A Holistic Design Approach for Propulsion Packages

Lars Greitsch[1], Markus Druckenbrod[2], Sven Bednarek[2], Hans-Jürgen Heinke[3]

[1]Mecklenburger Metallguss GmbH (MMG), Waren (Müritz), Germany
[2]Hamburg University of Technology, Hamburg, Germany [3]Potsdam Model Basin, Potsdam, Germany

ABSTRACT

This paper discusses an extended approach to ship design, which is focused on the propulsion package consisting of propeller and rudder and special hub following geometries in order to ensure high overall efficiencies. Therefore the approach includes a newly developed optimisation setup for so called junction caps between propeller hub and pro-pul-sion bulb. Calculations and model tests give first impression of the influence of the way of interaction between the cap shape and the costa bulb.

Keywords

Design Methods, RANSE, Propulsive Efficiency, Rudder, Optimisation

1 INTRODUCTION

New requirements regarding propulsive efficiency demand better and more holistic approaches within the field of ship design. The conventional design procedure of single and separated design steps carried out by each supplier on its own is not capable enough to ensure the design quality we need to reduce the fuel oil consumption to the required degree. Especially if the operational bandwidth of the planned vessel should be considered within the design phase. "Multi-Point"-Design or design based on statistical profiles will increase the operational efficiency of future vessel compared to the conventional designs based on one single specification point. The propulsion system consisting of propeller and rudder and additional propulsion improving devices has also to be designed considering such more realistic operational requirements.

In addition propulsion efficiency itself became significantly more important after the last economic crises and due to the steady rise of fuel prices. But the design procedures for merchant vessel still do not consider these new requirements. Often the main dimensions used to be fixed in a project phase where neither the propeller nor the rudder designer is yet involved. This may lead to suboptimal solutions and a potential for improvement based on a holistic approach. Furthermore the conventional design procedures consider only one specification point. Depending on the real operating profile the differences between this artificial optimum and a more adapted design might be significant. Especially in case of more detailed hydrodynamic designs the use of operation adapted design procedures becomes more important.

As the interaction between propeller and hull with appendages is highly dependent on the operational condition, like for example thrust loading, draught or drift angles, the design of these components has to be carried out more integrated. Especially the interaction between propeller and rudder has a significant influence on the overall performance of propulsion systems. A design of propeller and rudder as one unit is to be recommended. Therefore for example the distance between rudder and propeller and the twisted rudder design has to be based on simulations considering the operational profile or at least a "multi-point"-specification.

More detailed propulsion improving devices like propulsion bulbs came more into the focus. In addition special propeller caps help to reduce the losses due to the hub vortex. The research project "BossCEff" concentrates on the possibilities to increase the propulsive efficiency by reducing the losses in the hub near flow. The project was funded by the German Ministry of Economics. The developed methods are part of the holistic approach presented in this paper.

2 THE DESIGN APPROACH

The new holistic approach includes the assessment of main dimensions based on the operational profiles and the numerical design of hydrodynamic details as for example the leading edge of the rudder as well as the hub near region including an optimized combination of junction cap and propulsion bulb (see: figure 1).

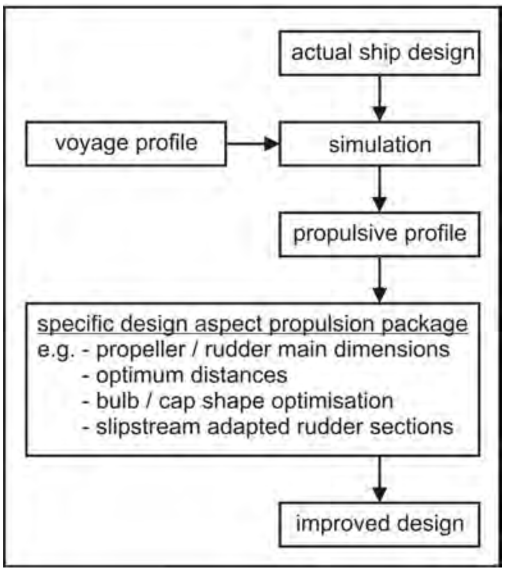


Figure 1: Schematic design approach

In order to cover all different level of information within the design phases the approach is consecutive. Thus the optimisation of the main dimensions can be carried out in a very early phase whereas later on the detailed design can be based on a more final status. Starting based on a conventional set of input data, given as a specification point, the design considerations can be refined by deciding some representative operational key points within the assumed operational profile ("multi-point"-design). The last and most detailed way to introduce more realistic requirements to the design is the fully operational based design. This requires simulation methods covering a statistical description of the transportation task as well as the operational behaviour of the vessel. This can be done by use of force-based manoeuvring algorithm considering the vessel operation and Monte-Carlo algorithm covering the statistical input data (Greitsch et. al. 2009).

3 SIMULATION OF THE PROPULSIVE PROFILE

The necessary input data has to be representative for the assumed operational profile of the projected vessel. Thus it has to be a very clear description of the desired transportation task. Based on later investigations focused on rudder cavitation within the operational bandwidth a statistical specification of the transportation task by frequency distributions of vessel speed and floating and weather conditions arised as sufficient to cover these influences. Figure 2 shows typical frequency distributions of vessel speeds for a container vessel (orange) and a RoRo vessel (blue).

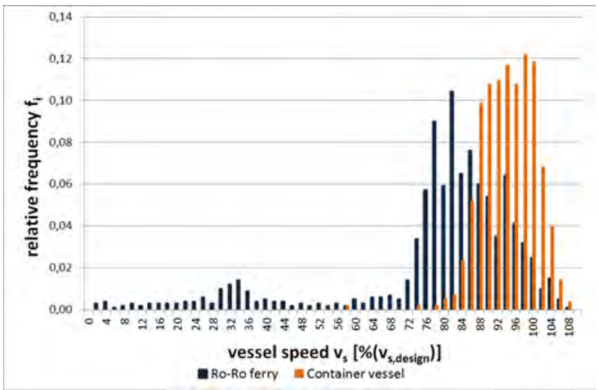


Figure 2: Typical vessel speed distributions

In order to ensure that the results of the simulation can picture the realistic vessel operation the data has to be checked for possible statistical dependencies. Only independent input data can be processed as a single condition. In case of higher correlations between the data (for example wind and sea state) the data has to be accessed by considering the dependencies. A possible mathematical tool for these data check is Kendall's correlation factor, which indicates the level of correlation in a range between -1 and 1, whereas values near 0 stand for a weak correlation respectively less dependencies in a statistical way.

These statistical distributions have to be preprocessed and described as cumulative distributions to be accessible for a numerical processing. Based on these cumulative distributions a Monte-Carlo algorithm can be used in order to recalculate discrete operation situations with the same frequency behaviour as the input data. For each diced random number between 0 and 1 the Monte-Carlo algorithm results in a specific value of the distribution of interest (see: figure 3).

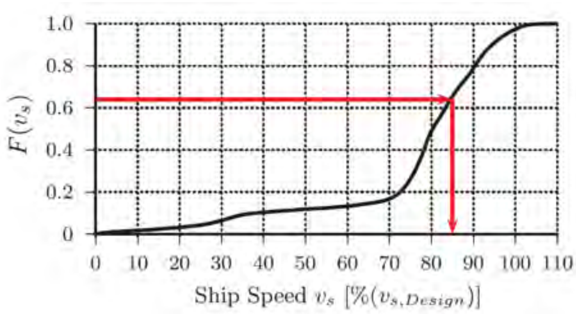


Figure 3: Recalculation of discrete operation conditions

These so determined operational situations can be accessed by a force-based manouevring algorithm which is capable to calculate the equilibrium condition (see: figure 4). Dices which lead to manouevring forces that can not be covered by the vessel design (e.g. maximum engine power exceeded) are rejected from the algorithm. Thus only diced and simulated operating points which can be covered by the ship design are saved within propulsive profile. From previous investigations can be derived that 2000 valid samples are sufficient to reproduce the operational input data (Eljardt et. al. 2009).

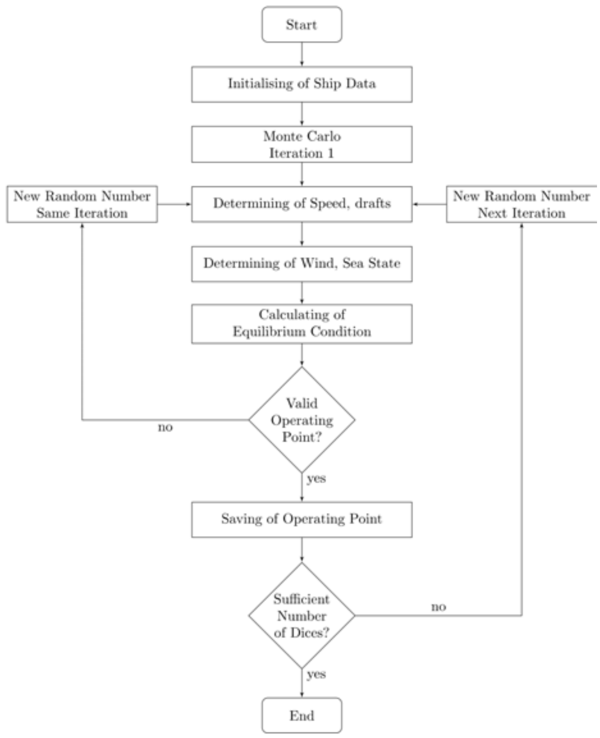


Figure 4: Operation simulation algorithm

In the following the propulsive profile consisting of the relevant system answers can be used as the data base for subsequent calculations and evaluations. In case of rudder design aspects all parameters with influence on the rudder flow have to be considered (see table 1). But this data has to be processed within the simulated data sets representing discrete operating points. According to the above mentioned convergence criterion the propulsive profile also consist of 2000 data sets in order to keep the relevance to the desired operational profile.

Table 1: Propulsive profile

value	unit	
vessel speed	$v_{s,i}$	$[m/s]$
wake fraction	$w_{eff,i}$	$[-]$
propeller pitch	P/D_i	$[-]$
propeller speed	n_i	$[1/min]$
rudder angle	δ_i	$[°]$
cross flow	$v_{c,i}$	$[m/s]$
draught at a.p.	$d_{ap,i}$	$[m]$

An evaluation of the design variants based on input data with this fine resolution can only be carried out by use of potential flow methods. In case of investigations with a higher numerical effort, either because of the necessity of the consideration of viscous effects or because of too many design parameters, calculations based on an averaged operating condition have to be carried out. For each design aspect has to be checked whether the numerical model can be used directly on the statistical data set or the design step has to be carried out based on this kind of representative of the statistical data. But in order to keep the influence of the operational profile on the design step this averaging has to be carried out for the technical consequence but not for the input data.

4 DESIGN CATEGORIES

Considering the propulsive profile is the basis of a design which is more adjusted to the needs. But in case of a propulsion package consisting of a solid rudder and a fixed pitch propeller (see figure 5) there is need for a transfer from the discretisised datasets back to averaged but best representing ”specification” point.

Depending on the design demand each design aspect has to be based on the most suitable design procedure. According to the possibilities of increasing the depth of detail can adapted. As a first distinction table 2 shows the identified design aspects and possible data bases.

Table 2: Design aspects

design aspect	design procedure
rudder main dimensions	conventional, acc. class
propulsion bulb	acc. best pratice guideline
twisted leading edge	averaged, equivalent flow
junction cap	generic optimisation

The first two design aspects are so far left out in the operational based design. The rudder main dimensions are so far determined according to the rules and are used as a start geometry, whereas the design of the propulsion bulb will be introduced within the procedure later on. Therefore the focus is on the design of the twisted leading edge and the so called junction cap for a reduced gap between propeller hub and propulsion bulb. The design of the twisted leading edge stand as an example of a statistical design evaluation combined with a direct optimisation based on the hydrodynamic average. Conversely the design of the junction cap is based on a generic optimisation based on a simplified, but viscous numerical model.

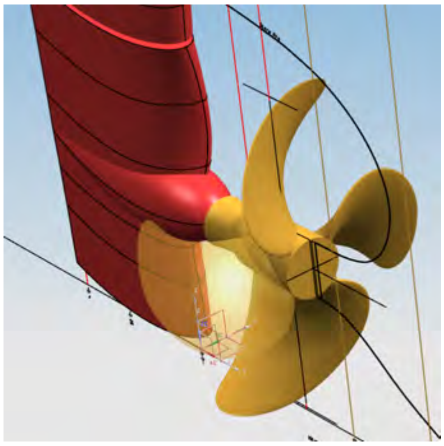


Figure 5: Propulsion package

4.1 The design of the twisted leading edge

In analogy to the idea of cavitation reduction due to twisted leading edges of the rudder profiles the aim of coming closer to the shock free entry of the flow is the basis of high efficiency rudder blades. As mentioned above this design aspect is to be directly based on the operational profile. Therefore a start geometry has to be calculated within the whole propulsive profile. Here the local pressure on the rudder blade $p_{loc,i}$ is a direct function of the propulsive profile consisting of i discrete operating situations.

$$p_{loc,i} = f(v_{s,i}, w_{eff,i}, P/D_i, n_i, \delta_i, v_{q,i}, d_{ap,i}) \qquad (1)$$

For a transfer from these i single pressure distributions on the rudder blade towards a representive flow situation an arithmetic average is be calculated for panel, repectively each local pressure.

$$p_{av,loc} = \frac{\sum_{k=1}^{i} p_{loc,k}}{n} \qquad (2)$$

Displaying all these averaged local pressure values leads to an averaged pressure distribution which is keeping the characteristic of the flow but with considering all occuring flow situations and the related frequencies. Figure 6 shows the averaged pressure distribution (A) in comparison to the pressure distribution for the original specification point (B).

The example stands for the same Ro-Ro-ferry as the above shown speed profile was derived from (Greitsch 2011). The direct comparison show the difference especially in the low pressure region at the upper leading edge due to the slipstream of the propeller. The pressure distribution based on the original specification point did not cover the average extend of this pressure region.

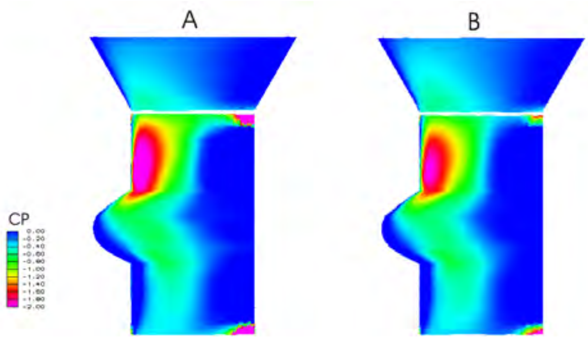


Figure 6: Averaged pressure distribution

Based on the averaged pressure distribution a determination of the inflow conditions for the rudder sections according to the method of equivalent flow (Greitsch 2011) is carried out. Here the inflow condition is equivalent if the pressure distribution on the rudder surface shows the most similar characteristic as a 2D-pressure distribution coming from calculations considering the same geometry as the rudder section but different inflow conditions depending on angle of attack and inflow speed. For this equivalence conditions height and location of the pressure minimum is to be observed. The comparing process is carried out by a tangent method. The result is an angle of attack and an inflow speed where the 2D-pressure distribution is most similar to the founded pressure distribution on the rudder blade.

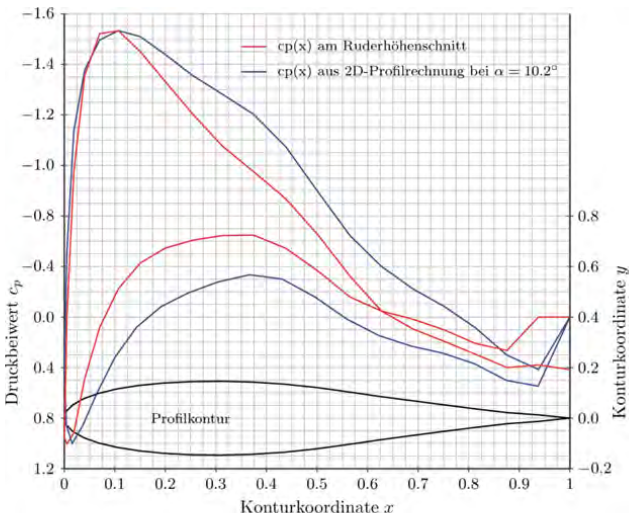


Figure 7: Equivalent pressure distribution

Of course these pressure distribution cannot be fully congruent, because in case of the 2D-calculations a homogeneous inflow is assumed, whereas in case of the pressure distributions the velocity of the surrounding flow is changing in direction of the rudder chord because of the propeller's slipstream.

Resulting from this 3D-2D-transfer a distribution of equivalent 2D inflow conditions can be derived. These inflow conditions are suitable as input data for geometrical optimisations of the rudder profiles.

Looking for a leading edge flow which comes closest to the ideal shock free entry the shape of the profile is optimised by use of the same tangent method and based on a simple 2D-calculation following the profile theory.

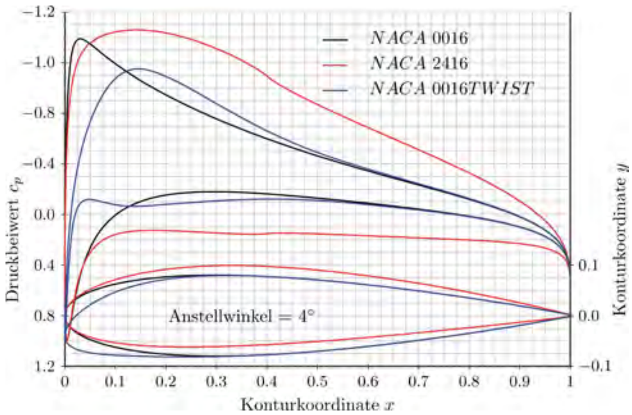


Figure 8: Optimisation of rudder profiles

In comparison between the symmetric profile to the twisted profile it can be seen that the pressure distribution is reduced due to the more smooth inflow (see figure 8). Therefore an adaption to the flow field given by the slipstream is achieved. The rudder resistance within the slipstream is reduced. These considerations lead to a distribution of different rudder profiles alongside the rudder height. A fully S-shaped rudder blade follows the discrete rudder sections (see figure 9)

Figure 9: S-shaped rudder blade

4.2 Cap shape optimisations

Propeller hub caps of course have been already investigated. Either in order to evaluate the capabilities of the numerical methods (Junglewitz 1996) or in order to investigate the influence of different cap shapes on the dead water area behind the cap (Maksoud 2004).

The aim within the project "BossCEff" was to find an optimisation algorithm in order to find the most suitable junction cap for a given rudder and propulsion bulb geometry and considering the propeller slipstream. Within the optimisation domain the propeller is represented by a body force model in order to decrease the numerical effort (see figure 10).

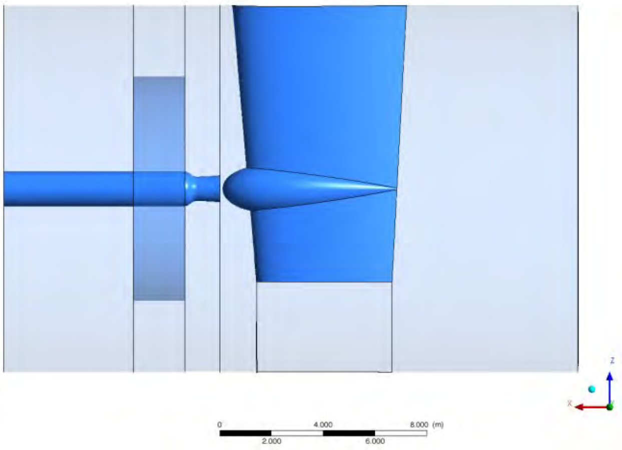


Figure 10: RANS domain

The optimisation has to include the parametric definition and generation of the geometry, the mesh generation and the numerical calculation of the propulsor performance. In order to achieve an automatic processing the algorithm has to be able to prepare all numerical setups for each variant by itself (see figure 11).

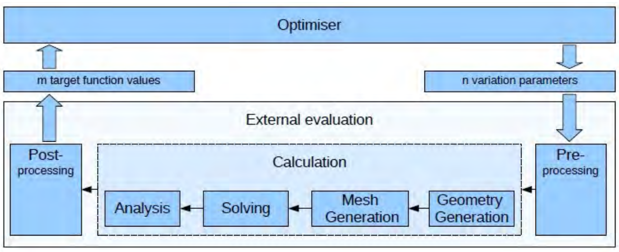


Figure 11: Optimisation process

This requires a fully parametric description of the cap shapes to be optimised. In order to cover even more complicated cap shapes (see figure 12) the description of the geometry was based on two independent functions $f(x)$ and $g(x)$ (Druckenbrod et. al. 2012).

For the propeller representation via the body force model the TUHH inhouse code $panMARE$ was used. For the hub near flow the influence of the propeller blades has to be introduced into the viscous calculation within the optimisation domain. An impression of these propeller influence shows figure 13.

For the coupling purpose the pressure values on each panel of the propeller calculation are transformed into body forces and imported into ANSYS CFX by adding them to the source term of the time-averaged Navier-Stokes equations. Hence, the propeller geometry does not need to be reflected

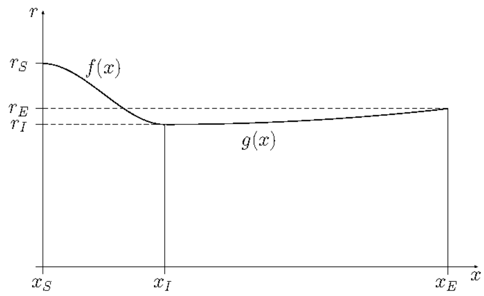


Figure 12: Geometry parameterisation

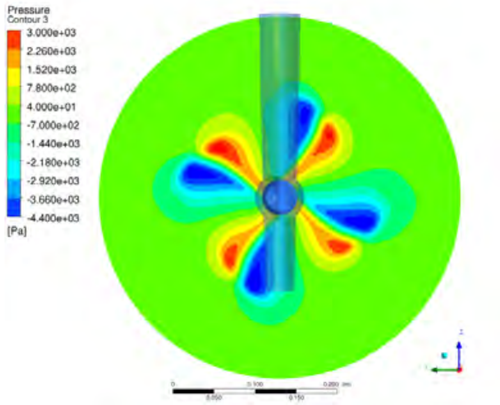


Figure 13: Propeller influence

in the volume mesh for the calculation method for viscous flow, resulting in a remarkable reduction in grid size and in calculation time.

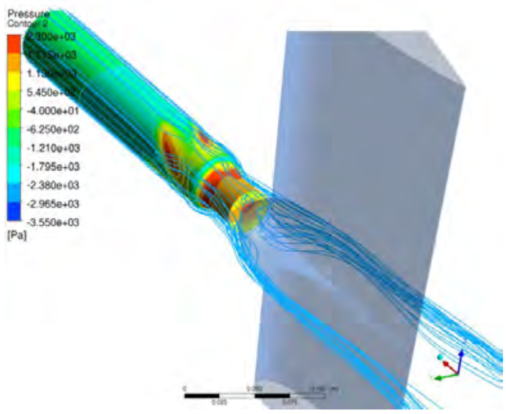


Figure 14: Hub near flow

5 MODEL TEST RESULTS

Within the research project "BossCEff" first model tests were carried out based on the free research geometry KCS 3600TEU from KRISO. The model tests were targeting the single influences of relevant design details like for example the distance between rudder shaft and the propeller plane or presence of a propulsion bulb.

For identifying the potential of the design of the twisted leading egde to rudders have been built. The first rudder was based on symmetric rudder profiles, whereas the second differs only in the twist of the leading edge. Both rudder were tested with and without propulsion bulb. In additon various different cap shapes were tested. Figure 15 gives an overview about the model test matrix which has been investigated.

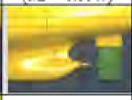
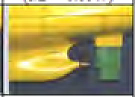
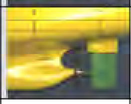
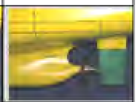
Ruder	Ruder 1	Ruder 2 (Bulb)	Ruder 2 (Bulb)	Ruder 4 (Bulb)
Position	vorn ($e/D = 0.4954$)	vorn ($e/D = 0.4954$)	hinten ($e/D = 0.6047$)	hinten ($e/D = 0.6047$)
Ablauf 1 (KON)				
Ablauf 2 (DIV)				
Ablauf 3 (KONDIV)				
Ablauf 4 (KONZYL)				
Ablauf 5 (KONDIV lang)				
Ablauf 6 (HVV)				

Figure 15: Model test matrix

The model test results show a noticeable influence of the distance between rudder and propeller. Here the higher efficiency (abt. 1%) was achieved with a smaller distance between propeller and rudder. In addition the rudder variant with twisted profiles shows a higher efficiency than the symmetric geometry. In this case the difference was about 1.2% on the propulsive efficiency. The propulsion bulb in any case has shown positive effect on the efficiency. The single effect was measured as a decrease of 1.3% of propulsive power.

6 CONCLUSIONS

As the design of propulsion devices is more and focused on even small design details which will bring small but further percentage of efficiency the effort to put on a design procedure is increasing. In order to scope with all main influences this paper gives the first impression of an advanced design approach, which will be capable to cover the realistic influences on the propulsor design. This is considered by a statistical description of the operational profile which leads into a propulsive profile after simulations based on the numerical model of the vessel.

The so derived propulsive profile is able to be processed in further partial design procedures. Therewith all necessary design aspects can be captured. Depending on the numerical modeling which has to be chosen for a proper capturing of the influences this statistical description has to be averaged. This averaging is carried out for the effect and not for the input data. This ensures, that the flow characteristic will not be lost during averaging.

This statistical design can be carried out for the leading edge design of the rudder without lack of operational influence. The evidence can be provided by realculation of the modified geometry again within the whole operational profile.

The design of the junction cap is carried out within a simplified domain, by replacing the propeller by its forces. This saves numerical effort, which can be put on an extension towards a "multi-point"-optimisation in order to achieve the link between cap optimisation and operational profile. The domain already is capable for combined optimisation of junction cap and propulsion bulb, whereas the existing calculations only consider a cap optimisation for a fixed bulb geometry. This has to be introduced as the next step. A design including all mentioned improvements will lead to an increase of propulsive efficiency of 2,5% up to 3% compared to a state of the art rudder-propeller configuration. Scheduled model test will bring verificaton of these values.

REFERENCES

Greitsch, L., Eljardt, G. & Krüger, S. (2009) First International Symposium on Marine Propulsors Trondheim, Norway.

Eljardt, G., Greitsch, L. & Mazza, G. (2009) 'Operation-Based Ship Design and Evaluation' International Marine Design Conference Trondheim, Norway.

Greitsch, L. (2011) 'Entwicklung eines Entwurfsverfahrens für Schiffsruder auf der Basis statistischer Betriebsprofile'. Ph.D. thesis, Hamburg University of Technology, Hamburg, Germany

Junglewitz, A. (1996) 'Der Nabeneinfluss beim Schraubenpropeller'. Ph.D. thesis, The University of Rostock Rostock, Germany

Abdel-Maksoud, M., et al. (2004) 'Numerical and Experimental Investigation of the Hub Vortex Flow of a Marine Propeller', 25th Symposium on Naval Hydrodynamics St. John's, Newfoundland and Labrador, Canada

Druckenbrod, M., et al. (2012) 'Geometric Modelling for Optimisation of Propeller Hub Caps', 15th Numerical Towing Tank Symposium Cortona, Italy