INTRODUCTION

Since the Energy Efficiency Design Index (EEDI) has been adopted, the installed power of ships is subject to a continuous reduction. Because the EEDI regime supports those ships which have a large capacity and a slow ship speed, and the fulfilment of the EEDI is hardly possible without a substantial reduction of the installed engine power. Therefore, the question has been put forward whether ships with reduced installed power can still be safely maneuvered in adverse weather conditions. The European research project SHOPERA has intensively studied this matter. Currently it is under discussion at IMO whether further regulations for minimum installed power shall be developed or not. In this context it must be mentioned that already two such rule sets exist: the minimum required power demands for safe navigation in ice and the minimum power requirements for safe return to port.

From the ship design point of view it clearly leads to severe design problems if one regulation prescribes a maximum installable power and a second regulation prescribes a minimum installable power. The EEDI formulates a maximum installable power, and the two above mentioned rule sets clearly describe a minimum power requirement. As it is presently not intended that a minimum power requirement (from safety considerations) will overrule the EEDI (environmental view point), ship design is confronted with two conflicting requirements concerning the selection of the main engine power. This problem will become really severe if in 2020, the next EEDI reduction phase will enter into force.

In the SHOPERA project, regulations have been suggested which focus on an achievable minimum speed against waves, which will result in a minimum power demand. The method was applied to some twin screw designs taking into account the future alteration of propulsive power due to the EEDI. It was found that the EEDI had little effect on future steering abilities of the investigated ships, and as a result it can be concluded that properly designed twin screw ships will still have sufficient maneuverability in the future. This suggests that possible future regulatory attempts for safe maneuvering in adverse weather conditions should not focus on twin screw ships. It was also found that when then course keeping problem is to be investigated, the focus should be on following seas.

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As the German Shipbuilding Industry mainly produces twin screw vessels which have a high maneuverability as key design feature, the question was put forward whether these ships are affected by the problem or not. For this purpose, it was found useful to apply a first principle based direct computational procedure to analyze maneuvering in adverse weather conditions, which is in our analysis defined as course keeping against wind and waves. The computational procedure must at the same time be fast enough for application during the basic design phase. It must also ensure that all maneuvering devices can be designed for a prescribed course keeping procedure.
The principal definitions of the course keeping problem are shown in Fig. 1. The ship travels with the ship speed $v_S$ and it is exposed to environmental forces, which may be a combination of wind, waves and current. These external forces result at first in a longitudinal force, which is called added resistance. This added resistance directly leads to an increase of the propulsion power. The external forces do also result in a hull cross force and a hull yawing moment. These are generated by a combination of drift motion of the ship (drift angle $\beta$) and a rudder yawing moment (rudder angle $\delta$). Both drift motion and the rudder action result in an additional longitudinal force which also increases the resistance. The propulsion efficiency of the ship is affected by the fact that the propulsor(s) now work(s) in oblique flow due to the drifting motion. From the viewpoint of maneuverability in heavy weather, the most important question is the ability of the rudder(s) to produce sufficient yaw moment to enable the ship to keep its course. As the inflow to the rudder(s) is strongly influenced by the propeller(s) (especially under the heavy loading), it is of interest whether the installed power is sufficient to guarantee the required inflow to the rudder(s).

The calculation is therefore divided into two steps: At first, two non-linear equations need to be solved to obtain the rudder angle and the drift angle. If the ship cannot keep its course, there exists no solution for the problem. During the second step, the added resistance, the propeller and rudder inflow need to be calculated. This results in propeller rpm and pitch setting and the delivered power of the drive train(s), if the torque/rpm combination is still located in the engine load diagram. The aim of the procedure is to identify limiting situations for the course keeping.

As the course keeping problem is a maneuvering problem, we use our maneuvering model for the computational procedures. This model is briefly described in the following section.

3. MANEUVERING MODEL

3.1 General

For the present investigations, we use the body fore maneuvering model which is implemented in the ship design system E4. The model was developed by Söding and it is continuously developed by Krüger et al. on the basis of full scale measurements of ships during sea trials and during the operation. The model is used during the initial design phase for the layout of the hull and the maneuvering devices as well as during the delivery of ship for the generation of the maneuvering booklet and the wheel house poster (see e.g. Fig. 2). The typical accuracy for full scale ships is about ship’s breath for distances such as tactical diameters or advances and about 2 degree for overshoot angles. This maneuvering model is now adapted to the course keeping problem.

3.2 Body Forces

Body Forces are computed according to the slender body theory developed by Söding (1993), see Eqn. 1, where $X_2$ denotes the longitudinal force, $Y_2$ the cross force and $N_2$ the yawing moment:
The cross force $Y_2$ and the yawing moment $N_2$ consist of two major contributions: The first part is due to the acceleration of the section added mass and the second part is due to the viscous cross resistance of a frame. Both contributions have to be integrated over ship length. For the course keeping problem, the drift angle can be assumed to be small, and therefore, the contribution of the section added mass part is dominating the hull forces. The drag coefficient $C_D$ can be identified from full scale measurements or from viscous calculations (Lübcke 2014) and it lies in the range of 0.3 (for frames with large bilge radii) to 1 (for V-shaped frames). But for the course keeping problem, the viscous contribution is small against the added mass part. It should be noted that the course keeping of a ship strongly depends on the longitudinal distribution of section added mass, where the section added mass depends on the hull form and on the floating condition. Fig. 3 shows the longitudinal distribution of section added mass for 0 and 15 degree heel floating condition for the sea trial design floating condition of example ship 1. Our body force model includes the roll degree of freedom indirectly: From hydrostatic considerations, the heel angle is found, and section added mass as well as viscous forces are corrected for the heel (Söding 1993).

The coefficient $X_{vv}$ which gives the longitudinal force per drift angle can be identified from full scale measurements.

### 3.3 Propeller and Rudder Forces

Propeller forces are obtained from lifting line calculations. This includes computations in oblique inflow to include the propeller cross forces and the alterations of thrust and torque. These calculations include alterations of the propeller blade angle if the propeller is a controllable pitch propeller. Rudder forces are computed by a direct panel method by Söding (Söding 1998) where the rudder inflow comes from a lifting line theory. Fig. 4 shows the propeller/rudder model of example ship 1 for zero degree rudder angle and design load.

![Figure 4. Panel model for rudder forces in the propeller slipstream for Example Ship 1.](image)

#### 3.4 Interaction Effects

Most important interaction effects are the alteration of the effective wake and the cross flow to the propeller. The cross flow $v_c$ to the propeller due to the drifting and turning motion can be modelled according to the Kose approach (Söding 1993) as:

$$V_c = k_1 v_y + k_2 \text{rot} x_P$$

Where $v_y$ and rot denote the rigid body lateral speed and turning rate of the ship, $x_P$ denotes the distance between propeller and pivoting point. $k_1$ and $k_2$ are factors which are below 1, because due to flow separations in the aft body the cross flow is smaller than the rigid body motion. For single screw vessels, $k_1$ and $k_2$ have been proposed as 0.36 and 0.66, but for twin screws this is not applicable as the cross flow depends on the combination of signs of turning rate and location of propeller. Furthermore, for twin screw vessels these factors depend also on the ratio of $v_y$ and rot, where for course keeping problems, the rate of turn can be assumed as zero. Fig. 5 shows computed values for the Kose factor $k_1$ for example ship 1 by a computational RANS-procedure developed by Vorhölter.
3.5 Propulsion Control system

The model includes a propulsion control system for the calculation of propeller pitch and rpm settings during each time step. The lever command sets initial values for rpm and pitch according to the predefined combinatory curve, and both overload and wind milling switches modify the rpm or pitch value. In case of transient maneuvers such as crash stop astern, there are predefined engine slowdown and startup ramps. For the course keeping analysis in the present context, only the predefined combinatory curve is relevant for pitch and rpm control, as we compute time averaged values only.

4 EXTERNAL LOADS

4.1 General

Wave loads, wind and current are acting on the ship, but in the present context, current is disregarded. Although all force modules work in time domain, we have taken time averaged values for the external forces and we search the course keeping equilibrium for these static values. See state and wind parameters can be selected independently from each other, but for the present analysis we have selected wave period and wave height depending on the wind force according to the established ERN-concept by DNV GL, if not stated otherwise.

4.2 Wind Forces

Wind forces are computed on the basis of Blendermann’s coefficients (Blendermann 2013).

4.3 Wave Drift forces

Second order wave drift forces are computed in the present context by means of a strip theory according to Augener. The investigated ships have a very low block coefficient and a relatively high forward speed, which justifies the application of a strip method. Alternatively, we can use the panel method NEWDRIFT by Papanikolau for these purposes in case it is doubtful whether the strip method is applicable.

5 VALIDATION

Measurements of the course keeping ability could be performed during the sea trials of ship 1. Ship 1 is a five Deck RoRo ferry with about 200m in length, beam 31m, draft 7.40. During the sea trial, the draft was 6.47m aft and 5.75 m fore. The windage area of the ship during sea trial amounted to 5900m². The vessel is a twin screw ship with controllable pitch propellers of 6.30m in diameter and 10800 kW per shaft line. The two full spade rudders are located in the propeller slipstream.

<table>
<thead>
<tr>
<th>Designation</th>
<th>measured</th>
<th>calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship speed</td>
<td>17.6-17.8</td>
<td>17.7</td>
</tr>
<tr>
<td>Wind speed</td>
<td>16.3-17.8</td>
<td>16.8</td>
</tr>
<tr>
<td>Wind Direction</td>
<td>228-234</td>
<td>230</td>
</tr>
<tr>
<td>Propeller rpm</td>
<td>102.9</td>
<td>102.9</td>
</tr>
<tr>
<td>Propeller pitch</td>
<td>77</td>
<td>73</td>
</tr>
<tr>
<td>Drift Angle</td>
<td>1.8-2.0</td>
<td>2.2</td>
</tr>
<tr>
<td>Rudder angle</td>
<td>2.7-2.9</td>
<td>3.2</td>
</tr>
<tr>
<td>Shaft Power PS</td>
<td>4680</td>
<td>4810</td>
</tr>
<tr>
<td>Shaft Power STB</td>
<td>4785</td>
<td>4920</td>
</tr>
</tbody>
</table>

During the sea trials, wind forces were between BFT 7 and BFT 8, and the sea was rough with wave heights about 2.5 m. The period was estimated to be about 5s. The measurements were performed in the Baltic Sea. The ships heading was about 118 Degree, wind and waves were coming from about 230 degree, which lead to a beam wind scenario. Meas-
measurements were taken from the bridge automation system (see Fig. 7).

Figure 7. Screen shot of the bridge display during yaw checking measurements of ship 1.

The measured values for the drift angle, rudder angle and wind speed varied slightly due to the unsteady nature of the environmental forces, due to the autopilot and the propulsion control system.

The computed drift and rudder angle are roughly in line with the measured values, it seems to be that our method slightly overestimates drift and rudder angle. The computed power values are slightly smaller compared to the measurements, this can be explained by the fact that the vessel performed better during sea trial compared to the model basin prognosis, and for the present analysis we have not made a correction to the model basin values. Most likely is that the full scale wake fraction differs from the model value, as there are also slight differences in the computed pitch settings. Although further validations would be useful, we assume for the moment that our model predicts the correct trends and we will apply this model for course keeping investigations.

6 COURSE KEEPING INVESTIGATIONS

6.1 General remarks

Currently, there is no agreed setup for the course keeping analysis. For the present analysis, we follow the safe-return-to-port regulations which define environmental conditions as BFT 8 and sea state 7. According to the DNV GL ERN concept, this results in a significant wave height \( H_{1/3} \) of 5.2m and a wave period \( T_1 \) of 9.6s. We will use these conditions during the following analyses. We further assume that wind and waves have the same direction. It is obvious that the critical condition for course keeping is the lightest seagoing condition, therefore we will carry out our analyses for the ballast arrival condition (which is close to the sea trial condition).

6.2 Ship 1

Although ship 1 does not need to comply with EEDI due to keel laying date, we use ship 1 as a first example because of its very large windage area. Fig. 8 shows the results of our analysis in form of polar plots of the required rudder angle for course keeping (top) and the resulting drift angle. The calculation speed was set between 6 and 20 knots. Due to the limited engine power, the achievable speed in head seas is smaller, that is why the polar plots have been cut accordingly. In following seas, the problem arises that at low ship speeds, there is no inflow to the rudders and consequently no rudder yaw moments, that is why certain areas in following seas between 20 and 40 degree can never be reached at slow speeds because the ship is unstable there. In head seas, the ship has not any problems to maintain its course. The polar plots do also show that the ship can reach more than 6 knots speed in all head and beam sea courses. If the speed is above 10 knots, the ship can reach all courses in following seas.

Figure 8. Course keeping polar diagrams for ship 1, trial draft, BFT 8 SS7. Top: Rudder angle, bottom: Drift angle.

\[^1\] During the measurement, the rpm bridge display calibration was not finished, the rpm value in Fig. 6 should be 103 instead of 126.
It has been mentioned that ship 1 does not need to comply with the EEDI. To study at least roughly the effect of future power limitations to the ship, we have computed the power demand of the ship during course keeping and plotted the results in Fig. 9.

![Image of power demand](image)

**Figure 9.** Required power for course keeping for ship 1, trial draft, BFT 8 SS7. Cutoff power was set to 10 MW.

Fig. 9 shows the required power during course keeping for ship 1 in a BFT 8 SS 7 scenario. The color scale was selected such that all power values below 10 MW get the same color index. It can easily be seen that even if the EEDI would reduce installed power by more than 50%, the ship would still be maneuverable in all head sea condition, but now only speeds between 9 and 11 knots can be reached in head seas. For the following sea scenarios, our assumed power reduction has no influence. The ship is even with reduced power fully maneuverable due to the fact that she is a twin screw vessel with two spade rudders which were designed for high maneuverability and due to the fact that the controllable pitch propellers can absorb 100% MCR at positive inflow to the propellers.

6.3 Ship 2

Ship 2 is a four-deck RoRo Ferry which complies with the current EEDI requirements. She was developed from a proven FSG design by adding a parallel mid body of 16.80m to increase the capacity. The layout of the maneuvering devices remained unchanged. The length of the ship is 209m, beam 26m, draft 6.45m. The windage area amounts to 4600m². The ship has two main engines with a total power of 19200kW. The twin full spade rudders are located in the slipstream of the two controllable pitch propellers of 5m diameter. This ship was chosen for one reason that she fulfills the existing EEDI regulations and for the other that the capacity of the ship was increased by keeping the maneuvering devices of the original design.

![Image of course keeping polar diagrams](image)

**Figure 10.** Course keeping polar diagrams for ship 2, light ballast draft, BFT 8 SS7. Top: Rudder angle, bottom: Drift angle

Fig. 10 shows the results of our course keeping analysis. The computations were performed for ship speeds between 6 and 20 knots where the vessel was running on the light ballast draft. In head seas, a maximum speed of abt. 15.5 knots is possible with the installed power. In following seas, we found the same situation as for ship 1: When the ship speed is low, the power requirement is too small to generate inflow to the rudders, that is why in following seas, certain speed/course combinations are impossible due the fact that the ship cannot keep its course. Compared to ship 1, there are more combinations of speed and encounter angles where the ship is not able to steer. This is reasonable, because the maneuvering devices were taken from the basic design and they remained unchanged. If the ship speed is more than 13 knots, the ship is maneuverable on all courses.

From operational view, one can say that in the assumed scenario, the ship is well maneuverable, because from practical considerations, the ship will not operate at very low speeds in following seas. One can further conclude that even after the lowering of the EEDI baseline in 2020 the ship will be fully maneuverable, because the EEDI has an effect on the installed power, and the installed power has no im-
impact on the situation on following seas. A reduced power would also reduce the achievable speed in head seas, but even with reduced power the speed will be abt. 13-14 knots.

The results do also show that if an EEDI-compliant ship shall have the same maneuverability compared to a pre-EEDI ship, the effectiveness of the rudders must be adapted. Critical in this respect is maneuvering in following seas with slow speeds. If future ships are designed for very low speeds following the EEDI reduction scheme, than it could be possible that operation in following seas is more limited or even hardly possible.

6.4 Ship 3

Ship 3 is built at Pella Sietas Yard in Hamburg. The type of the ship is a hopper dredger which is called Sietas Type 180. The ship has a length over all of 118.47m, a breadth of 21.10m and the draft is limited by 7.10m. The hopper dredger has a diesel-electric drive concept with two electric drive motors with a total power of 3400kW.

The ship does not need to comply with the EEDI-requirements due to the propulsion concept and the ship type. But it is a good example to show the course keeping capability of a small twin screw vessel with a relative low engine power and a fixed pitch propeller.

The results of the course keeping calculation in heavy weather are presented in fig. 11 for a ship speed between 6 and 13 knots. The figure above gives the required rudder angle to hold the course of the ship and below the resulting drift angle is shown. Similar to the ship 1 and 2 the capability of course keeping is limited by the available power and the maximum rudder angle. In case of head sea, the ship speed is reduced to 7.5 knots by the available power. The more critical situation is for small ship speeds in following seas. In this condition the rudder angle limits the course keeping capability which is caused by the reduced inflow velocity of the rudders. The results of the calculation confirm the previous investigations of ship 1 and 2.

7 CONCLUSIONS

A method was presented which allows to compute the course keeping problem in heavy weather. The method is based on our existing maneuvering code and it determines drift and rudder angle in the equilibrium of cross forces and yawing moments. Afterwards, the required power can be determined. The comparison of measurements for a sea trial in bad weather and the computed results was reasonable. The application to three twin screw designs showed the following results: In head or beam seas, all ships are fully maneuverable in all possible courses and speeds. Reasonable ship speeds could be reached. It could be shown that all investigated ships would still be fully maneuverable even if they would have to comply with EEDI after 2020. This is due to fact that all ships have been designed for good maneuverability, therefore they all have twin controllable pitch propellers and twin rudders. It could also be shown that critical situations with respect to course keeping will at first occur in following seas if the ship speed falls below a critical speed. This is due to the fact that in these situations, the effectiveness of the rudders is too low because there is not enough inflow from the propellers to the rudders. It might be possible for future ship designs that this problem becomes more severe if ships are designed for significantly lower speeds. It can also be concluded from our investigations that EEDI-compliant twin screw ships which are equipped with CPPs and twin rudders will always have sufficient maneuvering ability in adverse weather conditions if the design ship speed is still reasonable.

8 REFERENCES


