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THE COMPARISON OF THE HYDRODYNAMIC BEHAVIOUR OF THREE FAST PATROL BOATS WITH SPECIAL HULL GEOMETRIES

by

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Abstract

For a group of interested parties, i.e. the Royal Netherlands Navy, Damen Shipyards at Gorinchem (NL), the Royal Schelde Group at Vlissingen (NL) and the United States Coast Guard from Baltimore (USA) the Shiphydromechanics Department of the Delft University of Technology and MARIN at Wageningen carried out an extensive research program on three conceptual designs of a 55 meter long monohull Patrol Boat. The boat should be capable of achieving 50 knots and in particular so in waves. The aim of the project was to investigate the feasibility of the designs in achieving a very high "all year round" operability under typical North Sea conditions. The conceptual designs made for this Patrol Boat were designed according to:

- *The Enlarged Ship Concept (ESC)*
- *The AXE Bow Concept (ABC)*
- *The Wave Piercer Concept (WPC)*

The project consisted of a series of full scale measurements on board an existing Fast Patrol Boat of the UK Customs and a large series of towing tank measurements. These full scale tests were carried out in the winter period near the Scottish west coast and aimed at establishing operability criteria for the safe operation of fast ships in a seaway.
Subsequently the three designs were tested for their calm water resistance and their behavior in head seas and following waves in the Delft towing tank. For the head seas conditions a large series of wave spectra have been used with an ever increasing significant wave height, starting from 2.0 and reaching as high as 4.5 meters and at three different forward speeds, i.e. 25, 35 and 50 knots. During these tests the motions, added resistance and vertical accelerations have been measured. In the following waves tests special attention has been given to the possible occurrence of deck wetness and bow diving. The limiting conditions in that respect have been established.

Here after both the Enlarged Ship Concept and the AXE Bow Concept designs were extensively tested as free running models at MARIN in Wageningen in their new Ship Motion Basin (SMB). Particular attention in these tests has been paid at stern quartering seas. These tests were specifically carried out to compare the designs on their possible sensitivity towards broaching and capsizing.

In the present paper a selection of the obtained results will be presented and discussed. An analysis of the results will be given and a comparison between the three concepts on their main issues regarding the seakeeping behavior will be presented and discussed.

1. Introduction

Due to the fact that the fast planing or semi-planing monohull has become the most commonly used hull shape for fast patrol boats and the alike a considerable design and research effort has been put in optimizing their behavior in a seaway. For a considerable period of time this behavior in a seaway has been considered to be the Achilles' heel of these designs and severely limiting their operability in a seaway. Both from theory as from real life experience it is known that "tearing around" with a planing hull in waves of some significance leads to a strongly reduced comfort on board. In particular the level of vertical accelerations on board may lead to uncomfortable and even unendurable situations and could even severely hamper the safety of the ship. Considerable improvements in hull design have been achieved over the last decades to improve on this behavior.
Since the introduction of the Enlarged Ship Concept (ESC) in 1995, Ref [1], [2] and [3] and the successive very successful application of this concept by DAMEN Shipyards in their "Stan Patrol 4207" line of patrol boats the Delft Shiphydromechanics Laboratory of the Delft University of Technology draw the attention of a number of ship owners/navies and naval ship builders. Particular interest arose to the new developments at the Department in the area of improved operability of fast monohulls in a seaway.

It was decided to establish a considerable research project on the comparison of various new design concepts on their hydrodynamic performance as fast patrol boats. A first phase would be aimed at the testing of a number of these new designs to gain more insight in their merits. The second phase and in succession to phase 1 is aimed at the development of new mathematical tools for the assessment of the hydrodynamic behavior of fast ships in waves. Parties involved were: the Royal Netherlands Navy, the United States Coast Guard, MARIN, DAMEN Shipyards and the Royal Schelde Group.

First a selection was made of available new concepts to be tested. After careful consideration the parties involved agreed upon the following three concepts to be investigated:

- The Enlarged Ship Concept (ESC) also the benchmark
- The AXE Bow Concept (ABC) as extension of the ESC
- The Wave Piercer Concept

Care has been taken to make the resulting designs "feasible" and not to disrupt the hydrodynamic comparison by largely differing main dimensions.

Phase 1 of the project was intended to yield usable results on the comparison between these concepts in order to show the participants the most likely "way ahead" in the new designs. In addition the experimental results obtained would be used in phase 2: the development of new mathematical tools.

The first part of phase 1 of the project aimed at gathering more information about the limiting criteria which should be applied on the motions and accelerations etc on board fast ships for their safe (and comfortable) operation in a seaway. There for a team of experts went onboard of a Stan Patrol 4207 the "VALIANT" of the U.K. Customs and Excise. The motions and accelerations were monitored in conjunction with wave measurements and video recordings. The team observed and noted the response of the crew and analyzed their reactions to the prevailing conditions.

The second part of phase 1 contained very extensive tank testing of the models in head-, stern-quartering and following-waves. The head- and following wave tests were carried out with all three models. The tests in stern quartering waves were limited to only the two best performing models that far, which turned out to be the ESC and the ABC.

During these tests, which were performed in ever worsening environmental conditions, the limits of each of the designs were established. Special attention has been paid to the anticipated possible flaws of each of the designs. These were expected to be found in the shipping of green water in head waves, bow diving in following waves and broaching with associated capsize in stern quartering seas. The tests schedules have been adapted to make sure that the worst possible but still realistic environmental conditions were investigated.

2. The Designs

In order to make sure that the new designs were more or less realistic and feasible a considerable design effort has been put in generating a solid "starting point" or "base boat" for the new designs. This design was made by the design department of the U.S. Coast Guard from Baltimore (USA). Within the framework of the goals set for the design by the parties involved they came with the following main particulars of the design:

Table 1: Base Boat Main Particulars

Length Water Line	52.58	m
Beam, Water Line	8.4	m
Draft, molded	2.68	m
Displacement	+/- 526	tonnes
Prismatic Coefficient Cp	0.7502	
Power	2 * 3900 Diesel	BHP
	1 * 29500 Gas Turbine	BHP

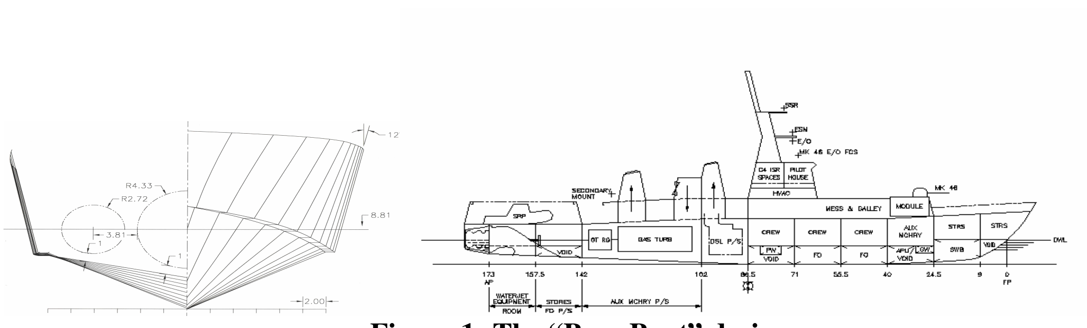


Figure 1: The "Base Boat" design

The boats were designed for an endurance of 7 days with a crew of 20. The "speed profile" was: 80% of the time at 10 knots, 15% at 17 knots and 5% at 50 knots. The speed range of 35-40 knots was to be considered quite feasible for present designs and ship owner requirements. The target of 50 knots maximum attainable speed was set to "pose a real challenge" for the future. The basic hull geometry and the principal profile of this base boat design are depicted in the Figure 1.

Using this data the Shiphydromechanics Department of the Delft University generated the three hull shapes for the research. The lines were generated along the lines of three rather new developed concepts for fast monohulls, i.e.:

- The Enlarged Ship Concept (ESC). Because it is used as the bench mark design for the others it is also referred to as Parent Hull Form (PHF)
- The AXE Bow Concept (ABC)
- The Wave Piercer Concept (WPC)

The philosophy behind the ESC and ABC is amply described in References [1], [2], [3] and [4] and will only very shortly be summarized here.

The ESC was first introduced in 1995. With the ESC the idea is to increase the length of the ship considerably with something like 25% whilst all other design characteristics such as speed, payload, functionalities and other dimensions are kept the same as much as possible. The void space thus generated in the design is used to optimize the hull geometry in particular at the bow sections from a hydrodynamic point of view. All this leads to a considerable improvement in the calm water resistance and the motions of the ship in a seaway. The resistance may be reduced by as much as 30% and the operability of a design along the ESC lines increases with some 70% when compared with the original (base) design. The building cost on the other hand increase only marginally with something between 3% and 5%. This concept has since 1997 been very successfully introduced on the market by DAMEN Shipyards with their Stan Patrol 4207 line of fast patrol craft.

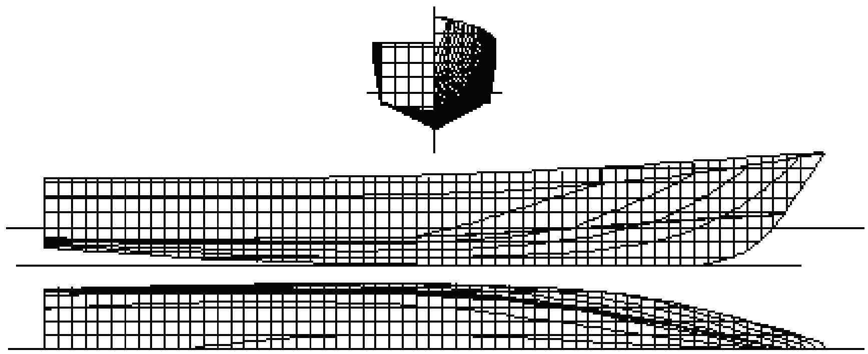
A further extension of this idea was introduced in 2001 also by the Shiphydromechanics Department of the Delft University. This became known as the AXE Bow Concept. In this ABC the sections in the fore ship have no flair (almost vertical sides), a vertical stem, the fore ship is very slender, there is a significantly increased sheer and a downwards sloping centerline at the bow. These modifications were aimed at reducing the wave exciting forces and the hydrodynamic lift in particular in the forward end of the ship whilst maintaining sufficient reserve buoyancy. For heave and pitch the resulting system could best be described as a “soft spring” system. Tests carried out till 2004 revealed a considerable improvement in seakeeping behavior with this concept when compared with the ESC. In particular the large peaks in the vertical accelerations at the bow and the wheelhouse were reduced significantly. Measurements and calculations however were mostly restricted to head wave conditions.

The Wave Piercer Concept has been introduced by various authors over the last decades. It comes in various shapes. The best known monohull applications were in the Very Slender Hull (VSH) and the Wave Piercer by Peter van Diepen in 2002. The principal idea behind the WPC is also to minimize the wave exciting forces by completely eliminating the above water part of the bow sections. Inevitably however this leads to a considerable decrement in the reserve buoyancy at the bow and in addition to this also in a significantly reduced deck area. At the time of starting of the present project no towing tank measurements of the motions in waves of this concept were available to any of the parties involved. Due to the very nature of the WPC design it was obvious that the deck area criterion in this design could not be met without increasing the size of the ship considerably. It was decided that this would lead to a disruption of the proper comparison of the three designs and therefore this criterion was not used for the WPC. In addition, also due to the shape of the WPC, this ship extends beyond the forward perpendicular and so has a slightly longer waterline than the other ships

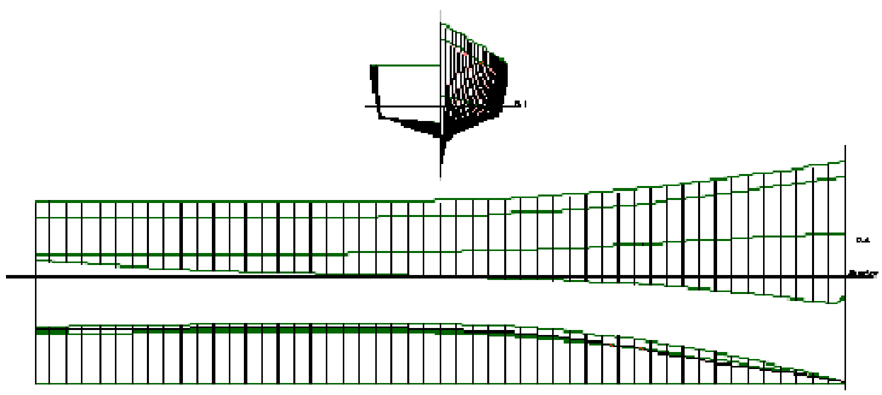
The beam of the ships was so chosen that an adequate stability of the craft with respect to their seakeeping behavior was guaranteed. A complete structural analysis of the ship was not made but the necessary vertical positions of the Center of Gravity of the three ships needed to establish sufficient transverse stability were considered realistic and feasible

Table 2 : Main Particulars of the three new designs

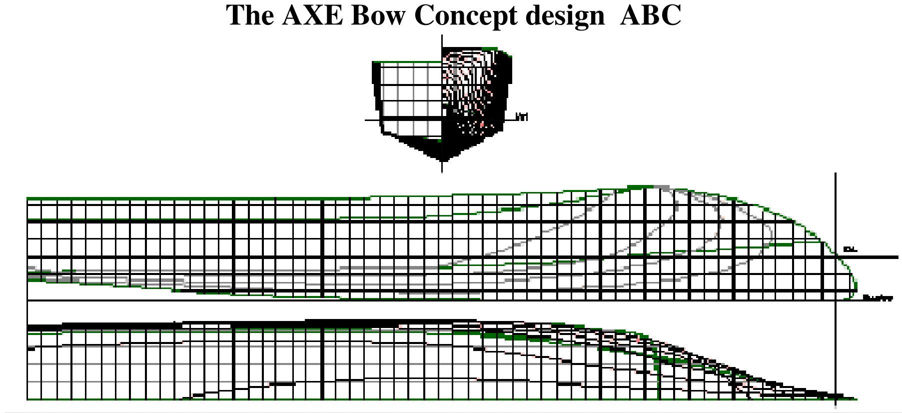
Designation	**Symbol**	**Unit**	**ESC (PHF)**	**ABC**	**WPC**
Length water line	Lwl	[m]	55	55	55.76
Breadth water line	Bwl	[m]	8.46	8.46	8.46
Volume of displacement	∇	[m^3]	516	517.4	515.9
Maximum draft	T	[m]	2.66	4.38	2.6
Wetted area	S	[m^2]	480.58	512.84	492.16
Metacentric height	GM	[m]	1.52	1.52	1.52



The Enlarged Ship Concept design ESC (PHF)



The AXE Bow Concept design ABC



The Wave Piercer Concept design WPC

Figure 2: The lines plans of the three new designs.

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3. The Full Scale results and criteria development.

In order to be able to compare the different design for their operability in a seaway it was felt necessary to gain some more insight in the "shape" and "threshold" values of the limiting criteria to be used in this respect.

In the commonly used operability analyses carried out for surface ships the operability in a particular operating area is determined using results of linear theory approach, i.e.: the response amplitude operators (RAO) of the motions under consideration are calculated, these RAO's are combined with the wave spectra derived from scatter diagrams and this yields the response of the ship in all those particular seastates. Applying a set of limiting criteria for motions and/or accelerations the operability of the craft in that particular operational area may be obtained. To be applicable in the "linear environment" used in this procedure most limiting criteria are formulated as significant motion values not to be exceeded. So in ship operability calculations it is quite customary to use the "root-mean-square" (rms) or the "significant values" ($a_{1/3}$) of the stochastic motions and accelerations under consideration as the formulations for criteria

For fast craft this procedure is not really applicable however, in particular when the vertical accelerations are concerned. This is due to the strong non linearity's in the response of the ship to the incoming waves. It was shown by amongst other Keuning in Ref [5] that the limiting criteria for safe operations for fast ships should be based on the actual distribution of the peaks and troughs of the responses (motions, accelerations) in the irregular waves rather then on the average or significant values. This implies that for each of the spectra denominated in the "wave scatter diagram" a full mission time simulation will have to be made in order to check whether the limiting criteria for the safe operation of the ship under consideration are superseded or not. This is by far a more time consuming procedure then the "linear" operability analyses carried out using the RAO's.

To determinate the most important limiting criterion or criteria for the operation of a fast ship in irregular waves an extensive series of full-scale experiments have been carried out by the Shiphydromechanics Department on board fast patrol boats and SAR vessels on the North Sea. In the frame work of the present study it was decided to put some more effort in defining the operability criteria by carrying out a extra series of full scale measurements on board real fast ships. Goal of these tests was to:

- gain more insight in what plays a role when the operability of these craft is considered and what should be used as a criterion
- try to establish limiting values for the criteria to be used
- define which design aspects are of particular importance for the safe operation of these craft

In combination with previous work carried out by the Shiphydromechanics Department measured results were now available from:

- full scale measurements on board the VALIANT , a Stan Patrol 4207 fast patrol boat (length 42 meter, speed 27 knots) of the UK Customs at the West Coast of Scotland..
- Extensive data from measurements and observations on board 3 different SAR vessels of the Royal Dutch Lifeboat Institution on the North Sea. Boats ranged from 10 to 16 meters and from 25 to 35 knots forward speed.
- Interviews with the crews of 3 Coast Guard cutters, Stan Patrol 4207 type ships

These ships have been instrumented, tested and monitored while performing their usual tasks under real circumstances at sea and operated by their professional crews during a large number of

runs. Besides the environmental conditions (wind and waves) the ship motions and accelerations as well as the "throttle control" and the voluntary speed reduction, as applied by the crew, have been recorded. In addition video recordings have been made of "the view from the bridge" during all tests. During all tests a team of experts from the Shiphydromechanics Department was on board to get their own impression of the circumstances, the behavior of the ship and the reactions of the crews. In the VALIANT tests also experts from MARIN and USCG were present. All measurements and visual observations during these tests were recorded and analyzed afterwards, including interviews with the crews and commanders about their findings, reactions and comments. Also the impressions and observations of the experienced members of the measurement teams formed a consistent part of the analysis of the results.
Due to the limited space available only a short resume of the findings of this research will be presented here. The most important conclusion drawn from these studies is that:

Generally spoken all crews imposed a voluntary speed reduction at roughly the same conditions on board the ship. It also showed clearly that the real measure for imposing a voluntary speed reduction was not the prevailing magnitude of the significant amplitude of the motions or vertical accelerations at that time, but the occurrence of the high peaks in particular in the vertical acceleration. The occurrence of such a "one big peak" generally provoked a speed reduction by all the crews just to "prevent it from happening again".
In fact such a reaction is more or less in line with a well known more general aspect of human behavior, namely that most people are inclined to react to "extremes" rather than to "averages".

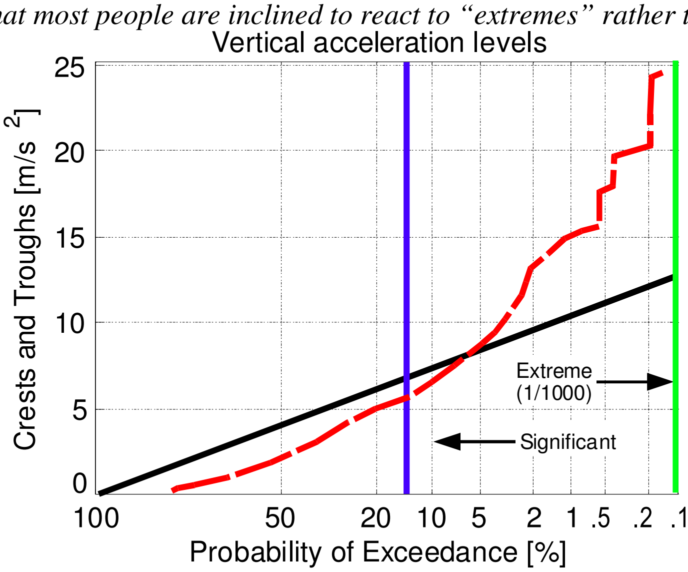


Figure 3: Distribution plot of crests and troughs of a stochastic signal.

A more detailed description of the findings in this criteria development study may be found in Ref [6]. In the frame work of the present paper it suffices to point out that of a stochastic signal (motion, acceleration etc) the significant value is not of interest but the occurrence of maximum peaks. For strong non linear systems, such as a fast planing boat in waves, this implies that time traces of the motion signals or results from time domain simulations must available and analyzed to produce the kind of distribution plots as shown in Figure 3.

From an operability point of view the ship with the black line result for the vertical acceleration is considerably better than the red-line result due to its higher extreme values. Even though the significant value (at roughly 13.5% probability of exceedance) is higher!! Some of the other findings of the research were:

- With designs like the "Valiant" and "Jaguar" (already optimized for the level of vertical accelerations in the wheelhouse) the prevailing vertical accelerations at the bridge or wheelhouse turned out to be not the determining factor for the crews to reduce speed. The occurrence of (very) high peaks at the bow (slamming) and the resulting all ship vibrations proved to be the limiting criterion for the crews to apply speed reduction.
- On the smaller SAR ships the occurrence of peaks in the vertical accelerations at the wheel house proved to be far more important. Here threshold values for both in the wheelhouse and at the bow should be applied.
- On smaller boats a higher level of vertical accelerations was accepted by the crews. On the smaller boats also active throttle control proved to be an important aspect for preventing high peaks in the vertical accelerations.
- Typical values for the maximum accepted vertical accelerations are: at the wheelhouse 8.0 m/sec^2 and at the bow 20 m/ sec$^{2.}$ For the smaller ships this proved to be 13 m/ sec^2 and 25 m/ sec^2 (Note: These values are based on elaboration and analysis of all the measurements carried out on the ships mentioned above. These reports are not available due to proprietary restrictions)

For the comparison of the three new designs in the present study these aspects have been used: i.e. the shape of the distribution curves of the vertical accelerations and he threshold values as formulated above.

4. The Calm Water Resistance

The calm water resistance of the three designs has been measured in the towing tank #1 of the Delft Shiphydromechanics Laboratory. The dimensions of this tank are: length 142 meter, width 4.25 meter and maximum water depth 2.5 meter. The towing carriage is capable of attaining speeds up to 7 m/sec. The model scale used during the experiments 1:20.

For the resistance experiments use has been made of the standard procedure as used in the Laboratory. This implies the use of a set of three carborundum stripes on the model for the turbulence stimulation in order to attain a fully turbulent boundary layer around the model. The increased of the drag due to the strips was determined using the standard procedure of the Delft Towing Tank. For the extrapolation according to Froude's method use has been made of the ITTC-57 extrapolation coefficient. The results are presented in Figure 4.

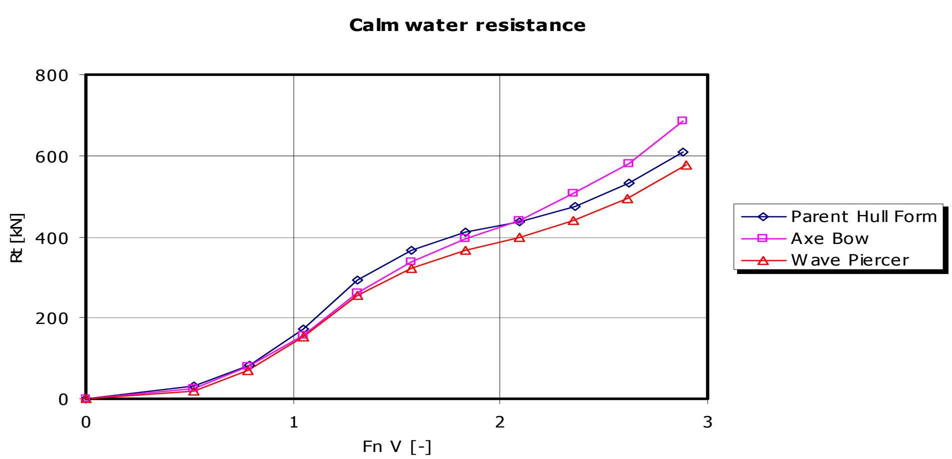
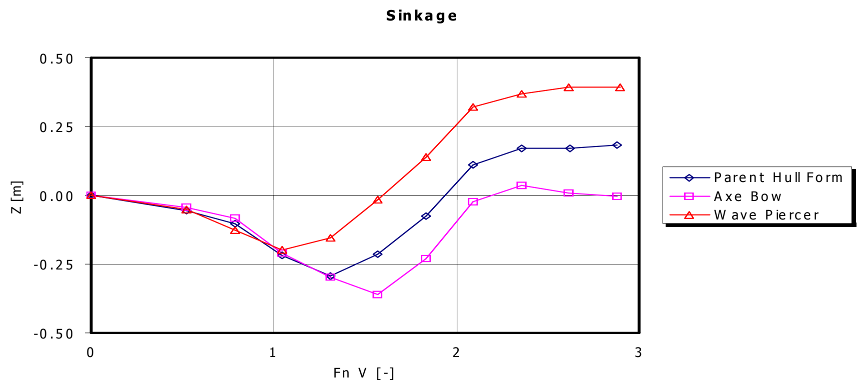


Figure 4:Calm Water Resistance of the three designs

As can be seen from these results the differences in the calm water resistance between the three designs are dependent on the speed range under consideration. Below circa 35 knots the ESC has a higher resistance when compared with the ABC. Above 35 knots this is reversed. The WPC generally has a lower resistance when compared with the other two.

Part of the explanation for these differences in resistance may be seen in Figure 5 in which the running trim and the sinkage (rise) of the designs are depicted. It is obvious from these plots that the WPC has the highest positive sinkage (i.e. comes out of the water most) in combination with the lowest trim (i.e. develops more dynamic lift). It should be noted however that the trim angles are rather small and the differences even smaller. The larger sinkage (rise) of the WPC will imply a larger reduction in wetted area likely to lead to a lower resistance.



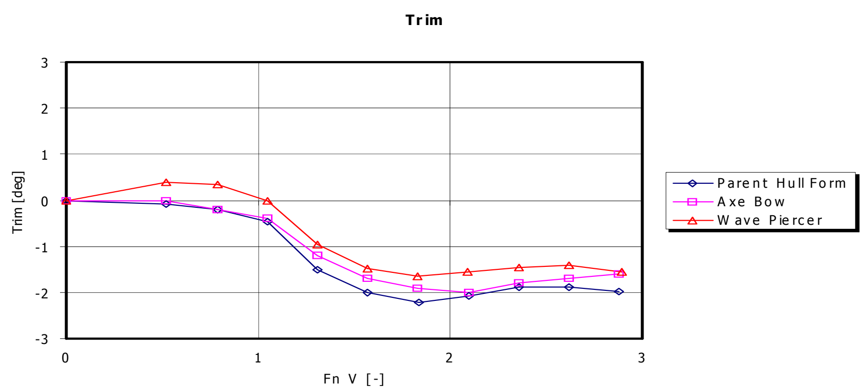


Figure 5: Trim and Sinkage of the three designs

5. Behavior in Head Waves

The same models of the new designs as used in the resistance tests have been used for the tests in waves. These tests have been carried out in the #1 towing tank of the Delft Shiphydromechanics Laboratory also. This tank is equipped with a hydraulically driven flap type wave generator capable of generating long crested regular and irregular waves. The models were towed in such a way that they were free to heave and pitch, but restrained in all other modes of motion

During these tests, the forward speed, the resistance, the heave- and pitch motion, the vertical accelerations at the Center of Gravity (CoG) and at the bow location have been measured. The heave and pitch displacements were measured using an optical tracking system. The resistance force is measured with a strain gauge force transducer and the accelerations are measured by means of gravity based acceleration transducers, which are mounted at the CoG and bow positions..

Prior to the test, the weight distribution of the models is adjusted to the design values of total displacement weight, longitudinal position and height of the CoG, i.e. LCG and KG and longitudinal radius of gyration :Kyy, according to the values presented in Table 2.
The elaboration of the measured data is as standard for these tests in the Delft Towing tank. This implies that for the heave, pitch, Az CoG and Az Bow signals so-called Rayleigh plots are presented. These are plots designed to plot the probability of exceedance of a random variable in such a way that a deviation of the variable's probability distribution of the Rayleigh one becomes immediately apparent. This is done by "pre-distorting" one of the axes in such a way that only the distribution of a Rayleigh distributed variable is plotted as a straight line. The plot can be used to check if the variable follows a Rayleigh distribution. Since the input signal for the system, i.e. the incoming environmental waves, are Rayleigh distributed, this is an efficient check on the linear behavior of the response under consideration.

For the tests in head waves, irregular wave trains are generated in the towing tank, which are presenting a JONSWAP wave spectrum shape. The integral wave parameters of the adopted wave spectra are presented in the tables below. In order to be able to define the limits of operability for each design within a manageable number of runs it was decided to use one spectrum shape with one particular peak period and with an increasing significant wave height. According to:

Table 3 : Wave conditions used during the head wave tests

Wave condition	Significant wave Height	Mean zero crossing period	Peak period Tp	Gamma
1	2	6	7.8	3.3
2	2.5	6	7.8	3.3
3	3	6	7.8	3.3
4	3.5	6	7.8	3.3
5	4	6	7.8	3.3

During all tests in addition to the measurements indicated above, video recordings have been made of the models for observing bow immergence, deck wetness and green water on deck.

Only the principal findings from the results of the head waves experiments will be summarized here:

- For all three designs when tested in comparable wave conditions, show roughly similar values for the significant amplitudes for the heave, pitch and vertical accelerations.
- Staying within the imposed limiting criteria was only possible with the ABC
- The maximum peaks encountered in the vertical accelerations at the CoG and in particular at the bow, showed large differences between the designs. The WPC generally had 40 % lower values when compared with the ESC (PHF). The ABC in general had more than 65% lower values when compared with the ESC (PHF)!
- The deck wetness of the WPC was quite considerable. It took on green water very often. This caused that carrying out the experiments in the higher seastates was impossible due to the enormous amount of (green) water on the deck. In real life this will pose serious problems and must certainly lead to a (impractical) fully water tight and streamlined

superstructure (if any). Breakwaters on deck will experience high loadings and inflict the philosophy behind the design.

The ABC design was the only one capable of sailing at 50 knots in the highest seastate tested. With this design no slamming and no green water was observed during any of the tests. To illustrate these findings the results a typical results of the distributions of the vertical accelerations at the bow is shown for all three designs at 35 knots and in a 3.5 meter significant wave height. The differences are obvious!

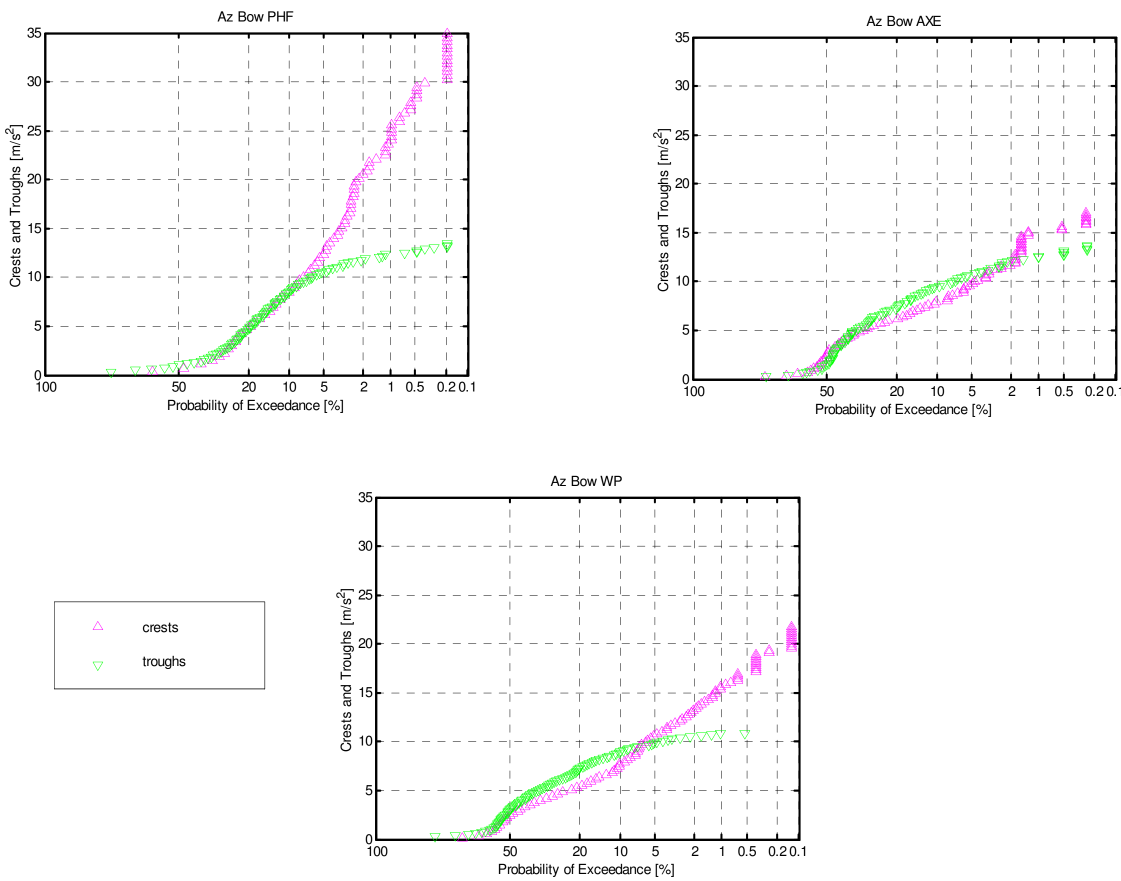


Figure 8 : Rayleigh plots of the vertical accelerations at the bow at V=35 knots and Hs= 3.5m for ESC (PHF) ABC and WPC

Applying the derived criteria for the acceptable occurrence of peaks in the vertical accelerations at CoG and Bow and the "acceptable" amount of deck wetness and solid water on deck taken into account, the following matrix for operability based on the experiments could be made (it should be noted that with the Wave Piercer design the limits of safe operability are also met by the enormous amount of green water on deck.) "Yes" means that the vessel can operate in that particular combination of speed and waves and "No" means that her motions and accelerations exceed the set criteria values.

These results implicate that with the AXE Bow Concept a 100 % all year operability may be achieved on all speeds investigated in a typical operational area as the North Sea based on the generally used scatter diagrams for this area.

Vs	25	25	25	25	25		35	35	35	35		50	50	50	50	50
H1/3	2.0	2.5	3.0	3.5	4.0		2.0	2.5	3.0	3.5		2.0	2.5	3.0	3.5	4.0
ESC	yes	yes	no	no	no		yes	no	no	no		no	no	no	no	no
ABC	yes	yes	yes	yes	no		yes	yes	yes	no		yes	yes	yes	yes	yes
WPC	yes	yes	yes	no	no		yes	yes	no	no		yes	yes	no	no	no

Table 4 : Operability matrix of the designs in the tested spectra using developed criteria

6. Behavior in Following and Stern Quartering Waves

6.1 Tests in following waves

Tests have been carried out in following waves to investigate the sensitivity of the three designs with respect to bow diving and green water. Visual observations and video recordings were important assets in judging the behavior of the designs.
In order to limit the amount of tests needed it was decided to perform these tests in regular following waves and at three speeds only, i.e. at 35 and 50 knots. The wave length at each forward speed of the ship was so chosen that the encounter frequencies were varied around the zero encounter frequency point. This implies that in these tests all situations were met, i.e.: the ship was overtaking the waves, the ship was going at wave speed (zero encounter frequency) and the waves were overtaking the ship. During the tests the wave height was systematically increased.
From these tests it became evident that:

- Bow diving did not occur with both the ESC and ABC designs in any of the conditions tested.
- Bow diving did occur with the WPC. Extreme deck wetness was regular.
- The tendency to bow diving diminished with increasing speed, partly due to the increased running trim at speed.
- The negative effects of bow diving did increase with speed.
- The response in heave was more or less linear with wave height and similar for all designs
- The response in pitch was almost linear with wave steepness and biggest with the WPC, and almost similar for the ESC and ABC designs.

6.2 Tests in stern quartering waves

The tests in stern quartering seas have been performed in the new Seakeeping and Maneuvering Basin (SMB) of MARIN in Wageningen. The dimensions of this tank are 170*40*5 meters. The towing carriage is capable of speeds up to 6 m/sec and spans the full 40 meters width of the basis. It supports a sub carriage capable of speeds up to 4 m/sec. On two sides the basis is equipped with segmented wave generators consisting of hinged flaps and capable of generating irregular and regular waves from any direction.

It was decided from the beginning of the research project that due to the limited time and money available only the two best performing designs so far would be used for the tests in stern quartering waves. This implies that only tests have been carried out with the ESC (PHF) and the ABC design.

From the beginning of the introduction of the AXE Bow Concept there were some serious concerns about her possible increased sensitivity towards broaching in following and stern quartering seas. So in the frame work of this research project it was decided that a thorough comparison between the two designs would yield the answer to this question. When no big differences would be found when compared with the more “usual” design such as the ESC this would certainly strengthen the introduction of the ABC.

The models used in the previous tests were now made suitable for free running tests by the implementation of propulsion and auto control. The propulsion consisted of electro motors and two water jets. The water jets had controllable nozzles for steering. The maximum nozzle rate was 10 degrees per second and is representative for high speed craft. The maximum attainable nozzle angle was 23 degrees both sides. Course control was established by auto pilot following standards used in the SMB. In addition both models have been fitted with a twin skeg arrangement at the stern for improved directional stability.

During these tests the models were completely free from the towing carriage. The sub towing carriage follows the model, which is under autopilot control. Due to the self propulsion and the added resistance in waves the model speed may vary somewhat during the runs. During the runs the waves close to the model, the forward speed of the model and all motions are measured. In addition the vertical accelerations at the same points as with the previous tests have been measured. Video recordings have been made of all runs. Care has been taken that both models met roughly the same part of the generated wave train in the various spectra used during the tests.

The wave spectrum used during the tests was a Jonswap energy distribution over the frequency range. The nominal spectrum had a significant wave height of 2.5 meters and a peak period of 6.75 seconds. This wave spectrum is representative for the North Sea conditions. In this area the probability of exceeding this wave height is about 15 % of the time. A limited number of tests have been performed in an increased wave height. For this condition the spectrum shape was the same but the significant wave height increased to 3.5 meters. Finally a series of tests has been carried out in what is known as a “bi-chromatic wave train”. These are semi regular waves consisting of two regular waves components with a slightly different period. The resulting wave train is a regular wave with increasing and decreasing wave amplitude in time. The primary wave length is so chosen as to be a sensitive situation for broaching for the particular model and forward speed. These tests are carried out to identify the sensitivity of the model under consideration towards broaching and to identify the limiting wave height for broaching in stern quartering waves.

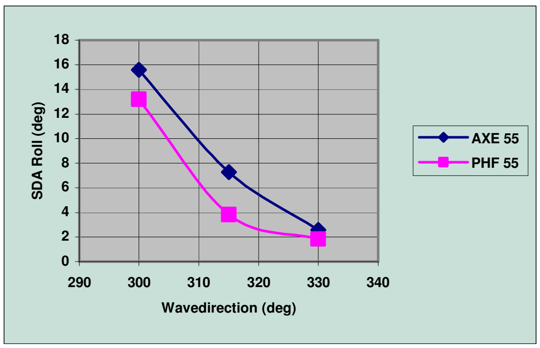
The general findings from this research may be summarized as follows:

- The ESC (PHF) design nor the ABC design performed any real broach (i.e. exceeding maximum heel angle of more than 50 degrees and yaw angle of 40 degrees) during any of the tests.
- There was not a large difference in broaching tendency or behavior between the ESC (PHF) design and the ABC design in this aspect.
- In general the ABC design had larger roll angles than the ESC design. The difference being not very large.
- Maximum roll angles for both designs did not exceed 35 degrees.
- Maximum yaw angles for both designs did not exceed 40 degrees.

- There was no significant difference between the two designs at either speed, i.e. 20 or 50 knots.
- Relative small changes in heading (wave direction) resulted in large differences in both the roll and the yaw behavior.

Some typical results of these tests will be shown here after. The results that are shown are limited in number but are typical for all the findings from this part of the project.

First the Significant Double Amplitude (SDA) of the roll motion at 20 knots and in 2.5 meters significant wave height will be compared for different wave directions, i.e. 300, 315 and 330 degrees is depicted in Figure 9 & 10:



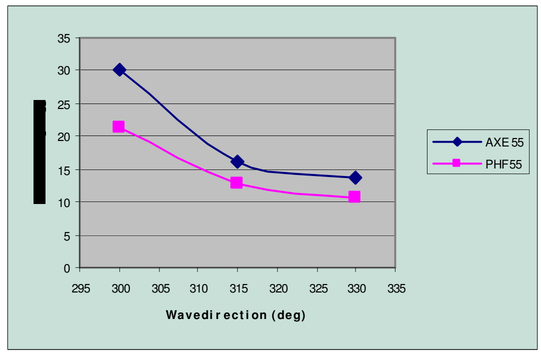
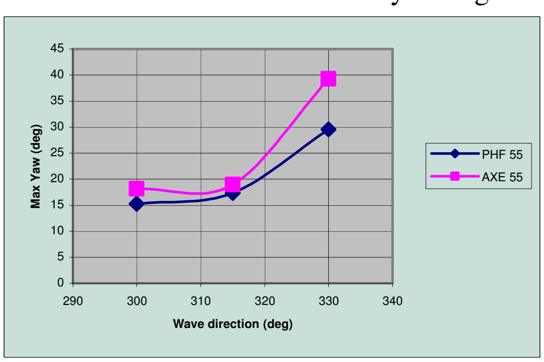


Figure 9 & 10: SDA and MAX Roll versus wave direction in Hs=2.5 m and Vs=20 knots

From this plot it is obvious that the ABC design rolls slightly more than the PHF design but the difference is rather marginal. It is obvious also that a slight change of heading may reduce the SDA for roll significantly. This is an important operational aspect, which should be considered also, because it has a strong influence in the final assessment of the operability of fast ships in rough seas. A similar trend with dependency on heading may be observed when the maximum roll amplitude, observed during the tests, is considered. This result is also shown in the Figure 9.

The results for the yaw motion are shown in the Figure 10. The plot for the SDA in yaw is presented. The result is similar as for roll although here the trend with wave direction is reversed, i.e. the models yaw more at 330 degrees and this yawing motion decreases at 300 degrees. Also here the differences between the two designs are small, except maybe for the 330 degrees heading in which condition the maximum yaw angle with the ESC (PHF) is some 10 degrees larger.



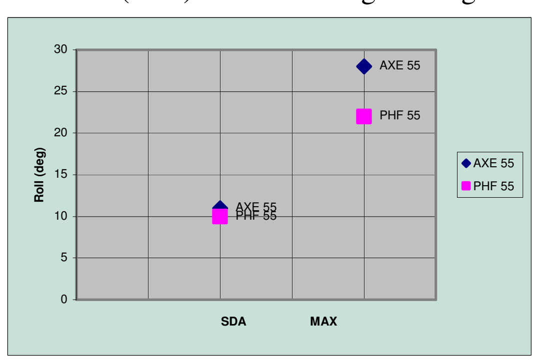


Figure 11 : Max Yaw vs. wave direction

Figure 12 SDA and MAX in roll at 50 kts.

The general trend in these findings holds trough also for the high speed of 50 knots. In this condition only the results for the SDA and maximum angle are shown in Figure 11 and 12 and only for one heading of 315 degrees Once again the differences between the two designs in the SDA are small, i.e. within 2 degrees difference and with the maximum there is a somewhat larger difference of around 8 degrees.

In general the conclusion from the tests in stern quartering seas was that there was no big difference between the two designs with respect to their sensitivity towards broaching. No extreme values for either roll or yaw have been observed during the tests.
It should be noted that although the trend in the difference between the two designs as far as the maximum angles is concerned is persistent, the maximum values for both the yaw and the roll angle are statistically not very reliable. It is based on the occurrence of just one "out shooter" that may be caused by the actual execution of the experiment which is difficult in particular at the higher speeds. The results for the maxima should be considered therefore with some "margin" of accuracy.

7. Conclusions

The conclusions of the research project can be shortly summarized as follows:

- The AXE Bow Concept has better performance in head when compared with the others.
- In following and stern quartering seas the behavior of the ABC and the ESC do not differ significantly.
- Criteria for fast ships should be based on extremes and not on averages (significant values)
- The differences in operability become in particular evident when the proper criteria for the assessment of the safe and comfortable operation of fast craft in waves are used.
- The Wave Piercer Concept suffers from serious deck wetness and green water in head waves and a tendency to bow diving in following waves.
- It should be noted that the Enlarged Ship Concept, which has been used as the Base boat or bench mark design in the present study, already yields a 40-50 % increase in operability when compared with "normal" designs.
- With the design along the ABC a 100% all year operability should be possible at the North Sea with a speed ranging from 35 to 50 knots.

These results have lead to the actual design and building of a new ship according to the AXE Bow Concept. Extensive full scale testing with this prototype in April 2006 has lead to a verification of the results obtained from the model testing and calculations. A photo of one of this new ship is depicted in the figure below.

Figure 13 : First AXE Bow prototype at trails

8. Acknowledgement.

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