Efficient hull forms – What can be gained?

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1 Introduction

Under the pressure of rising fuel oil costs the interest in measures reducing energy consumption on board ships is rapidly increasing. Ship owners and operators are looking for measures to reduce fuel oil consumption over the whole life time of a ship. At HSVA a long experience is available with various measures improving the propulsive efficiency. In this article different measures which can be taken are described and possible improvements in the fuel oil consumption are discussed.

2 Optimal Main Dimensions

The most effective measure to minimise the vessels resistance is to choose suitable main dimensions in the first place, after which the optimisation of the form should be considered. Often we have to deal with designs which either have a too high block coefficient or a too short length for the selected target speed. Furthermore the design is influenced by measures for maximising the cargo carrying capacity or reducing the vessels length. Both measures can reduce the fabrication costs of a vessel, but may cost additional propulsion power which the owner or the operator has to pay for day by day, year by year, over the whole lifetime of the vessel.

Two different strategies can be observed for the optimisation process today. On the one hand most of the shipyards follow the strategy of increasing the block coefficient without increasing the resistance. On the other hand ship owners and a few shipyards investigate in variants with lower block coefficient and therefore lower resistance, especially for vessels in a seaway. Having in mind the actual fuel prices which have almost tripled during the last years, this strategy may be more successful to cover future demands.

The following comparison may illustrate, in which way the choice of the main dimensions influence the power demand of a new building project:

The Product Tanker on the photo to the left with main dimensions 135.7 m x 19.6 m x 8.4 m requires an engine output of 3,000 kW to achieve a service speed of 14.5 knots (at sea state 4, wind Beaufort 5).

A design with the same cargo carrying capacity, but with limited length (e.g. due to owner restrictions – or to cut the new building price), main dimensions 118.5 m x 21.5 m x 8.5 m, requires an engine output of 3,750 kW for the same service speed. This is an increase of 25%.

To optimise a vessels main dimensions all parties involved have to join forces in an very early stage of the design. While the ship owner contributes the expected costs and income (charter rate) and the financing concept, the shipyard contributes the fabrication costs of different variations in main dimensions, and the model basin, in cooperation with suppliers of propeller and rudder, contributes the power demand for actual loading conditions and expected environmental conditions. With these information not only the new building costs, but as well the cumulated cash flow and the cumulated profit for different variants can be estimated and the variant which offers the maximum benefit for the ship owner can be chosen.

The “Quick Check” of main dimensions based on HSVA’s database supports this optimisation step, giving an indication whether a certain project is within typical limits, or if main dimensions are outside of the typical range and that some extra effort might be necessary for optimisation of the design. This “Quick Check” includes advise regarding a maximum economical speed for the customers vessel which should not be exceeded in service in order to avoid an excessive fuel consumption. This will help designers at shipyards and in design offices as well as decision makers at shipping companies when selecting main dimensions in an early stage of project development.

3 Optimised Hull Form

The hull form design and the experience of the lines designer influence the quality of the hydrodynamic performance of a new building. To achieve an optimised hull form design still the experience of the designer is of utmost importance. Furthermore it is of advantage for the ship owner, if the lines designer has shipyard experience and can include multiple requirements from the general design into the new hull form to be developed.

CFD methods are widely used optimising the hull form. But at the end of the optimisation chain model tests are required to validate the predicted improvements, to avoid mistakes, to recognise errors and to validate new ideas. During this optimisation process the customers should use the vast experience available at the model basins.

Optimisation of a vessels hull form may have different goals. While the shipyard aims to have best performance on design draught and at design speed in calm water conditions (the contract condition), it will be much more advantageous for the ship owner to have a superior performance for actual loading conditions (e.g. a draught range) at a certain speed range and for real environmental conditions (e.g. sea state 4, wind Beaufort 5). This may result in a slightly less performance on design draught and at design speed, but will pay off in real service conditions.

During the design phase several measures can be taken improving a hull form design to reduce fuel oil consumption. Prerequisite for this is, that the general arrangement has enough “potential” included – for example that the engine room and the cargo area can be adjusted according to requirements from the hydrodynamic design. A sophisticated hull form design with soft forward and aft shoulders only can be achieved, when there are no restrictive hard points (e.g. from main engine, gear box or the cargo hold) or too severe requirements regarding block coefficient and/or longitudinal centre of gravity. An optimal hull design can only be achieved, when the general design follows the hydrodynamic design, and not the other way round.

Too strict requirements from the general arrangement may cost up to 10-15% in fuel oil consumption, depending on the ship type and ship speed!

Table 1. Maximum possible improvements by medications of the hull form

	Possible Gain	**Model Tests required?**
Fore Body Hull Form		
Small modifications at the bulbous bow	2 %	Yes
Small modifications in the bilge area and at the forward shoulder	2 %	Yes
Form variations using automatic optimisation strategies (possible gains depend on the height of the wave making resistance)	2-5 %	Yes
Mid Ship Hull Form		
Variation of the mid ship section coefficient	1 %	Yes
Aft Body Hull Form		
Small modifications in the bilge area and the waterline angles	2 %	Yes
Small modification in the area of the propeller boss	1 %	Yes
Small modifications in the area of the stern bulb	1 %	Yes
Transom elongations – without and with trim wedge	2-4 %	Yes
Note: Possible gains are not fully cumulative!		

If the projected vessel does not achieve the target speed or a further optimisation of the vessel is wanted the first step should be a comparison of the vessels performance with the characteristics of comparable ships previously investigated at the model basin. The experienced engineers and experts for hydrodynamics will investigate the potential for improvement and possible measures to improve the vessel. In cases the hull lines are already well optimised, only small gains can be expected by reshaping the hull. But small gains here and there may sum up to significant improvements. This requires time, endurance, experience and last but not least a budget allowing the thorough optimisation and extensive model testing.

If the main dimensions and the propeller diameter are already fixed and the hull form is almost of good quality, in most cases the potentials for improvement of the ship's resistance remain (see Table 1).

4 Optimising the Hull Surface

Lately new anti-fouling paints based on silicone have been developed. These special paintings offer a very low average hull roughness (ARH) down to about 65 microns. As a standard value model basins consider an ARH of 150 microns. But also vessels delivered with sub-optimal surface finish (ARH-values exceeding 200 microns) have been reported.

As an example the influence of the hull roughness on the power consumption and the achievable speed for a 4200 TEU container vessel has been predicted. The difference between an excellent, smooth hull surface (65 microns) and a poor hull surface (200 microns) equals to nearly 6% in total resistance or 0.3 knots in speed. In consequence every ship owner is well advised to maintain a hull as clean and smooth as possible. Spending more money for a clean and very smooth hull surface and propeller is a good investment.

5 Best Wake Field

Expecting rising fuel oil costs it is the aim of all shipyards, to design vessels with the lowest power demand possible for the contract conditions. To achieve this, the designer has to find the best compromise between propeller efficiency and pressure pulses to suit ship owners needs. On one hand the larger propeller diameter leads to higher propeller efficiency, on the other hand the larger propeller diameter may cause a slight decrease in hull efficiency and most probably will cause higher pressure pulses due to reduced propeller tip clearance.

HSVA investigated a large number of vessels which have been investigated in resistance and propulsion tests in the large towing tank and in cavitation tests for pressure pulse measurements in HYKAT. From these test results empirical formulas have been derived to assess hull efficiency and pressure pulses for such variations.

For a 4200 TEU container vessel the following variations in propeller diameter have been assessed. The original propeller diameter is 7.75 m When increasing the propeller diameter in two steps up to 8.0 m and 8.2 m thus reducing the propeller tip clearance from 2.65 m down to 2.40 m and 2.20 m one can expect the following gains in speed at constant propulsion power and an increase in pressure pulses as presented in Table 2.

Table 2. Predicted pressure fluctuation for a CV 4200

D_P	η_H[1] [-]	η_0[2] [-]	V_S [kts]	Δp [kPa]
7.75 m	1.095	0.699	24.57	5.2
8.00 m	1.090	0.707	24.61	5.6
8.20 m	1.087	0.713	24.63	5.9

Few shipyards spend time and money to improve the quality of the wake field by further modifications to the aft body of the vessel. It is sometimes overseen that a wake field of good quality helps to reduce the pressure pulses of the propeller and minimises the danger of propeller induced vibrations in the structure.

To judge the quality of the wake field a special "axial wake quality factor" (AWQF) has been defined, taking into account the non-uniformity of the axial inflow to the propeller. The average AWQF for container vessels in the 4200 TEU class size is about 0.70, with a range between about 0.65 and 0.74. Higher values are more favorable.

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[1] η_H = hull efficiency

[2] η_0 = propeller open water efficiency

The expected influence of the quality of the wake field on the pressure pulses for our example 4200 TEU container vessel is presented in Table 3. In this example a wake field of superior quality reduces the pressure pulses by about 0.4 kPa compared with an average quality wake field. A wake field of poor quality will increase the pressure pulses by about 0.6 kPa.

Table 3. Influence of axial quality wake factor on expected pressure pulses

D_P	AWQF [-]	Δp [kPa]
7.75 m	0.65	5.8
7.75 m	0.70	5.2
7.75 m	0.74	4.8

6 Propeller – Rudder Interaction

By optimising arrangement and shape of the rudder and the propeller further savings are possible:

Table 4. Maximum possible improvements by optimising the arrangement of propeller and rudder

	Possible Gain	Model Tests required?
Arrangement of Rudder and Propeller		
Increasing the propeller efficiency (will in most cases increase risk of cavitation as well)	3 %	Proposed
Optimum longitudinal position of rudder and propeller in aft ship	2 %	Yes
High lift profile (e.g. HSVA MP 73) to reduce the rudder area	1 %	Proposed
		Note: Possible gains are not fully cumulative!

Table 5. Maximum possible gains by measures increasing propulsive efficiency

		Possible Gain	Model Tests required?
Reducing Separations, / Improving the Quality of the Wake Field			
Grothues wake equalising spoiler		3 %	Yes
Schneekluth wake equalising duct		4 %	Yes
Sumitomo integrated Lammeren duct	(SILD)	6 %	Yes
Recovering Rotational Losses			
Twist ruder without rudder bulb	(BMS / HSVA)	2 %	Yes
Single pre swirl fin	(Peters / Mewis)	3 %	Yes
Pre swirl fin systems	(DSME, Korea)	4 %	Yes
Rudder thrust fins	(HHI, Korea)	4 %	Yes
Reducing Hub Vortex Losses			
Divergent propeller boss cap		2 %	Yes
Ruder with rudder bulb		2 %	Yes
Propeller boss cap fins	(PBCF)	3 %	Proposed
Reducing Rotational and Hub Vortex Losses			
Twist ruder with rudder bulb	(BMS / HSVA)	4 %	Yes
High Efficiency Rudders	(Wärtsilä, Rolls Royce)	6 %	Yes
			Note: Possible gains are not fully cumulative!

By application of propulsion improving devices the additional gains are possible (see table 5). These devices have different working principles. The first reduce flow separations and improve the inflow to the propeller. The second recover energy contained in the rotation of the propeller slip stream. The third reduce the losses in the propeller hob vortex by reducing or eliminating it completely.

7 Optimisation for Service Conditions

Today vessels are often optimised for the contract condition (usually design draft) in calm water only. From the operators point of view it can be much more advantageous to optimize the vessels hull form for the actual environmental conditions and the individual operating profile expected for their new buildings. Some designers consider the seaworthiness as an important design constraint, thus designing fine waterline entrance angles, fore ship sections with moderate bow flare, not too extreme bulbous bows and moderate transom stern designs. Other designers, optimizing their vessels for calm water condition only and neglecting the importance of seaworthiness, introduce more bow flare, pronounced bulbous bows and wide, flat transom stern designs.

Usually both, shipyards and ship owners do not care about wind resistance of their vessels. The effect of wind according to contract conditions on the trial prediction is very small. Usually a wind force according to Beaufort 0 or Beaufort 2 is taken into account for the trial prediction. Under these conditions the wind resistance contributes only with a few percent to the power demand. The situation changes completely, when it comes to service predictions.

In side wind conditions wind forces and moments acting on the vessel cause a drift angle and it is necessary to lay the rudder to keep the course. The drifting vessel and the laid rudder as well cause an additional resistance in service conditions.

The effect of the roll motion on a vessels power demand is almost unknown. Neither roll motions are predicted for most vessels as a standard, nor are self propulsion tests in combination with roll excitation tests performed in a systematic manner.

At HSVA for one container vessel project self propulsion tests in combination with roll excitation tests have been performed. Furthermore sea-keeping calculations have been performed to predict the significant roll angles expected for the different sea states and angles of encounter. The test results indicate that roll motions contribute significantly to the power demand of a vessel, depending on the mean roll amplitudes and the ship speed.

As an example, for a 4200 TEU Container Vessel the additional power demand due to seaway, due to wind, due to drift arising from side wind and due to roll motions has been estimated for different angles of encounter and for various sea states / wind conditions. The results are shown in Table 6.

Table 6. Total additional power demand in service conditions for a 4200 TEU CV

Wind force	**0 [deg]**	**45 [deg]**	**90 [deg]**	**135 [deg]**	**180 [deg]**
Bft. 2	+1%	+2%	+2%	+0%	-1%
Bft. 4	+6%	+9%	+11%	+10%	+10%
Bft. 6	+23%	+30%	+33%	+25%	+23%
Bft. 8	+61%	+74%	+57%	+38%	+32%

Assuming a probability distribution of 5% for Wind Beaufort 2 and less, 50% of Wind Beaufort 4, 40% of Wind Beaufort 6 and 5% for Wind Beaufort 8 and above, the average additional power demand for a 4200 TEU container vessel is about 27%.

Since nobody performs optimisation of vessels taking into account real environmental conditions up to now, one can assume that larger reductions in the additional power demand should be possible.

An advanced hull design may reduce the additional power demand in a seaway by up to 10%. An optimised container stowage may already reduce the additional power demand due to wind by up to 20%; an advanced aerodynamic design should cut the additional power demand due to wind even to the half.

The effect of drifting and rolling on the power demand needs further investigations. But it can be assumed that this as well can be reduced to a certain amount. When the additional resistance in service conditions can be reduced by 10% to 20%, this improves the overall performance in case of the 4200 TEU Container Vessel by 3% to 5% consequently.

The hull form, and especially the design of the bulbous bow and the transom stern, usually is optimised for the design draft on level trim. Considering actual loading conditions most probably will result in different hull form designs compared to those we have today. The hull form must not only be optimized for the design draft, but for a much wider range of drafts. To cover 90% of a typical operational profile of Container Vessels, the draught range for the optimisation should cover the interval between 85% and 115% of the design draught.
In case of the example 4200 TEU Container Vessel this means a draft range between 9.35 m and 12.65 m approximately. The same yields for the trim range. In case 90% of the operating profile shall be covered, the performance of this 4200 TEU Container Vessel has to be optimised covering a trim range between zero trim and 1.3 m trim aft approximately.
Designing new hull forms for real environmental conditions and actual loading conditions requires much more input from the ship owners and operators of a new building project as in the past. They have to define requirements to the designer, in which way they later on will operate their vessel.

8 Conclusions

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.
- 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 optimised by the model basin of your choice.

Not only in the design phase, but as well 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.
- Optimise your routes and reduce the service speed as far as practicable.

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