Combined roll and yaw control on fast ships with an axe bow in stern quartering and following waves using a vertical magnus rotor

By

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Report No. 1648-P

10th international conference on fast sea transportation

Edited by
G. Grigoropoulos, M. Samuelides, N. Tsouvalis

Volume I
10th international conference on fast sea transportation

FAST 2009
5-8 OCTOBER 2009
DIVANI PALACE ACROPOLIS HOTEL, ATHENS, GREECE

Edited by
G. Grigoropoulos, M. Samuelides, N. Tsouvalis

PROCEEDINGS
Volume I
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PREFACE

Started in Trondheim, Norway, in 1991, FAST conferences take place every two years and are the world's leading conferences addressing fast sea transportation issues. FAST 2009, the 10th International Conference on Fast Sea Transportation is held in Athens, Greece, from October 5 to 8, 2009. The 10th anniversary of FAST coincides with a difficult period for the shipbuilding industry and shipping suffering under the impact of a worldwide recession. The latter is apparent through a common slowdown in the growth of the national economies, though the demand for energy, raw materials and finished goods is continuously raising, while banks are anxious for the recovery of their loans and restrict severely the capital flow towards the shipping industry. At the same time environmental issues emerged to major parameters of all production and operation activities.

Under these circumstances FAST 2009 brings together specialists from all over the world in all fields of naval architecture and marine engineering, namely from hydrodynamics, structures, ship design, propulsion and safety to present and discuss the current state of the art, the most recent research results and technologies, trends and future needs and opportunities that relate to fast ships.

This year in Athens, FAST conference includes two keynote speeches. One presents the future for commercial fast crafts and discusses the experience and lessons learned from events since the first FAST conference in 1991. The other addresses environmental issues that are of paramount importance and a matter of high concern for societies during the last decade.

In order to ensure the high quality of FAST 2009, all papers that are presented in the Conference and are included in the Conference Proceedings went a thorough two-stage review process of both abstracts and full manuscripts. The organizing committee wishes to express its thanks to all prominent members of the academia and the industry that participated in the process of review. Furthermore, we would like to express our thanks to the sponsors who supported the organization of the event. The experience and the advice that was provided to us by the international committee are also acknowledged.

Last but not least we would like to thank all of you who contributed either with papers or with your active participation in the audience of the conference for a successful event.

We wish you a fruitful and enjoyable stay in Athens,

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“COMBINED ROLL AND YAW CONTROL ON FAST SHIPS WITH AN AXE BOW IN STERN QUARTERING AND FOLLOWING WAVES USING A VERTICAL MAGNUS ROTOR”

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ABSTRACT
In the present study a research project is described which was carried out by the Shiphydromechanics Department of the Delft University of Technology in cooperation with DAMEN Shipyards in Gorinchem to investigate how the use of a vertical controllable bow fin or “magnus rotor” could improve the sea keeping behaviour of fast ships in stern quartering and following waves. In particular the resistance against large combined yaw and roll motions in these conditions with large waves, should be improved, because it is a known challenge with these ships in those conditions. The study showed that the application of a vertical bow magnus rotor placed on a so called AXE Bow yielded excellent results in that respect.

The results of this study together with the relevant results of earlier studies are presented in this report.

NOMENCLATURE

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1. INTRODUCTION
The use of fast craft in a seaway has always posed many challenges to the comfort of those on board and the safety of the ship. This is partly due to the fact that most applications of fast ships are restricted to the relatively smaller vessels. If we consider ships with speeds in excess of $F_n = 0.70$ as “fast”, their typical length is generally restricted to 50 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. Improvement of the sea keeping behaviour of these ships may be typically found in increasing the pure size of the ship, which obviously comes at a cost. Improving the sea keeping behaviour of the smaller sized fast ships remains a challenge.

In the past decades considerable attention has been paid to improve the operability of fast ships in head waves 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. Typical improved hull forms for mono hulls in that respect have been developed amongst others by the Ship hydromechanics Department of the Delft University of Technology, such as the Enlarged Ship Concept (ESC),
and the AXE Bow Concept (ABC), as described in the References. Much has been achieved with respect to the elimination of the high peaks in these vertical accelerations and by doing so the operability has been increased significantly.

In the present study, emphasis is now more placed on a few other restricting phenomena for the safe operation of a fast ship when sailing in a seaway. One of these limiting phenomena is the tendency to broach when sailing at speed in following or stern quartering seas.

2. THE BROACHING PHENOMENON

Broaching is a well known phenomenon. It may be best described as a coupled roll-yaw motion of the ship. From full scale experience and systematic research carried out with free sailing models in the model basin, it is found by physical observations and time trace analysis that this broaching behaviour is often introduced through a combination of a lack of transverse stability of the ship (at speed), insufficient directional stability and control and applied rudder action.

What generally happens can, in physical terms, 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 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 then not the sterns 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 deeper submergence of the bow in combination with the roll angle introduces an asymmetry, both in longitudinal and athwart direction, and so a considerable yawing moment on the ship is generated. This yaw moment is such that it is 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 side 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 the original desired 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 this is to starboard, which leads to an even further increase in the already established and undesirable roll motion.
If all goes well control is maintained and the boat is brought back to its original course with the roll- and yaw angle brought back at reasonable and manageable values. In the worst case however the yaw motion gets out of control and the ship usually ends up beam to the seas and possibly at excessive heel. In extreme cases this may even lead 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. In general evasive action by the crew will be taken by either a speed reduction or a change of heading, both leading to a loss of operability of the craft in service.

3. THE VERTICAL BOW FIN

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

This was a small part of a research project carried out by the Delft University in a joint industry project called “FAST”. This project was sponsored by the Royal Netherlands Navy, the U S Coast Guard, DAMEN Shipyards and MARIN, and aimed at developing a fast patrol boat of around 50 meters length capable of maintaining full operability at the North Sea all year round, at a maximum of 50 knots forward speed. The main results of this study were reported by Keuning and Van Walree in 2006 (HIPER 2006). The principal result was that the AXE Bow Concept came out best of the three concepts tested.

Although the emphasis of this particular FAST study was on the behaviour in head seas of various design concepts, also a considerable number of tests were performed in the new Sea keeping and Manoeuvring Basin (SMB) of MARIN at Wageningen, with free sailing models to investigate their behaviour in following and stern quartering seas.

In the frame work of this FAST project a vertical bow fin was also applied. It was designed to reduce the roll and yaw motion simultaneously in stern quartering waves and so reduce any possible tendency to broach. It was applied on the AXE Bow model. The very shape of the AXE Bow hull and fore body makes it possible to introduce such a vertical bow fin without much difficulty.

The typical lines of an AXE Bow Concept design are depicted in Fig. 2.

![Fig. 2. Typical lines of an AXE Bow Concept design.](image)

The philosophy behind this vertical bow fin forwards is that it effectively generates the desired yawing moment to keep the ship “on track”, because it decreases directional stability, so it increases manoeuvrability, and it is more immersed and less emerged at critical moments in following waves, as is the opposite case with the usual rudders aft. At the same
time it produces a roll moment that actually reduces the prevailing roll angle instead of increasing it. This is illustrated in Fig. 3.

![Diagram showing forces and moments](image)

**Fig. 3. The Principle of the bow fin.**

A typical vertical bow fin or bow rudder fitted on an AXE Bow could look like depicted in Fig. 4.

![Diagram showing bow fin arrangement](image)

**Fig. 4. Typical vertical bow fin arrangement on the AXE Bow.**

First, in a small series of dedicated experiments carried out at the SMB of MARIN with a free sailing model of the AXE Bow, as depicted in Fig. 2, the feasibility of the concept of the vertical bow fin needed to be demonstrated. The results turned out successfully: it reduced the yaw motion with some 40% and the roll motions by some 30%, in sea conditions corresponding to the worst 15% of the North Sea environment.

Then, in an extensive study the efficiency of various seized vertical bow fins in generating side force, yaw moment and heeling moment at various speeds and various yaw angles was investigated. The tests were carried out with a 6-DOF oscillator “Hexamove” used to position the model during the tests in all modes wanted.

These tests have been carried out with the same model as used in the FAST project. During these tests the model was always put in its calm water trim and sinkage reference position,
corresponding to the forward speed, as this was measured earlier. The following parameters and all their possible combinations have been varied during the tests:

- Forward speed of the model at 15, 25 and 35 knots full scale for the bow rudders.
- Forward speed of the model at 15 and 20 knots for the fixed rotors, due to limitations imposed by the available facilities at that time.
- An additional forward speed of the model at 25 and 35 knots for the retractable rotor.
- 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.
- Five different yaw angles, i.e. from 0 to plus and minus 5 degrees with a step size of 2.5 degrees for the rotors.
- In the case of the Magnus rotors different relations between forward and rotational velocity of the rotor expressed in the “k” factor (Eq. 1.), i.e. 0 to 5 with a step size of 1 for every forward speed.

\[
k = \frac{n \pi \sqrt{D}}{V_s}
\]

The tests generated a large amount of results for use in the mathematical model. The results presented here are primarily aimed at facilitating the comparison between the various configurations.

From this study it became apparent that the larger fin, with dimensions as shown in Fig. 4, was the most effective both in yaw and in roll. It also generated the largest increase in the calm water resistance when not in use however. Since this would be the case in a normal operational profile of a patrol boat for a considerable amount of time another solution was asked for.

This other solution was found in using a so called “Magnus rotor” as a lift generating device. These rotors (cylinders) generate lift very efficiently when rotating in a free flow. The relation between rotational speed, diameter of the cylinder and the free flow velocity, determines the magnitude of the lift force. Originally it was intended for this rotor to be incorporated in the bow shape of the AXE Bow, since these hulls have a bow radius of around 30 centimetres. These configurations, named “faired in” in Figure 6, showed however only effective when there was more than sufficient “free space” behind the rotor to guarantee sufficient “accessibility” of water flow around the cylinder. This layout is named “free” in Figure 6. Once again also this “free” layout of the rotor had a significant negative effect on the calm water resistance.

So another solution was developed: the **retractable rotor extending below the lowest part of the bow**. This configuration is depicted in Fig 5.

The very shape of the AXE Bow hull lends itself very well for such a layout. To which extend this holds true for more conventional bow shapes remains still to be seen. No attempt has been made so far to investigate this.

![Fig. 5. Retractable bow rotor layout on the AXE Bow model.](image)
The relative performance in side force, yaw moment and heel moment production of the best performing (the largest) vertical bow fin and the retractable bow rotor underneath the AXE Bow of the ship are presented in Figure 6.

From these results it may be seen that the retractable rotor is very efficient in generating the side force, yaw moment and roll moment. This can be attributed to both the efficiency of the rotor itself but also to its 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 the feasibility 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 of MARIN at Wageningen.

These tests were carried out using the same model as previously used in the FAST Project described in previous publications. The model used was the AXE Bow model of the FAST project, a 55 meter long patrol boat capable of attaining forward speeds up to 50 knots. The main particulars of this ship are:

- Lwl = 55.0 m
- Bwl = 8.46 m
- T = 2.26 m
- D = 517 tons
- Vmax = 50 knots
- GMT = 2.50 m

Due to limitations of the available time in the SMB a selection of the different bow rudder devices that would undergo the tests had to be made.

Based on the presented results obtained 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 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 and 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 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. The auto pilot that was used only took the yaw angle (course) 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.

The resulting algorithm used was of the following form:

\[ \delta_s = h_{\psi} \psi + c_{\psi} \psi \]

\[ n_r = h_{\psi} \psi + c_{\psi} \psi \]

During the tests with the bow fins there was a direct 1:1 mechanical link between the steering adjustment 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 was fitted with different values for the control constants, controlling the gain and the damping.

The unique SMB facility of MARIN allows the model to run completely free of the towing carriage in irregular waves from any direction. The basin is circa 200 meters long and circa 75 meters wide and has a waterdepth of circa 5 meters. Two multi flap wave makers on the long and the short side of the basin can generate waves of any direction. The free sailing model is "followed" by a combination of two towing carriages.

The tests were carried out in two typical North Sea wave spectra. These spectra were chosen using the available wave scatter diagrams of that area. The spectra were chosen to represent conditions which are only exceeded 15% and 5% of the time all year round. The main particulars of this spectrum are:

- A significant wave height $H_s$ equal to 2.50 and 3.50 meters respectively,
- A peak period $T_p$ equal to circa 6.75 seconds,
- An 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 the occurrence of large coupled roll and yaw motions possibly leading to a broach with a wave incidence angle of 315 degrees (i.e. port stern quartering). Other tests were performed also at higher speeds, i.e. 35 knots full scale. At that speed however an ever larger amount of the waves were overtaken by the ship resulting in a more and more head sea condition.

In all the spectra realizations a considerable number of tests were carried out to obtain a full scale test duration of almost 1 hour. The number of test runs in each spectrum was between 10 and 13. For the sake of comparison between the different model-configurations all the tests were carried out in as much as possible the same part of the time realizations of the spectra , i.e. all the models were sailing in more or less the same waves. Because free sailing models were used this is however not always possible to realize exactly. Due to the different responses to the disturbance of the waves a difference in position of the models in the towing tank as function of the time during the tests will occur.

All runs with the different models started at exactly the same position time in the wave train realization and on exactly the same position in the tank. The Rayleigh plots of the waves encountered by the various models show the very large agreement between the different tests in this respect.

In Fig. 7 the motions of the model with the Bow Rudder are compared with the motions obtained in the same conditions, i.e. $H_s = 2.5$ meter, with the model controlled with the nozzles only.

In Fig. 8 the motions of the model with the Bow Rotor are compared with the motions obtained in the same condition with the model controlled with the nozzles only in $H_s =2.5m$.

In Fig. 9 the motions of the model with the Bow Rotor are compared with the motions of the model controlled with the nozzles only, but now in $H_s=3.5m$.

In addition, in Fig. 10, a short time trace of the waves and the motions are presented for the runs in $H_s=3.5m$. 

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Fig. 7. Rayleigh Distributions and Statistics Free Sailing tests: Nozzles Only and Nozzles and Bow Rudder. With: Dir = 315 deg., Vs = 20 kn. and Hs = 2.5 m
Fig. 8. Rayleigh Distribution and Statistics Free Sailing tests: Nozzles Only and Retractable Vertical Bow Rotor. With: Dir = 315 deg., Vs = 20 kn. and Hs = 2.5 m

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Fig. 9. Rayleigh Distribution and Statistics Free Sailing tests: Nozzles Only and Retractable Vertical Bow Rotor. With: Dir = 315 deg., Vs = 20 kn. and Hs = 3.5 m

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In addition, in Fig.11, the wave spectrum and the distribution of peaks and troughs are presented for the 2.5 m significant wave height spectrum as measured during the tests in the SMB. The results presented in this plot are from the wave measurements carried out without forward speed and without any model in the basin. These are used to check on the correctness of the wave spectrum used. The spectrum with the Hs = 3.5 m has the same peak period as this one with Hs = 2.5 m and has also an energy distribution over the frequency range according to the JONSWAP formulations.

The wave time trace in Fig. 10 is measured 6.35 m in front of the model during the actual tests. It should be noted that the actual track of the models through the tank during the tests may differ for each test in the various conditions since it is a “free sailing” test. This will cause small differences in the wave time traces for each test. To obtain sufficient statistical accuracy, at least 10 – 12 runs were performed for each condition. This resulted in a total test run duration of approximately 2500 seconds at full scale. This was achieved for all conditions except for the condition with the model controlled by the nozzles only in the Hs = 3.5 m waves.

In this particular condition the yaw and roll response of the model got so large that it was decided, after two test runs, to cancel the further test runs in this condition, to avoid possible capsizing of the model or crashing of the model underneath the carriage, trying to “pursue” the model. This resulted therefore in a total run duration of that particular condition of about 550 seconds full scale. During these runs however rather extreme waves of around 6.5 meters in height were encountered. The Rayleigh plots presented in Figure 9 are derived from the same part of the wave realization in that spectrum for both conditions.
From all these results presented it is obvious that the application of the vertical bow rotor significantly reduces the roll and in particular the yaw motion of the ship sailing in stern quartering waves. From other tests carried out with the higher forward speed of 35 knots (full scale), of which no results are presented here, a similar trend (or even slightly better results) also became apparent. This is probably caused by the increased efficiency of the rotor in generating lift at this higher forward speed. The beneficial effect of the rotor remains when the heading of the ship with respect to the waves was changed to 300 and to 330 degrees respectively.

From analysis of the time traces of the various signals it showed that the control of the rotor rpm was not fully satisfactory during these tests. The electro motor used to drive the rotor had some physical difficulties in changing the direction of rotation from say 5000 rpm to the left to 5000 rpm to the right at a very short instant. There was some time lag between the control signal from the auto pilot and the actual activation of the rotor motor. This could lead to a phase shift (phase lag) of some 10 to 20 degrees in certain conditions. In future tests this phenomenon has to be overcome and it is certainly also an attention point for the full scale realisation of the system, although the rpm needed in full scale will be considerably lower than at model scale. To which extend this phase lag influenced the results obtained during these tests is not known yet.

From analysis of the time traces of the signals during the tests it also became apparent that the reduction is in particular large in the yaw motions, when the bow rotor is applied, more then in roll. Without the bow rotor the yaw angle, as in the time trace presented above, may increase to more than 30 degrees, which means in this case the ship comes beam to the seas. This results immediately in larger roll angles.

It should be noted that in the present tests the autopilot was only controlling the yaw motion. The positive effect of the yaw control on the roll motion is evident from the results. In the foreseeable future, also the roll motion will be introduced in the auto pilot controlling the rotor, to investigate if the application can be extended to a wider range of wave incidence angles.

4. 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. Actually in none of the rather extreme wave conditions tested the model with the bow rotor performed anything like a broach. In some of these conditions the model without rotor did showed a tendency to
broach, although the (combined) maximum yaw and roll angles never approached seriously
dangerous values. But they were certainly very uncomfortable.

The application of such a rotor on a more conventional bow will be an area of research in
the future, but some of the positive effects will be smaller when the rotor is applied on a less
deeply submerged bow.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the kind cooperation of DAMEN Shipyards in allowing
them to publish the results of this investigation.

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