Adaptive pitch control: Simulation performance evaluation against conventional propulsion control

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Synopsis

Naval vessels, and especially frigates, require careful optimization of their propulsion systems in order to achieve better manoeuvrability, fuel efficiency, and signature reduction, while also delivering an overall high-end operational performance. The main topic of this paper is the performance evaluation of an alternative control strategy: Adaptive Pitch Control (APC). This strategy involves a feedback-controlled adaptation of the propeller pitch and shaft speed to maintain an effective angle of attack of the propeller blades at which the chance of cavitation is minimal, thereby reducing signatures and operating in a favorable area in the engine envelope in terms of efficiency and engine loading. The performance evaluation of APC against conventional control with combinator curves is performed using a simulation model of a notional future frigate of the Royal Netherlands Navy. The propulsion plant consists of main diesel engines with supporting electric drives for top speed and low-end silent speed, also known as a COmbined Diesel-eLectric And Diesel (CODLAD) propulsion plant. For both control strategies, additional care is taken to create a load-sharing technique for parallel operation that leverages the dynamic load response of the electric drive while ensuring that the main engines are still efficiently loaded. The simulation study demonstrates the expected performance gains of APC in the following key performance metrics: cavitation noise, acceleration behavior, fuel consumption, and engine loading under various operational conditions.

Keywords: Power & Propulsion, Propulsion plant modelling and control, Signature reduction, Anti-submarine warfare

1 Introduction

The increasing operational demands of modern naval vessels require versatile platforms that meet the highest performance requirements and adapt to different operational environments. Hybrid diesel-electric propulsion concepts in combination with advanced propulsion control strategies have shown promising potential (Geertsma et al., 2017b) to improve the efficiency of the plants, while at the same time, delivering high-end operational performance (ie. manoeuvrability, signature reduction). This performance is of even greater importance when an Anti-Submarine Warfare Frigate is considered, where high manoeuvrerability while remaining silent is crucial for detecting, locating and chasing a target submarine.

In most current applications, propulsion control strategies involve control with fixed combinator curves. Those combinator curves translate the lever position, selected in the propulsion control system, to a pre-determined combination of engine speed and propeller pitch, which in turn are controlled in separate control loops. The main disadvantage of this approach is that it is almost impossible to optimize the controller in all performance aspects simultaneously (e.g. fuel consumption, manoeuvrability, engine thermal loading, and cavitation), especially during changing operating conditions, like sea state or hull resistance (Vrijdag et al., 2008). The alternative control strategy being evaluated in this study, the Adaptive Pitch Control (APC), has the potential to achieve this multi-aspect optimization of the propulsion control system. The concept was investigated extensively in the PhD studies of (Vrijdag, 2009) and (Geertsma, 2019). This novel approach involves a feedback-controlled loop where the propeller pitch is frequently adjusted to maintain an effective angle of attack at which the chance of cavitation is minimal. The effective angle of attack is defined as the flow angle at which the water enters the propeller blade profile (see also section 2.2.2). By doing this, APC limits cavitation, improves fuel consumption and engine thermal loading while ensuring that the desired ship speed (i.e. lever setting), as requested by the operator, is delivered.

The present simulation study attempts to quantify the benefits of the APC strategy in terms of cavitation noise, acceleration behavior, fuel consumption and engine loading, under various operational conditions. The baseline propulsion control system (without APC), against which APC is compared, features a well-tuned control strategy, ensuring that all differences found are due to the addition of APC. This includes a strategy for parallel operation of the main diesel engine (MDE) with the electric propulsion motor (EPM), which leverages the fast torque characteristics of electric drives to support not only in reaching the top speed of the vessel, but also to assist during heavy transients. The proposed control strategies are implemented on a COmbined Diesel-eLectric And Diesel (CODLAD) propulsion plant of a notional frigate of 5200 tons.

2 Ship simulation model

In order to compare the performance of the baseline control strategy to APC, a simulation model of a vessel with hybrid propulsion was employed. An overview of the ship simulation model is given in figure 1. In this diagram, n refers to rotational speeds, M to torque, T to thrust, θ to propeller pitch and v_s to ship speed. The ship model consists of the Propulsion Control System (PCS) and the propulsion plant. The considered frigate features two independent shafts, each with one main diesel engine (MDE), one electric propulsion motor (EPM), a gearbox and a controllable pitch propeller (CPP).

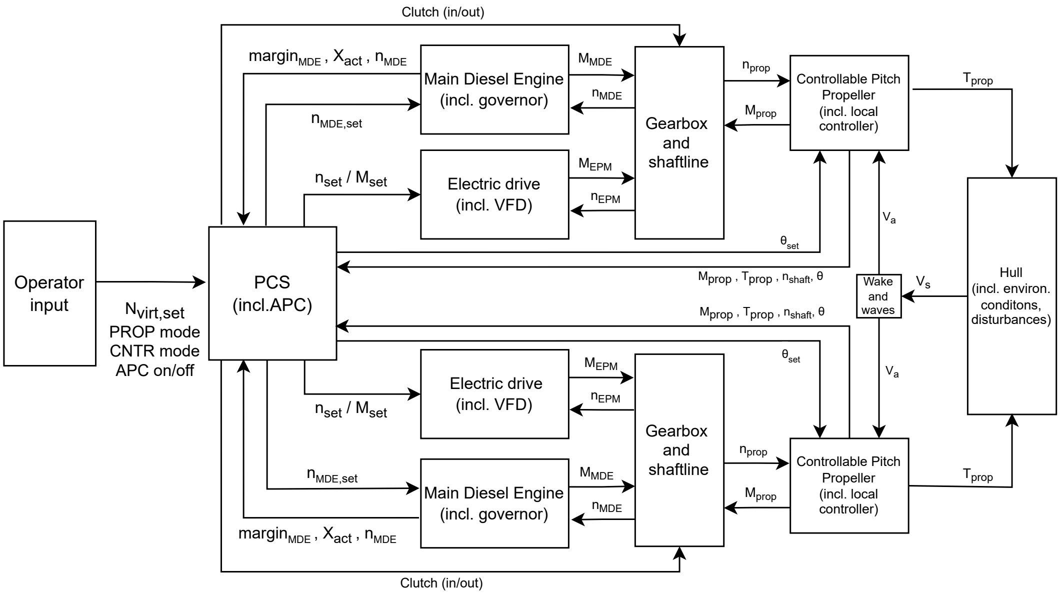


Figure 1: Overview simulation model

The arrows on the left represent the operator input to the PCS. The operators selects the speed setpoint ($N_{virt,set}$), the propulsion configuration (*PROP* mode), the control model (*CNTR* mode) and finally whether the APC module will be active (on/off). Those inputs are translated to specific setpoints for the propulsion plant, which are further processed by the local controllers, i.e. the engine governor, the variable frequency drive (VFD), and the controller of the CPP hydraulic system. The PCS subsystem consists of the baseline PCS and an integrated APC module. A more detailed overview and description of the propulsion plant and the PCS can be found in sections 2.1 and 2.2 respectively.

2.1 Propulsion Plant

The propulsion plant model is based on the work of (Geertsma, 2019). For the detailed description of the models of the diesel engine, the electric drive, the gearbox, shaft-line, propeller and hull, the reader is referred to the aforementioned PhD-thesis. Only part of the propulsion plant model has been modified to further improve the representation of the considered propulsion configuration or to make certain parameters adjustable during the runtime of the simulation. An overview of the parameters used in the case study simulation is presented in a group of tables at the end of this document. The parameters of the Main Diesel Engines are presented in table 5a, the parameters of the propeller in table 5b, the parameters of the gearbox in table 5c, the parameters of the electric drive in table 5d, and finally the parameters of the hull in table 5e.

Modification MDE: The inclusion of sequential turbocharging by changing the effective area of the turbocharger has been implemented, as proposed by (Geertsma et al., 2017a). Accordingly, the effective area is reduced with a factor of 2 at engine speeds below 750 rpm.

Modification EPM: The parameters of the electric motor have been adjusted to consider a low-voltage low-speed electric motor that directly drives the shaft-line. The electric parameters and rotational inertia of the low-voltage low-speed electric motor play a significant role in the electromagnetic and mechanical transient behaviour. Next to this, it is important to mention that the present study does not intend to study the dynamics of the electrical network. Therefore, it is assumed that the variable frequency drive is an ideal voltage source providing the requested frequency and voltage to the electric drive. Power limitations are included in the VFD to keep (transient) loading of the generators within an acceptable range.

Modification gearbox and shaft-line: The model of the gearbox was modified to represent the torque losses (M_{loss}) based on a loss model provided by a major gearbox supplier for various gearboxes (equation 1). Next to this, a clutch was introduced which allows the gearbox to disengage from the shaft-line while sailing in the EPM mode for silent operation.

$$M_{loss}(t) = \left((1 - a_{gb}) \left(\frac{M_{MDE}(t)}{M_{MDE,nom}} - 1 \right) + \left(\frac{n(t)}{n_{nom}} \right)^{b_{gb}} \right) M_{loss,nom} \quad (1)$$

2.2 *Propulsion Control System (PCS)*

The model of the PCS combines both the baseline PCS and the additional APC module. The primary control objective is the delivery of propulsive power at the requested virtual shaft speed (N_{virt}) in rpm, which is almost linearly related to the ship speed. The virtual shaft speed is derived by combining the pitch angle (θ) and the shaft speed (n_s) in rpm, as introduced by (Vrijdag, 2009):

$$N_{virt}(t) = \frac{\theta(t) - \theta_0}{\theta_{nom} - \theta_0} n_s(t) \quad (2)$$

where θ_{nom} and θ_0 are the nominal and the zero-thrust pitch respectively.

The PCS has three (3) *PROP* modes, namely the *MDE* mode, the *EPM* mode and the *COMB* mode, which respectively correspond to sailing only with the main diesel engines, only with the electric motors, and lastly, sailing with the diesel engines and the electric motors working in parallel, either as power-take-in (*PTI*) or power-take-off (*PTO*).

Next to the *PROP* modes, there have been three (3) *CNTR* modes considered in the baseline PCS. Namely, these are the manoeuvring (*MAN*), the economy (*ECO*) and the silent (*SIL*) mode. Each *CNTR* mode focuses on a different objective, as follows:

- *MAN* mode focuses on high acceleration and deceleration of the vessel;
- *ECO* mode aims at better fuel efficiency;
- *SIL* mode focuses on low underwater radiated noise by limiting the chance of cavitation.

Since the objective of each *CNTR* mode is different, the applied rates for the adjustment of the pitch and shaft speed were carefully selected to the various objectives. For example, in *MAN* mode, where manoeuvrability is the primary objective, the speed adjustment rate of the MDE or EPM is higher than in *SIL* mode, where slower transients are required to prevent sudden changes of the water inflow angle to the propeller blades, thus to limit the likelihood of cavitation.

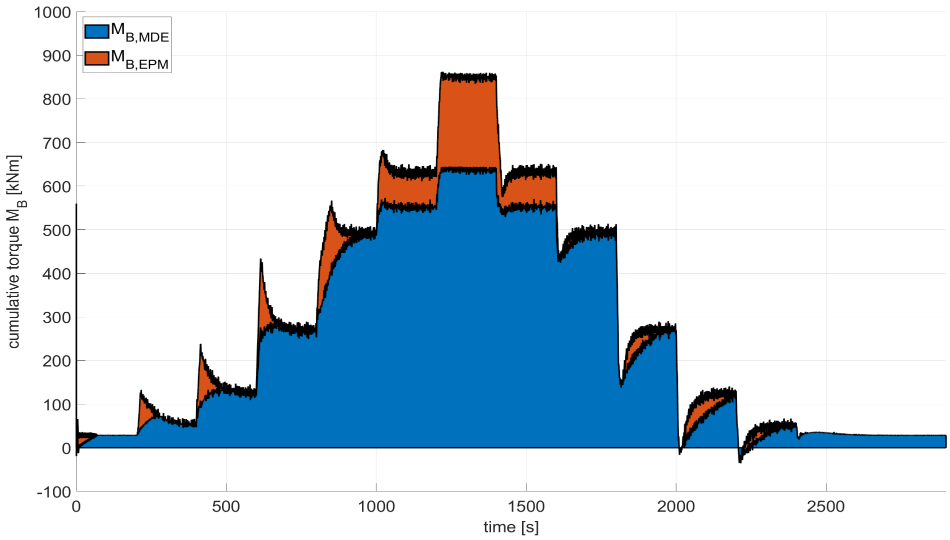


Figure 2: Load sharing in *COMB PTI* mode

Regarding the *PROP* modes; special attention was given in optimizing the parallel operation in the *COMB* propulsion mode, where the MDE and EPM are working in parallel. During the combined operation, a speed setpoint is given to the governor and a torque setpoint is given to the electric drive. The torque contribution of the EPM in *COMB PTI* is based on the position of the fuel rack (X_{act}), the margin of the MDE (allowing for dynamic support by the EPM for big transients) and the difference between the governor setpoint and the actual MDE speed (acceleration support of the MDE). The aforementioned engine margin is a measure to define the remaining available power of the MDE, equal to the distance between the limit of the power envelope and the current operating point. In figure 2, where a staircase manoeuvre (from zero to maximum ship speed, and back down to zero ship speed) is presented, one can clearly see how the fast torque response of the EPM is assisting the MDE during the intermediate sprints and that the EPM only provides a static contribution when the MDE is close to its maximum torque output.

2.2.1 *Baseline control strategy*

In the baseline control strategy, the propulsion system is controlled with the so-called combinator curves. These combinator curves provide maps (i.e. look-up tables) that define the relationship between a requested virtual shaft speed N_{virt} (i.e. lever position) and a combination of pitch angle and shaft speed to achieve it. Those predetermined combinations ensure that the engines have sufficient margin to the limit of the engine envelope and the propellers are working at an efficient operating point. The used look-up tables are dependent on the selected propulsion configuration (*PROP mode*) and control mode (*CNTR mode*). The high level combinator curve outputs are limited with respect to rate by using integrated dynamic rate limiters in order to regulate transitions from one to another lever setpoint in a controlled manner. These non-linear rate limiters have a dependency on actual shaft speed, shaft speed setpoint, actual pitch, propulsion modes, control modes and lever setpoint. Next to this, the baseline strategy includes functionality that protects the propulsion diesel engines from overloading by retracting the pitch when the engine margin drops below a predetermined value, in this case a limit margin of 1-3%.

2.2.2 *Adaptive Pitch Control (APC)*

The primary goal of this study is to quantify the performance gains of a control strategy named Adaptive Pitch Control. As the name suggests, this is a novel approach for propulsion control which can adapt to different operational conditions by constantly assessing and adjusting the operating point of the propeller. The concept was first introduced and tested on a frigate of the Royal Netherlands Navy in the PhD work of (Vrijdag, 2009) and it was later integrated into an advanced propulsion control strategy of a hybrid propulsion system in the PhD work of (Geertsma, 2019). Those studies concluded that apart from minimizing cavitation, this approach improves acceleration behaviour and prevents the loss of ship speed due to pitch reduction when preventing engine overloading. The control objective of this strategy is the delivery of propulsive power at the requested virtual shaft

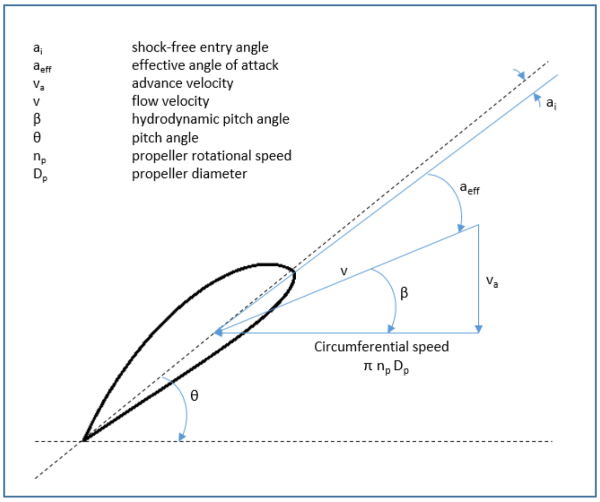


Figure 3: Flow around the propeller blade section

speed ($N_{virt,set}$), while maintaining an effective angle of attack (a_{eff}) of the propeller blade at which the chance of cavitation is minimal. As can also be seen in figure 3, the effective angle of attack of the propeller is defined as the difference between the actual pitch angle of the propeller blade (θ) and the hydrodynamic pitch angle (β), minus the shock free entry angle (a_i) related to the chord line at the leading edge, which is the ideal angle of attack of the propeller blade (i.e. optimal efficiency). The mathematical representation of the effective angle of attack at propeller radius 0.7, which is used as a representative radius for the blade pitch, is as follows:

$$a_{eff}(t) = arctan\left(\frac{\theta(t)}{0.7\pi}\right) - arctan\left(\frac{c_1\, v_a(t)}{0.7\pi\, n_p(t)\, D_p}\right) - a_i \quad (3)$$

where v_a the advance velocity of the water, D_p is the propeller diameter, n_p is the rotational speed of the propeller, and finally, c_1 is the coefficient to calibrate the effective angle of attack with the center point of the experimentally determined cavitation bucket (Vrijdag, 2009). The cavitation bucket diagram is plotted as a function of the cavitation number σ_n against the effective angle of attack a_{eff} (figure 4), with the cavitation number defined as follows:

$$\sigma_n = \frac{p_0 - p_v}{\frac{1}{2}\rho n_p^2 D_p^2} \quad (4)$$

where p_0 is the ambient water pressure and p_v is the vapour pressure, both expressed in [Pa]. This graph is useful because it captures in a two-dimensional plane the cavitation behaviour of the propeller. The center of the cavitation bucket is defined as the cavitation-free area. For gaining a more in-depth understanding of propeller cavitation, the interested reader is referred to (Carlton, 2019).

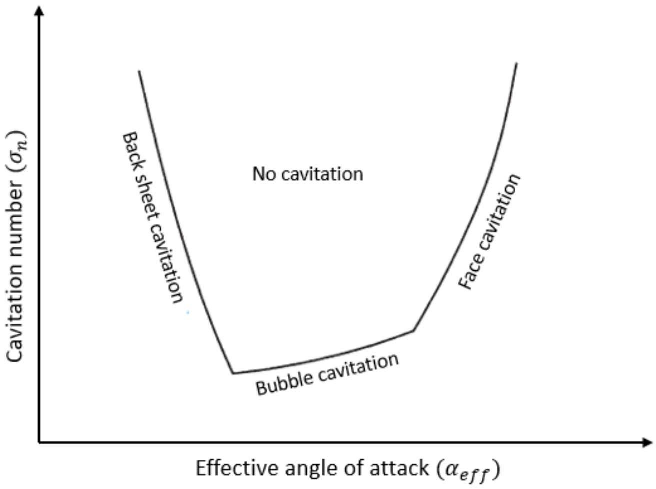


Figure 4: Example of a cavitation bucket diagram

The APC module was built as an addition to the baseline strategy. When activated, this module continuously provides corrections to the pitch setpoint, to the MDE speed setpoint and (when the EPM is the driving machine) to the EPM speed setpoint. The correction of the pitch setpoint is such that the desired angle of attack is achieved, as described in (Vrijdag, 2009). This pitch correction limits cavitation inception by maintaining the propeller operation as far as practically possible at the center of the cavitation bucket, however the effect of this correction is that the pitch usually deviates from the value set by the combinator curve. This means that an adjustment of the shaft speed (MDE or EPM setpoint corrections) is required to compensate for the pitch deviation and to ensure that the desired virtual shaft speed (and therefore vessel speed) is maintained. As can be seen in equation 3, in order to calculate the actual effective angle of attack, the algorithm requires, apart from the propeller speed and pitch, also the advance velocity (v_a). This speed cannot be directly measured but can be estimated based on other measurable quantities such as thrust and/or torque combined with shaft speed and actual pitch, in a reverse use of the open water diagram of the propeller, as done by (Vrijdag, 2009).

3 Scenarios

3.1 Scenarios definition

With the aim to quantify the benefits of APC, a set of scenarios have been selected and simulated. Those scenarios focus on manoeuvres that highlight aspects of behaviour where APC could potentially provide benefits. The scenarios include accelerations and decelerations like slam starts, crash stops, small in-between sprints, as well as runs with varying operating conditions in terms of sea state, hull condition and wake field disturbances.

The tested scenarios differentiate on the basis of the following inputs:

- $N_{virt,set}$: virtual level command
- CNTR mode: *MAN*, *ECO* or *SIL*
- PROP mode: *MDE*, *EPM* or *COMB*
- APC: *APC ON* or *APC OFF*
- Environmental conditions: *Base*, *A* or *B* (table 1)

As presented in table 1, three variations of environmental conditions have been considered. For the *Base* condition, the wake disturbance is disabled in contrast to environmental condition *A* and *B* for which the wake disturbance is enabled. Depending on the selected sea state, the definitions for sea state as outlined in STANAG 4194 are used to obtain the peak wave frequency/period, significant wave height and wind speed.

Table 1: Environmental conditions

	Sea state	Wake disturbance	Top of SS	Wave heading
Base	3	None	Y	180
A	3	irregular	Y	180
B	6	irregular	N	180

Regarding the manoeuvres selected to evaluate the performance of APC; The manoeuvres included slam starts and staircase sprints. During the slam start manoeuvres, the vessel was accelerated from a standstill to the maximum speed that corresponds to the selected propulsion mode. During the staircase sprints, the vessel was performing intermediate sprints with step increases and decreases of the lever position ($N_{virt,set}$). This manoeuvre includes steps of 25 rpm up to the maximum speed step that corresponds to the selected propulsion mode (e.g. 0, 25, 50, 75, 100, 125, 100, 75, 50, 25, 0 rpm).

The simulated scenarios, which are presented in table 2, can generally be grouped in three categories:

1. **Cavitation performance**: Scenarios 1-4 focus on cavitation performance. This is particularly relevant for the silent control mode (SIL) when sailing with the EPMs. For the purpose of comparing the two control strategies, a representative fictive cavitation bucket is represented with two solid black lines in the $a_{eff} - \sigma_n$ phase plane.
2. **Acceleration performance**: Scenarios 5-10 focus on demonstrating the acceleration performance in *CNTR* mode *MAN* and *PROP* modes *MDE* and *COMB*. Two of the scenarios are dedicated to the staircase sprints and the rest of the scenarios to the slam starts followed by a crash stop. During these manoeuvres engine loading (i.e. path taken through the engine envelope) is also an important performance metric.
3. **APC specific**: Scenarios 11, 12 focus on the behaviour of the baseline control strategy and *APC* in changing weather conditions.

Table 2: Scenarios definition

Scenario	**Environmental condition**	**Manoeuvres**			**APC ON/OFF**	**CNTR mode**	**PROP mode**
		Stair case	Slam start	Fixed lever			
1	base, A	x			OFF	SIL	EPM
2	base, A		x		OFF	SIL	EPM
3	base, A	x			ON	SIL	EPM
4	base, A		x		ON	SIL	EPM
5	base, A, B	x			OFF	MAN	MDE
6	base, A		x		OFF	MAN	MDE
7	base, A		x		OFF	MAN	COMB
8	base, A, B	x			ON	MAN	MDE
9	base, A		x		ON	MAN	MDE
10	base, A		x		ON	MAN	COMB
11	various			x	OFF	ECO	MDE
12	various			x	ON	ECO	MDE

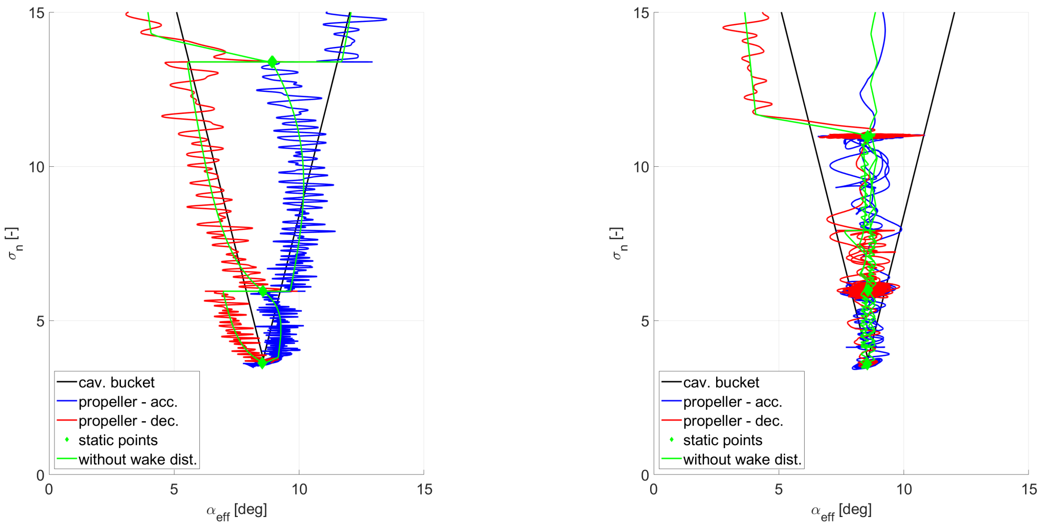
3.2 Scenarios results and comparison

The aspects used to evaluate the performance of APC against conventional control are: 1) cavitation, 2) acceleration performance, 3) engine loading, and 4) fuel consumption. As discussed earlier, each *CNTR* mode has a different control objective (i.e. manoeuvrability, signature reduction etc.), therefore the results of the scenarios are discussed separately for each of the CNTR modes, namely SIL, MAN and ECO mode.

3.2.1 Impact of APC in SIL mode

As mentioned in paragraph 2.2, the primary objective of *SIL* mode is signature reduction by limiting cavitation. In order to achieve this objective with the baseline control strategy, slow pitch and shaft speed transients were required following the change in ship speed. By doing this, it was possible to obtain cavitation performance equal to that of the APC strategy at the costly expense of acceleration times. However, this acceptable cavitation performance of the baseline strategy when using the slow transients is very sensitive to changes in the ship resistance. As soon as the hull resistance changes due to fouling, wind or waves, a towed array or simply displacement growth, the baseline strategy will most likely operate outside the cavitation bucket, while APC, due to its adaptive nature, will operate mostly at the center of the cavitation bucket, with the associated benefits on cavitation inception. This fact is true for all the simulated manoeuvres in *SIL* mode.

Staircase manoeuvres (scenario 1 vs 3): For the baseline strategy, the slow pitch and shaft speed transients resulted in relatively low thrust peaks and therefore a slow acceleration in order to stay as much as possible within the limits of the cavitation bucket. For the APC control strategy, these slow transients were not necessary due to the ability of the feedback-loop to maintain a relatively constant angle of attack and thus operate at the center of the bucket (figure 5). This resulted in a significantly higher propeller thrust peak, and superior acceleration performance compared to the baseline by a factor of 2 to 3. During deceleration, the shaft speed transient for the baseline PCS is slightly faster compared to the setting used for acceleration. The negative thrust peaks resulting from this are comparable to what is observed for the APC control strategy, even though the combinations of pitch and shaft speed are very different. Therefore, ship deceleration performance of the baseline PCS is close to what is achieved by APC.

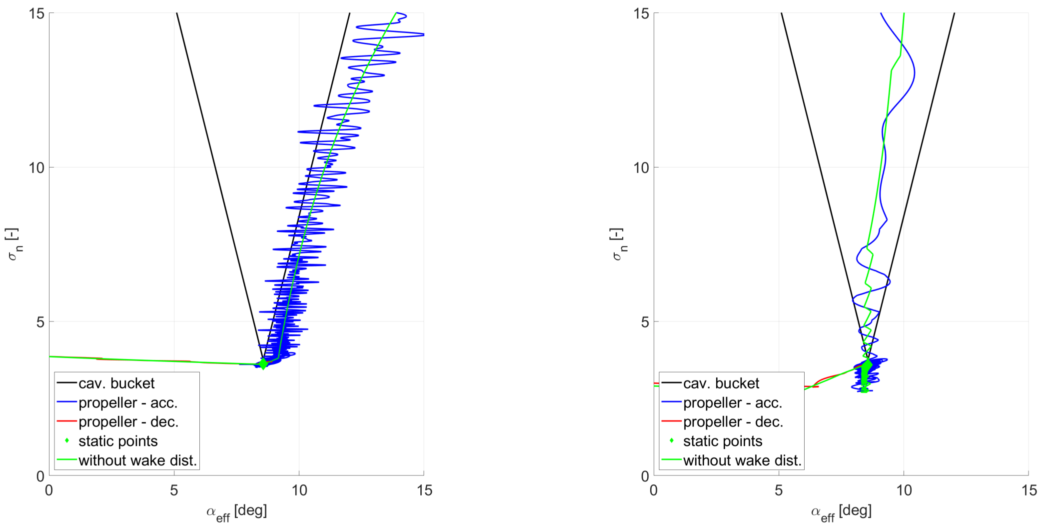


(a) Scenario 1 (APC OFF)

(b) Scenario 3 (APC ON)

Figure 5: Cavitation bucket - Staircase manoeuvre SIL mode

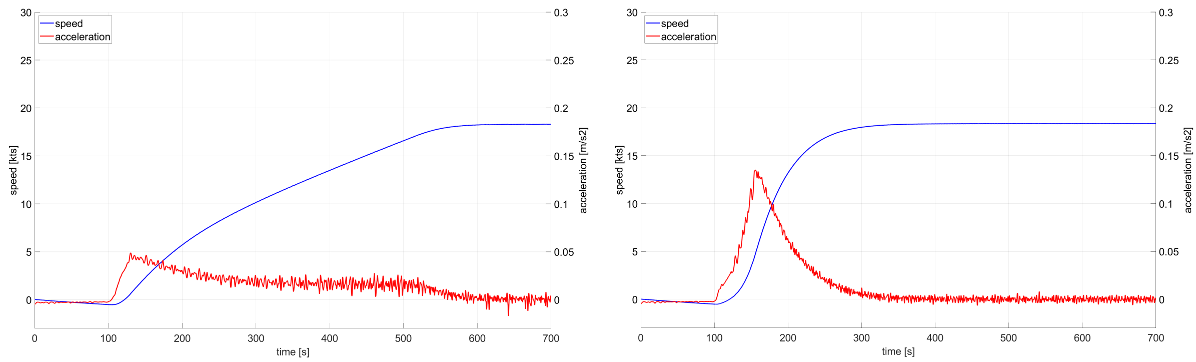
Slam start manoeuvre (scenario 2 vs 4): By applying appropriate limitations on the pitch and shaft speed change rates, the baseline strategy obtained cavitation performance similar to *APC* during the slam start manoeuvre (figure 6). However, similar to scenario 1, the slow transients of the baseline strategy have a significant impact on the acceleration performance. As one can see in figure 7, the slam start manoeuvre starts at 100 s after the start of the simulation, and then it takes 427 sec for the baseline strategy to reach the maximum silent speed, whereas it only takes 153 sec for the APC controller.



(a) Scenario 2 (APC OFF)

(b) Scenario 4 (APC ON)

Figure 6: Cavitation bucket - Slam start acceleration SIL mode



(a) Scenario 2 (APC OFF)

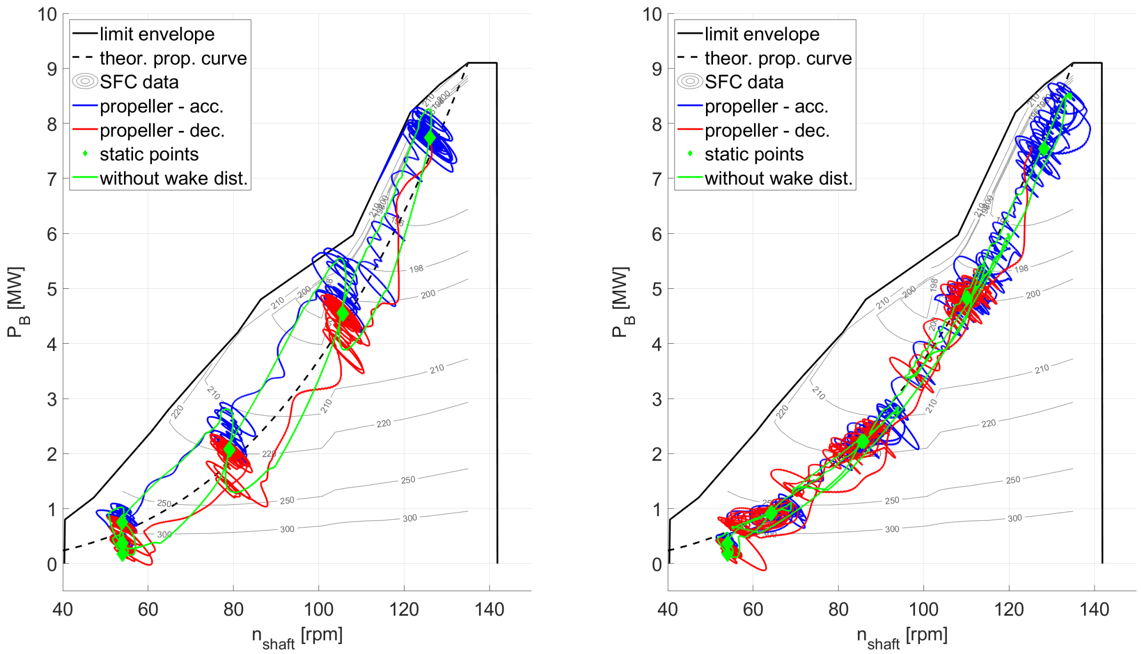
(b) Scenario 4 (APC ON)

Figure 7: Ship motion - Slam start acceleration SIL mode

3.2.2 Impact of APC in MAN control mode

The primary objective in *MAN* mode is to deliver the best possible manoeuvrability of the vessel. This often comes at the expense of fuel economy and radiated noise (cavitation inception), therefore those are not explicitly considered in the evaluation. However, it should be mentioned that APC managed in all the simulated manoeuvres to maintain most of the time the desired angle of attack, thus it performed considerably better than the baseline in terms of cavitation performance.

Staircase manoeuvres (scenario 5 vs 8): When looking at the stair case manoeuvres performed in MAN mode, it was observed that the acceleration performance of *APC* is similar to that the baseline strategy. Due to the fact that for the baseline control, pitch and shaft speed are increased irrespective of vessel speed, this results to slightly higher thrust peaks. On the other hand, APC maintained the propeller angle of attack within the predefined limits and this resulted to slightly lower and wider thrust peaks, thus a more evenly distributed thrust load during the manoeuvres.



(a) Scenario 5 (APC OFF)

(b) Scenario 8 (APC ON)

Figure 8: Engine diagram - Staircase manoeuvre MAN mode (SS6)

As it was expected based on results of previous studies (Vrijdag, 2009; Geertsma, 2019), APC demonstrated a better performance when it comes to engine loading during the transients of the staircase manoeuvres. Due to the nature of APC, which maintains a more stable load on the propeller blades by adjusting the pitch and shaft speed, the loading of the engine during the manoeuvres moves on an imaginary static propeller operating curve, visualized in figure 8 and 9 by the dotted black lines in the engine diagrams. By operating along this curve, APC ensures that there is sufficient amount of charge air available for combustion as it operates with a bigger margin from the limits of the engine envelope. As can be seen in figure 8, this attribute of APC becomes more clear in off-design conditions (SS6), where the baseline controller reaches much closer to the load limit of the engine envelope (turbocharger limit) and even hits the limit in the top right operating point, possibly resulting in lower air excess ratios and higher thermal loading of the main engines.

Slam start manoeuvres (scenario 6 vs 9, 7 vs 10): When comparing the slam start manoeuvres in *MDE* and *COMB* propulsion modes, where the vessel was accelerated from a standstill to the maximum sailing speed that corresponded to the selected PROP mode, no performance improvements in terms of acceleration times were observed between the baseline control and APC. As can be seen in table 3, the acceleration times in MAN mode are comparable, with the baseline performing slightly better. Next to this, it is also worth mentioning that the baseline control strategy did not show any highly loaded transient, due to the build-in features that manage loading during large step accelerations.

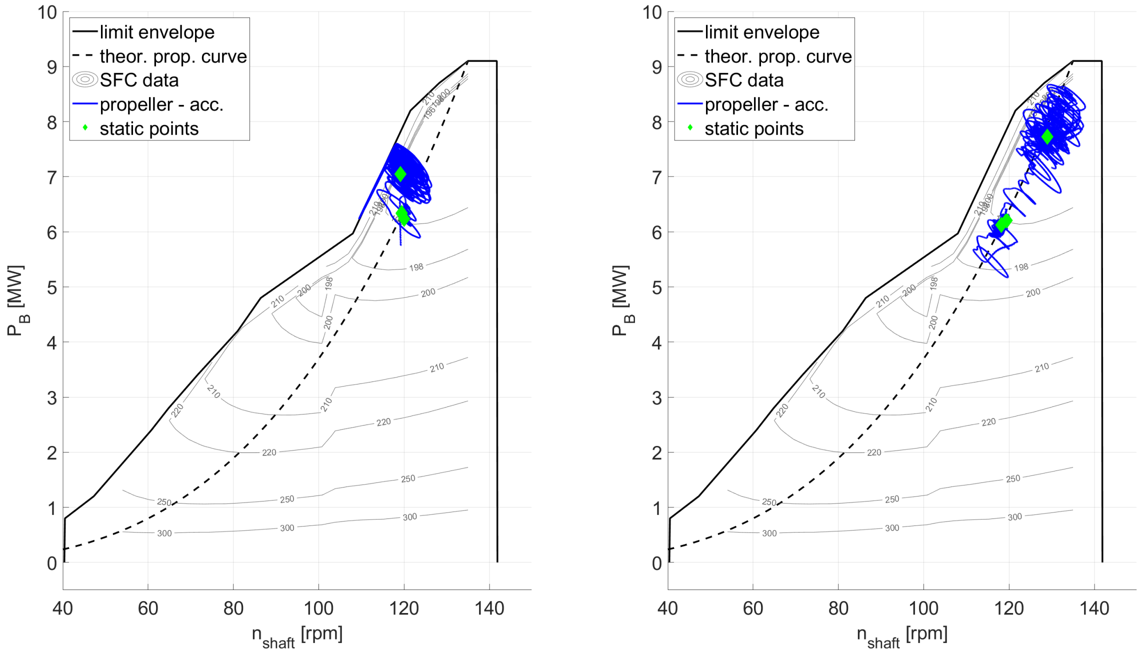
	APC OFF		APC ON	
Speed (kts)	MAN-MDE	MAN-COMB	MAN-MDE	MAN-COMB
From 0 to 22	115 s	88 s	120 s	90 s
From 0 to 27		114 s		117 s

Table 3: Acceleration time(s) - Slam start manoeuvre MAN mode (SS3)

3.2.3 Impact of APC in ECO mode

In order to evaluate the impact in *ECO* mode, constant speed sailing (transit) was simulated in scenarios 11 and 12, with $APC\,OFF$ and $APC\,ON$ respectively. During these scenarios the vessel was sailing at a constant N_{virt} of 100 rpm and the environmental conditions were varying between the conditions defined in table 1. From 0 to

200 sec the base condition was used (SS3, no wake disturbances), from 200 to 600 sec environmental condition A (SS3, irregular waves), and lastly, from 600 to 1000 sec environmental condition B (SS6, irregular waves).



(a) Scenario 11 (APC OFF)

(b) Scenario 12 (APC ON)

Figure 9: Engine diagram - Constant speed sailing ECO mode (varying conditions)

As can be seen in figure 9 where the operating points are plotted in the engine diagram, there is again a more effective loading of the engines. For the baseline strategy, the operating point moves vertically (constant shaft speed) as the resistance increases due to the worsening environmental conditions. This led to an operation closer to the limit of the engine envelope, thus to more frequent pitch retractions to prevent engine overloading. On the other hand, when *APC* was activated, the operating points moved along the theoretical propeller curve, which led to a more effective loading of the diesel engines (less pitch retractions due to engine overloading) and allowed for a higher average vessel speed in rough weather conditions (SS6). When it comes to fuel consumption, *APC* achieved equal or slightly better results compared to the baseline ECO mode.

4 Conclusions and recommendations

This paper investigated the performance gains of a novel control strategy called Adaptive Pitch Control (*APC*) against a highly tuned conventional strategy based on fixed combinator curves. The performed simulations indicated that *APC* can have a significant contribution to the delivered performance of the propulsion plant, in terms of acceleration, cavitation, engine loading and fuel consumption. As can be seen in table 4 where the performance comparisons are summarized, *APC* managed to achieve equal or better performance in all control modes, while at the same time minimizing the chance of cavitation and improving engine loading.

Table 4: Summary of APC performance per aspect

			ASPECTS			
	match-up	description	**acceleration**	**cavitation**	**engine loading**	**fuel**
SIL APC ON vs APC OFF	1 vs 3	staircase EPM - SIL	+	$=_{(1)}$	$+_{(2)}$	
	2 vs 4	slam start EPM - SIL	+	$=_{(1)}$	$+_{(2)}$	
MAN APC ON vs APC OFF	5 vs 8	staircase MDE - MAN	=	+	+	
	6 vs 9	slam start MDE - MAN	=	+	=	
	7 vs 10	slam start COMB - MAN	=	+		
ECO resistance change	11 vs 12	SS3 to SS6, MDE - ECO		$+_{(3)}$	$+_{(3)}$	+

(1) significant improvements for increased sea states, cavitation performance only equal for specific scenario

(2) engine loading is closer to ideal propeller curve, but offer no real benefits for electric motor

(3) improvements carry over to other scenarios, especially when comparing variants A and B

More specifically, in *SIL* mode, where the primary objective was signature reduction (e.g. during ASW operations), the *APC* strategy dominated the conventional strategy in terms of manoeuvring performance, achieving the top speed during a slam start manoeuvre 280% faster than the baseline. The accurate tuning of the baseline strategy accomplished acceptable cavitation performance, however at the cost of drastically lowered acceleration performance. Next to this, the *APC* strategy was much more robust against changes in resistance, irrespective of whether these changes in resistance are caused by loading conditions, heavy weather, or deployment of a towed array sonar. However, it should be noted that certain effects cannot be fully captured by models (e.g. the impact of sharp turns on cavitation performance). This is where full scale (sea) trials with an APC-equipped naval vessel are especially recommended to drive down the uncertainties and to gather the data needed to validate the findings of this study.

Acceleration performance in *MAN* mode was very similar for both strategies, with *APC* showing a minor improvement over the baseline control strategy during the staircase accelerations, and the baseline showing a slightly better acceleration time during a slam start manoeuvre. However, for the baseline strategy this performance came at the cost of reduced cavitation performance. *APC* allowed the ship to maintain an acceptable manoeuvring performance while limiting the chance of propeller cavitation and loading the engine in a favorable way, which potentially can lead to reduced lifecycle maintenance costs.

Regarding fuel consumption, APC managed to achieve comparable results to the *ECO* mode of the baseline strategy. However, the ability of *APC* to keep operating on the ideal propeller curve, even in off-design conditions (i.e. changes in resistance), is a clear benefit over the *ECO* mode combinator curves which are optimized for a single (design) condition. In addition to this, it is expected that in real operating conditions *APC* will most likely perform better in terms of total fuel consumption due to the fact that it does not require 'active' operator input. The baseline strategy requires the operator to consciously select *ECO* mode to focus on better fuel consumption, whereas APC operates close to the optimum efficiency of the MDE and the propeller, irrespective of the CNTR mode.

In conclusion, this study has demonstrated the potential of the *APC* strategy to improve the delivered performance of the propulsion plant. Not only cavitation and manoeuvring are positively affected by the robust adaptive behaviour of *APC*, the effect also propagates to more favorable diesel engine loading and reduced fuel consumption, since it is no longer required to select a defensive combinatory curve to cope with adverse weather conditions, at the cost of fuel consumption in calm conditions. The inability of the baseline strategy to combine objectives (e.g. cavitation aspect with the aspect of high manoeuvrability) and adapt to changes of the operating conditions, underlines the significance of further developing and integrating advanced propulsion control strategies, as the Adaptive Pitch Control (*APC*).

Table 5: Parameters of the simulation model

(a) **Diesel engine model parameters**

nominal engine power $P_{e_{nom}}$	9100 kW
nominal engine speed $n_{e_{nom}}$	16.7 rev/s
number of cylinders i_e	20
number of revolutions per cycle k_e	2
bore diameter D_B	0.28 m
stroke length L_S	0.33 m
crank rod length L_{CR}	0.64 mm
crank angle after TDC, inlet closure a_{IC}	225^o
crank angle after TDC, exh open a_{EO}	119^o
nominal spec. fuel cons. $m_{bsfc_{nom}}$	189 g/kWh
heat release efficiency η_q	0.915
geometric compression ratio ε_c	13.8
total nominal mass flow $\dot{m}_{t_{nom}}$	17.26 kg/s
cylinder volume at state 1 V_1	0.0199 m^3
nominal pressure at state 1 $p_{1_{nom}}$	$4.52e^5$ Pa
maximum cylinder pressure $p_{max_{nom}}$	$206e^5$ Pa
temperature after intercooler T_c	323 K
temperature of the inlet duct T_{inl}	423 K
parasitic heat exch effectiveness ε_{inl}	0.05
fuel injection time delay τ_X	0.015 s
turbocharger time constant τ_{TC}	5 s
exhaust receiver time constant τ_{p_d}	0.01 s
gas constant of air R_a	287 J/kgK
specific heat at constant vol. of air c_{V_a}	717.5 J/kgK
specific heat at constant press. of air c_{p_a}	1005 J/kgK
specific heat at const. press. of exhaust c_{p_g}	1100 J/kgK
isentropic index of air κ_a	1.4
isentropic index of exhaust gas κ_g	1.353
lower heating value of fuel h^L	42700 J/kg
stoichiometric air to fuel ratio σ_f	14.5
polytropic exponent for expansion η_{exp}	1.38
polytropic exponent for blowdown η_{bld}	1.38
nominal mechanical efficiency $\eta_{m_{nom}}$	0.90
constant volume portion grad $X_{cv_{grad}}$	-0.4560
constant temperature portion $X_{ct_{nom}}$	0.4
turbocharger factor a_η	$-2.80e^{-12}$
turbocharger factor b_η	$2.28e^{-6}$
turbocharger factor c_η	0.1877
ambient pressure p_{amb}	$1e^5$ Pa
ambient temperature T_{amb}	300 K

(b) **Propeller parameters**

wake fraction w	0.09
relative rotative efficiency η_R	1
propeller diameter D	4.9 m
design pitch ratio at 0.7R P_d	1.451
nominal pitch ratio at 0.7R P_{nom}	1.647
pitch ratio for zero thrust P_0	0.278
pitch actuation speed	2-3 deg/s
Vrijdag coefficient c_1	0.75
shock free entry angle α_i	4.4

(c) **Gearbox parameters**

nominal torque $M_{MDE,nom}$	86.9 kNm
nominal torque loss $M_{loss,nom}$	3.47 kNm (4%)
gearbox loss parameter a_{gb}	0.75
gearbox loss parameter b_{gb}	0.75
gearbox reduction ratio i_{gb}	7.407
nominal shaft speed $n_{s,nom}$	135 rpm

(d) **Induction machine parameters**

pole pairs P	8
nominal voltage V	660 V
base speed ω_b	72.26 rad/s
mutual reactance x_m	481.6 $m\Omega$
stator self reactance x_s	32.4 $m\Omega$
rotor self reactance x_r	15.2 $m\Omega$
stator resistance r_s	3.95 $m\Omega$
rotor resistance r_r	3.46 $m\Omega$
nominal power P_{nom}	3000 kW

(e) **Hull model parameters**

ship mass m	5200 tons
number of propeller	2
thrust deduction factor t	0.124

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