship propeller using collective and cyclic pitch in order to assist in ship manoeuvring, while Lindahl (1966) did not state a specific application purpose when describing a propeller with adjustable blades. Around the same time in the United States, Haselton (1963) proposed, and later improved (Haselton, 1966), a tandem propeller system based on a large hub-to-diameter ratio propeller concept. The system consisted of a combination of front and aft propellers, thereby introducing the capability of the vehicle to operate in all six degrees of freedom (including movement perpendicular to the longitudinal axis of the submarine). Later, Wham *et al.* (1987) introduced a new design based on the work of Haselton, while Haselton himself filed complemented and reviewed patents (Haselton, 1969; Haselton & Stenovec, 1987).

Later, patents emerged detailing designs of single and more traditional propellers, capable of collective and cyclic pitch control, for both underwater vehicles and other marine vessels (Reich & Ulrich, 1990; Peterson *et al.*, 1991; Schneider, 1993). More recently, Duncan (2007) patented a generic hub, capable of actuating blade pitch in a collective, cyclic and dihedral manner, while Silberg *et al.* (2015) suggested the implementation of blade flapping and propeller articulation in addition to collective and cyclic pitch capabilities.

3.2 RESEARCH HISTORY

Besides patents, several research efforts focused on experimental (and limited numerical) determination of the hydrodynamic properties and capabilities of collective and cyclic pitch propulsion systems. Early experimental research showed the capabilities of the concept in generating transverse forces of any magnitude and direction at all speeds (Joosen *et al.*, 1963; Haselton & Rice, 1966; Haselton, 1969). Furthermore, the feasibility study by Joosen *et al.* (1963) identified the capabilities of the concept in reducing unsteady flow effects, a therefore unexplored potential application of collective and cyclic pitch control. Jessup (1976) confirmed the newly identified abilities by showing improvements in propulsive power combined with enhanced (visible) cavitation and vibration performance when applying cyclic pitch control. Simonsson (1981, 1984) constructed and tested a pinnate propeller, a design consisting of an even number of blades with the opposite blades connected through a pinnate axle. Based on experimental investigations and full-scale sea trials of the pinnate propeller, similar conclusions on the cavitation and vibration behaviour were reported. Gabriel & Atlar (1998) confirmed aforementioned abilities, when investigating the optimal cyclic pitch profiles of a single propeller for a traditional ship.
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Further investigation of the manoeuvring capabilities of the concept were reported by Murray *et al.* (1994). He identified the full potential of collective and cyclic pitch propellers through numerical evaluation and rapid prototype development of such a propeller for various Navy vehicles. Similar systems were tested by Nagashima *et al.* (2006) now referred to as a variable vector propeller (VARIVEC), to be used in the control and operation of a real-time imaging underwater vehicle. Furthermore, Chang *et al.* (2007) investigated the influence of different oscillation cycle profiles on the performance of a similar variable vector propeller. Further research into Haselton's tandem propeller system was also conducted after being revived by a different research group. Chen *et al.* (2008, 2009) combined numerical prediction and simulation with experimental work to develop a demo vehicle, and a preliminary controller for it, capable of executing motions in six degrees of freedom through the tandem propeller system.

3.3 CCPP CONCEPT

Concurrent to the research efforts in the early 2000s, Humphrey (2005) developed, built, and tested a working propeller as part of a MSc project at Memorial University of Newfoundland (Canada). The work continued an initial investigation of a two-bladed cyclic pitch propeller, performed within the same research group. Humphrey developed a four-bladed propeller, referred to as the Collective and Cyclic Pitch Propeller or CCPP, as seen modelled in Figure 1.

Through experimental testing, Humphrey (2005) showed the ability of the CCPP to control a torpedo-shaped underwater vehicle at low or no forward speed. Furthermore, unsteady flow effects, shifting the orientation of the generated manoeuvring or side-force away from the intended side force direction, were observed. The phenomenon of the side-force shift was identified before by Haselton and Rice (1966), Murray *et al.* (1994) and also mentioned by Theodorsen (1949) in his two-dimensional thin airfoil theory. The apparent shift was shown to have a strong dependence on the collective pitch magnitude. Consequently, continued research into the aforementioned unsteady side-force phase shift was recommended. Additional recommendations included the development of an extended and improved control algorithm to realise a deployable propeller and self-propulsion tests as basis for a numerical prediction model to be used for design evaluations.

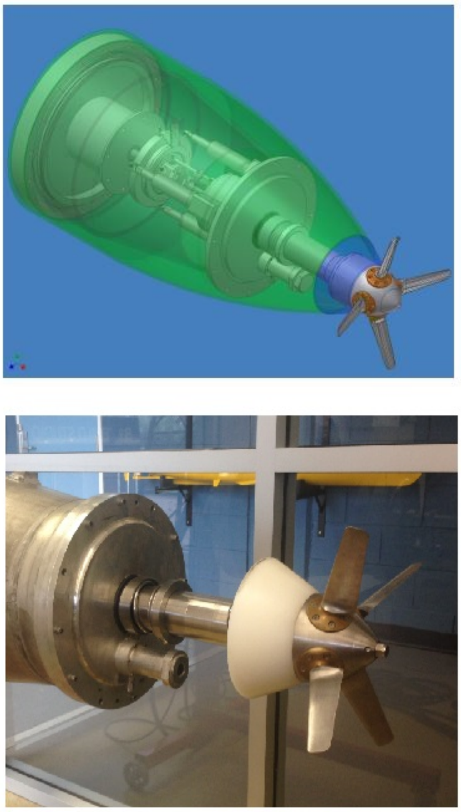

Figure 1: CCPP as designed by Humphrey (2005)

Research on the CCPP continued at the Australian Maritime College, University of Tasmania (Australia) in the form of several PhD research projects. First, Niyomka (2014) extended the towing tank experimental envelope, increasing the range of tested pitch and advance ratios, in combination with the development of a performance prediction program, based on unsteady blade element momentum theory (BEMT). The manoeuvring capabilities of the propeller were evaluated and re-confirmed by the experiments and a manoeuvrability simulation program. Additionally, the experiments showed the side-force phase shift to increase at larger collective pitch settings, re-affirming the occurrence of the unsteady flow lag. Large discrepancies between the numerical results and the available experimental data predicting the propeller's performance warranted more experiments and / or advanced numerical modelling approaches.

The work was continued by Tran (2018), who focused his research efforts on gaining more understanding of the system, especially the steady and unsteady manoeuvring forces involved (Tran *et al.*, 2015) Through quantitative analysis, a comparison study into the hydrodynamic performance of an FPP and the CCPP was performed. The research used experimental towing tank results of both the FPP and the CCPP (Tran *et al.*, 2018b), to develop a numerical simulation program called AUVSIPRO (Tran *et al.*, 2018a). The research concluded that the CCPP, despite not representing the best trade-off in all situations, is a feasible alternative for AUV propulsion and manoeuvring. The results also showed that the CCPP provided greater manoeuvrability capabilities than a FPP with traditional control surfaces. Furthermore, the CCPP was demonstrated to be able to generate low enough continuous thrust to enable and allow an AUV to accurately manoeuvre and inspect a site at low speed. Finally, the work included an initial design of a controller for an AUV equipped with a CCPP, providing the groundwork for future controller design.

3.4 CURRENT RESEARCH FRAMEWORK

The primary author of the current paper took on the further development of the CCPP as part of his PhD research project (Dubois, 2019). An important part of the initial research stages was the coalescence of the earlier conducted research to understand the problem and, most importantly, motivate the need for further research. Through the identification of concrete merits of the concept, the author aims to spark renewed interest in the concept and its potential to be deployed as a true propulsion and manoeuvring alternative in the AUV / maritime industry.

The research focused on the development of an advanced numerical methodology to investigate the manoeuvring or side-force generated by the CCPP. To quantify the CCPP's performance, the generated side-force is decomposed in a magnitude and a phase shift component. The magnitude of the side-force defines the force generation's effectiveness in manoeuvring the AUV, while the phase shift, as a result from a discrepancy between the intended and resulting force orientation, characterises the efficiency of the AUV manoeuvring. An overview of the methodology development and the results of the work conducted is provided after the merit identification section presented next.

4. MERIT IDENTIFICATION

4.1 IMPROVED OVERALL MANOEUVRING

The ability of collective and cyclic pitch control to generate both propulsion and manoeuvring forces has always been the main behind the development of the concept. Through the introduction of cyclic pitch control in one (or multiple) propellers, the generation of usable manoeuvring forces in all three principal directions becomes possible. Furthermore, implementation of a collective and cyclic pitch propeller on an AUV was identified to provide improved overall manoeuvring capabilities for the vehicle. From literature, improved manoeuvring capabilities can be divided into two areas of interest: a reduction of the turning circle radius (enabling tighter turns) and the introduction of more complex, non-traditional manoeuvring modes (such as a turn-in-place manoeuvre).

Importantly, the main function of any propulsor cannot be disregarded. The generated forward propulsion forces, and the related overall propulsive efficiency, have to be closely monitored when implementing changes to allow for the generation of manoeuvring forces. Early on, Joosen *et al.* (1963) concluded from model-scale tow tank experiments that a large hub-to-diameter ratio propeller was capable of matching the propulsive efficiency of a more traditional propulsor. The focus of later research shifted to investigating actual improvements of the overall manoeuvring capabilities, disregarding the propulsive efficiency aspect.

The tandem propeller system was developed by Haselton & Rice (1966) with the specific objective of creating a marine vehicle capable of complex motions in six degrees of freedom. Early experimental results showed the feasibility of the large hub-to-diameter concept and its potential to improve vehicle manoeuvrability at both high and low speeds. Different thrust-modes were investigated and the counter-thrust mode, in which the two propellers generate opposing thrust forces, was identified as the best option for advanced manoeuvring operations. Even when generating a net thrust force, the counter-thrust mode was shown to enable independently controllable motions in all six degrees of freedom. Later work by Chen *et al.* (2008, 2009) further investigated the tandem propeller concept and again showed the conceptual capabilities of unconventional manoeuvring operations through both numerical work and experimental testing of an initial demo vehicle. The demo vehicle satisfactorily performed three advanced manoeuvring modes: a turn-in-place manoeuvre, a sideways motion, and a station-keeping operation.

The work by Murray *et al.* (1994) investigated the potential of a cyclic pitch propulsion system for applications within a navy setting. The work involved both the development of a numerical method and the execution of real-life sea trials. Using an unsteady panel code, the turning performance of a small generic submersible, equipped both with and without a collective and cyclic pitch propeller, was analysed. Based on the numerical results, the introduction of cyclic pitch was shown to drastically reduce the turning circle radius, despite generating a lower peak manoeuvring force than a traditional control surface. The observed improvement was attributed to the fact that the propeller generated forces are impervious to the yaw motion. Traditional control surfaces are affected by the yaw angle, as the performance rapidly declines as the local angle of attack decreases during the yaw motion. The sea trials, conducted with a rapidly developed experimental navy submersible, had operators report and observe a much smaller and tighter turning radius when compared to that of the same vehicle equipped with conventional control surfaces and a traditional propeller.

4.2 LOW SPEED MANOEUVRABILITY

The improved overall manoeuvrability capabilities of the concept are further complemented by the propeller's ability to generate manoeuvring forces at low to zero forward speeds. AUVs have become more and more versatile and their mission profiles more diverse and complex. As such, a combination of efficient travelling to and from the location of interest with effective manoeuvring at that location became an essential AUV feature. Collective and cyclic pitch propellers have shown to be able to address the `long-endurance travelling efficiency vs low speed manoeuvrability'-dilemma in an effective manner. Even though low speed manoeuvrability can easily be considered an improved manoeuvrability aspect, the merit is considered essential and fundamental and is, as such, discussed independently.

Haselton & Rice (1966) concluded in their work that the tandem propeller concept ‘has potential for substantial improvements in the low speed manoeuvrability of underwater craft’ after conducting a series of free running tests. In a review paper, Haselton (1969) again justified the expected low-speed manoeuvring abilities by demonstrating the concept could achieve force-to-power ratios equivalent to that of a ducted thruster system (traditionally used as an effective low speed manoeuvring aid). Further support of the low speed manoeuvring capabilities of collective and cyclic pitch propellers can be found in the research by Murray *et al.* (1994). Through numerical simulations, the ability of the propeller to generate manoeuvring forces at zero forward velocity or without inflow was shown. Additionally, the sea-trials showed the model to be able to hover without moving forward. Chen *et al.* (2008, 2009)’s continued numerical and experimental work on a tandem propeller concept established effective AUV control during low speed operation such as a turn-in-place manoeuvre, a sideways motion, and station keeping.

A number of patents on collective and cyclic pitch propellers clearly mentioned low speed manoeuvring capabilities as a key attribute of the concept. Despite the inability of the patents to directly show actual performance results their mention of the merit is considered of importance. Reich & Uhrich (1990) stated that the combination of a traditional aft mounted propeller and control surfaces does not perform satisfactory in low speed manoeuvring of a navy search and rescue vehicle. A concept, referred to as an `omni-directional variable thrust propeller', based on the application of collective and cyclic pitch control, is suggested as ideal to obtain both thrust and manoeuvring from a single propeller at all speeds. The poor directional stability and slow helm reaction at low speeds of, in particular, lightweight planing craft is cited by Duncan

(2007) as the main reason for the development of a propeller concept able of direct blade pitch control. Duncan (2007) further specified the ability of the concept to be used for dynamic positioning, and thus the generation of manoeuvring forces at zero forward velocity. Finally, a concept by Silberg *et al.* (2015) suggested a system of fore and aft contra-rotating propellers with collective and cyclic pitch control. The concept's implementation is aimed to replace multiple systems otherwise needed to generate both cruise and low-speed propulsion and manoeuvring forces. The patent specifically notes the capability of the proposed device to propel and manoeuvre an AUV `regardless of the vehicle speed through water'.

4.3 UNSTEADY WAKE EFFECTS

The maritime implementation of collective and cyclic pitch control is mainly aimed at generating manoeuvring forces by creating a force imbalance over the propeller cycle. However, the opposite could also be of value, as was originally shown when applied to helicopter flight control. Marine propellers are generally mounted behind the hull of a vehicle or ship and operate in unsteady flows. During their operation, the propellers will thus experience a non-uniform flow or wake field. As a result of the operation in a non-uniform wake field, the propeller blades will encounter an unsteady loading profile, which can result in cavitation inception, vibrations, and severe noise production. The concept of collective and cyclic pitch control can address such issues in two different manners. First, a more streamlined hull shape and thus a more uniform inflow into the propeller becomes possible by rendering additional control surfaces obsolete (as shown in both previous merits). Secondly, direct control over the blade pitch angle during the azimuthal cycle enables the propeller to efficiently and (pro-)actively address the unsteady blade loading profile.

A feasibility study by Joosen *et al.* (1963) performed model experiments in a towing tank on a large hub-to-diameter ratio propeller intended for both submersibles as well as surface vessels. The results showed the ability to generate transverse forces and to reduce cavitation and vibration due to unsteady flow effects. While demonstrating a maximum propulsive efficiency of similar order as other propeller types and promising side-force generation capabilities, the research did not further discuss the specific addressing of unsteady wake effects through the propeller. A decade later, Jessup (1976) did perform model tests on a four-bladed propeller with the pitch of a single blade controlled in order to affect the resulting propeller and ship hull vibrations. Visible improvements of the cavitation and vibration performance, in combination with a slight improvement in propulsive power, were achieved through cyclic pitch induced reduction of the angle of attack fluctuations. Research by Simonsson (1981, 1984) obtained similar results using the pinnate propeller fixed on a Swedish Navy patrol vessel. Both an experimental set-up and full-scale sea trials demonstrated that the pinnate propeller was able to eliminate transient cavitation, vibration and noises originating from the non-uniform wake field by varying the blade pitch with its angular position through programmable pitch control. The sea trials confirmed the technical feasibility of the concept, reporting reduced hull pressures above the propeller and an increase in the maximum achievable cavitation-free cruising speed.

Murray *et al.* (1994) used their numerical panel method, with experimental wake fraction data as input, to successfully `smooth' the thrust force generated over a single revolution. Despite the cyclic pitch adjustments not being optimised in full, the results exhibited considerable improvements over the original condition. Additionally, Gabriel & Atlar (1998) used an unsteady lifting surface procedure to investigate a five-bladed ship propeller with cyclic blade pitch control and compare the performance to a similar conventional propeller. The numerical work concluded that a non-sinusoidal pitch profile allowed for adaptation to the non-uniform loads and resulted in a reduction of the harmonic amplitudes of the blade forces in combination with slightly improved cavitation patterns.

4.4 RESISTANCE REDUCTION

Traditional AUV manoeuvring aids such as control surfaces, tunnel thrusters, and podded or azimuthal propulsors tend to increase the overall resistance of a vehicle. Control surfaces increase the form and viscous resistance of the maritime vehicle and negatively influence the added mass and moment of inertia. Appendage-based alternatives, e.g. podded and azimuthal propulsors, have similar effects and present the additional risk of being snagged by cables or other obstacles. Even tunnelled side thrusters, not extending beyond the shape of the hull, influence the hull resistance negatively by altering the pressure distribution along the hull or body. A collective and cyclic pitch propeller allows for a more streamlined, energy efficient hull shape design by making the aforementioned additional sources of resistance obsolete.

No direct measurements or research, comparing the overall resistance of different vehicles, both with and without collective and cyclic pitch control abilities, has been conducted yet. Despite the apparent research and knowledge gap, mentions of the potential resistance reduction are plentiful. Both Murray *et al.* (1994) and Chen *et al.* (2008) discussed the opportunity of reducing drag through elimination of various conventional controls surfaces after implementation of their respective collective and cyclic pitch concepts. Moreover, a range of patents explicitly discussed the implementation of collective and cyclic pitch control to reduce the overall vehicle resistance. When Haselton (1966) patented his tandem propeller system, he discussed the difficulties in realising combined manoeuvrability and mobility while maintaining overall operational efficiency, and the ability of his design to do provide just that. Reich & Uhrich (1990) stated in their patent that traditional underwater search vehicles are configured as a rectangular body combined with conventional thrusters to achieve omni-directional thrust. The bulky nature of such vehicles results in considerable drag generation and an optimised long narrow cylinder or torpedo-shaped body will reduce the propulsive energy needed. The patented propeller provides the opportunity to combine an efficient body shape with variable thrust generation in all directions. Finally, in the patent of Schneider (1993), a single propeller is deemed capable of controlling a submersible or a surface vessel in three degrees of motion, while eliminating the need for non-essential drag generating control surfaces and rudders for motions control.

4.5 OPTIMISED SPACE / POWER UTILISATION

By combining the propulsion and manoeuvring systems into a single hybrid system, a collective and cyclic pitch propeller allows to optimise both the space and power utilisation of an AUV. A hybrid system facilitates the elimination of other systems, thereby saving space and reducing the overall system complexity. Additionally, optimised space utilisation allows for the introduction of additional mission-related systems or for a reduction of the overall vehicle dimensions, further decreasing the potential hull resistance. Optimisation of the power utilisation is achieved by a cutback of power consuming systems, in turn allowing for the available power to be utilised for extended autonomous underwater operation.

Similar to the resistance reduction merit, little to no actual work has been conducted to show the actual optimised space and power utilisation abilities. The main reasons behind the inability to show and actually support the merit lay with the fact that no actual full systems have been designed, built, and / or have been deployed. Additionally, the fact that direct comparison is hard to achieve as nobody will fund the construction of two vehicles merely for comparison reasons. Different patents do mention the merit both directly and indirectly. In reviewing progress on the development of the tandem propeller system, Haselton (1969) specifically stated that `although it is true that manoeuvring capability equal to system may be obtained through utilisation of a multiplicity of simpler devices, no combination of them provides a more efficient and flexible utilisation of installed power'. Reich & Uhrich (1990) focused on the ability to effectively manoeuvre a torpedo-shaped vehicle, thereby minimising the required propulsion energy and, as such, extending the duration of potential marine search operations. Finally, Duncan (2007) again stressed the possibility to eliminate multiple systems needed to combine cruise and low speed operation and realise both with a single system capable of collective and cyclic pitch control.

5. MAGNITUDE AND PHASE SHIFT OF THE SIDE-FORCE GENERATED BY A CCPP

Based on the presented research overview and merit identification, Dubois (2019) continued research on the CCPP. The PhD research project was driven by the investigation of the mechanisms behind the efficient and effective generation of the manoeuvring force or side-force. Through understanding of the physical mechanisms enabling the side-force generation, the influence and significance of the operational conditions on the CCPP's hydrodynamic performance was established. Finally, the research was able to examine potential operational and design alternatives to improve the CCPP's hydrodynamic performance. The definition of the hydrodynamic performance, as discussed before, was of key importance. In the current work, the CCPP's performance is quantified by the de-composition of the generated side-force in a magnitude and a phase shift component. The magnitude and phase shift of the side-force characterise the effectiveness and efficiency of the generated force, respectively. Additional discussion of both components is provided in the further discussion.

In order to develop the CCPP into a viable and realisable propulsion and manoeuvring system for AUVs and achieve the project's objectives, a two-part numerical methodology was established. First, a two-dimensional numerical model was conceptualised (Dubois *et al.*, 2106) to then evaluate the effect of cyclic pitch at zero collective pitch under bollard pull condition (Dubois *et al.*, 2018). The model reduced the complex flow problem to the evaluation of sinusoidally pitching hydrofoils through a force break-down model. A sliding, fully structured mesh approach was used to allow an inner zone to pitch independently of a stationary outer zone and efficiently solve the Unsteady Reynolds-averaged Navier-Stokes equations (URANS) with k-omega SST transition turbulence modelling. Extending the methodology in a third dimension allowed for the extended evaluation of the CCPP's performance (Dubois *et al.*, 2017). A periodic domain strategy, modelling a single blade to represent the entire propeller's performance and using a quaternion-based motion algorithm was applied. The three-dimensional model, again using a two-zone and sliding mesh approach, was verified (Dubois *et al.*, 2019b) and validated (Dubois, 2019) to allow the methodology to be used for the further analysis and improvement studies into the CCPP's performance.

The initial two-dimensional methodology (Dubois *et al.*, 2018) was used to evaluate the performance under the evaluated conditions, under bollard pull condition and a selected range of collective and cyclic pitch angles. A clear dependency was shown between the generated drag at higher collective pitch angles and the generated side-force. Later work (Dubois *et al.*, 2019a) confirmed the relation and established the discrepancy between effective and efficient side-force generation. At higher pitch angles, the side-force magnitude is sufficiently large and effective, but the occurrence of the associated drag makes the force generation highly inefficient, i.e. a large phase shift occurs. The full three-dimensional periodic methodology did proof to be able to predict the force behaviour and could thus be used to analyse and design the forces involved. Further research was set-up with a single objective: increase the generated side-force magnitude, and thus the effectiveness of the force generation, at lower pitch angles, i.e. without compromising the side-force phase shift. A parameter analysis, based on the results of the aforementioned studies, established the blade surface area as the most straightforward pathway to alter the side-force effectiveness, since the force magnitude is proportional to the surface area, while allowing the CCPP to operate at smaller (collective) pitch angles. An investigation of three alternative blade designs (Dubois, 2019), altering the blade span and aspect ratio, was conducted. The study concluded that the most effective performance improvement could be realised by increasing the blade surface area through a larger blade span only, thereby increasing the blade aspect ratio.

The recent work by Dubois (2019) split up discussion of possibilities for future work into three parts, formulating recommendations for each part. First, the methodology was evaluated and suggested extensions for both the numerical methodologies and potential future experimental work. Second, the research discussed potential further research into the CCPP concept, as originally developed by Humphrey (2005), through evaluation of additional blade designs and untested operational conditions. All suggested future research aims to further realise the concept as a viable AUV propulsion and manoeuvring system. Third and finally, suggestions were made concerning alternative designs, applying collective and cyclic pitch control in various manners to control, manoeuvre and propel AUVs.

6. CONCLUSIONS

Five distinct merits of collective and cyclic pitch control in AUV propulsion and manoeuvring have been identified. Together, the merits demonstrate the viability of the concept as an alternative system for effective and efficient AUV propulsion and manoeuvring. Through experimental observations, numerical simulations, patent history, and sheer reasoning, the conceptual abilities to improve overall manoeuvrability, provide low speed manoeuvring capabilities, address unsteady wake effects, reduce overall vehicle resistance, and optimise space and power utilisation have been demonstrated.

The presented review, together with recent progress by the authors, suggest more work should be undertaken to further develop the concept of collective and cyclic pitch control for AUV propulsion and manoeuvring. The authors investigated the CCPP by using an URANS-based numerical approach to identify improvements to the CCPP's effectiveness and efficiency. Dubois (2019) provides an extended analysis of the CCPP's performance and establishes the potential of the numerical methodology to (re-)design the forces generated by the CCPP. Additionally, the work showed that increasing the blade span and aspect ratio will result in a more effective and efficient side-force generation.

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