CONTROL OF PROPELLER CAVITATION DURING A DECELERATION

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ABSTRACT

Off design conditions can have a severe impact on ship propulsion system behaviour. Resistance increase for instance leads to a higher engine loading, and can also easily lead to a decrease of cavitation inception speed with respect to calm water conditions. Wakefield variations due to ship motions, waves and manoeuvres also have effect on engine loading and on propeller cavitation. This paper discusses the model based development of a propulsion control system aiming at increased cavitation free time in operational conditions, while preventing engine overloading and keeping manoeuvring characteristics acceptable. The developed propulsion control system has been tested extensively in a simulation environment before full scale trials took place in February 2008, onboard a frigate of the Royal Netherlands Navy. Results in terms of full scale propulsion system behaviour during a deceleration are presented, including photos showing the propeller cavitation behaviour.

KEY WORDS

propulsion control system, cavitation, deceleration, frigate, diesel engine, acoustic signature management.

1. INTRODUCTION

Because of the shift of naval operations towards shallow coastal waters and the associated increasing mine threat, underwater signature management is of growing importance for naval ships. At the same time the number of countries that operate submarines is growing, suggesting that navies should be prepared for possible increased torpedo threat.

Due to the resulting strict demands on inboard as well as outboard noise levels, increasing effort is being put into the investigation, monitoring and control of noise sources, such as vibrating machinery and cavitation of the propellers. For naval vessels, acoustic signature management serves multiple goals. First of all, the risk of being detected by acoustic sensors of the opponent (including acoustically triggered mines and torpedoes), is greatly dependent on the acoustic signature. Secondly the own acoustic detection range is decreased by self-noise, which increases the chance of being detected before having detected.

From full scale measurements it is known that off-design conditions have a considerable influence on cavitation performance of ships propellers, and thus on the ships acoustic signature. The effects of seastate and manoeuvring are reported in for instance [1]. Measurements onboard the oceanographic research vessel HNLMS Tydeman of the Royal Netherlands Navy (RNLN), show that, compared to the calm water condition, the cavitation inception speed is reduced by as much as 75% in bow quartering waves, seastate 5. As can be seen in Fig 1, head waves result in a decrease of 100%: No cavitation free speed is left for this condition. The use of 20 degrees rudder in calm seas is reported to give a decrease of as much as 55%, as can be seen in Fig 1.

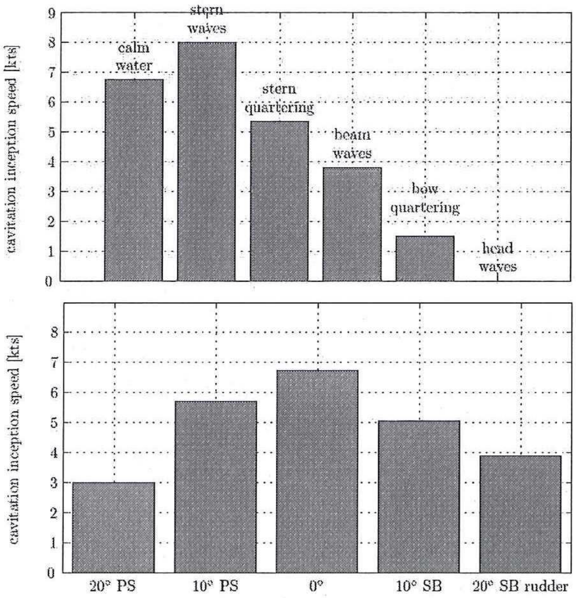

Fig 1: Effect of wave direction and rudder angle on Cavitation Inception Speed. Reproduced from [1]

The research project that resulted in this paper aims at implementation of a propulsion control system that increases cavitation free time in operational conditions. To develop such a control system use is made of a ship propulsion simulation model, that has systematically been developed, verified, calibrated and validated in [2]. Only after these laborious tasks, the simulation model can rightfully be used to make predictions instead of, or prior to measurements. It is chosen to limit the practical implementation to a controller aiming at an increase of cavitation free time, while preventing thermal overloading of the engine, and keeping manoeuvring characteristics within acceptable limits. The research is further limited with respect to the type of operational conditions that are considered: the current research is limited to straight line manoeuvring characteristics. The objectives and their related research questions that are dealt with in this paper are summarized by:

- Use the earlier developed simulation [2] to develop a propulsion control system that aims at increased cavitation free time in operational conditions, and test this propulsion control system on full scale.
  - How should ship propulsion simulation models be used in order to have maximum benefit during development and testing of a practically applicable ship propulsion control system?
  - How should a newly developed propulsion control system be tested in order to asses its performance?
- Investigate the effects of operational conditions on the performance of the propulsion system.
  - What is the effect of acceleration and deceleration on the system performance?
  - What is the effect of added resistance (due to for instance wind or fouling) on the system performance?
  - What is the effect of waves on the propulsion system performance?

In February 2008, the cavitation-reducing propulsion control system was tested on full scale, onboard an M-frigate of the RNLN. The goal of these trials was to demonstrate the effect of the developed new propulsion control system on the propulsion system in general and on propeller cavitation in particular. A comparison with the existing propulsion control system was also made. Time-synchronized measurements of both engine and propeller variables were made, including high- speed video recordings of the propeller.

This paper gives an overview of the global controller structure, and presents some of the full scale trial results.

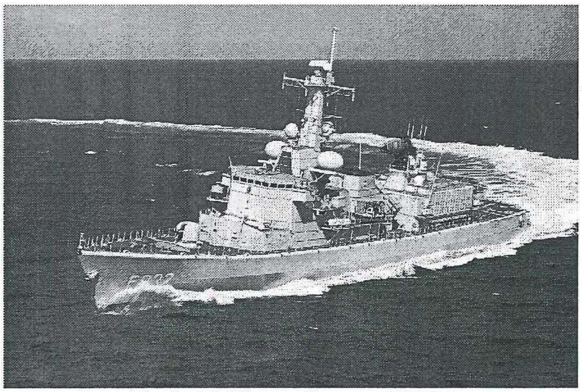

Fig 2: M-frigate. Source: RNLN

2. THE SIMULATION MODEL

The simulation model is extensively discussed in [2], and is therefore only briefly described here. The ship under consideration is the M-frigate of the RNLN, shown in Fig 2. The propulsion plant is of the CODOG-type, with two identical shaft lines for port and starboard side, both driving a controllable pitch propeller (CPP), as shown in Fig 3.

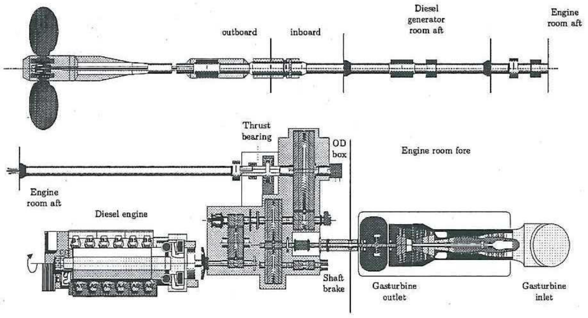

Fig 3: The M-frigate propulsion plant. Source: RNLN

The original system can be split up in several stable subsystems, with measurable linking variables, as shown in Fig 4.

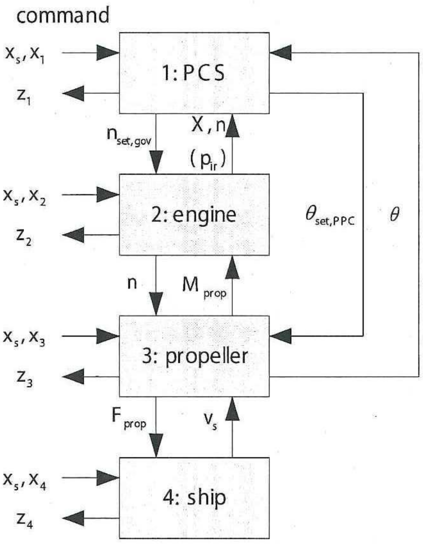

Fig 4: Schematic overview of the conceptual model

Four different submodels are visible: the propulsion control system (PCS), the engine including gearbox, the propeller, and the ship. Linking variables between the lower three models are the shaft speed n, pitch θ, propeller thrust F_{prop}, ship speed v_s, fuelrack position X, and propeller torque M_{prop}. The PCS gives its setpoints to the plant via the two variables "governor

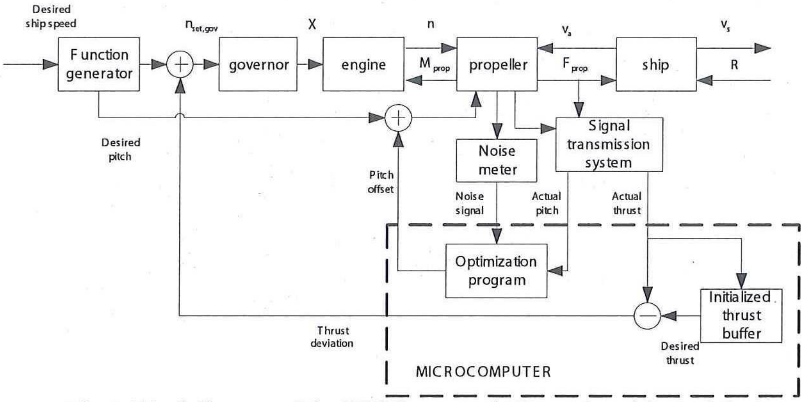

Fig 5: Blockdiagram of the "VS4" approach. Reproduced from: [4]

setpoint $n_{set,gov}$ ” and “propeller pitch controller setpoint $\theta_{set,ppc}$ ”.

3. THE PROPULSION CONTROL SYSTEM

The existing Propulsion Control System (PCS) determines the setpoints for the engine speed and the propeller pitch based on the ship-speed related command of the user, via the combinator curve that is programmed in the PCS. This combinator curve fixes the combinations of shaft speed and pitch that are used to effectuate the command of the user, while in principle there exist many possible combinations of pitch and shaft speed that result in the same ship speed. This is visualised in Fig 9, showing three regimes of the combinator curve. In the low ship speed range, shaft speed remains constant, while only pitch is changed. In the second horizontal leg, pitch remains constant at 26 degrees, while shaft speed is changed. In the third leg, both pitch and shaft speed change.

The design of a combinator curve in a conventional propulsion control system is a compromise between many performance aspects. One of these aspects is propeller cavitation. If this aspect is considered of importance one could, for instance, design the combinator in such a way that during some resistance condition (say nominal or perhaps mean resistance conditions), the propeller operating points all have maximum margin against cavitation. Such an approach will lead to satisfactory performance as long as no disturbances act on the system.

Sailing with one trailing shaft will for instance increase the loading on the other. The propeller operating point is further affected by waves, wind, manoeuvres and ship motions. The impossibility of designing a single combinator curve that meets cavitation requirements in varying weather conditions is explicitly demonstrated in [3]. However, the currently applied feedforward approach has the advantage that the plant is not continuously actuated by the controller, which is beneficial with regards to wear of the installation. Especially the continuous adjustment of the CPP is not common nowadays, and related wear aspects are not fully understood, which partly explains the common choice for the combinator curve approach.

A feedback approach to reduce acoustic underwater signature, involving measurement of underwater noise, has been tested onboard an S-frigate of the RNLN in the 1980's. The project was carried out in cooperation with industry and was titled "VS4". As reported in [4], the developed propulsion control system minimized the noise emitted by the propellers by adapting the propeller pitch while ensuring constant average thrust by adjustment of the shaft speed.

A blockdiagram of the approach, designated PCS+, is shown in Fig 5. Acceleration sensors were installed near the propellers, which generated input to the optimization program. The optimization program used a steepest descent algorithm to iteratively determine the pitch offset that led to the minimum of measured noise. At the same time, the microcomputer added a correction to the governor setpoint to ensure that the desired average thrust was maintained. The thrust was measured by means of strain gauges on the shaft. The optimization program was not active during transients because the applied method needed sufficient time to find the optimal pitch angle with the least noise. It is reported that, in case of twin screw ships such as the S-frigate, the method dealt with each propeller successively to prevent interaction between the propellers.

Noise reductions up to 12 dB are reported at speeds below 12 kts. Between 12 and 18 kts no noise reduction was found, and in the range from 18 to 24 kts a reduction up to 3 dB has been observed. The exact conditions under which these gains have been found are not reported.

It is noteworthy to mention that the "VS4"-approach led to the mounting of propeller noise sensors on the M-frigates. The noise optimization approach was however never applied onboard the M-frigates, although two sensor readouts are still available on the navigation bridge nowadays. As mentioned in [4], the M-frigates were also

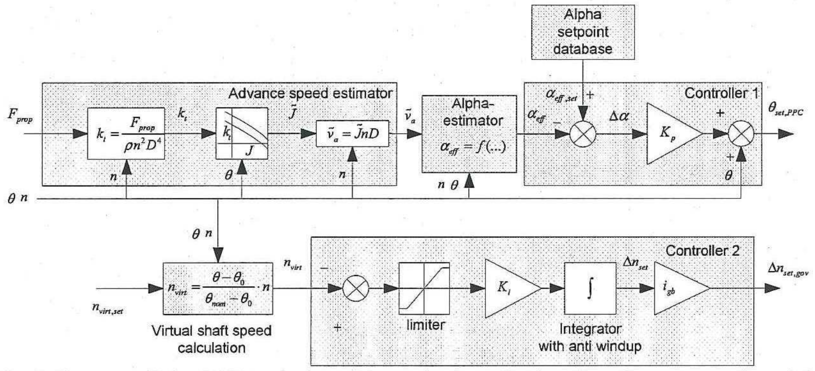

Fig 6: Blockdiagram of the PCS+ aiming at increased cavitation free time. Reproduced from: [2]

fitted with provisions for a technological spin-off regarding fuel optimization. As far as known to the author these "provisions for" are limited to a sole pushbutton on the bridge console, and no fuel optimization program has ever been applied.

Based on the reported method and results it is concluded that a feedback approach based on measurement of noise is feasible. However, due to the time necessary to find an optimum pitch-shaft speed combination, combined with the fact that the port and starboard shaft have to be optimized sequentially, it is expected that such an approach is not suited for noise reduction during ship speed transients. Wave frequent adjustments of propeller pitch are also not considered possible.

In this project a combination of feedback and feedforward is applied, thereby combining desirable characteristics of both. Disturbance rejection due to feedback helps to make the system performance robust against the ever changing environment in which the propeller operates. On the other hand a feedforward approach is applied to operate the propeller in such an operating point that it is least susceptible to cavitation. This "optimal operating point" is based on prior knowledge and understanding of the system. This approach can help to overcome the difficulties in measurement and feedback of underwater noise. Because the proposed feedforward approach does not rely on noise measurements, no interaction effects are to be expected in case of twin shaft ships. A further advantage is that the feedforward approach can react to undesirable propeller inflow before actual noise is generated, while a noise feedback approach reacts when noise has already been generated, which in principle is too late. On the downside feedforward requires knowledge of the propeller operating points that are least susceptible to cavitation.

The structure of the suggested combined approach is shown schematically in Fig 6. Analogue to Fig 5, corrections to the governor setpoint $\Delta n_{set,gov}$ are generated, but now based on the signals n_{virt} and $n_{set,virt}$ instead of the desired and actual thrust signal as applied in the VS4-project. The virtual shaft speed n_{virt} is a compound variable that contains both actual shaft speed and actual pitch. It is defined as $n_{virt} = \frac{\theta - \theta_0}{\theta_{nom} - \theta_0} \cdot n$, where θ_{nom} and θ_0 are constants that stand for the nominal and the zero-thrust pitch angle. In static conditions, the virtual shaft speed is almost linearly related to the ship speed [2], which allows for an intuitive use by the watch keepers.

The noise feedback is replaced by feedback of a derived signal α_{eff}, which can be seen as some derived mean angle of attack of the propeller. This effective angle of attack is derived from thrust measurement. Measured thrust is used to calculate the thrust coefficient k_t. Via reverse use of the (known) open water diagram the advance speed v_a is determined (estimated) via the advance ratio $\tilde{v}_a = \tilde{J}nD$. Given this estimated advance speed, and known pitch angle and shaft speed, an estimate can be made of the angle of attack of a specific section via $\alpha \approx \theta - \beta$, with β being the flow angle due to axial inflow and rotational speed of the propeller. From basic airfoil theory it is known that the angle of attack is a dominant player in the occurrence of cavitation. To increase the margin against cavitation inception, the proposed control system aims at keeping the estimated angle of attack at a value with equal margin towards suction side and pressure side inception. This is effectuated by continuous adaptation of the pitch angle θ to the actual inflow angle β.

Since this simplified approach does not capture the wakefield induced inflow variations and the inception radius can change with propeller operating point, the definition of α requires calibration, which was possible by making use of full scale observed cavitation buckets at various pitch angles of the propeller under consideration.

This continuous variation of pitch can result in a mean pitch deviation. Without compensation, this mean pitch deviation would lead to a non-effectuated virtual shaft speed setpoint, and thus a deviation from the desired ship speed. Since this is highly undesirable, a second control loop (controller 2) is added, to ensure that the mean virtual shaft speed will still be effectuated by compensating a possible pitch deviation by means of additional shaft speed

$\Delta n_{set,gov}$. To prevent overactuation of the engine by the governor, the gain in this controller loop (K_i) is chosen such that only the low frequency disturbances in n_{virt} are compensated for. Wave frequent variations regularly have a higher frequency which, due to the ship mass does not result in ship speed variations, so that no immediate compensation is necessary.

Although not part of the control system, during the trials noise sensors were mounted above the propeller shafts to measure the noise levels (or better the acceleration levels) for reasons of afterward analysis and comparison.

4. FULL SCALE RESULTS

To test the performance of the new developed propulsion control system, full scale trials were carried out onboard HNLMS van Galen, in February and March 2008. The operating area was the Caribbean Sea, where the ship was deployed at that time. The system performance using the PCS+ is compared with the system performance when using the existing PCS. Where considered useful or necessary to increase understanding use is made of extra simulation predictions. Such predictions can be used instead of measurements that where not carried out, and can be carried out under exactly the same conditions, so that external disturbances due to for instance waves do not contaminate the output variables.

The experiments that were planned and communicated with the ships crew were described in a test-protocol. This protocol contained various types of tests that were designed with the goals of the project in mind.

It is chosen to discuss the deceleration test here. The acceleration test has already been discussed in [2,5] .

5. THE DECELERATION TEST

To verify the controller performance during deceleration, the manoeuvre from ≈ 14-10 kts is analysed in the same way as the acceleration test. The discussion of the results is split up into separate sections subsequently covering the aspects propeller behaviour, engine behaviour, and manoeuvring behaviour. The deceleration test was successively carried out with the existing and the new PCS+ driving the starboard shaft. The port shaft was continuously driven by the "old" PCS. Results obtained with both the old and the new PCS+ are shown in Fig 7 to Fig 25. The command change from 91 to 67 virtual rpm is given at t=301.5s as shown in Fig 7. The rudder was controlled by the autopilot, which as shown in Fig 8, gave less than 5 degrees rudder during the manoeuvre.

Propeller Behaviour

First, the behaviour of the old PCS will be discussed, followed by a discussion of the new PCS+.

old PCS: As shown in Fig 9, Fig 10 and Fig 11, both shaft speed and pitch follow the combinator curve, which dictates that the deceleration is effectuated by sole reduction of shaft speed.

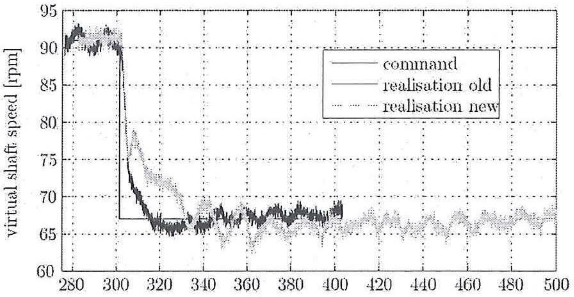

Fig 7: Command

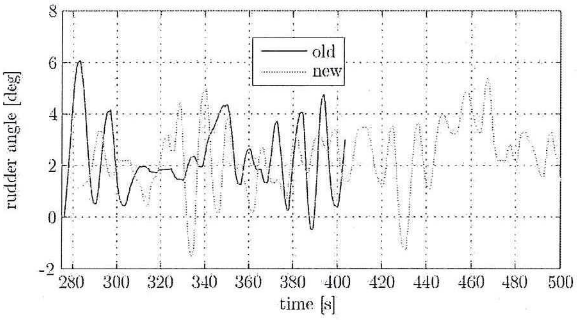

Fig 8: Rudder

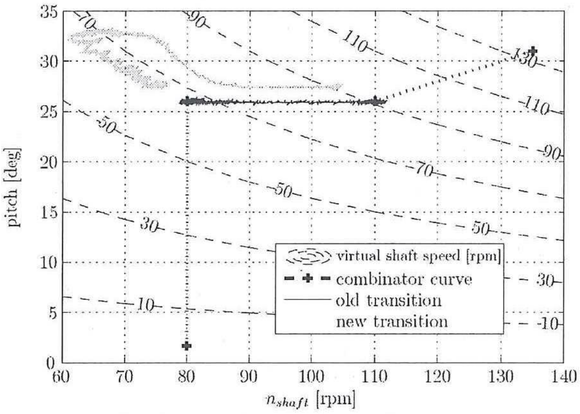

Fig 9: Transient in the n − θ plane

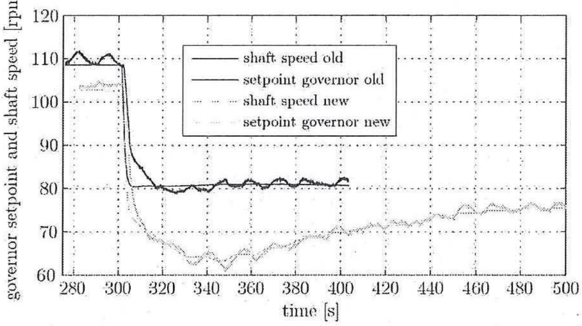

Fig 10: Governor setpoint and shaft speed

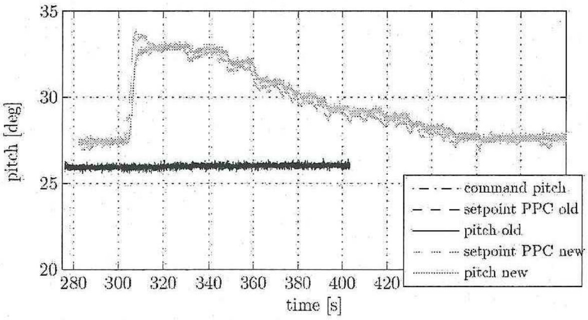

Fig 11: Propeller pitch

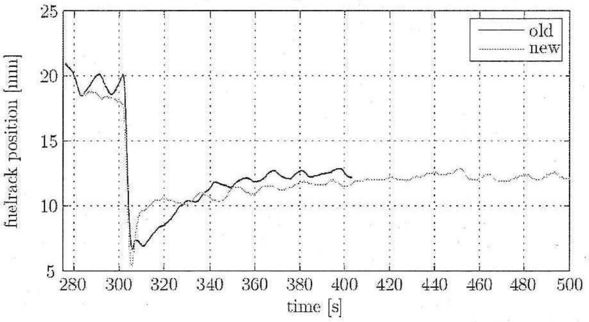

Fig 12: Fuelrack position

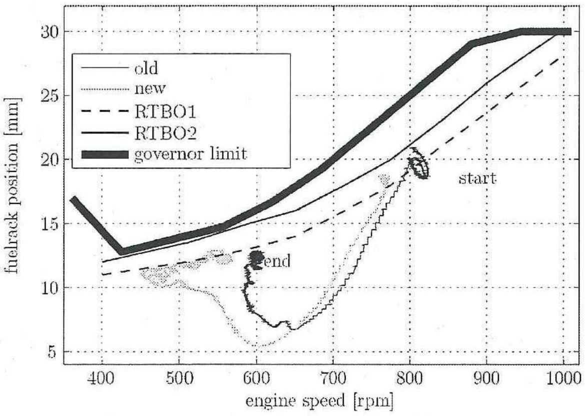

Fig 13: Transient in the engine diagram

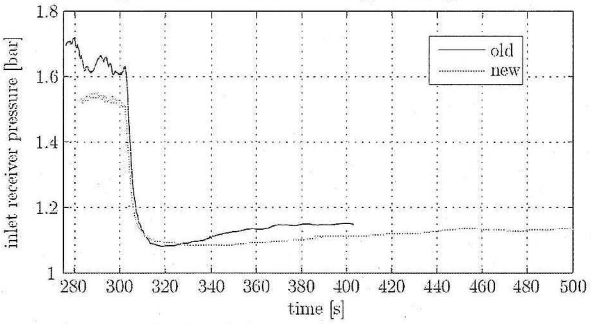

Fig 14: Inlet receiver pressure

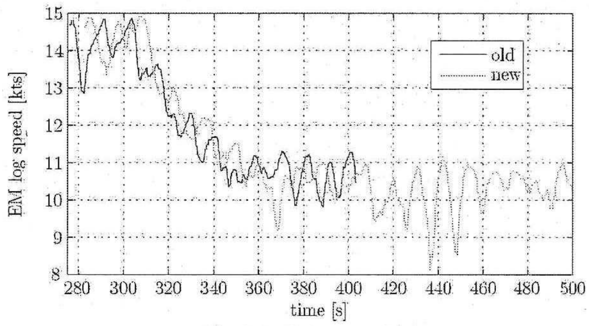

Fig 15: Ship speed

The steep drop in shaft speed immediately results in a drop of effective angle of attack down to ≈ 0.5 degrees, as shown in Fig 18. As a result the thrust drops below 0 kN (Fig 17) for approximately 15s, which means that both propellers are acting as brakes. The angle of attack is restored at the rate of the ship deceleration, which is considerably slow due to the ship mass. Only around t=360s, the angle of attack has found its approximate steady value again. In terms of the bucket presented in Fig 20, this means that the restoring rightward movement of the operating point takes a long time, during which the propeller is very vulnerable to pressure side cavitation inception. The resulting cavitation behaviour during the manoeuvre is presented in Fig 24, showing pictures that were taken with the high speed video camera. Close inspection shows that even the last picture at t=319s shows small traces of pressure side cavitation. The signals from the acceleration sensors are shown in Fig 21. The two small humps around t=280s and t=295s are attributed to wave induced cavitation. Note that the highest acceleration amplitude occurs around t=310s, which aligns with the time that the visual cavitation is most pronounced in Fig 24.

new PCS+: As shown in Fig 9 and Fig 11, the steady state propeller pitch before and after the manoeuvre lies around 27 degrees. During the manoeuvre the PCS+ orders a pitch increase up to 33 degrees, after which pitch gradually comes back to 27 degrees. This pitch increase might seem strange, but can be explained by the attempt of the PCS+ to maintain the desired angle of attack after a sudden drop in shaft speed, while ship speed initially stays approximately constant due to the inertia of the ship. As shown in Fig 18, the drop in angle of attack is corrected by the pitch increase of ≈ 6 degrees. This correction is however not fast enough to prevent the angle of attack from deviating from the middle of the cavitation free area, as shown in Fig 20. Ideally the operating point would only shift vertically, which would continuously guarantee maximum margin against inception.
Although the propeller operating point stays inside the schematic bucket, it is noted that this is no guarantee for cavitation free operation.

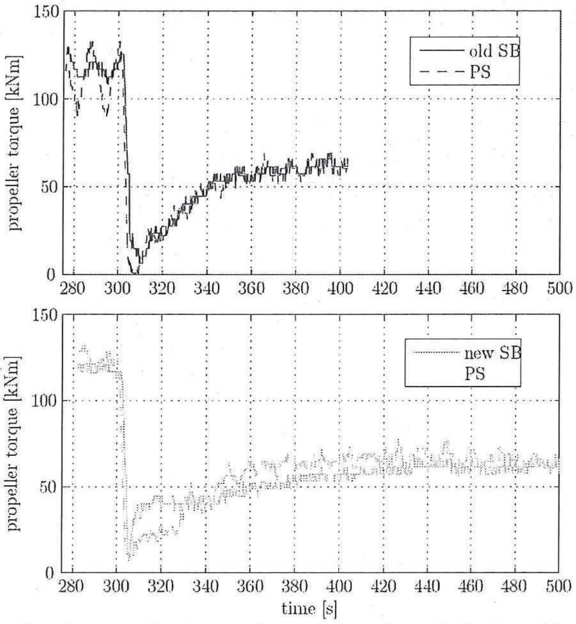

Fig 16: Propeller torque (port and starboard) for the old PCS and the new PCS+

Due to for instance the α-estimation errors and local wakefield disturbances, both the location of the operating point and the shape of the bucket are affected by uncertainty. Furthermore the bucket that is shown here is only indicative. Nevertheless, Fig 20, combined with Fig 18 and Fig 19 does show that the operating point is quickly restored to the desired $\alpha_{eff,set}$, which despite all uncertainties in both operating point and bucket, is expected to have maximum margin against cavitation inception. The improved cavitation behaviour of the PCS+ system is demonstrated in Fig 22 and Fig 25. Although cavitation is present, its time wise extent has decreased significantly when compared to the old PCS. The interval at which cavitation is visible has also decreased significantly. The acceleration sensor- signals above the port and starboard propeller are shown in Fig 22. The hump around t=290s is attributed to wave induced cavitation. The signal level of especially the starboard sensor has decreased when compared to Fig 21. The interval of increased acceleration has also decreased which agrees with the visual observations of the starboard propeller. The portside acceleration signal indicates slightly higher acceleration levels, and if inspected closely, reveals a longer "tail" of slightly increased acceleration levels up to t=330s. This agrees with expectations because the portside shaft was continuously controlled by the old PCS. Based on the combined photographs and the acceleration signals, it is very likely that the PCS+ has significantly increased the cavitation free time of the starboard propeller during the manoeuvre. Further improvements can be made by faster pitch actuation, or by slower shaft deceleration. More advanced controller techniques might help to take into account the (nonlinear) dynamics of the propulsion plant, including the CPP hydraulics and its limitations.

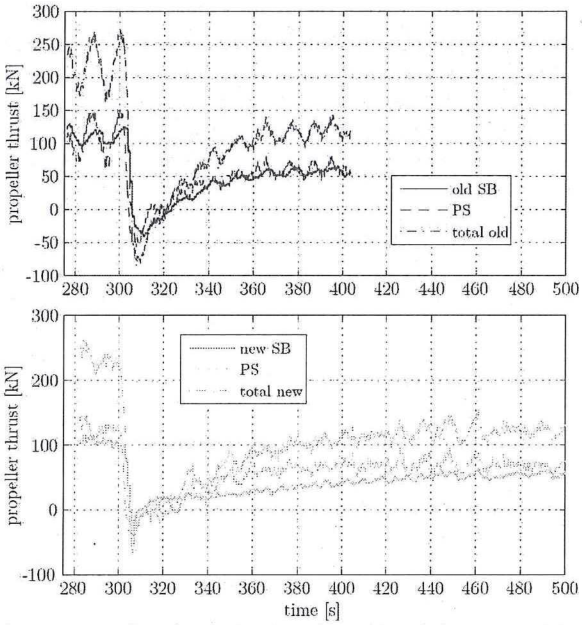

Fig 17: Propeller thrust for the old PCS and the new PCS+

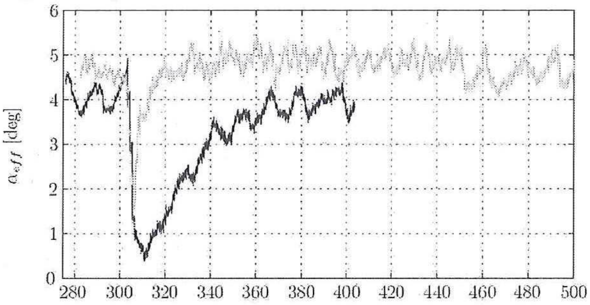

Fig 18: Estimated effective angle of attack

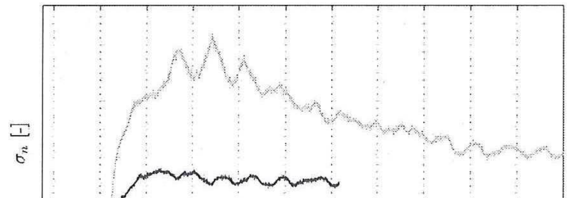

Fig 19: Cavitation number

Engine Behaviour

The behaviour in the engine diagram (Fig 13) is quite similar for both control systems. The sudden drop in governor setpoint $n_{set,gov}$ results in a reduction of fuelrack by the engine governor. This drop in fuelrack results in a drop of engine torque so that the engine speed n_{eng} starts to reduce. As shown in Fig 12, in case of the old PCS, the fuelrack starts to increase again with the same rate as the ship speed decrease, which is shown in Fig 15. Around t=380s the ship speed and thus the propeller torque and thrust (Fig 16 and Fig 17) are approximately constant again. After the initial drop of fuelrack, the PCS+ increases the propeller pitch for reasons of cavitation prevention as shown in Fig 11. However, the shaft speed is further reduced to ensure that the (ship speed related) virtual setpoint (the command) is still effectuated regardless of the pitch increase. As shown in Fig 7, the command is effectuated around t=335s, from where on the pitch-shaft speed balance is slowly shifted towards higher shaft speed again.

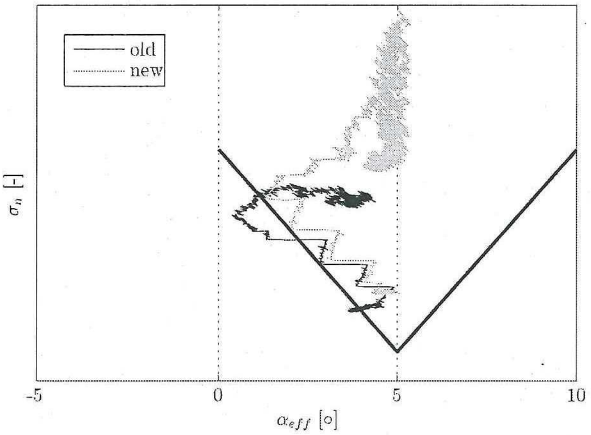

Fig 20: Transient in the α_{eff} bucket

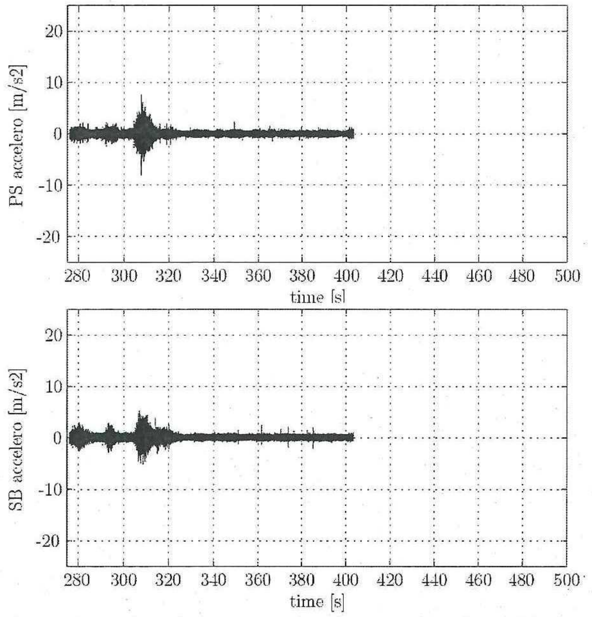

Fig 21: Acceleration sensor signals. Deceleration with the old PCS

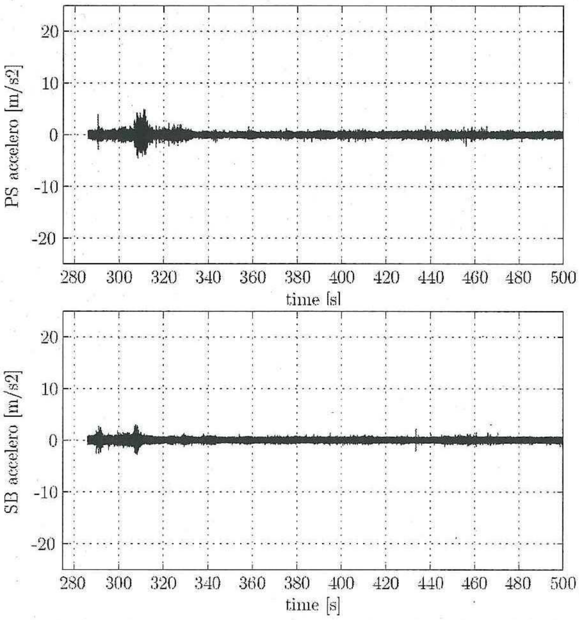

Fig 22: Acceleration sensor signals. Deceleration with the new PCS+

Manoeuvring Behaviour

From the thrust figure (Fig 17) and the ship speed figure (Fig 15) it can be concluded that the resistance conditions for both manoeuvres were approximately equal. Although a non oscillating rudder angle would have been better, the small oscillations shown in Fig 8, are not expected to have a great effect on the manoeuvre. When closely inspecting the thrust of the new PCS in Fig 17, it is clear that after the initial drop in thrust, the pitch increase increases the thrust towards low positive values. This is to be expected since the pitch is used to ensure a positive inflow angle. This should initially lead to a lower ship deceleration rate, but due to wave disturbances this cannot be confirmed by the ship speed signal of Fig 15. Due to the reduced shaft speed, after t ≈ 330s the thrust is lower than the thrust that was delivered by the old PCS. The latter helps to decelerate the ship speed faster, but again this is not confirmed by the ship speed signal. To further inspect the effect of the two control systems on the deceleration behaviour, few extra simulation results are shown in Fig 23. The absence of disturbances, together with the possibility to simulate a system with both port as starboard side controlled by the PCS+, enables a fair comparison. Due to the pitch increase, the initial deceleration rate is slightly lower compared to the old PCS. The new PCS+ shows a small undershoot of ≈ 0.3 kts, after which the ship speed converges to the static value. If desired, the undershoot can of course be tailored by further tuning of coefficients of the PCS+.

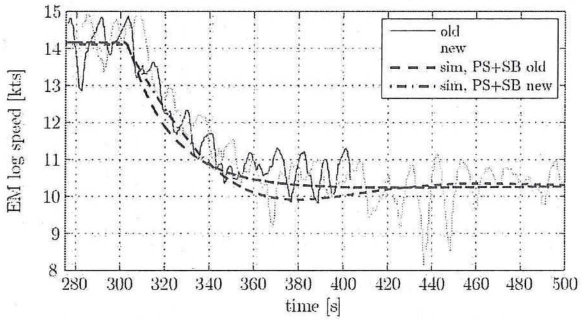

Fig 23: Ship speed measurement and simulation

6. CONCLUSIONS

A simulation model of a ship propulsion plant has been developed earlier [2]. From the validation phase that was not presented in this paper it was concluded that the model is adequate for development and testing of a new propulsion control system. This PCS+, aiming at increased cavitation free time in operational conditions was developed, and tested on full scale.

The limited full scale results that have been presented here show a significant increase in cavitation free time during deceleration. Further gains are expected if a faster responding pitch actuating system is used, and if the shaft deceleration speed is decreased. With the help of extra predictive simulations, the manoeuvring capability was shown to be comparable.

On the whole it is concluded that model based ship propulsion controller development is very well possible, and can lead to improved system behaviour. As shown, it is even possible to increase propeller cavitation free-time by application of a specialised PCS.

In the long run, the model based development of specialised propulsion controllers for specific missions/ goals is expected to lead to a more effective use of propulsion installations.

7. ACKNOWLEDGEMENTS

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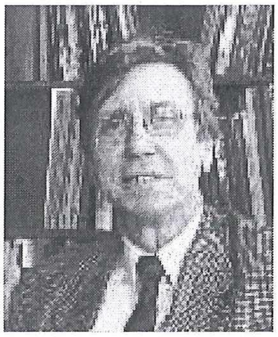
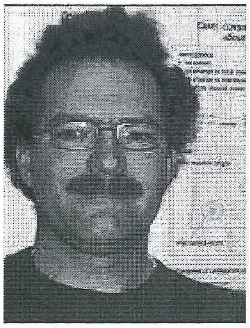
BIOGRAPHY AND CONTACT INFORMATION

Arthur Vrijdag graduated from the Royal Netherlands Naval College in 2004 and in the same year he obtained his masters degree in ship hydromechanics at Delft University of Technology. He has recently finished his PhD thesis titled 'Control of Propeller Cavitation in Operational Conditions^{2}.' The associated research project was sponsored by the Netherlands Defence Academy and Delft University of Technology and carried out in close cooperation with the Royal Netherlands Navy, Defence Research and Development Canada, the Royal Australian Navy, Wärtsilä Propulsion Netherlands, IMTECH and MARIN. Arthur currently works at Rolls-Royce Naval, Bristol, UK and can be contacted via arthur.vrijdag@rolls-royce.com



Douwe Stapersma, after graduating in 1973 at Delft University of Technology in the field of gas turbines, joined NEVESBU - a design bureau for naval ships - and was involved in the design and engineering of the machinery installation of the Standard frigate. After that he co-ordinated the integration of the automatic propulsion

control system for a class of export corvettes. From 1980 onward he was responsible for the design and engineering of the machinery installation of the Walrus class submarines and in particular the machinery automation. After that he was in charge of the design of the Moray class submarines in a joint project organisation with RDM. Nowadays he is professor of Marine Engineering at the Netherlands Defence Academy and of Marine Diesel Engines at Delft University of Technology, and can be reached via d.stapersma@tudelft.nl



Hugo T. Grimmelius obtained a bachelor's degree in Marine Engineering in 1986, and sailed on merchant ships as engineer for a short period. In 1992, he graduated from Delft University of Technology in Marine Engineering, on a thesis on condition monitoring and obtained his PhD on the same subject. In 1996, he became assistant professor Marine Engineering at the Delft University. He published over 50 papers on various Marine Engineering topics.
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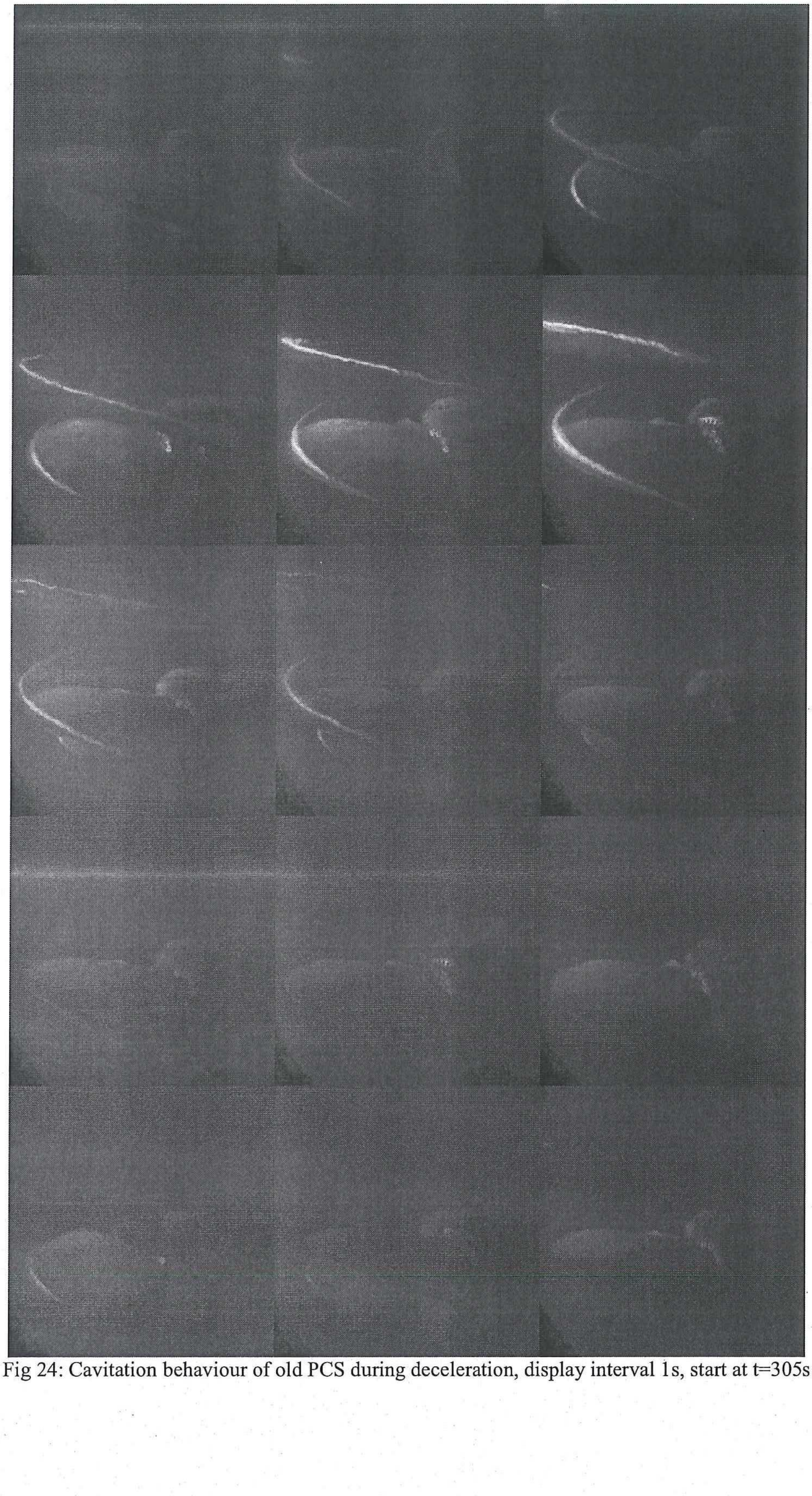

Fig 24: Cavitation behaviour of old PCS during deceleration, display interval 1s, start at t=305s

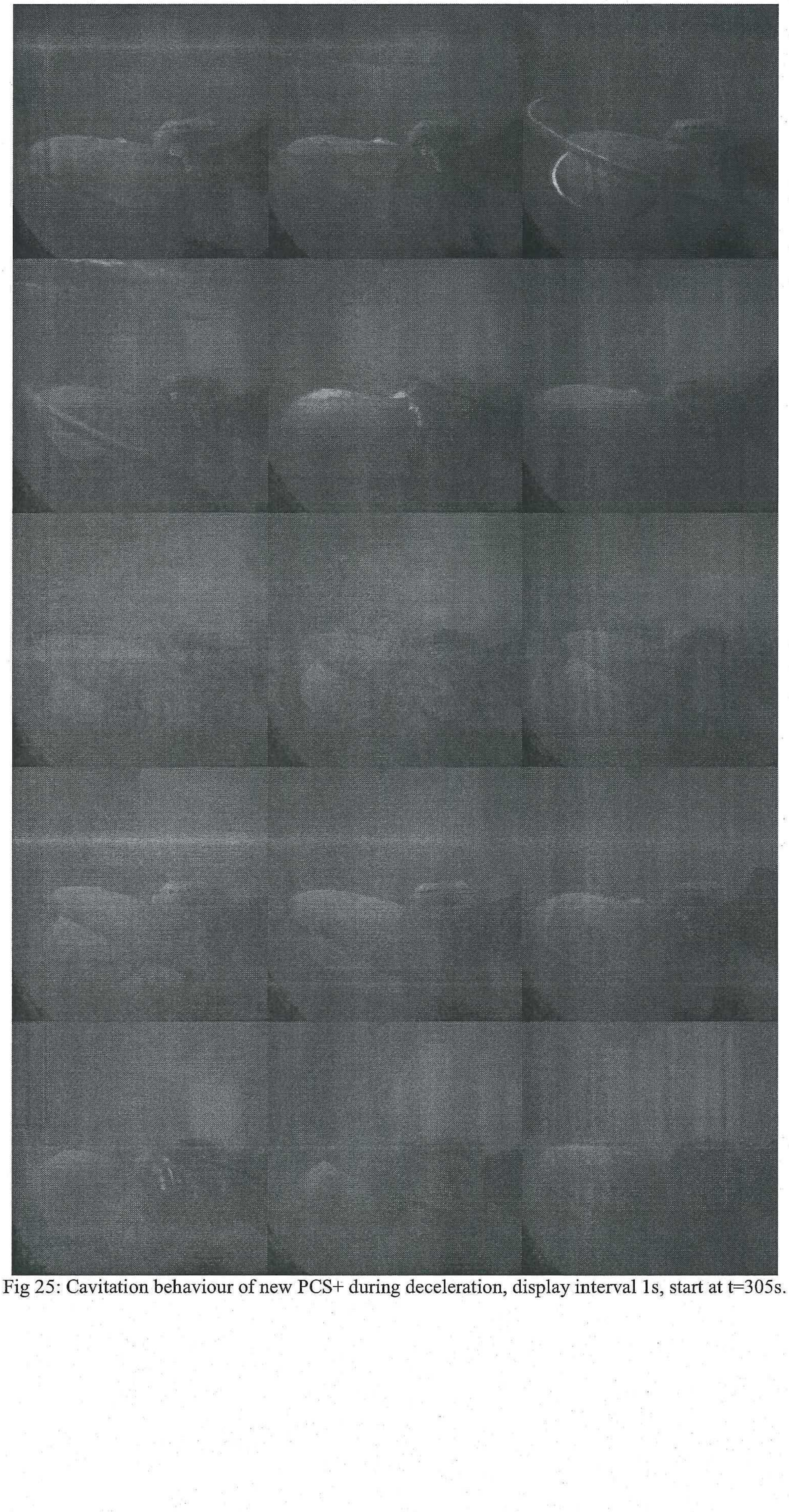

Fig 25: Cavitation behaviour of new PCS+ during deceleration, display interval 1s, start at t=305s.