INTRODUCTION

Especially in the last few years the customer’s demands regarding a new ship design as well as regarding the optimised operation of vessels already in service increased considerably. Contrary to that, methods attempting to benchmark a specific ship design are still focused on only a few operating points (if not only one), thus they are not able to give realistic numbers regarding economics considering the vessel’s life cycle. The newly developed approach described in this paper illustrates a procedure on how to gain the information needed for providing a prognosis on various design- and operation-relevant issues. Deploying the Monte Carlo Method (Sobol, 1984), the implemented algorithm features the ability to simulate the operation profile of a vessel according to a specific trade, taking into account the cargo amount, the routing and the mostly anticipated weather conditions. Because of fairly low CPU times, this task can be performed for the extent of a vessel’s lifetime already at early design stages.

As a subsequent application, the evaluation of the rudder cavitation risk has already been implemented. Each manoeuvring situation leads to a specific flow condition around the rudder. On basis of the determined vessel speeds and rudder angles, the cavitation distribution on the rudder can be estimated. Therefore the flow around the rudder geometry is calculated for all combinations of the predicted rudder angles and ship speeds, considering the propeller load resulting from the ship’s resistance, its floating condition and the wake field. The occurrence of cavitation for each situation is weighted by the relative frequency of the operation condition. Thus the implemented method provides a prognosis of the cavitation risk distribution on the rudder considering the complete operational profile. Now it is possible to evaluate different rudder designs for the vessel on the basis of differences in the cavitation risk.

MONTE CARLO SIMULATION

The Monte Carlo Simulation is a statistical method. With its application it is possible to solve mathematical problems numerically, that are not or only with great effort analytically solvable. The basis of Monte-Carlo-Simulations is a large number of random experiments. These experiments are commonly realised by generating uniformly distributed random numbers. The method is justified by the law of large numbers (the accuracy increases with the number of experiments).

In this particular case, the Monte-Carlo-Simulation is applied in order to inversely reproduce cumulative distribution functions (CDF) of the vessel’s operating parameters. Randomly generated and uniformly distributed numbers in [0,1] are assigned to their explicit abscissa values. Figure 1 shows the proceeding for one value $F(v_s)$.

![Figure 1: Scheme of Monte Carlo Simulation](image)

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OVERVIEW OF ALGORITHM

Figure 2 gives an overview of the program cycle. The black boxes represent the conventional way of predicting the required power output numerically, whereas the blue boxes symbolise the extensions of the MonteProp algorithm:

Starting with a projected or existing ship design, the best matching input data have to be selected. Applying the Monte Carlo Method, the necessary vessel-specific and environmental parameters are determined for a given sample number (has to be set before starting MonteProp). Relating to the voyage profile’s characteristics, a minimum of 2000 samples proved to be a reasonable compromise between CPU time and accuracy. For each generated operating point, the propulsion’s equilibrium condition is determined, using a state-of-the-art manoeuvring algorithm (Krueger, 1998). The stillwater resistance is determined according to Eljardt (2006). Additional resistances originating from environmental or vessel-specific conditions are considered according to a scheme developed at TUHH by Eljardt and Greitsch (2009). A simulation of 2000 operating points takes roughly 20 minutes on a 2 GHz Dual-Core CPU with 4.0GB RAM.

OPERATION PROFILE

For analysis, data from two reference vessels have been utilised. The first vessel is a container carrier with a capacity of 8200TEU. Its data has been available in terms of noon-to-noon-reports, which implies averaged values for a 24-hours-period. The second vessel is a RoRo-ferry, containing 3900 lane metres. Its operating data has been recorded during regular service in the North Sea within a time period of 9 months. The floating condition has been observed once per day, the other operational parameters have been averaged from measurement recordings to one value for each 30 minutes (original sampling rate: 1 second).

Since the method for rudder cavitation risk prediction has been validated with the RoRo-ferry, the following paragraph will focus on this reference vessel. More information on the operation profile of the first reference vessel can be taken from Eljardt, Greitsch and Mazza (2009).

The speed profile (q.v. Figure 3) of the ferry shows that it sails with average speed values about 20 percent below design speed most of the time and that there is a small accumulation of vessel speeds in the range of 30 percent of design speed, which indicates slow speed manoeuvring during the estuary trading.
Depending on the vessel’s designated route, the expected weather may differ significantly. In order to simulate the resulting added resistances as correct as possible, it is important to gather the necessary environmental data. This can either be done by observation (e.g. during the operation of similar vessels) or the data can be attained from hindcast weather reports. For the presented case, both ways have been employed. The wind force and the angle of attack (aoa) were recorded after observation, whereas the sea state and the correlation of wave height and period were hindcasted. The data was collected and averaged over a period of 10 years from 1990 to 1999 by the GKSS Research Centre, located in Geesthacht, Germany. It was provided in the course of the research project ADOPT (http://adopt.rtdproject.net/). Figure 4 shows the data points and the symbolic path of the vessel’s route across the Skagerrak and the North Sea between Gothenburg and Gent.

Since the highlighted points along the route are rather equidistantly distributed, they have been taken into account with equal weighting. This has been done in order to determine one averaged CDF for each weather parameter (Figure 5).

Worldwide sea state data can be obtained from Soeding (2001). E.g. the second reference vessel, a container carrier with a geometric capacity of 8200 TEU, operates on a liner service between Europe and Asia, thus Soeding’s data has been applied.

Both parameters wind and sea state are correlated. This dependency has to be acknowledged when applying the subsequently described MonteProp-algorithm. During the analysis of the 8200-TEU-vessel, it proved to be feasible to incorporate the correlation through the following proceeding. At first, the wind force in Beaufort is determined as a floating point number. The sea state is derived afterwards by simply reducing the Beaufort number with a constant subtrahend of 1. For the described vessel and its voyage profile this procedure is slightly suboptimal, since the wind force’s statistical spread is wider than the sea state’s one, q.v. Figure 6.
Before implementing the algorithm the other input data has been analysed regarding the extent of correlation between the parameters. The extent is specified in terms of a correlation factor. It can take values between -1.0 and 1.0, where small factors near 0 indicate a low grade of correlation and values near 1 respectively -1 indicate strongly correlated data. In the present work Kendall’s correlation factor $\tau$ has been chosen, because it is insensitive against outliers and also suitable for huge data volumes (Kendall, 1970).

<table>
<thead>
<tr>
<th>Compared Parameter</th>
<th>Kendall’s $\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vessel speed vs. propeller RPM</td>
<td>0.97</td>
</tr>
<tr>
<td>Vessel speed vs. propeller pitch</td>
<td>0.89</td>
</tr>
<tr>
<td>Vessel speed vs. propeller thrust</td>
<td>0.94</td>
</tr>
<tr>
<td>Vessel speed vs. rudder angle</td>
<td>-0.11</td>
</tr>
</tbody>
</table>

**COMPUTATION OF PROPULSION EQUILIBRIUM**

In order to compute the required main engine’s power output, a manoeuvring algorithm is employed. It has been developed and validated at TUHH in cooperation with Flensburger Schiffbaugesellschaft. Computed examples and detailed information can be taken from Haack and Krueger (2004) and Haack (2006). The algorithm has been in practical use for prediction of manoeuvring behaviour for several years since then. Resulting from close cooperation between TUHH and the shipyard, the manoeuvring model of the analysed vessel is very detailed. The implemented numeric model includes the propulsion plant and the controllable pitch propeller. Two-quadrant-diagrams are used to describe the propeller itself. The possible combinations of shaft speed and propeller pitch result from the combinator diagram.

**VALIDATION OF ALGORITHM**

The implemented MonteProp-algorithm has been validated, using recorded measurements of both reference vessels. The main engine’s power output was recorded only for the container carrier. This has been realized with the help of a shaft power measuring system and can be used directly for comparison. Eljardt (2006) investigated the accuracy of this method and proved it to be sufficient.
The diagram shown in Figure 7 compares the simulated and the measured shaft power CDFs of the 8200-TEU-class vessel. The function’s congruence is satisfactory, especially when considering the applied input data, its simplifications and the utilised methods with their incorporated numeric models.

Other operation data, such as main engine revolution speed, propeller pitch and rudder angle have been compared to recorded data from the RoRo-Ferry. Figure 8 shows also good resemblance between measured and computed data.

![Figure 8: Comparison of Simulated and Measured Parameters (RoRo-Ferry)](image)

**CAVITATION RISK ANALYSIS**

The cavitation risk for the rudder design is calculated as a risk distribution on the surface area of the rudder. For each discretised panel there is the calculated probability of cavitation occurrence within the whole operational profile. The cavitation prognosis is carried out by means of a panel code based on the potential flow theory. This allows very fast calculations and therefore the analysis of the large number of observed operation cases in a finite time period.

The used CFD code takes into account the wake field of the observed vessel and the propeller slipstream, the latter of which is calculated with the lifting line method. The cavitation is calculated by comparing the local pressure with the vapour pressure of the passing water at the observed location. It is not distinguished between higher and lower pressure gradients. The interpretation of the results is carried out by a cavitation coefficient $c_{cav}$ as a saltus function which has the value 0 for non-cavitating situations of this panel and the value 1 in case of cavitation on the observed panel. In order to benchmark the cavitation risk for different regions on the rudder the cavitation pattern is calculated for each single simulated operating situation. The cavitation coefficient $c_{cav}$ therefore is a function of all major operational influences.

$$c_{cav,i} = f\{v_{S,i}, w_{eff}, P/D, n_i, \delta_i, V_{cross,i}, T_{AP,i}\}$$

with:

$v_{S,i}$ = Vessel speed

$w_{eff}$ = Effective wake fraction

$P/D$ = Pitch to diameter ratio (propeller)

$n_i$ = Propeller rpm

$\delta_i$ = Rudder angle

$V_{cross}$ = Cross flow

$T_{AP,i}$ = Draft at aft perpendicular

This leads to a safety against cavitation $S_{cav}$ for each panel

$$S_{cav} = 1 - \frac{\sum_{i=1}^{m} c_{cav,i}}{m}$$

As shown in Figure 9, a value of $S_{cav} = 1$ specifies a 100 percent safety against cavitation for the observed panel in the range of operation situations. Resulting from the saltus function there can be no safety greater than 1. In the same manner a value of $S_{cav} = 0$ indicates that the observed panel would cavitate in all operation situations. On basis of the cavitation risk distribution the benefit of a new rudder design can be evaluated directly. The capability of this approach has been presented at NuTTS (Greitsch, 2008) and 1st Symposium on Marine Propulsors (Greitsch and Eljaradt, 2009).
CONCLUSIONS

This paper showed a new approach to benchmark different ship designs, keeping a clear focus on the operation. It has been proved that it is possible to simulate a complete lifecycle of a projected or existing vessel, using fore- and hindcasted operation data (ship-specific and environmental). The simulation results, regarding the power demand, are available in rather short computation time. The use of an entire manoeuvring simulation leads to a complete database of operational data. On the basis of this simulation it is possible to implement various successive methods in order to evaluate and optimise the design regarding operational efficiency and also ship safety. In addition it is now possible to reliably number the achievable savings or contrary the additional expenditures of an inferior design on a lifetime basis. The determination of the rudder cavitation risk, as shown, allows the comparison of different rudder designs within the expected operational profile of the vessel.

REFERENCES


