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FULL POWER AHEAD TO A HYBRID FUTURE

Propulsion and energy supply for future frigates

The Dutch Ministry of Defence has the ambition to reduce its dependency on fossil fuels in order to improve the effectiveness of its operations and reduce its impact on the environment. At the same time, the diversity of current threats during maritime operations require ships that are more silent, that manoeuvre better and require less maintenance.

The Dutch Government has set out its ambitions in the Operational Energy Strategy (OES, Ministry of Defence, 2015) and the Defense Energy and Environmental Strategy (DEOS, Bijleveld-Schouten, 2019). In general, hybrid propulsion, with a combination of diesel engines and electric motors (figure 1), can significantly reduce fuel consumption compared to propulsion on gas turbines. Yet, current naval vessels that sail on propulsion diesel engines, like the Karel Doorman class multi-purpose frigates (MFs), the Zeven Provinciën class Air Defence and Command Frigates (ADCFs), and the Holland class Patrol Vessels (PVs) have some serious shortcomings. Due to the very dynamic character of frigate operations, main engines seriously risk dynamic overloading. The propulsion control system of the MF, ADCF and PV includes various measures that effectively prevent overloading of its propulsion diesel engines. While these measures prevent overloading, acceleration performance is seriously limited, such that many commanding officers want to switch to gas turbine propulsion when they need to manoeuvre or replenish at sea. Moreover, the propulsion control strategy that prevents overloading leads to increased propeller cavitation and thus underwater radiated noise, which is unfavourable for detection by submarines.

Research at the NLDA and TU Delft

Extensive research has been performed at the Netherlands Defence Academy (NLDA) and Delft University of Technology (TU Delft) in order to understand, predict and improve the behaviour of frigates sailing on diesel engines. From 2001 to 2005, Lt (E) Dr ir Paul Schulten developed a dynamic model of diesel engine propulsion on an ADCF and validated the model with measurements on HNLMS De Ruyter (Schulten, 2005). Subsequently, Dr ir Arthur Vrijdag developed a propulsion control strategy to improve cavitation behaviour of diesel-driven frigates. This strategy was implemented and extensively tested on an MF, HNLMS Van Galen, in close cooperation with Wärtsilä, Imtech, MARIN, and the Canadian and Australian

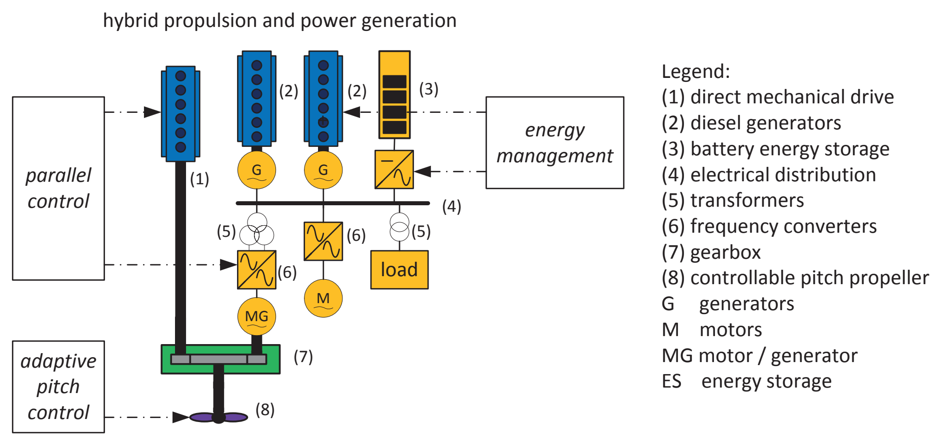

Figure 1. Schematic illustration of hybrid propulsion and power supply. Propulsion can be provided by a diesel engine, an electric motor or both. Electrical energy can be supplied by diesel generators and batteries. The control strategy consists of adaptive pitch control, which maintains a constant angle of attack, parallel control for the electric motor, which supplies instant torque during acceleration, and energy management, which shares load between generator and battery (Geertsma, 2019).

Figure 2. An ADCF during a manoeuvre on gas turbines. Can a frigate with hybrid propulsion on diesel engines accelerate just as fast? (Picture by Royal Netherlands Navy.)

Navy. These tests demonstrated that overloading was prevented and acceleration behaviour improved. The main idea of this control strategy was to continually adapt the propeller pitch to maintain an optimal angle of attack of the water flow onto the propeller blade profile, also during sailing in waves, manoeuvring and ship acceleration and deceleration (Vrijdag, 2009). From 2014 to 2018, Lt Cdr (E) Dr ir Rinze Geertsma, CEng, performed research into hybrid propulsion, using a combination of diesel engines and electric motors and hybrid power supply, from a combination of diesel generators and batteries. In his research, he further developed the previous models and control strategies for hybrid propulsion and power supply, to reduce fuel consumption, improve acceleration and cavitation behaviour, and prevent engine overloading (Geertsma, 2019).

Diesel engines lack the aggressive acceleration of gas turbines

In this article, which has previously been published in Dutch in *"Het Marineblad van de Koninklijke Vereniging van Marine Officieren (KVMO)"* (Geertsma & Vrijdag, 2020), we will discuss the recent achievements of this research and compare the performance of frigates with hybrid propulsion and power supply and the proposed control strategy with frigates propelled by gas turbines and electric motors. We will demonstrate how this advanced control strategy with hybrid propulsion can achieve reduced cavitation, comparable acceleration, and a thirty per cent reduction in fuel consumption compared to current frigates. Finally, we will discuss how this control strategy can be implemented on future frigates without excessive project risk.

Manoeuvring on diesel engines

Every watch officer that has sailed on an MF or ADCF will recognise that, for example during replenishment at sea, these naval vessels react very slowly to commands to accelerate when sailing on diesel engines, certainly compared to the aggressive acceleration that can be achieved on gas turbines. Especially during an emergency breakaway – the manoeuvre to quickly break away from a supply vessel during a dangerous situation – this is a huge limitation. During other manoeuvres, for example in air defence or anti-submarine warfare exercises, this also leads to operational flaws. The preference for gas turbines in these situations is common sense due to its superior available torque, which is higher at low shaft speed than at high shaft speeds, and leads to impressive ship acceleration, as illustrated in figure 2.

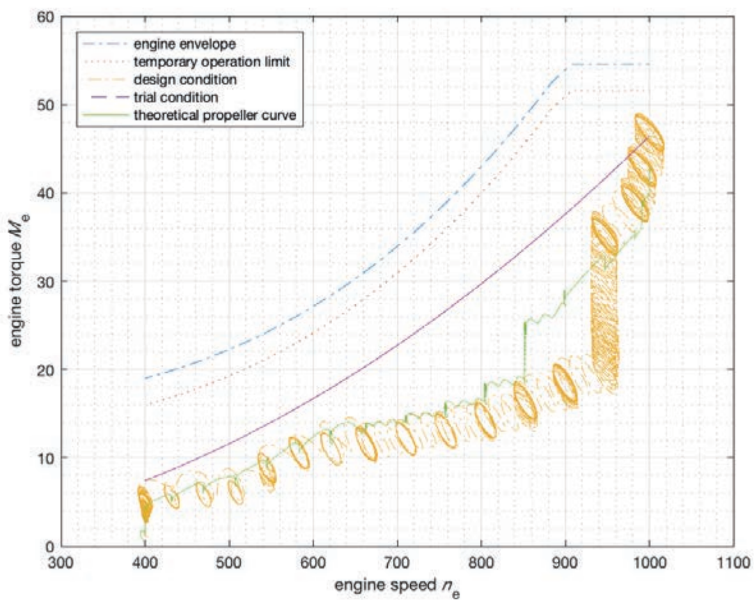

Figure 3. Operating envelope of the propulsion engines on a Holland class Patrol Vessel. The blue and red lines feature maximum toque of the engine envelope and the limit at which the engine can work only temporarily. At 400 rpm, the engine has a maximum torque of 20 kNm and a power of 650 kW, and at 1000 rpm, the maximum torque is 52 kNm and maximum power is 5400 kW. The yellow and green lines illustrate the working points at various speed settings in design and trial conditions (Geertsma, Visser, & Negenborn, 2018).

Overloading

The limited acceleration of ships on diesel engines appears in contradiction with diesel engines in cars that can deliver high torque at low revolutions. The use of turbochargers in maritime diesel engines, which increases the charge pressure of the engine, causes their limited torque at low revolutions. Due to the high charge pressure – typically around 3 bar – the engine breathes in three times as much air into its cylinder and thus can produce three times as much power. However, when the engine runs at low speed, the turbocharger receives insufficient energy from the exhaust gas flow to work properly, which can lead to engine overloading. To prevent overloading, maritime diesel engines have a limited operating envelope, as illustrated in figure 3.

Cavitation behaviour

Frigates with propulsion diesel engines use controllable pitch propellers, to enable slow sailing. At slow speed, the engine runs at its minimum speed and ship speed is controlled by changing propeller pitch. The control strategy also uses the propeller to prevent overloading, when the load of the propeller is too high for a certain engine speed. By reducing pitch when overloading impends, engine load can be reduced. This reduction, which is applied aggressively, has one big disadvantage: the disturbance of the angle of attack of the waterflow onto the propeller blades in many cases leads to propeller cavitation and thus underwater radiated noise. For the MF, research showed that pitch reduction during acceleration was so aggressive that thrust initially was negative for a couple of seconds (Vrijdag, Stapersma, & Terwisga, 2010). Cavitation behaviour during deceleration and the effect of an alternative control strategy has also been investigated in full scale trials (Vrijdag, Stapersma, & Grimmelius, 2009).

> Acceleration with hybrid propulsion is approximately as fast or faster as on gas turbines

Acceleration with original control

On a frigate's bridge, the duty watch officer orders a virtual shaft speed, as opposed to a lever setting on many commercial vessels. This virtual shaft speed represents the product of normalised pitch and shaft speed. As such, the bridge officer can intuitively achieve the required ship speed through a single shaft speed setting, without having to worry about engine speed and pitch setpoints. The original control strategy uses a combinator curve to establish the engine speed and pitch setpoints. Each virtual shaft speed is associated with a setpoint for propeller pitch and engine speed. In order to limit engine loading during acceleration – and prevent the engine running outside its engine envelope – the virtual shaft speed is increased at a limited, slow, rate. Thus, it takes a long time for the engine to reach its maximum revolutions. As the turbocharger only works well at the engines' maximum revolutions, engine torque is very limited during acceleration.

Thus, it takes a long time for the engine to reach its design speed. Only after reaching the design speed, the turbocharger can operate at its design point, and achieve maximum charge pressure to deliver maximum engine torque.

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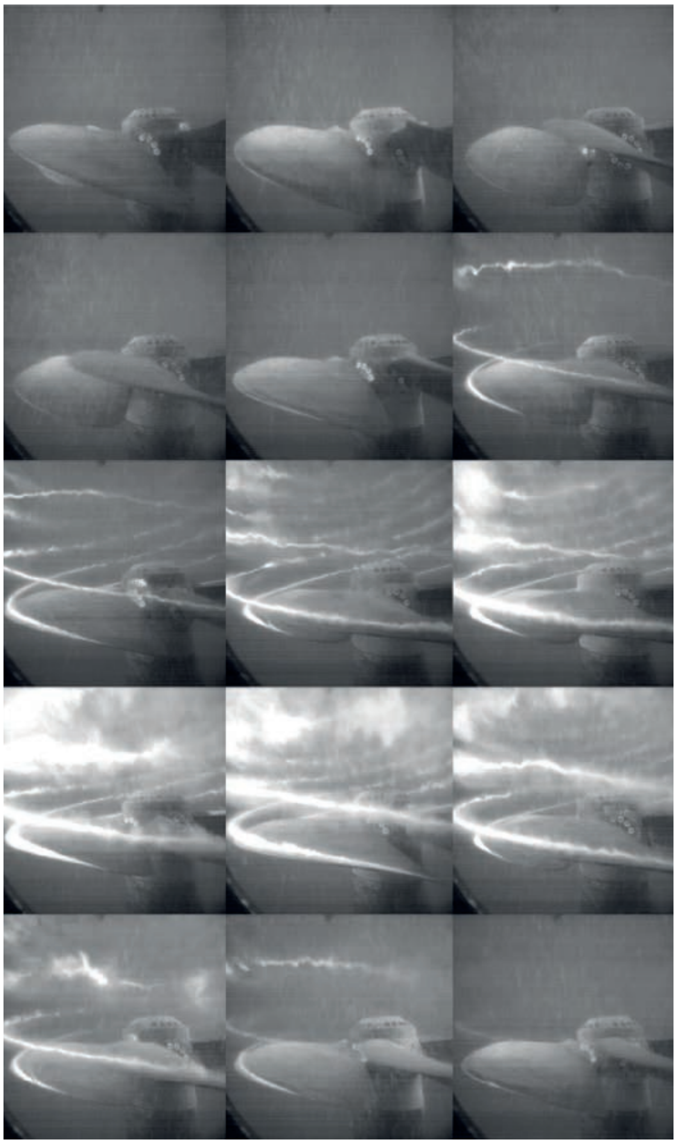

Figure 4. Cavitation behaviour of an MF propeller during acceleration with the original control strategy. The illustrated white trace occurs due to cavitation. This trace consists of water vapour bubbles that occur due to local low pressure on or around the propeller surface when the angle of attack of the water flow is too large or too small (Vrijdag, Stapersma, & Terwisga, 2010).

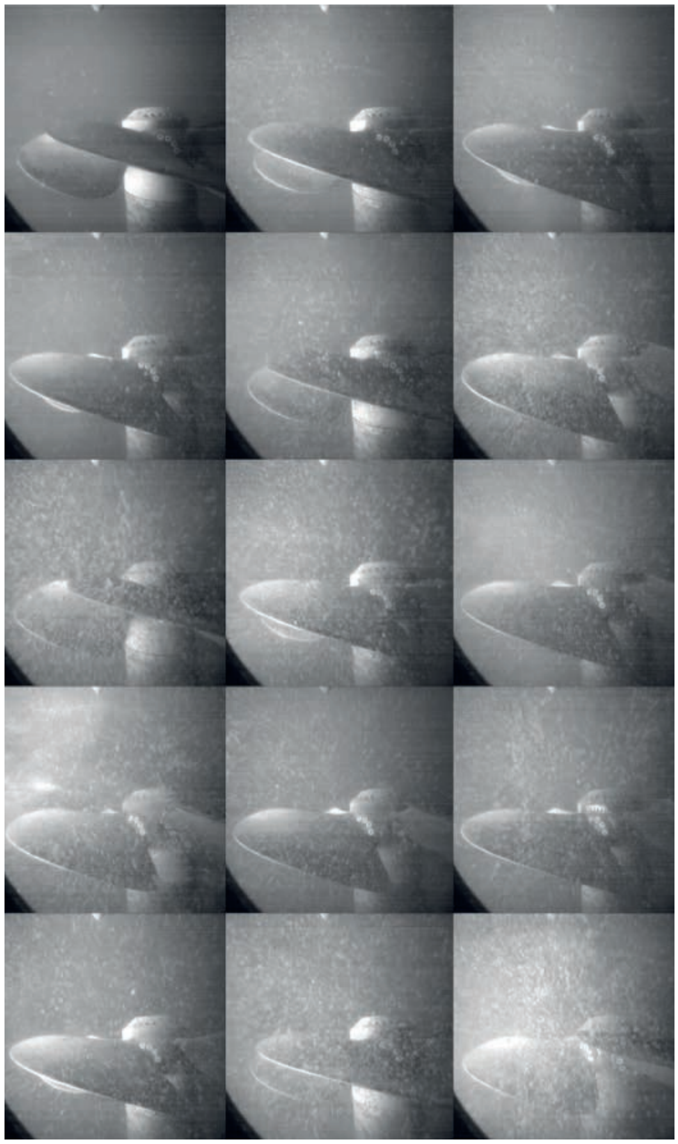

Figure 5. Cavitation behaviour of an MF propeller during acceleration with a temporarily installed experimental pitch control strategy aimed at maintaining a constant angle of attack (Vrijdag, Stapersma, & Terwisga, 2010).

Adaptive pitch control strategy

It turns out that cavitation behaviour, engine thermal loading and acceleration behaviour of a vessel can be carefully balanced by actively controlling the angle of attack of the water flow onto the propeller blade profile, in particular during dynamic conditions such as waves, manoeuvring, acceleration and deceleration. In order to control the angle of attack, it is required to continuously measure or accurately estimate engine speed, propeller pitch and flow speed of water into the propeller disc, the speed of advance. The first two can be measured by sensors. The third cannot be directly measured in practice. A solution to this is a computer algorithm developed at TU Delft, that estimates the speed of advance using variables that can be directly measured, such as shaft torque and thrust. Figure 4 illustrates what happens when the angle of attack is not actively controlled during a ship acceleration from 10 to 14 knots, when an aggressive pitch reduction is applied to prevent engine overloading. During a couple of seconds significant pressure side tip vortex cavitation occurs, shown by the white helical traces. Figure 5 illustrates the behaviour when the angle of attack is actively controlled during the same ship acceleration. While hardly visible, in this case, pitch is also slightly, but more gradually, reduced, thus continually balancing pitch with measured shaft speed and estimated advance speed. The result of this strategy is a strongly improved cavitation behaviour, improved ship acceleration and acceptable engine loading. This proposed control strategy also results in a different pitch-revolutions combination in high sea states than in low sea states, when maintaining the requested virtual shaft speed. Therefore, this control strategy can be considered adaptive to its conditions, as opposed to the current fixed combinator curves associated with transit and manoeuvre modes, which lead to higher engine loading in heavier conditions.

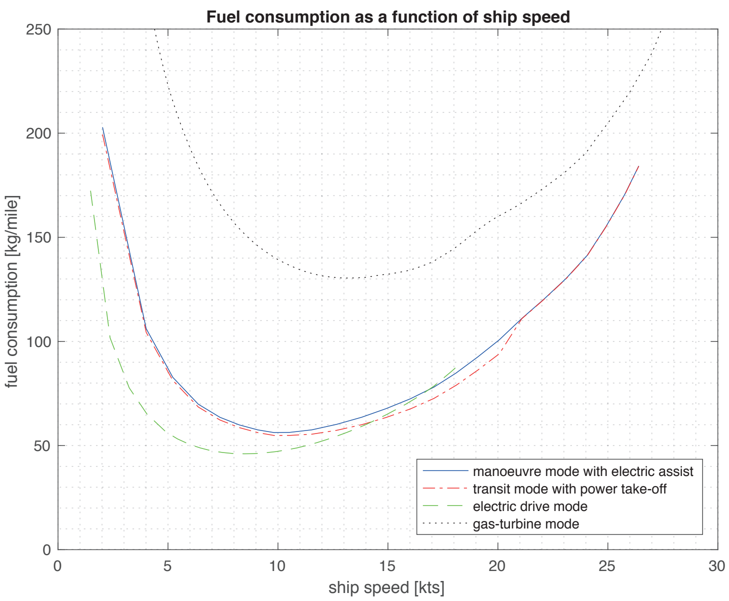

Figure 6. Fuel consumption per travelled mile for a 5200-tonne frigate with gas turbine propulsion (black), hybrid propulsion on diesel engines and electric motors (red and blue) and propulsion on electric motors (green).

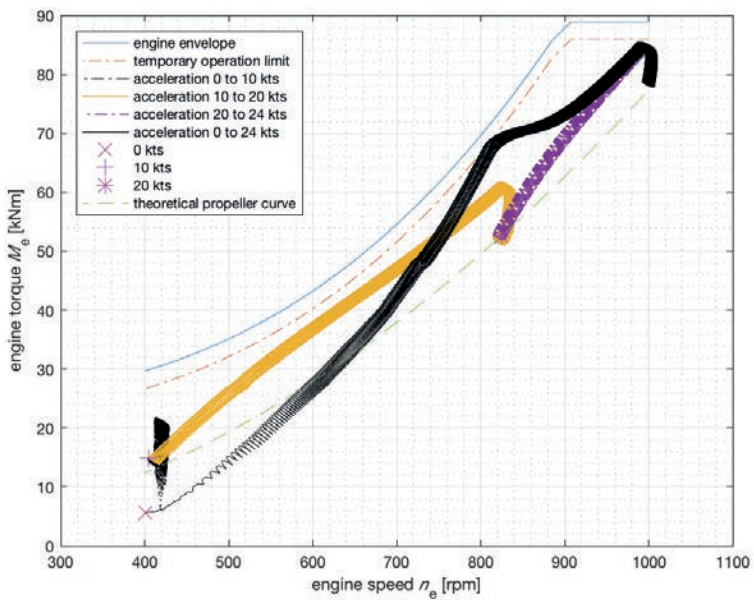

Figure 7. Operating envelope with operating behaviour during acceleration with existing speed-and-pitch control strategy without pitch reduction. The black line left below illustrates an acceleration from 0 (x) to 10 (+) knots, yellow from 10 (+) to 20 (*) knots, purple from 20 (*) knots to 24 knots and black from 0 knots to top speed. During acceleration, engine load reaches limitations of the operating envelope and gradually increases engine speed. This introduces a high risk of overloading, which can be prevented with a pitch reduction strategy as applied on MFs, ADCFs and PVs, and leads to increased cavitation and slower acceleration (Geertsma, 2019).

Hybrid parallel control strategy

The proposed parallel adaptive pitch control strategy in essence uses the same principle as the adaptive pitch control strategy: it maintains a constant angle of attack. As this control strategy can also use the electric motor of the hybrid propulsion plant, it can increase acceleration by using additional torque from the electric motor. Moreover, the control strategy can use both the maximum torque of the diesel engine and the maximum torque of the electric motor, to achieve higher maximum speed. The electric motor has the additional advantage that it can almost instantaneously provide maximum torque, independent of shaft speed. This increased torque can also assist the diesel engine to reach its maximum speed and maximum charge pressure more quickly, thus further improving acceleration and reducing engine loading. Subsequently, after acceleration, the energy management strategy ensures optimal power sharing between diesel generators and batteries, in order to achieve the best possible working point for the generators and batteries, and minimise fuel consumption. This control strategy is schematically illustrated in figure 1.

Simulation models

In order to assess the newly proposed control strategy for frigates and compare its performance with the performance of current frigates and control strategies, simulation models have been developed, based on previous research and validation of simulation models with measurement campaigns on board of MFs, ADCFs and PVs (Schulten & Stapersma, 2007; Vrijdag, Stapersma & Terwisga, 2010; Geertsma, Negenborn, Visser & Hopman, 2017; Vrijdag, Stapersma & Terwisga, 2009). A schematic representation of the simulation models is shown in figure 1, together with the elements of the control strategy. This article presents the results of a comparison of the behaviour of a notional future frigate of 5200 tonnes with hybrid gas turbine and electric propulsion and a similar frigate with hybrid diesel electric propulsion. The main parameter of these vessels is presented in tables 1 and 2. The models and model parameters have been described in detail in: Geertsma, 2019 and Geertsma, Vollbrandt, Negenborn, Visser & Hopman, 2017.

Ship's mass	5200 tonnes
Power gas turbines	18 MW
Power electric motors	3 MW
Diameter fixed pitch propeller	4.8 metres

Table 1. Main parameters of a notional future frigate with hybrid gas turbine electric propulsion.

Ship's mass	5200 tonnes
Power diesel engines	9.1 MW
Power electric motors	3 MW
Diameter controllable pitch propeller	4.8 metres

Table 2. Main parameters of a notional future frigate with hybrid diesel electric propulsion.

Results of simulations and measurement campaigns

The goal of the comparison presented in this article is to compare hybrid propulsion with 18-MW gas turbines and 3-MW electric motors, with hybrid propulsion with 9.1 MW diesel engines and 3 MW electric motors, with both a traditional combinator curve control strategy and the novel parallel adaptive pitch control strategy, based on the research in Geertsma, 2019. The difference in performance between these configurations is very sensitive to the ship type, the requirements for the vessel and the chosen propulsion powers, but this comparison is indicative of the possibilities with different propulsion configurations of a future frigate, in particular when top speed is not very high.

Figure 6 presents the fuel consumption of the propulsion and electric power supply in the various operating modes. The fuel consumption on gas turbines between 18 and 26 knots is remarkably higher than on diesel engines and electric motors: 25 per cent higher at top speed to 50 per cent higher at 18 knots. The diesel engine is the most efficient mode of propulsion between 15 and 20 knots, which can be further improved by supplying auxiliary power with the electric drive, used as a generator, and switching of the diesel generators (presented as transit mode with power take-off). For this specific configuration, propulsion on the electric motor using power supplied by the diesel generators is the most efficient propulsion mode, because the main diesel engine and propeller are not operating at their most efficient working points (Geertsma, Vollbrandt, Negenborn, Visser, & Hopman, 2017).

The new control strategy significantly reduces cavitation during acceleration

And what about the acceleration performance? See table 3, figure 7 and figure 8 for a comparison in acceleration times and behaviour between propulsion on gas turbines and diesel engines with the current pitch-and-speed control strategy and the parallel adaptive pitch control strategy. Table 3 shows that the acceleration time on gas turbines from 0 to 24 knots is less than 50 per cent of the acceleration time on diesel engines with the current pitch-and-speed control strategy. While the difference between acceleration times from 10 to 20, and 20 to 24 does not appear as excessive, this is caused by not taking the pitch reduction strategy into account. Figure 7 illustrates that the diesel engines operate very close to the limits of the operating envelope, which leads to a risk of engine overloading. In practice, a pitch reduction strategy, as applied on MFs, ADCFs and PVs, will have to be implemented, causing increased acceleration time and cavitation noise.

Another point to note is that the intermediate accelerations, from 0 to 10, 10 to 20 and 20 to 24 knots, appear to take much more time than acceleration from 0 to 24 knots. This is caused by the reduced speed setting that is used for these intermediate sprints. If the speed setting for these sprints was requested at full speed ahead, then the same acceleration would be achieved as for acceleration from 0 to 24 knots.

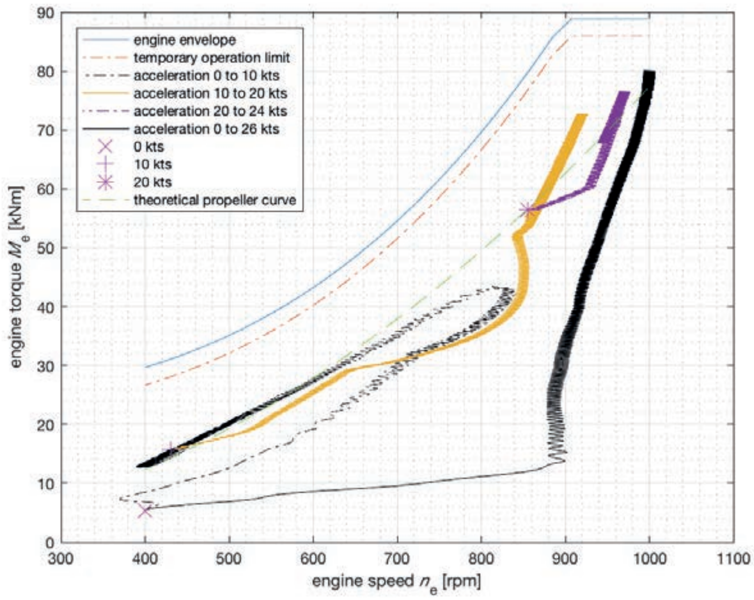

Figure 8. Operating envelope with operating behaviour during acceleration with parallel adaptive pitch control strategy. The black line left below illustrates an acceleration from 0 (x) to 10 (+) knots, yellow from 10 (+) to 20 (*) knots, purple from 20 (*) knots to 24 knots and black from 0 knots to top speed. During acceleration, pitch is reduced to maintain a constant angle of attack. Thus, the engine operates on or below the theoretical propeller curve, shown with the green dashed line, which is the optimal operating line of the engine (Geertsma, 2019).

Propulsion configuration	0-10	10-20	20-24	0-24
Gas turbines	339	100	45	82
Diesel engines	269	138	77	204
Hybrid propulsion	59	74	32	86

Table 3. Acceleration times in seconds for a notional future frigate with propulsion on gas turbines, propulsion on diesel engines with pitch-and-speed control strategy and hybrid propulsion with parallel adaptive pitch control strategy during maximum acceleration to top speed and during intermediate acceleration to an increased virtual shaft speed setting associated with the required ship speed. The pitch-and-speed control strategy of both diesel engines and gas turbines leads to slow intermediate sprints, as the control strategy gradually increases to the new speed setpoint and thrust increases very slowly at the end of acceleration. The parallel adaptive pitch control strategy compensates reduced pitch directly with increased engine and electric motor speed, as shown in figure 8.

Back to table 3. Acceleration with hybrid propulsion on diesel engines and electric motors from 0 to 24 knots is approximately as fast as acceleration on gas turbines. This is because the engine, as shown in figure 8, initially speeds up to 900 rpm very quickly, supported by the electric motor. Therefore, the turbocharger can quick-

Figure 9. Conceptual design of one of the many considered options for the replacement of the M-frigate (source: Defence Materiel Organisation).

ly reach a higher charge pressure and the engine can thus provide power more quickly, without thermal overloading. Together with the constant angle of attack and a gradually increasing propeller pitch, this leads to a high engine torque and speed without overloading the engine.

During intermediate sprints from 0 to 10 knots, from 10 to 20 knots and from 20 to 24 knots, hybrid propulsion accelerates even faster than gas turbines. The adaptive pitch control strategy will reduce propeller pitch to maintain a constant angle of attack. In order to maintain the requested virtual shaft speed, the controller compensates reduced pitch with increased engine speed. During an acceleration from 10 to 20 knots, shown in yellow, figure 8 shows engine speed first increases to 910 rpm, before reducing to its final working point at 840 rpm. Torque also first increases above its final working point, causing faster acceleration. Alternatively, the gas turbine with speed-and-pitch control strategy gradually increases engine power and speed to the required engine speed and pitch. To achieve an equally fast acceleration on gas turbines, the operator first has to request maximum virtual shaft speed to increase speed and power beyond the final working point for the required ship speed.

During trials on an MF with adaptive pitch control, the adaptive pitch control strategy maintained the angle of attack closer to its desired value. The control strategy was not fast enough to maintain a constant angle of attack in waves, due to inertia and actuation delays in the existing hydraulic pitch actuation. During acceleration, the angle of attack was maintained closer to the desired value, reducing cavitation compared to original control. This is illustrated in figures 4 and 5, which are recordings through the aperture in the ships' hull during acceleration: the new control strategy significantly reduces cavitation during acceleration.

Towards a prototype production system

The studies and presented results discussed clearly demonstrate that application of hybrid propulsion with diesel engines and electric motors on frigates with a top speed around 25 knots can achieve a reduction in fuel consumption at speeds above 18 knots of 25 to 50 per cent compared to gas turbine propulsion. The proposed parallel adaptive pitch control strategy achieves comparable acceleration behaviour for hybrid propulsion from "dead in the water" to 24 knots in comparison with gas turbine propulsion. This strategy achieves even faster acceleration than gas turbines during intermediate sprints with speed settings associated with the required ship speed. Last but not least, trials with adaptive pitch control on MF have demonstrated that propeller cavitation reduces during operation in waves and acceleration.

Based on these promising results, the Defence Materiel Organisation is preparing successive studies and trials with industrial partners, in order to further develop this control strategy into a prototype production system, through software demonstrators, hardware-in-the-loop trials and further tests on an existing naval vessel. These studies and trials have to further reduce the project risk of implementation onto future frigates.

Ultimately, the goal of these studies is to improve performance of propulsion systems while reducing the dependency on fossil fuels. This is to be achieved by implementing hybrid propulsion with parallel adaptive pitch control on future naval vessels, such as the replacement of the M-frigates, of which one of the many considered conceptual designs is shown in figure 9.

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