**ABSTRACT**

The behavior of fast and relatively small ships in large following seas has been a serious concern for the operators for a long time now due to the possible occurrence of “broaching”. Due to the relatively low encounter frequency of these fast boats with respect to the large and high following and stern quartering seas an intensive coupling between surge, roll and yaw may occur which may finally lead to a capsize of the boat. The applied (and necessary) rudder control using the conventional rudder layout to prevent the excessive yaw motion may even further aggravate the situation.

In an extensive research project the Delft Shiphydromechanics Laboratory of the Delft University of Technology has constituted, developed, tested and evaluated the application of a “bow rudder” to control this situation much better. In conjunction with the conventional rudders (or waterjets) at the stern the application of such a bow rudder yielded a significant (up to 50%) reduction of the both the yaw and the roll motion in these conditions. Comparative studies of models with and without such a “bow rudder” in the towing tank showed no tendency to broaching of the boat with bow rudder at all any more. In a later design evolution this bow rudder has evolved into the development of a “retractable bow rotor”, using the well-known Magnus effect as the lift (steering) force generator. This made it possible to retract the rotor when it’s application was not asked for and thereby eliminating any possible negative effect on the resistance of the boat.

The results of earlier studies will be shown in this publication together with the obtained results of various towing tank test campaigns carried out to develop the rotor and also some different design concepts. Based on these tests an actual rotor has been build and placed on board a real ship, a DAMEN Stan Pilot 2205, a pilot boat of circa 22 meters long and capable of attaining a maximum speed of 25 knots. Herewith full scale measurement have been carried out at the North Sea and these results will also be presented here. In addition the results of tests specially of interest for a typical Pilot Boat operation will be shown.

**NOMENCLATURE**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tr>
<td>Lwl</td>
<td>Length waterline m</td>
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<tr>
<td>Bwl</td>
<td>Breadth waterline m</td>
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<tr>
<td>T</td>
<td>Draft amidships m</td>
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<tr>
<td>Δ</td>
<td>Displacement tons</td>
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<tr>
<td>Vs</td>
<td>Forward Speed knots</td>
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<td>Angle of wave incidence</td>
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<td>Significant waveheight m</td>
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<td>Metacentric Height m</td>
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<td>k</td>
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<tr>
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<td>Side Force N</td>
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<tr>
<td>Mz</td>
<td>Yaw Moment Nm</td>
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<tr>
<td>Mx</td>
<td>Roll Moment Nm</td>
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1. INTRODUCTION

The use of fast craft in a seaway has always posed many challenges to the comfort and safety of those on board and the ship itself. For a bigger part this is due to the fact that most applications of high speed with ships become more and more restricted to relatively smaller vessels. The combination of a high forward speeds and big ships is economically less interesting and also not very environmentally friendly. If we consider ships with speeds in excess of 25 knots as “fast”, their typical length is generally restricted to 50 – 60 meters over all. This implies that the waves they may encounter a significant amount of the time tend to be relatively large compared to the actual ship size. Improving sea keeping behaviour of these smaller seized fast ships remains still a challenge.

In the past decades considerable attention has been paid to improving the operability of fast ships in head waves. This because in those conditions severe discomfort to the people on board or even damage to the ship itself could be experienced. There was a strong focus on the vertical accelerations and so the emphasis was on the limitation of these vertical accelerations and in particular the limitation of the very high peaks, i.e. the slams. Emphasis in that time was on improving the hull shape. Typical improved hull forms in that respect have also been developed by the Shiphydromechanics Department of the Delft University of Technology and build by DAMEN Shipyards, such as the Enlarged Ship Concept (ESC), as described in the References [1] and [2] and the AXE Bow Concept (ABC), as described in References [3] and [4]. Much has been achieved with respect to the elimination of high peaks in these vertical accelerations and by doing so the operability has been increased significantly. In the recent past more emphasis has been placed on the introduction of improved control of the ship operating in waves by the introduction of automated thrust control and foils, Ref [5] and new type of interceptors Ref [6].

The present study is focusing on applying improved control when dealing with another restricting phenomenon for the safe operation of a fast ship when sailing in a seaway: broaching in stern quartering and following waves.

2. THE BROACHING PHENOMENON

Broaching is a well known phenomenon. Reference is made to an earlier publication of the author during the FAST Conference 2009 Ref [7].

Broaching may be best described as a coupled roll-yaw and pitch motion of the ship. From full scale experience and systematic research it is known that this broaching behaviour is often introduced through a unfavourable combination of lack of transverse stability of the ship (in particular at high at speed) and insufficient directional stability.

What generally happens can, in physical term, best be described as follows and is depicted in the accompanying Fig 1.
The ship under consideration is sailing at high speed in stern quartering seas. Through the high forward speed the encounter frequency of the ship with the waves surrounding the ship is generally low. Let us now assume the waves come in from the port quarter. When a high wave reaches the stern of the ship the stern is lifted. Because more often than not the stems of these ships are broad and flat the ship is simultaneously heeled to starboard. Through this combined pitch and roll motion the bow is now more deeply submerged. This deep submergence in combination with the roll angle introduces an asymmetry both longitudinal as athwart and so a considerable yawing moment on the ship is generated pushing the bow of the boat to port. In addition the whole sequence of events leads to a considerable loss of directional stability. This is further aggravated by the fact that these ships in most cases have two rudders each at one of the ship of which the port (windward) rudder will now most likely be partly lifted out of the water. In order to keep the ship as much as possible on a straight track or re-establish the original heading considerable rudder action is required. The rudders are pulled over to starboard to correct for the course change and the yawing moment. The rudders, both placed aft and underneath the hull, generate a lift force to port and so a counter balancing yawing moment to starboard. Simultaneously however they also generate a considerable rolling moment and in the particular situation under consideration to starboard, which leads to an increase in the already established and undesirable roll motion.

If all goes well control over the ship is maintained and the boat can be brought back to its original course with the roll- and the pitch angles re-established at reasonable (and manageable) values. In the worst case however the yaw motion gets out of control and the ship ends up beam to the seas and possibly at excessive heeling angle. In extreme cases this may even be leading to a capsize.

It is known from both extensive model experiments and full scale experience that the broaching phenomenon is most eminent in (steep) waves with a length in between 1.3 and 1.7 times the ship length. Therefore for a circa 40 to 50 meter length vessel this implies that the encounter frequency becomes almost zero with (deep water) waves with a wavelength of 60-80 meters, which are travelling at or around 20 to 23 knots.

3. THE VERTICAL BOW FIN

In an earlier publication Keuning and Visch at HIPER 2008 Reference [8], already reported about the beneficial effect on the coupled yaw and roll reduction in stern quartering waves which was achieved by installing a so called “vertical bow fin” at the bow of an fast 50 meter patrol boat designed according to the AXE Bow Concept.

In the “FAST project” the possible application of a vertical bow rudder to reduce the yaw and roll motions (and so the broach tendency) was already investigated. The very shape of the AXE Bow hull and in particular the fore body shape facilitated the introduction of such a vertical bow fin without much difficulty. The typical lines of an AXE Bow Concept design are depicted in Fig. 2.

![Figure 2: Typical lines of an AXE Bow Concept design](image-url)
The philosophy behind this vertical bow fin forwards is that it effectively generates the desired yawing moment to keep the ship on track. It decreases directional stability so increasing manoeuvrability and in addition it is more immersed and less emerged at critical situations in following waves. This is opposite to what happens with the usual rudders aft. At the same time: when controlling the yaw it produces a roll moment that actually reduces the prevailing roll angle instead of increasing it as is the case with the rudders aft. This is illustrated in Fig. 3.

The vertical bow fin (or bow rudder) as fitted on the AXE Bow model in the FAST project is depicted in Fig. 4.

First, in a small series of dedicated experiments carried out at the SMB of MARIN with this free sailing model of the AXE Bow, as depicted in Figure 2, the feasibility of the concept of the vertical bow fin to reduce roll and yaw in following waves was investigated and demonstrated. It reduced the yaw motion with some 40% and the roll motions by some 30% in challenging sea conditions.

Then, in an extensive study, reported by Keuning and Visch, see Reference [9], the efficiency of various seized vertical bow fins was investigated. These all had the same height (span) but different chord lengths. Their effectiveness in generating side force, yaw moment and heeling moment at various forward speeds and various yaw angles was investigated.
These tests have been carried out with the same model from the FAST Project. It was kept in its calm water trim and sinkage reference position as obtained from the earlier experiments. The following variables (and all their possible combinations) have been varied during these tests:

- Forward speed at 15, 25 and 35 knots full scale
- The fin angle between minus 20 and plus 20 degrees
- Three different yaw angles, i.e. 0 and plus and minus 5 degrees for the bow rudders

The tests generated a large amount of results. The general conclusion from these tests was that (not unexpected) the larger fin, with dimensions as shown in Figure 2, was the most effective one both in yaw and in roll. However it also generated the largest increase in the calm water resistance, and this also when the rudder was “not in use”, for instance in calm water or head waves conditions.

So an alternative configuration to the bow rudder was looked for. This was found in using a Magnus Rotor as the lift generating device instead of a wing. These rotors generate their lift very efficiently when rotated around their vertical axis and when placed in a free flow, just as a wing. An important parameter for the amount of lift generated is the relation between the rotational speed of the cylinder, the diameter of the cylinder and the free flow velocity (in this case the forward speed of the ship) These three determine the magnitude of the lift force generated.

Originally it was intended that this Magnus Rotor could be incorporated in the bow shape of the AXE Bow. These type of hulls have a vertical bow extending over the full height with a radius of circa 0.30 metres.

Extensive tests in the Delft towing tank with various configurations of the Magnus Rotor used as a bow rudder have been carried out. During these tests various layouts of the Rotor have been tested. Amongst these the concept in which the Rotor was incorporated in the AXE bow and then with various “gap” sizes, i.e. the clearance between the Rotor itself and the hull. But also a Magnus Rotor extending below the hull at the bow.

In these tests with the Magnus rotors different relations between the forward speed the and rotational velocity of the rotor, usually expressed in the “k” factor (Eq.1.), have been investigated. In the tests “k” varied between $k = 0$ and $k = 5$ with a step size of 1 for every forward speed.

$$k = \frac{Rpm \times \pi \times Dm}{Vm}$$  \hspace{1cm} (Eq 1)

From these tests with the various layouts of the Magnus Rotor it became evident that the configuration when the Rotor was extruding below the bow was by far the most effective. It did not suffer from any ventilation effects, as was frequently the case with the other configurations, because it was so far below the free surface. Also, due to its low position and large vertical distance from the Centre of Gravity of the ship, it generated the highest (beneficial) roll moment when in use. This particular layout could be rather vulnerable however. As it increases the draft significantly and is also the deepest part of the hull.

So yet another concept of the bow rudder was developed: i.e. the Retractable Magnus Rotor extending below the lowest (most forward) part of the AXE bow. Considerable benefit of this configuration is that the Rotor may be retracted when not in use. In that case there is also no negative effect on the resistance.

This configuration is depicted in Fig 5. During these tests the Magnus Rotor was placed underneath the same model as the one used for the earlier tests with the vertical bow fin.
For the sake of comparison the following Figures show the relative performance in \textit{side force} generated, resulting \textbf{yaw moment} and \textbf{heel moment} of the best performing (the largest) vertical bow fin and the retractable Magnus Bow Rotor underneath the AXE Bow of the ship.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5}
\caption{Retractable Magnus Bow Rotor layout on the AXE Bow model (measures in brackets are modelscale)}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6}
\caption{Side force, yaw and roll moment of the various bow fins and rotor configurations}
\end{figure}
From these results it may be seen that the retractable rotor is very efficient in generating the side force, the yaw moment and the roll moment. This can be attributed to both the efficiency of the rotor itself but also to its favorable position underneath the AXE Bow. Due to the geometry of the AXE Bow the rotor is far beneath the free surface, also when sailing in waves. This implies that no free surface effects occur on the rotor, such as loss of lift and ventilation. Also the relatively large distance to the Centre of Gravity of the ship implies that a considerable roll motion is generated, which significantly helps in reducing the roll motion.

4. FREE SAILING MODEL TESTS

In order to further check on the feasibility and effectiveness of the Vertical Bow Fin or the Bow Rotor it was decided to carry out a considerable number of tests with a free sailing model of the AXE Bow in irregular stern quartering seas. Since the Delft University has no facility in which such tests may be carried out these tests have been carried out in the Sea keeping and Maneuvering Basin (SMB) of MARIN at Wageningen. These tests were carried out using the same model as previously used in the FAST Project and earlier tests with Fin and Rotor as described in previous publications, See Ref [4] and Ref [5]. The main particulars of this ship are:

<table>
<thead>
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<th>Value</th>
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<tr>
<td>Length</td>
<td>55.0 meter</td>
</tr>
<tr>
<td>Beam WL</td>
<td>8.46 meter</td>
</tr>
<tr>
<td>Draft midship</td>
<td>2.26 meter</td>
</tr>
<tr>
<td>Displacement</td>
<td>517 tons</td>
</tr>
<tr>
<td>Speed max</td>
<td>50 knots</td>
</tr>
<tr>
<td>GMt</td>
<td>2.50 meter</td>
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</table>

Due to limitations of the available time in the SMB at MARIN a selection of the different bow rudder devices that would undergo the tests had to be made. Based on the results obtained so far on the effectiveness of the variously seized vertical bow fins it was decided to check on the largest bow fin only. The effectiveness of the side force production was the dominant factor in this choice and the larger extra calm water resistance taken as a point for further consideration in the future, maybe leading to a slightly modified section shape in that particular part of the fore body.

For the bow rotors the choice fell on the vertical retractable Magnus Rotor extending underneath the bow. Apart from its high efficiency this choice was further stimulated by the fact that this layout of the rotor yielded no additional resistance when not in use, because it is then retracted. Another benefit is that it is largely “fail save” in a sense that in the worst case, i.e. total mechanical failure, only a cylinder would protrude from the bow with no significant effect on the safety of the ship.

The tests were carried out with the free running model. The model was solely propelled by two waterjets. To make the model free sailing and controllable it was equipped with two water jets with steerable nozzles. The maximum deflection angle of the nozzles was restricted to 23 degrees either side. At the extreme aft end of the hull also two fixed skegs were fitted underneath the hull bottom, as is the case with all AXE Bow designs. The auto pilot used only took the yaw angle (actually the course) of the model and the yaw velocity of the model as an input. At this point no attempt was made to include the roll into the control algorithm of the autopilot.

During the tests with the bow fins there was a direct 1:1 mechanical link between the steering gear of the waterjet nozzles and the bow rudder. Only the direction of the deflection of the forward bow fin was reversed with respect to the aft “rudders” (i.e. the nozzles) to yield a
similar yaw moment resulting from the bow fin as was established with the steering nozzles aft. This implies that the maximum bow fin angle was also restricted to 23 degrees either side. During the tests with the bow rotor there were two autopilots used: one for the waterjet nozzles aft and one for the bow rotor forward. The auto pilot for the waterjets aft was completely identical to the one used during the tests with the vertical bow fins. The auto pilot for the bow rotor was slightly different in the aspect that it could be fitted with different control constants controlling the gain and the damping. It was further modified to yield as an output the rpm and direction of rotation (!) of the motor driving the rotor and needed to produce a desired side force at the particular forward speed of the ship at that moment. The unique SMB facility of MARIN allows the model to run completely free of the towing carriage in irregular waves from any direction. The course of the model is controlled by the autopilot.

The tests were carried out in a number of typical North Sea wave spectra. These spectra were chosen using the available wave scatter diagrams of that particular area. The first spectrum was chosen to represent conditions with respect to Significant wave height $H_s$ and Peak period $T_p$ which are only exceeded in 10% of the time all year round on the southern North Sea, i.e. $H_s = 2.5$ and $T_p = 6.75$ m. The second spectrum was chosen to yield steep (almost breaking) waves. The main particulars of these spectra are:

- a significant wave height $H_s$ equal to 2.50 and 3.50 meters,
- a peak period $T_p$ equal to circa 6.75 sec and
- a energy distribution over the frequency range according to the normalized Jonswap spectrum.

Considering the wavelengths in the spectra a forward speed of around 20 knots was chosen to give the largest likelihood of broaching in the situation chosen, i.e. a wave incidence angle of 315 degrees (i.e. port stern quartering). Other tests were performed also at higher speeds. In all the spectrum realization a considerable number of tests were carried out to obtain typical full scale test run duration of circa 2 hours. Some typical results in the worst conditions are presented in the following figures.
The results obtained during these model tests in the higher sea state, i.e. in the spectrum with a significant wave height of 3.5 meter, showed the same trend. The result of the roll and yaw motion with and without bow rotor when sailing in the higher seastate, i.e. $H_s = 3.5 \text{ m}$ at wave angle of 315 degrees and $V_s = 20 \text{ knots}$ are presented as Significant Double Amplitudes in Figure 9.
From all the results of the model tests it became evident that the Magnus Bow Rotor significantly reduces the roll and (in particular) the yaw motion of the ship sailing in high stern quartering waves.

4. FULL SCALE TESTS

Based on the promising results obtained so far it was decided in 2014 to build a full size prototype of the Retractable Magnus Bow Rotor in order to be able to carry out full scale measurements for a final "prove of concept". DAMEN Shipyards at Gorinchem, The Netherlands, as partner in the research project, offered the use of a newly developed Pilot Boat design the StanPilot 2205. This design was developed along the lines of the AXE Bow Concept. Length of the boat is 22.0 meter, Beam 5.0 meter and the maximum attainable speed is 25 knots. De boat is depicted in the Figure below.
Applying the Retractable Magnus Bow Rotor on a Pilot boat was expected to yield an important additional benefit in its operational use apart from the motion control in following waves.

When boarding (or un boarding) a pilot to a vessel generally spoken a forward speed of around 8 – 10 knots of both vessels is maintained. This to guarantee sufficient manoeuvrability of both vessels when so close together. A bow thruster is not effective anymore at those forward speeds. Using a bow rotor on the other hand would benefit from the forward speed and would make the necessary “crabbing” motion of the Pilot boat under forward speed close to the bigger ship highly controllable. In particular moving the Pilot boat away from the vessel after the pilot has boarded (or un boarded) is sometimes a difficult or even hazardous manoeuvre which can now be completely controlled.

The company Quantum Control was asked to design and build the Retractable Magnus Bow Rotor prototype together with the associated controller. All to the specifications supplied. Overall dimensions of this Retractable Magnus Bow Rotor were: Rotor Length 1.0 meter and Rotor Diameter 0.10 meter. Maximum rpm 1200. Electric Power 11 kW.

Some of the results of these full scale trials are presented here. Tests have been carried out on the North Sea between Hook of Holland and Scheveningen. Wind ZW to W 5 to 6 Bf. Significant wave height around 2.0 meters

In Figure 12 the distribution plots obtained for the yaw and roll motion at a forward speed of 17 knots and in stern quartering seas. The encounter frequency with the waves was almost zero (on average) Results are presented for both with and without rotor.

![Figure 12 Distribution plots for yaw and roll motion amplitudes at 17 knots with and without rotor](image-url)
At the higher forward speed of circa 19 knots the boat was overtaking the waves (on average) and the effect of the bow rotor was obviously less as shown in Figure 13 below. Although the extreme values were significantly lower for the situation with the rotor. Same legend as in Figure 12 applies

![Graph showing the distribution of yaw and roll motion amplitudes at 19 knots with and without the rotor.]

**Figure 13** Distribution of yaw and roll motion amplitudes at 19 knots
With and without rotor

Similar results were found for the all the other tests.

So the reduction in the sway and the roll motion with the application of the bow rotor is evident. The trend in the results found during the full scale trials confirm and closely relate to the earlier results found in the experiments carried out in the towing tank. During these full scale tests at the end of the tests some modest modifications have been applied to the steering gear of the craft to stimulate broaching under the given conditions. It turned out that the application of the rotor was even more beneficial then. To all people on board during the tests the effect of the rotor was obvious just already from visual observations alone.

Finally another interesting observation was made from the results obtained from these tests. This related to the lateral motions (combined sway and yaw motion) on the fore (at the bow) and the aft ship (at the transom) with and without the use of the rotor. These results are presented in the Figure 14.
This result may be of particular interest for (bigger) ships which can be equipped with helicopter landing decks on the aft ship. Smaller lateral motions in particular at the heli deck are crucially important for safe helicopter operations at sea.

5. CONCLUSIONS

From these tests it may be concluded that the application of a vertical bow rotor at the bow increased the control of a fast ship in stern quartering seas significantly. The reduction in the yaw and sway motions is up to 50% and therefore significant. Actually in none of the rather extreme wave conditions tested in the towing tank the model with the bow rotor performed anything like a broach. In some of these conditions the model without the rotor showed some tendency to broach although the (combined) maximum yaw and roll angles never approached seriously dangerous values but they were certainly uncomfortable. Also the reduction found during the full scale tests was significant and from the same order of magnitude as found during the model tests. Although the conditions met during the full scale tests did not provoke a broach, the reduction in the yaw and sway motion. Also interesting additional benefits may be used such as crabbing at higher forward speeds and reduced lateral motions on the helicopter deck.
ACKNOWLEDGEMENTS

The author wish to acknowledge the kind cooperation of the High Speed Craft Department of DAMEN Shipyards in Gorinchem for allowing the publication of thee results of this research.

References
Ref [1]:

Ref [2]:

Ref [3]:

Ref [4]:

Ref [5]:

Ref [6]:

Ref [7]:

Ref [8]:

Ref [9]: