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Hydrodynamic Trends in Optimizing Propulsion

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ABSTRACT

This article presents a number of state-of-the-art optimization approaches and corresponding model test results.

The parametric hull form definitions, together with modern optimization tools, allow for the numerical evaluation of a large number of variants in the shortest amount of time, aiming at further reducing the resistance of already good hull forms. Benefits and drawbacks of these modern tools are discussed.

There is an increasing demand for optimizing hull forms, not only for the design condition, but for "off-design" conditions as well. The expected gains derived from numerical calculations and the gains predicted on the basis of later model tests of the best performing variant are presented.

Further potential for reducing the power demand can be gained by selecting the most suitable propeller, by optimizing the appendages, and by application of energy saving devices. Energy saving devices target improvements in propulsion efficiency by recovering losses from the propeller slipstream or improvements in the water flow to the propeller, allowing a propeller design with higher efficiency. The latest model test results with these devices, including full-scale results of the novel Mewis Duct®, are presented.

Especially smaller ships, such as coastal vessels, are equipped with variable pitch propeller plants. The pros and cons of such installations are discussed with special attention again to the "off-design" condition.

Furthermore, we present examples of hull form modifications, a possible refit of some propulsion improving devices, and alternative propeller designs to ships in service.

Keywords

Hull Form; Optimization; Off-Design; Efficiency; Propulsion; Propulsion Improving Device; Mewis Duct®

1 Introduction

High fuel oil costs are the reason shipyards and ship owners are now focusing more than ever on the reduction of propulsion power. For new building projects, the most effective measure to minimize the vessels resistance is to choose suitable main dimensions in the first place, after which the optimization of the form should be considered. Both the main dimensions and the hull form can hardly be modified for vessels already in service. But there are still a lot of measures where the hydrodynamic performance of existing vessels can be improved, too.

2 Parametric Hull Form Optimization

At the end of the year 2007, HSVA extended its hull form design capabilities by purchasing the *FRIENDSHIP Framework* CAE environment.

Its main feature is the sophisticated hull form variation via fully or partially parametric modeling of the hull surface and the embedded optimization strategies. This allows for the evaluation of a multitude (from a few hundred up to several thousands) of automatically generated hull forms by potential flow calculations during the optimization process. HSVA's free surface potential flow code ν-SHALLO is directly linked to the framework.

It must be clearly stated that this new tool does not replace the experienced hull form designer, nor does it speed up the whole optimization process. In fact, it is more time consuming and thus more costly. Further, it requires accurate definition of the design constraints to be taken into account. The benefit from this process is the possibility of further improving already good hull forms to a remarkable degree, often beyond a level usually achieved by conventional optimization.

3 Optimizing Hull Forms for "Off-Design" Conditions

Based on an existing hull form, which has been thoroughly optimized for design draught and design speed already, HSVA has been contracted in a number of projects during the last year, from ship owner side or from charter party side, to optimize their existing hull form for "off-design" conditions. "Off-design" conditions in this context means not only the design speed, but a number of additional (lower) speeds, and not only the design draught, but a number of different draughts covering a wider range from scantling draught down to a partial loaded draught of approximately 70% of the design draught.

Typically, such an investigation starts with potential flow calculations of the initial hull form for all draughts and speeds to be investigated, and with a comparison of the

corresponding wave photos from the model tests. Exemplary, Figure 1 shows the pressure distribution and the excellent wave profile (calculated and during model test) of the initial hull on design draught and at design speed.

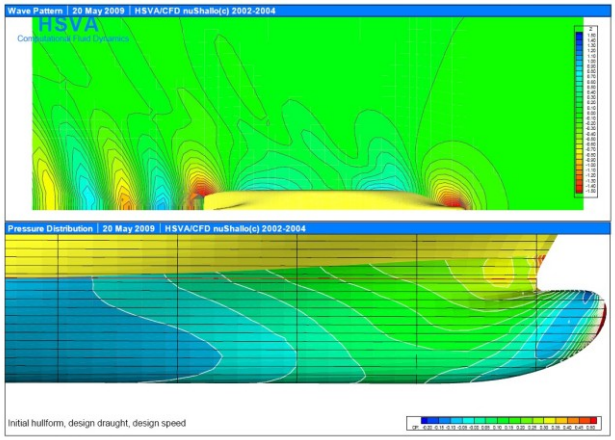

Figure 1 – CFD result of the initial hull form for design draught and design speed

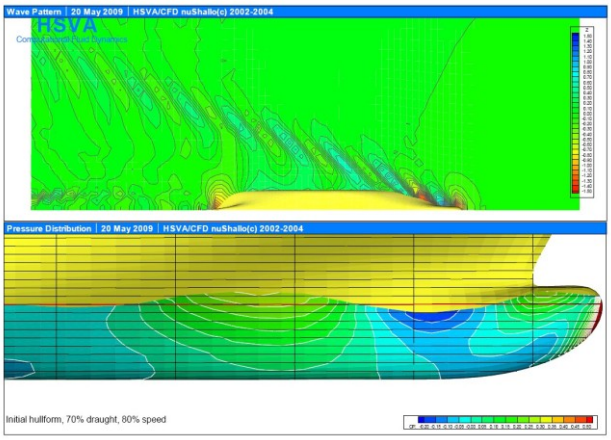

Figure 2 – CFD result of the initial hull form for partial draught and 80% of design speed

For the same hull form, Figure 2 illustrates the pressure distribution and the wave profile, which have been calculated for a partial loaded draught of about 70% of the design draught and a speed corresponding to about 80% of the design speed.

It is noted that with reduced speed and reduced draught, the originally excellent wave profile gets entirely lost and remarkable wave crests and wave troughs occur along the ships length. This corresponds to a dramatic increase of power demand compared to the design draught and design speed condition. The required power at the 80% speed on the 70% draught has been about 15% higher compared to the design draught at the same speed.

To improve the situation, the "worst-case" condition has been especially analyzed by HSVA hull form designers. Step by step, the fore body shape and the design of the bulbous have been improved, supported by potential flow calculations and ending up with two most promising design variants.

The two most promising candidates have been manufactured and model tested again. Although potential flow method cannot predict breaking waves or spray, the expected gains predicted by the numerical methods have been surprisingly accurate. Figure 3 shows the expected gains derived from numerical calculations (left-hand side) and the gains predicted on basis of later model tests of the best performing variant.

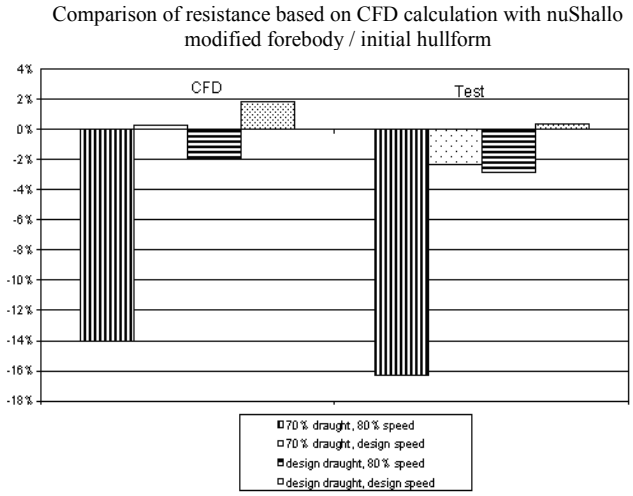

Figure 3 – CFD predicted gains verified by model tests

4 Optimizing Twin-Screw Appendages

Navy vessels of various kinds (Patrol Boats, Corvettes, Frigates, Destroyers, etc.) are typically designed with open shaft arrangements supported by a set of V- and/or I-type shaft bracket arms. The design of shaft bracket arms involves structure, vibration and hydrodynamic analysis and design. The hydrodynamic design goals are to reduce the resistance of the vessel, to minimize the strut shadow in way of the wake field, and to avoid separation and cavitation on the struts. This aims in finding the best compromise between hydrodynamic, structure (strength, vibration), and fabrication (cost) requirements.

After having selected a suitable strut profile a detailed investigation of a proposed strut configuration is performed either by model tests or by numerical calculations.

Model tests have the advantage that special effects, e.g., a rotating shaft, can be considered, which influences the local flow around the shaft and thus the inflow to the strut profile. However, scale effects may have a remarkable influence on boundary layer and thus on the measured results. Numerical methods, in principal, allow for calculating the flow condition both for model scale and for full scale. Furthermore, the calculation delivers the whole flow field around the hull and gives much better insight into the flow behavior in total.

The numerical analysis of the proposed arrangement and design of the bracket arms is typically performed in several steps. In a first step, a RANS calculation of the ship condition "bare hull + shafts" is performed, using the commercial viscous flow code COMET (solving the Reynolds Averaged Navier Stokes equation[1]). The aim of this investigation is to determine the cross flow of the undisturbed flow field along the strut axis.

Based on the results of the RANS calculation, the sections over the length of each strut arm are aligned to the cross flow, which results in an individually twisted shaft bracket arm geometry.

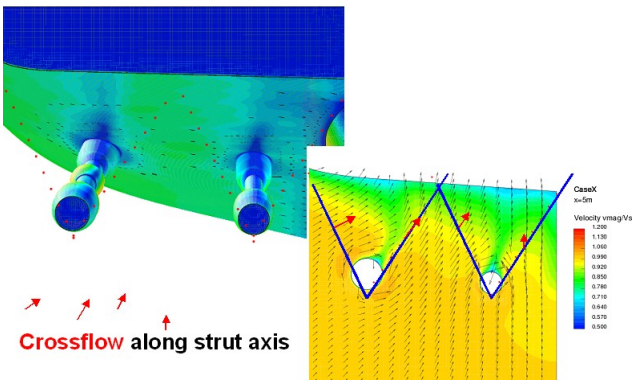

Figure 4 - Determination of the undisturbed cross flow along the strut axis by RANS

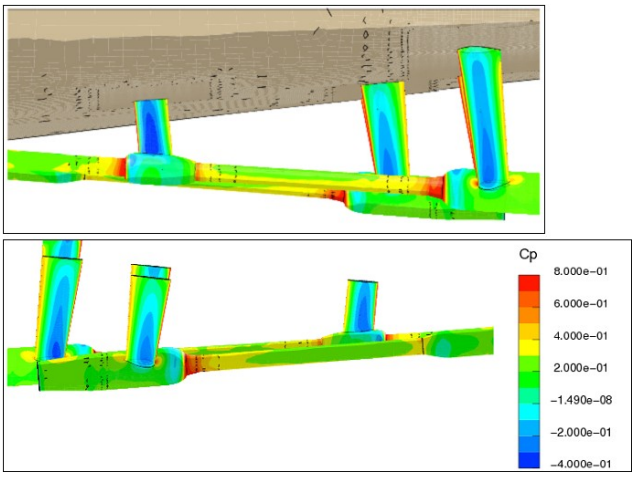

Figure 5 - Surface pressure of the struts by RANS

In a second step, a RANS calculation of the ship condition "bare hull + shafts + brackets" is performed. This investigation aims at judging the surface pressure of the struts on one hand, and at judging the wake field and the quality of the inflow to the propellers.

For the alignment of shaft line appendages, we propose using a simple propeller model, realized via body forces within a RANS simulation. This model is considered accurate enough to include the upstream disturbances due to the working propeller.

The RANS calculations can be performed in parallel to the hull form development well in advance to the model tests. The results can already be taken into account during hull form optimization and can help speed up the whole design process.

5 State of the Art Propulsion Improving Devices (PID)

Propulsion Improving Devices are stationary flow-directing devices positioned near the propeller. These can be positioned either ahead of the propeller fixed to the ship's structure, or behind, fixed either to the rudder or the propeller itself.

Ideally, a model test campaign on PID should be accompanied by a RANS analysis for both model and full scale. The comparison of calculations and model tests can confirm the RANS predictions for the model scale. This then gives sufficient support to let the calculated scale effects enter the full scale prediction, the latter still generally based on the measured model scale propulsion performance.

Well known devices for reducing the wake losses are the WED (Wake Equalising Duct), see Schneekluth (1986), and the SILD (Sumitomo Integrated Lammeren Duct) as detailed in Sasaki and Aono (1997). Devices for reducing the rotational losses include the SVA fin system (Mewis & Peters 1986), the Daewoo Pre Swirl Fin system (Lee et al 1992), and the Hyundai Thrust Fin system, which is fitted to the rudder, see Hyundai (2005). A well-known solution to reduce the losses in the propeller hub vortex is the PBCF (Propeller Boss Cap Fins) (Ouchi et al 1990). The Kappel propeller utilizes a special tip fin integrated into the propeller blades to reduce the tip vortex losses, see Andersen et al (1992).

Today, primarily the large Korean shipyards including *Daewoo Shipbuilding & Marine Engineering Co., Ltd (DSME)*, *Hyundai Heavy Industries Co., Ltd (HHI)* and *Samsung Heavy Industries Co., Ltd (SHI)* and the large Japanese shipyards including *Sumitomo Heavy Industries* and *Kawasaki Shipbuilding Corporation* are investigating the means for recovering the losses in the propeller slipstream. In the last years, the following concepts have been tested at HSVA.

6 The Pre-Swirl Stator of DSME

DSME has been developing the pre-swirl stator concept for more than ten years now. The *DSME* pre-swirl stator concept consists of three to four stator blades mounted on the boss end of the hull in front of the propeller.

Figure 6 – *DSME* pre-swirl stator

The stator does not on its own save energy or create forward thrust; in fact, it adds to the resistance. Despite the added resistance, the stator blades induce a favorable asymmetric inflow to the propeller and thus improve the propulsion efficiency. In the case of a four-blade stator as is typical for Container Vessels, three blades are arranged

on the port side and one blade is arranged on the starboard side. The main role of the three blades on the port side is to reduce the slip loss of the propeller encountered when the blades pass upwards on the port side. The single blade on the starboard side is adopted to increase the wake fraction for higher hull efficiency while at the same time minimizing any unfavorable effect on propeller cavitation.

7 The Thrust Fin of HHI

HHI has been developing the thrust-fin concept for several years. Both x-shaped thrust fin configurations with four blades and thrust fins consisting of only two blades have been investigated. The thrust fins are designed such that the blades generate thrust in the rotating propeller slipstream.

The design of the twisted blades requires highly sophisticated numerical simulations and vast experience. During model tests, the generated thrust can be recognized in a reduced thrust deduction fraction. This results in higher hull efficiency and thus better propulsive efficiency.

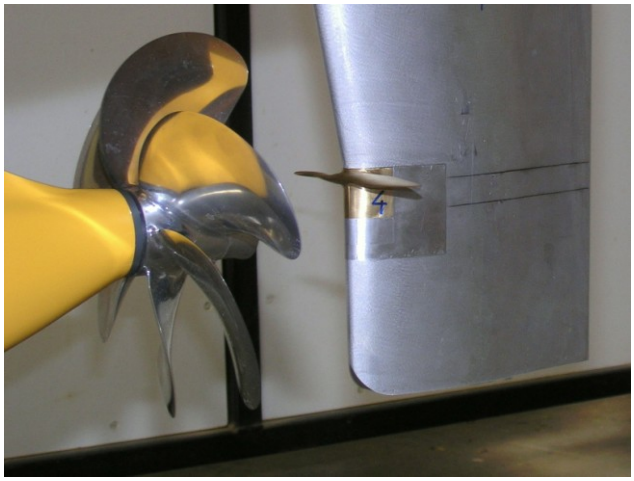

Figure 7 – HHI thrust-fin

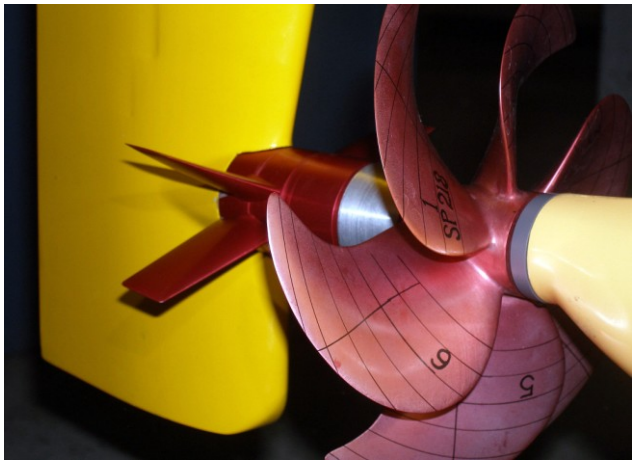

Figure 8 – SHI post stator

8 The Post Stator of SHI

SHI is developing a Post Stator concept. X-shaped fins located aft of the propeller are combined with an integrated propeller cap and rudder bulb. This concept aims at reducing the losses due to propeller hub vortex and at recovering energy from the rotational losses in the propeller slipstream similar to the thrust fin concept.

Compared to the pre-swirl stator, the post stator is relatively moderate in size (less than 80% of the propeller diameter) and does not have any effect on the propeller cavitation.

9 Safer Fins of SHI

Vortex generator fins (VG-fins) are sometimes applied to container ships aiming at improving the inflow to the propeller, and thus reducing pressure pulses and the vibration level in the aft superstructure above the propeller. Properly arranged, these fins typically reduce pressure pulses by about 50%. At container ship, the application of VG fins “costs” up to 2% increase in power demand.

SHI proposes application of similar Safer Fins at full block vessels to reduce the bilge vortex and thus reduce flow separations in the aft body. This results in lower resistance and thus better propulsive efficiency.

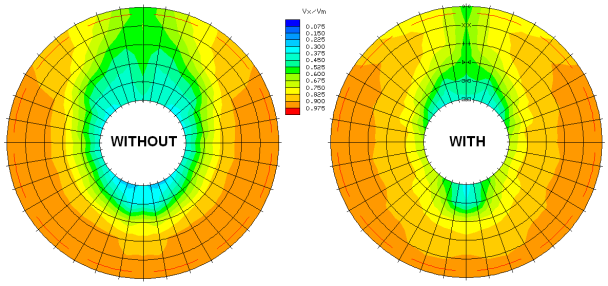

Figure 9 – Wakefield with and without VG-fins

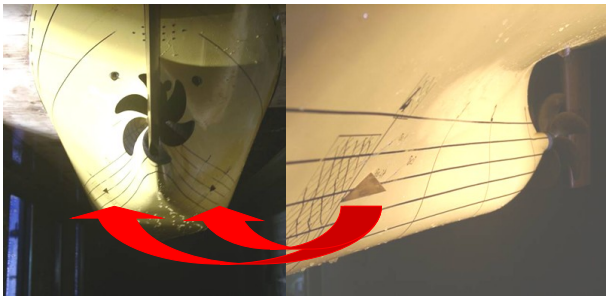

Figure 10 – Arrangement of VG-fins at a Container Vessel

Figure 11 – Sumitomo Integrated Lammeren Duct (SILD)

10 The Sumitomo Integrated Lammeren Duct

Sumitomo has been successfully applying a duct forward of the propeller to their new projects for several years now. The duct aims at improving the quality of the inflow to the propeller and at the same time reduces separations in the aft body of full block vessels.

Today, this concept is combined with additional fins ahead of the SILD. Depending on the magnitude of the separations, remarkable gains in propulsion power have been found during model testing for a number of Sumitomo projects.

11 Typical Gains by PIDs

Between 2005 and 2011, HSVA tested the following PIDs on different projects:

Table 1 – Typical Gains of PIDs

Year	Ship Type	Device	Gain in Power	
			Design Draught	Ballast Draught
2010	ConRo Vessel	*DSME* Pre-Swirl Stator	3.7%	Not investigated
2009	Kamsarmax Bulk Carrier	*DSME* Pre-Swirl Stator	6.3%	1.4%
2009	7,450 TEU	*DSME* Pre-Swirl Stator	3.6%	Not investigated
2008	16,000 TEU	*DSME* Pre-Swirl Stator	3.8%	Not investigated
2008	13,050 TEU	*DSME* Pre-Swirl Stator	4.5%	3.2%
2008	14,000 TEU	*DSME* Pre-Swirl Stator	4.5%	4.7%
2008	4,400 TEU	*DSME* Pre-Swirl Stator	1.0%	Not investigated
2008	7,090 TEU	*DSME* Pre-Swirl Stator	3.3%	0.4%
2007	VLCC	*DSME* Pre-Swirl Stator	5.6%	5.5%
2007	6,300 TEU	*DSME* Pre-Swirl Stator	3.3%	Not investigated
2007	8,400 TEU	*DSME* Pre-Swirl Stator	3.5%	1.1%
2005	VLCC	*DSME* Pre-Swirl Stator	4.8%	Not investigated
2011	158k DWT Tanker	*SHI* Safer Fins	3.2%	Not investigated
2007	8,000 TEU	*SHI* Post Stator	3.9% *	Not investigated
2005	8,000 TEU	HHI Thrust Fin	4.9%	Not investigated
2007	Aframax Tanker	Sumitomo SILD	8.7%	Not investigated
2003	Aframax Tanker	Sumitomo SILD	6.0%	Not investigated

* measured in HSVA's large cavitation tunnel HYKAT at higher Reynolds Numbers

12 The Pre-Swirl Mewis Duct® (PSD)

A novel approach for a PID is the Pre-Swirl Duct (PSD), which is marketed under the trademark Mewis Duct®. This power-saving device consists of a wake equalizing duct combined with an integrated pre-swirl fin system positioned ahead of the propeller. By pre-correcting the flow into the propeller, the device essentially reduces the rotational losses in the resulting propeller slipstream and increases the flow velocity towards the inner radii of the propeller.

The PSD is suited to vessels with high block coefficient and speeds lower than 20 knots. This encompasses tankers and bulk carriers of every size, together with multi-purpose carriers and feeder type container vessels. The expected power reduction is in the range of 3% to 9%, depending on the propeller loading, and is virtually independent of ship draught and speed.

Mewis Ship Hydrodynamics (MSH), Dresden, Germany, has developed the PSD in co-operation with *Becker Marine Systems GmbH & Co. KG (BMS)*, Hamburg, Germany.

On behalf of *BMS*, model tests were carried out at *HSVA* for an open hatch bulker, owned by a Scandinavian Shipping Group, to be refitted with the *BMS* Mewis Duct®. After optimization of the pitch settings of the fins, self-propulsion tests have been performed with and without the Mewis Duct® at the design draught and a light loaded draught with trim down by the stern. At design, draught the power gain by the Mewis Duct® was found to be about 6.0% at 16 knots, corresponding to a speed in crease of 0.27 knots. At the light loaded draught, the power gain was 5.4% at 16 knots, corresponding to a speed increase of 0.24 knots.

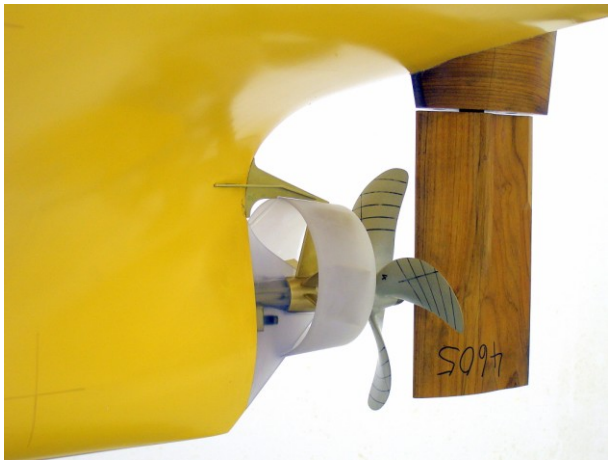

Figure 12 – Bulk carrier model with *BMS* Mewis Duct®

To date, the *BMS* Mewis Duct® has been tested for nine different projects at HSVA. Notable is the very high power reduction by the PSD of the ship with a controllable pitch propeller fitted (high hub to propeller diameter ratio), as well as the virtual independence of the ship's draught to the performance of the PID. For all three projects, the rpm reduction achieved by the PSD at constant power is less than 1%, which makes this PSD especially suitable for refit projects.

In the meantime, the predicted performance has been successfully proven by sea-trials for two projects performed with and without the Mewis Duct®.

Several further projects that are to be equipped with the *BMS* Mewis Duct® are due for model testing at HSVA during 2011.

Table 2 – Model test results with BMS Mewis Duct®

Year	Ship Type	Gain in Power	
		Design Draught	Ballast Draught
2011	151k DWT Tanker	4.7%	Not investigated
2010	75k DWT Tanker	3.9%	7.2%
2010	163k DWT Tanker	4.7%	7.1%
2010	158k DWT Tanker	3.8%	Not investigated
2010	57k DWT Bulker	5.4%	7.8%
2010	20,000 DWT MPC	1.5%	Not investigated
2009	45k DWT Bulker	6.0%	5.4% *
2008	12,000 DWT MPC	7.7%	7.4%
2008	Aframax Bulk Carrier	6.9%	Not investigated

* light loaded draught condition

13 Propulsion Improvements by Alternative Propeller Designs

As a promising device regarding reduction of fuel consumption, the *Mecklenburger Metallguss GmbH (MMG)*, Waren, Germany, together with the well-known European Shipping Group and *HSVA* have investigated possibilities to apply a three-bladed propeller to increase the propulsive efficiency of a very large crude oil carrier (VLCC).

This ship had been in service with quite a conventional four-bladed propeller already for some years without any complaint.

Figure 13 – VLCC ship model tested with a 3-bladed propeller designed by *MMG*

Within the investigation, *MMG* has calculated the performance of three- and four-bladed propeller alternatives with varying diameters for the ship. For all variants the radial pitch and camber distribution was re-evaluated to achieve best wake adaptation in each case. The latter is of extreme importance for full block ships as considered here. The final calculations promised a significant efficiency improvement, based on the unconventional choice of the propeller blade number.

Since both the ship hull and the conventional propeller were available at *HSVA* in model scale from the development phase of the ship, comparative tests could now be carried out with reasonable expense. The encouraging model test results showed that the three-bladed propeller gains up to 3.3% in power requirement.

It had to be expected that this efficiency increase would be accompanied by an extensive amount of cavitation, resulting in large propeller induced hull pressure pulses. To investigate this matter, the cavitation behavior of both propellers was subsequently tests in HSVA's large Hydrodynamic and Cavitation Tunnel HYKAT.

The sheet cavitation of the three-bladed propeller was somewhat more extended indeed, but its character was very similar to the conventional propeller. The cavitation was still smooth and non-erosive. The hull pressure pulses were higher as well, but did not exceed the level acceptable for a VLCC.

Of course, a three-bladed propeller is not an alternative for a highly loaded propeller of a fast container vessel. But for tankers or bulkers, the new propulsion concept has shown very encouraging results.

14 Operating CP Propellers in "Off-Design" Conditions

Small- and medium-sized merchant ships such as container ships, multi-purpose vessels, tankers, RoRo and RoPax ships and passenger ferries operating in coastal areas are often equipped with controllable pitch (CP) propeller plants. The CP propeller plant offers a flexible operation of the ship, excellent stopping abilities without the need of reversing the main engine and, in combination with a shaft generator, to generate the electricity for the sea load by the main engine. To supply electric power, the CP propeller plant is operated in the constant rpm mode. As an alternative, a thyristor-controlled generator could be used, but this is quite an expensive solution. For the design condition of a ship, the efficiency of the CP propeller is almost the same as with a fixed pitch propeller. However, this may change when it comes to "off-design" conditions.

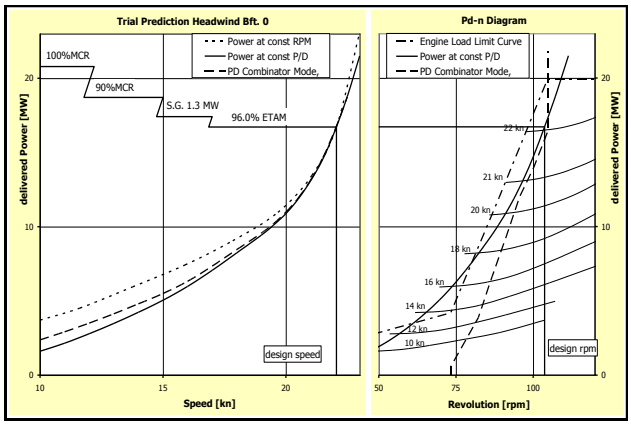

Figure 14 – Speed-power and rpm-power prediction for a CP propeller

For an existing ship in service, HSVA has been contracted by a ship owner to investigate the behavior of the CP

propeller plant, especially in "off-design" conditions. Preconditions for such an investigation is the availability of model test results for the draught and speed range of interest, and the availability of open water curves of the CP propeller for a set of pitch settings from the "zero-thrust" condition up to the maximum pitch.

The most reliable information on the propeller performance can be gathered from propeller open water tests performed for different pitch settings. Alternatively, as has been done in this case, the propeller manufacturer can supply the propeller open water curves.

As a reference, for each draught condition, the performance of the CP propeller for the "fixed pitch mode" has been calculated. Further, the performance of the CP propeller in the "constant rpm mode" has been calculated, and finally the performance in the "combinator mode". In Figure 13, the power requirement in the different modes is shown for one draught condition.

It is noted that with reduced speed, the power demand in the "constant rpm mode" is significantly higher than in the reference condition "fixed pitch mode". In the "combinator mode", the power demand is almost as low as in the reference condition. In the example presented in Figure 14, the required power at the 70% speed in the "constant rpm mode" is about 35% higher compared to the "fixed pitch mode".

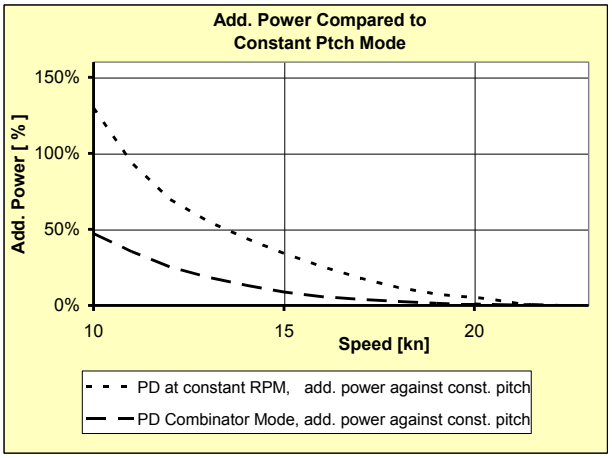

Figure 15 – Additional power demand of a CP propeller in different modes

Such an investigation of the performance of a CP propeller plant can be performed for a range of draughts and ship speeds, and for various wind and sea conditions. All information at hand allows the ship owner and operator to decide upon the optimal operating mode of his CP propeller plant within the allowed envelope of the engine load diagram. He then can decide whether it is more efficient to operate the CP propeller in "constant rpm mode" in combination with the shaft generator, or to switch to the "combinator-mode" and generate the needed electric power by an additional auxiliary engine. In this particular case, the engine load limit curve allows combinator settings which are rather close to the fixed pitch situation. In cases where the engine has a very narrow load limit curve, the resulting combinator setting can be closer to the constant rpm situation. The more expensive option with a thyristor-controlled generator may also pay off, when compared with additional fuel oil costs due to CP propeller operation in the "constant rpm mode".

Investigations for different type of propellers conclude that highly loaded CP propellers typically have a much higher power demand than low-loaded CP propellers in "off-design" conditions. Even trickier to judge is the operation of CP propeller plants of twin-screw vessels (e.g., single shaft operation) or propulsion plants, where two main engines are operating on a single propeller.

15 Fitting a Bulk Carrier with an Interceptor and a Rudder Bulb

On behalf of a Scandinavian consultancy company, model tests were carried out at *HSVA* for a Panamax Bulk Carrier Project. As, after extensive tests for hull form optimization, the designers still expected a potential for further improvements on the propulsions side, further tests with different rudder bulb configurations and also with an interceptor were performed.

Figure 16 – Bulk carrier ship model with rudder bulb

The best rudder bulb required about 4.0% less power than the standard case without rudder bulb. In conjunction with an interceptor, the total power reduction was 4.4%. This variant was chosen as the best variant tested.

16 Tanker Conversion Project

On behalf of a Scandinavian shipping company, model tests were carried out at *HSVA* for a tanker conversion project. The aim of these tests was to improve the performance of this ship in service by a bow modification. Further, the ship owner was interested in receiving guidelines for operating the ship on ballast draught conditions.

The investigated bow modifications do not offer a sufficient enough reduction in power consumption to be economical. The small gain in power consumption by the investigated bow modification (about 1.0% at most) led to the decision to do a trim optimization for the ship as in service at service draught.

With a static trim to the stern of 1.5 m, a reduction of the

power consumption by about 1.9% was obtained.

Following the tests at service draught, a variation of the ballast draught was investigated. The results show that the hull form has only a low sensitivity to changes in draught at a speed of 16.0 kts. At 17.0 kts, the highest forward draught shows a clear tendency to increased power consumption (7.6% compared to the lowest forward draught). At even higher speeds, the lowest forward draught offers a significant advantage in power consumption (13.3% at 17.5 kts compared to the highest forward draught).

Figure 17 – Proposed fore body modification for a Tanker conversion project

In a second step of investigations, a large modification of the under-water part of the fore body was investigated using potential flow CFD-calculations. The results of the model tests proved a significant reduction in power consumption of 4.1% at 16.0 kts at service draught. A further reduction of about 2.5% compared to the even keel condition could be obtained by trimming the vessel to the stern. At the ballast draught, the bow modification had no influence on the power consumption within accuracy of the model tests.

17 Hydrodynamic Upgrade for the MV 'Hammerodde'

The MV 'Hammerodde' is a RoPax ferry, which serves Rønne on the island of Bornholm from the Danish port of Køge near Copenhagen and from the mainland port of Ystad in Sweden. She was built in the Netherlands by *Merwede Shipyard* and has been in service since April 2005. Together with her sister ship, the MV 'Dueodde', she sails under Danish flag for *Bornholmstrafikken A/S*.

In order to fulfill a new contract with the Danish Ministry of Traffic, the MV 'Hammerodde' will now be required to increase her cargo-carrying capacity from the present 1200 lane meters up to 1500 lane meters. The required space will be made available by adding a further RoRo deck. The corresponding demand for about 10% more displacement will be fulfilled by increasing the draught and at the same time adding a set of sponsons and ducktail. The sponsons and ducktail not only provide more displacement, but at the same time, a larger waterplane area to ensure sufficient stability for the 'after conversion' hull form.

A further and somewhat more challenging feature of the new contract is that the present speed of the vessel, which is now 18.5 knots, must be maintained. The idea of fulfilling this requirement via an expensive machinery upgrade is not particularly appealing to the ship owner. Therefore, the Finnish marine consultants *Foreship Ltd.* were requested to add more than 800 m^3 to the volume while at the same time maintaining the speed without increasing the power requirement.

Figure 18 – The MV ´Hammerodde´

In November 2008, *HSVA* was contracted to perform the model tests for the MV 'Hammerodde' conversion project. The targets of the investigation included the sponsons/ducktail, an alternative bulbous bow, and the introduction of an interceptor plate on the ducktail transom. For this purpose, a very time- and cost-efficient test program was agreed upon and a multi-component ship model was manufactured.

Figure 19 – The model showing the 'after conversion' condition

In Phase 1 of the testing work, the hull form modifications and interceptor performance were investigated. In Phase 2, the concentration will be placed on the rudder design and also on a shift of the rudder position. It is expected that the installation of a high efficiency rudder system in conjunction with flap rudders will not only increase the propulsive efficiency, but will also especially improve the harbor manoeuvering capabilities. These will be further investigated in a series of crabbing tests.

In the meantime, the first phase of testing has been completed with a very encouraging result for the ship owner. In the past, conversions of this magnitude have usually resulted in an overall speed loss for the vessel. In the case of the MV 'Hammerodde', however, the speed loss of about 0.5 knots due to the added volume and increased draught was simply compensated by the

introduction of the interceptor. Thus, the contract point concerning maintaining the 18.5 knots speed has been met. Why invest in an expensive machinery upgrade when you can avoid it by upgrading the hydrodynamics instead? Due to the introduction of a tailor-made rudder-propeller package with high-efficiency flap rudders, another impressive 4.5% power reduction at the target speed could be achieved. The MV 'Hammerodde' will thus be fulfilling her new contract with a reduced fuel bill

18 Conclusions

The state-of-the-art techniques not only allow for optimizing the hull form itself, but for the optimization of the propulsion arrangement as well. The most effective measures to save propulsion power can be taken in the definition phase and in the design stage of a new building project:

- Carefully select main dimensions, required service speed and the propulsion device. Design your new building vessel as long and as slender as possible.
- Avoid too strict hard point requirements in the engine room and the cargo hold. The general design has to follow the hydrodynamic design, and not the other way round.
- Thoroughly investigate the possibilities applying PIDs on your vessel. Most effective are tailor made applications taking into account the ship type and the operational profile of the vessel.
- Cooperate with an independent model basin in the definition and design phase of a new building project. The most effective team consists of shipyard + ship owner + model basin.
- Let your vessels being optimized by the model basin of your choice.

Not only in the design phase, but during the whole lifetime of a vessel several measures can be taken to save fuel oil costs:

- Maintain the hull surface and the propeller as smooth and clean as possible.
- Operate your vessel in optimum trim conditions.
- Optimize your routes and reduce the service speed as far as practicable.

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