"Further Investigation into the Hydrodynamic Performance of the AXE Bow Concept"

by

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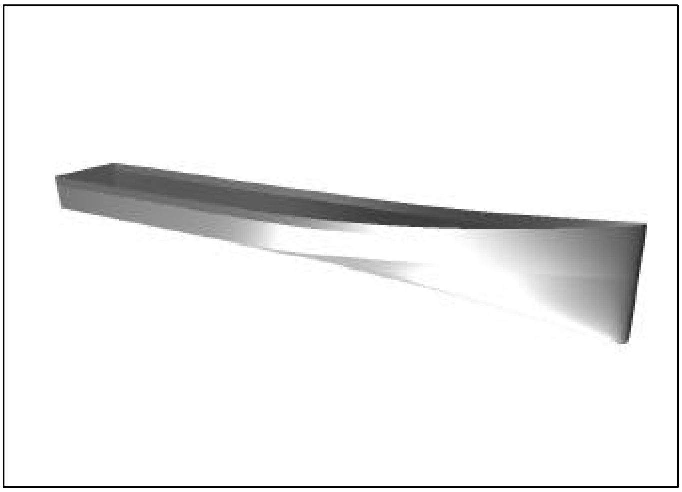
Abstract.

In an earlier paper the first two authors presented the results, which they obtained from a desk study on the influence of a rather pronounced bow shape modification on the seakeeping behavior of a fast patrol boat. This bow shape modification (the so called AXE bow) became possible after applying the Enlarged Ship Concept on a 26 meter length over all patrol boat and was first introduced by the first two authors in 1995.

In this paper the results of extensive towing tank measurements with the AXE Bow model and the same model with a conventional bow are presented and compared. These model tests have been carried out in the Delft Shiphydromechanics Laboratory. Tests have been carried out in calm water to measure the calm water resistance, the sinkage and the trim of the designs. In addition ship motion measurements have been carried out, primarily in head waves conditions, which were aimed at a validation of the computational results as presented in the previous paper, which were obtained from calculations with the nonlinear code "FASTSHIP". In addition a number of numerical simulations have been carried out with these two designs in moderate to high stern quartering sea states using the nonlinear code "FREDYN" of MARIN. Aim of these calculations was to compare both designs with respect to their motions in following waves (not available during the tests) and on their possible sensitivity for the broaching phenomenon and/or heavy rolling in those conditions.

The results of these tests and calculations and the comparisons between the two designs are presented and discussed in this report.



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NOMENCLATURE

L_{WL}	Length water line [m]
L_{OA}	Length overall [m]
FPP	Forward perpendicular
LCB	Longitudinal center of buoyancy [% L_{WL} aft FPP]
LCF	Longitudinal center of floatation [% L_{WL} aft FPP]
$H_{1/3}$	Significant wave height [m]
T_P	Peak period of wave spectrum [s]
RMS	Root mean square
GM_T	Initial transverse metacentre height [m]
GM_L	Initial longitudinal metacentre height [m]

1-INTRODUCTION

The application of fast monohulls in the role as patrol-, coastguard-, survey- and naval vessels has increased considerably over the last decades. The improvement of the seakeeping behavior of these fast monohulls has been a research topic for an even considerable longer period of time.

The seakeeping behavior of a fast patrol boat and more in particular the level of vertical accelerations onboard of the ship is the most important factor determining the operability of these craft in a seaway. From earlier studies, see for instance Reference [1], [2], and [3], it became apparent that the occurrence of (only a few) very high peaks in the vertical accelerations, in particular at the working area's onboard the ship, is a very important phenomenon for applying voluntary speed reductions by the crew and hence loosing the full operability of the ship. This effect of "responding to a single extreme" proved to be even more determining for the voluntary speed reduction than the prevailing significant value of the vertical accelerations. Improving on the operability of the ship therefore implies preventing these peaks in the vertical accelerations together with reducing the significant values of motions and accelerations.

This brought Keuning and Pinkster in 1995 Reference [1] and 1997 Reference [2] to the introduction of the Enlarged Ship Concept (ESC) in which concept the length of the ship is significantly increased, whilst keeping all other parameters and functions, such as beam, forward speed and payload, equal. This improved the resistance characteristics and the seakeeping behavior of the ship considerably with only a small penalty in building costs. In addition the longer length enabled the principal working areas to be located on (or closer to) their optimal position along the length of the ship, improving the operability in a seaway even further. Because in the application of the ESC room becomes available, in particular in the fore body of the ship, the bow sections of the ESC were modified in order to prevent the build up of large wave exciting forces when the ship is performing large relative motions with respect to the incoming waves. This introduced a bow with a very deep forefoot, very little flare, high deadrise, small volume and high sheer. By so reducing the nonlinear Froude Kriloff forces and the forces associated with hydrodynamic (planing) lift, the peaks in the vertical accelerations could be largely reduced.

In their paper at FAST 2001 they brought this concept a little further by introducing the AXE Bow concept. In this concept the stem is now vertical, the sheer largely increased, the bottom centerline sloped down towards the bow and the (bow) sections very, very narrow with almost vertical sides. The shape of the ESC design with this AXE bow is depicted in Figure 1.

In this study they based their conclusions on calculations and simulations with both design versions of the same patrol boat, i.e. with a conventional and with an AXE bow. Apart from calm water resistance and motions in a seaway consideration was also given to the course keeping capabilities of both designs. Although the tools used for these calculations were not specifically aimed at such radical designs as the AXE bow, the results promised an improved operability with hardly any high peaks in the vertical accelerations in a typical North Sea environment. There was some concern however as to the possibility of a greater likelihood of broaching in high following seas with the AXE bow concept.

So in the present study the emphasis is placed on validating the results obtained by the calculations and researching the possible vulnerability with respect to broaching in more detail. The first aspect has been dealt with by carrying out extensive model tests in the Delft towing tank with two models of the respective designs. Since ship motion tests in oblique waves are not possible in the Delft towing tank the second aspect has been dealt with by carrying out extensive computer simulations using the nonlinear time domain code “FREDYN” of MARIN at Wageningen. This computer code is based on a set of nonlinear equations in six degrees of freedom for large ship motions in severe wave conditions in order to be able to investigate safety aspects, such as the ultimate stability of ships. It has been extensively validated for all kind of commercial and naval applications. Both ships, i.e. the AXE bow and the conventional bow, were sailed “side-by-side” through a number of seastates and the resulting motions, i.e. yaw, sway and roll in particular, and the mutual differences analyzed. In the foreseeable future model tests will also be carried out with the two models in similar wave conditions to further validate the outcome of these simulations.

2-THE MODELS

The models used for the present study are the two designs as they were presented previously in Reference [3] to study the effect of bow shape on seakeeping performance of fast ships, i.e. the ESC 4100 and the AXE 4100 respectively.

The ESC 4100 is the design that was obtained when the original base boat from the study presented in 1995, the Stan Patrol 2600, was enlarged with some 50% without modifying the bow sections. In the present report she will be referred to as ESC 4100 and conventional bow. Here lines are depicted in Figure 2.

The other design is the AXE 4100. Her lines from stern to the mid-ship section are identical to the ESC 4100 but the fore body and in particular the bow shape has been developed along the lines of the bow shape modification as described in Reference [3]. Use is being made of the “void” space that is being created in the ESC to optimize the hull geometry of the design with respect to the wave exciting forces. From the results obtained from earlier studies, it was known that the major contribution to the wave exciting forces on a fast monohull in head waves originate from the non-linear Froude Krilov forces and the forces associated with non-linear hydrodynamic lift. The non-linear Froude Krilov force is found by integrating the hydrodynamic pressure in the undisturbed incoming wave over the actual momentaneous submerged volume of the hull, whilst this is performing large relative motions with respect to this incoming wave. The hydrodynamic lift is found by the change of momentum of the incoming fluid expressed in terms of added mass of the sections. This introduces a time dependent added mass of the sections, which also originates from the non-small relative motions of that section with respect to the

waves. By minimizing the change in submerged beam of the section this change in momentum and thus the hydrodynamic lift is minimized. This leads to very high deadrise sections in the bow area with little (change in) volume when heaving and pitching, with an increased sheer and a negative sloped centerline towards the bow. Emphasis is placed on maintaining sufficient reserve buoyancy in the bow and a comparable value for the longitudinal metacenter height. A more elaborated description of the design philosophy behind this design may be found in Reference [3]. The resulting lines plan of this AXE 4100 design is depicted in Figure 3.
The main particulars of both designs are presented in the Table 1.

TABLE 1. Main data of ESC 4100 and AXE4100

	Dimension	ESC4100	AXE4100
Length waterline	[m]	36.31	41.00
Length overall	[m]	41.00	41.00
Beam waterline	[m]	5.63	5.61
Draft	[m]	1.43	2.71
Design speed	[knots]	25.00	25.00
Volume	[m^3]	111.30	111.60
LCB	[%L_{WL} aft FPP]	55.40	54.90
LCF	[%L_{WL} aft FPP]	57.60	62.50
Wetted surface	[m^2]	193.80	222.30
Waterplane area	[m^2]	168.20	162.10
GM_T	[m]	3.06	2.54
GM_L	[m]	124.40	134.10

Details of the appendage and rudder configuration are not presented in these figures. The model tests in the tank have all been carried out with un-appended models. In the FREDYN simulations however both models have been equipped with two propellers, two shafts and two rudders. No additional (fixed) skegs have been added, although for the AXE 4100 they were considered to be appropriate in order to maintain sufficient course stability. For the sake of fair comparison however they have been omitted. The rudder areas for both the ESC 4100 and AXE 4100 were 2x1.20 m^2 (i.e. span 1.50 m and average chord 0.8 m).

3-THE MASUREMENT SETUP, -SCHEME AND CALCULATIONS

3-1 Towing tank experiments

The models of the designs for the experiments in the towing tank have been constructed of glass fiber reinforced plastic. The model scale used for the experiments is 1:20.
The tests have been carried out in the #1 towing tank of the Delft Shiphydromechanics Laboratory. The dimensions of this tank are: length 145 meter, width 4.25 meter and maximum water depth 2.50 meter. The towing carriage is capable of attaining speeds up to 8 meter per second. At one end the tank is equipped with a hydraulically actuated wave generator for both regular and irregular waves.
The models have been connected to the towing carriage by means of a so called “nut cracker”, a mechanical device that allows the model to heave and pitch freely but restrain it in all modes of motion. The resistance force is measured at the connection of the pivot point of the “nut cracker” situated in the Center of Gravity of the model. Two vertical accelerometers have been placed inside the models at 10% Loa from the bow and at 5% Loa in front of the Center of Gravity (the supposed position of the wheelhouse) respectively.
During the calm water resistance tests the sinkage, the trim and the resistance of the models has been measured over a speed range from 10 to 30 knots full scale.
Due to the strong non-linear behavior of these ships no regular wave tests have been carried out. All the tests in waves have been carried out in two different wave spectra and with the models towed at the design speed of 25 knots. These two conditions are summarized in Table 2.
The ship motions heave, pitch, the added resistance due to waves and the vertical accelerations at the two positions indicated have been measured. For each

condition at least 20 different runs have been performed in order to obtain statistically sufficiently reliable data for the probability of exceedance curves.

TABLE 2. Definition wave conditions for model tests

	Description of condition			Vessel speed prototype
Condition #	Wave direction (deg)	Sign. wave height (m)	Peak period (sec)	knots
1	180	1.25	6.00	25.0
2	180	2.25	8.00	25.0

The simulations in the head seas conditions have been carried out using the code FASTSHIP [4] of the Delft Shiphydromechanics Laboratory. This code is a non-linear strip theory based model describing the heave and pitch motions of fast monohulls in head waves. The actual “reference position” of the craft at high forward speed with respect to the sinkage and the trim is determined using the database of the Delft Systematic Deadrise Series. Using this steady state position the unknowns in the equations of the hydrodynamic-lift, the cross flow drag and -buoyancy forces are solved. In waves the prime exciting forces originate from the non-linear Froude Krilov force, obtained by integrating the pressure in the undisturbed wave over the actual submerged wetted area of the hull whilst performing (large) relative motions and the hydrodynamic lift associated with the change of momentum of the non-linear added mass of the heaving 2-D sections. This model is described in more detail in Reference [3]

3-2 FREDYN simulations

The simulations in the stern quartering seas have been carried out with FREDYN, a computer code developed at MARIN, Reference [5]. This code is based on a non-linear strip theory time domain six degrees of freedom mathematical model, in which linear and non-linear potential flow forces are combined with maneuvering and viscous drag forces. The non-potential force contributions are of a non-linear nature and are based on (semi) empirical models. The force contributions taken into account are:

- Froude Krilov forces (non-linear).
- Wave radiation (linear).
- Diffraction (linear).
- Viscous- and maneuvering-forces (non-linear).
- Propeller thrust and hull resistance.
- Appendages, rudders, skeg, active fins.
- Wind (non-linear).

In this model too, one of the most important contributions originates from the non-linear Froude Krilov force. The viscous effects include roll damping due to hull and bilge keels, wave induced drag due to wave orbital velocities and non-linear maneuvering forces with empirically determined coefficients.

In the FREDYN calculations slightly different conditions have been used. The maximum forward speed of the ships in FREDYN was restricted to a Froude number of approximately Fn = 0.38, which equals for the ships under consideration to a forward speed of 15 to 16 knots. The wave headings investigated were stern quartering and therefore the peak periods of the wave spectra have been slightly reduced in order to obtain a realistically low encounter frequency with

TABLE 3. Definition wave conditions for calculations

Condition #	Wave direction (deg)	Sign. wave height (m)	Peak period (sec)
1	60	1.10	5.0
2	60	2.25	7.0
3	60	2.25	5.0
4	30	1.10	5.0
5	30	2.25	7.0
6	30	2.25	5.0

(i.e. head waves is 180 degrees)

the waves to “stimulate” broaching. Six different conditions have been tested with changes in significant wave height and peak period of the wave spectrum. The duration of each simulation run was 1200 seconds full scale and each model was run through exactly identical wave realizations. The conditions tested are summarized in Table 3.

4-DISCUSSION OF RESULTS

4-1 Calm water results

In Figure 4 the results of the calm water resistance measurements are presented. The resistance, the running trim and the sinkage are presented as a function of forward speed for both models. All data are extrapolated to full scale.

From these results of the resistance as shown in Figure 4 it is obvious that the AXE 4100 has more calm water resistance than the ESC 4100. This may in part be attributed to her larger wetted area. Also the attempt made in designing the AXE bow, i.e. to minimize the development of the hydrodynamic lift in particular in the fore part of the hull, leads to a significantly lower running trim and a ship that “sits deeper” in the water (i.e. less rise of the center of gravity) when compared to the same hull with the conventional bow. Both models show hardly any hump in their resistance curve versus speed, which is in agreement with the very high Length to Beam ratio hulls coupled with a high Length Displacement ratio. This may be seen of the Figures 5 and 6.

In Figures 4, 5 and 6, also the results of an approximation of resistance, trim and sinkage based on the database obtained from the tests of the Delft Systematic Deadrise Series may be found. It should be noted that the ESC 4100 is “on the edge” of applicability of this database, considering the types of hulls used in the DSDS experiments and the high length to displacement ratio combined with a high L/B ratio of the ESC 4100. The AXE 4100 is out of range “by definition” due to her very different fore body shape. The correlation between the measured and the calculated results is nevertheless quite satisfactory for the ESC 4100 but not that good for the AXE 4100 design.

4-2 Head waves results

The results of the vertical accelerations in the head seas condition as measured in the towing tank are presented in the Figure 7 for Condition #1 and in Figure 8 for Condition #2. Due to space limitations, only a few results will be shown here. In figure 7 the vertical acceleration at a position 10% L_{WL} aft of the FPP are presented for condition #1. In figure 8 the vertical acceleration in the CoG are compared for condition #2. For operability assessment the accelerations at the wheelhouse are dominant. The accelerations at the bow are important with respect to slamming. Due to limitations in the amount of data obtained during the tank tests, the plots presenting the probability of exceedance do not fully extend into the low probabilities (less than 0.2 percent). So comparison between the two designs is best based on say a probability of 1%, since for this probability of exceedance enough statistical reliability (i.e. encountered waves) from the model tests is obtained.

From the results in Condition #1 (representing a quite frequent North Sea condition), which are depicted in Figure 7, it may be seen that the significant value of the vertical accelerations at the bow (which lies at roughly 13% probability of exceedance) in this seastate is roughly the same for both designs. However there is a considerable difference between the two designs at the lower probabilities, i.e. at the more extreme peaks. For instance: at 1% probability of exceedance (so for every one out of hundred waves) it reads approximately 17 m/s^2 for the

TABLE 4. Results of FREDYN simulations for rudder motion

	Description of condition			FREDYN results for ESC4100			FREDYN results for AXE4100		
Condition #	Wave direction (deg)	Sign. wave height (m)	Peak period (sec)	rms (deg)	min (deg)	max (deg)	rms (deg)	min (deg)	max (deg)
1	60	1.1	5	2.48	-6.63	6.90	4.46	-14.23	9.49
2	60	2.25	7	3.89	-7.23	14.61	5.76	-20.65	16.35
3	60	2.25	5	6.67	-21.33	35.00	9.18	-35.00	24.98
4	30	1.1	5	1.97	-3.97	5.50	3.85	-10.28	10.14
5	30	2.25	7	2.48	-5.02	7.57	4.49	-15.55	8.79
6	30	2.25	5	4.96	-15.60	19.87	6.93	-15.44	25.75

conventional bow versus just 12 m/s^2 for the AXE bow. Also the curve shown for the conventional bow is much steeper at the end then the curve of the AXE bow, making the assumption that much, much higher peaks will be reached with the conventional bow quite justifiable. Although not shown here the results at the wheelhouse position in condition #1 show that the extremes there, even at 0.1% of exceedance (one out of a thousand), remain well below the value of 9 m/s^2 for the AXE bow. This means full operability in that wave condition when asked to meet the standard criteria set by the Dutch National Authorities for patrol boats.
For Condition #2, which represents a “wave condition” of roughly double wave height but with a much longer wavelength (representing a condition equally frequently met in a more Atlantic Ocean type of environment) the same result is found: i.e. at 1% exceedance the AXE bow performs considerably better with respect to the extremes. These are some 35% lower, i.e. 14 m/s^2 versus 19 m/s^2, for the AXE bow design in comparison with the conventional bow. The peaks (0.2 % probability of exceedance) in the vertical accelerations at the wheelhouse in this condition, as shown in Figure 8, reach values of circa 12 m/s^2 versus 15 m/s^2 for the AXE and the conventional bow respectively.
The results obtained from the simulations with FASTSHIP are plotted in the same figures. From comparison with the towing tank results it may be concluded that for the condition #1 the correlation between measured and calculated results is quite satisfactory for the ESC 4100 design. For the AXE 4100 however the results for the “downwards” accelerations show a satisfactory agreement while at the same time the simulated “upward” accelerations show a considerable difference, i.e. the simulated results are some 20% higher than the measured results. The cause of this discrepancy is not yet clear but will be further investigated. The calculated and measured curves however do show very similar trends over the entire range.

4-3 Results of the FREDYN simulations in stern quartering seas.

The results of the FREDYN simulations are presented in a somewhat different way. In order to make the comparison between much more motions possible within the context of this paper the “r.m.s.” values have been plotted for both designs on a basis of a variation in the significant wave height $H_{1/3}$ and the peak period T_p of the wave spectrum for the two headings tested. The results plotted on basis of the significant wave height (keeping T_p constant) are presented in Figure 9 and the results plotted on basis of the peak period of the wave spectrum (keeping $H_{1/3}$ constant) in Figure 10.
First of all it should be noted that neither of the two designs ever performed anything like even the beginning of a

broach or even a severe rolling motion during any of the performed simulations.

For the 30 degrees heading situation the differences between the designs in the low significant wave condition are marginal. For the high wave condition the AXE bow has significant lower level of vertical accelerations both at the bow and the wheelhouse and less heave and pitch. The rolling and the yawing however is significantly higher for the AXE bow, nevertheless the response is still quite moderate (highest r.m.s. values are 5 and 3 degrees respectively).

This difference in roll and yaw generally holds true for the 60 degrees heading situations too, in which condition however the differences in the level of the vertical accelerations, the heave and the pitch between the two designs becomes marginal. But these values are quite marginal all together in these conditions.

The results plotted on basis of the peak period show in general an increased response with the shorter (and therefore steeper) waves. Again with 30 degrees of heading the AXE bow shows lower values for the vertical accelerations, the heave and the pitch but higher r.m.s. values for the roll- and yaw motions. In the 60 degrees of heading condition the influence of the peak period becomes marginal, but still the AXE bow rolls and yaws more. In general the AXE bow showed significantly more roll and yaw (course deviation).

From the simulations it was noticed that for condition #6 the craft with the conventional bow showed a “surf riding” behavior (7 occurrences) associated with high pitch angles and corresponding high vertical accelerations. The same surf riding behavior happened with the conventional bow in condition #3. The AXE bow concept did not show this behavior in the same wave realizations.

Finally it is of interest to compare the rudder motion of both designs necessary to maintain the ships course (as much as possible). These results are presented in Table 4. These results (r.m.s. and maxima) reveal that the AXE bow needs considerably more rudder motion to keep its track and this increases with the wave steepness. This is in line with the earlier findings by Keuning et al in their previous report on the application of the AXE bow concept, Reference [3], in which a certain tendency for course instability was noticed for the AXE bow concept. Although it obviously does not lead to any broaching and/or course instability in the conditions investigated here it may very well lead to an adaptation of the AXE bow design towards an increased rudder area and/or larger skegs aft. In the present study these have been omitted to make a fair comparison between the two design concepts feasible. In a later study these will be added to investigate how much bigger they should be and if these have any effect on the other motions.

5-CONLUSIONS

From the present study it may be concluded that the application of the AXE bow concept shows very good promise for optimizing the seakeeping behavior and operability of fast patrol boats in a seaway.

The peaks in the vertical accelerations in the head seas conditions are some 40% lower with the AXE bow.

Although roll and yaw do increase with the AXE bow concept there appears to be no increased tendency for broaching and/or course instabilities in following and stern quartering seas. In the simulations surf riding did occur with the conventional bow and not with the AXE bow.

The available computational methods used in this study still lack sufficient accuracy in certain conditions for a proper prediction of all the hydro-mechanical aspects involved when assessing the behavior of something like the AXE bow design.

6-RECOMMENDATIONS

In particular, the maneuvering and broaching result will be validated in the near future.

Further research to assess all aspect involved, also structural- and design aspects, is recommended.

References:

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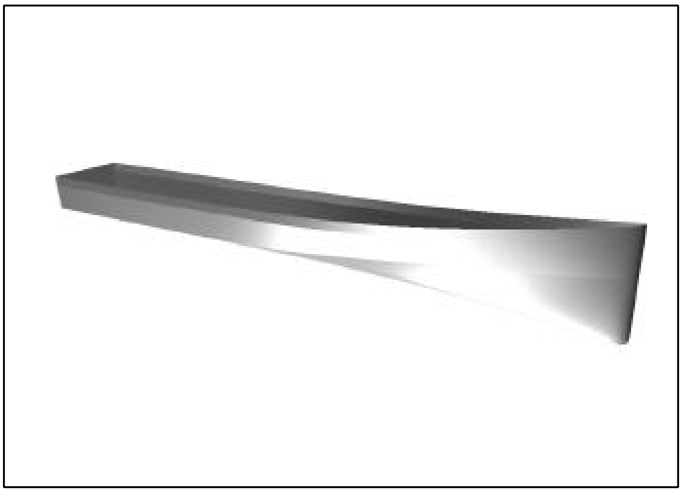


Figure 1. 3-D rendering of shape of ESC with the Axe bow.

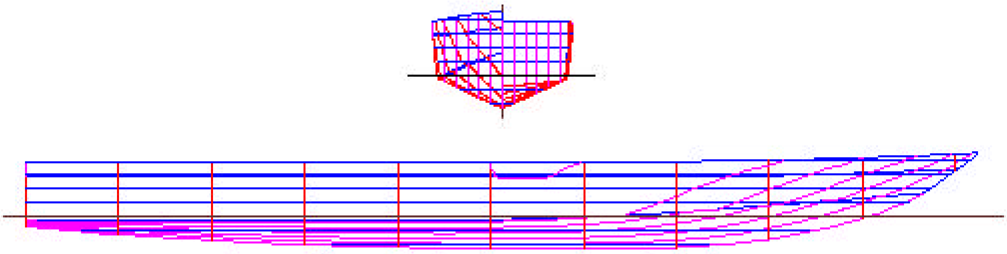


Figure 2. Body lines of the ESC4100.

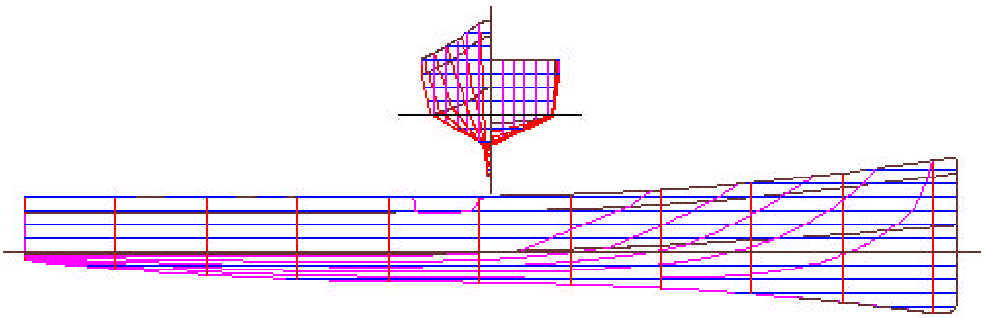


Figure 3. Body lines of the AXE4100.

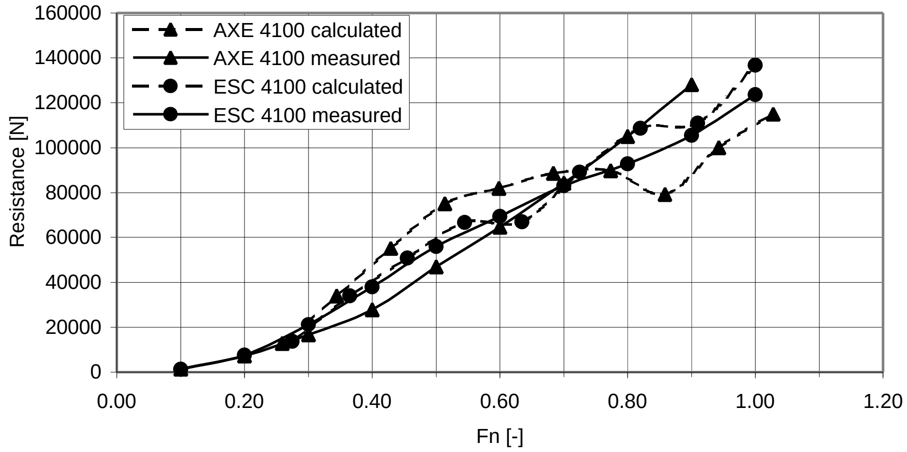


Figure 4. Calm water resistance of ESC4100 and AXE4100.

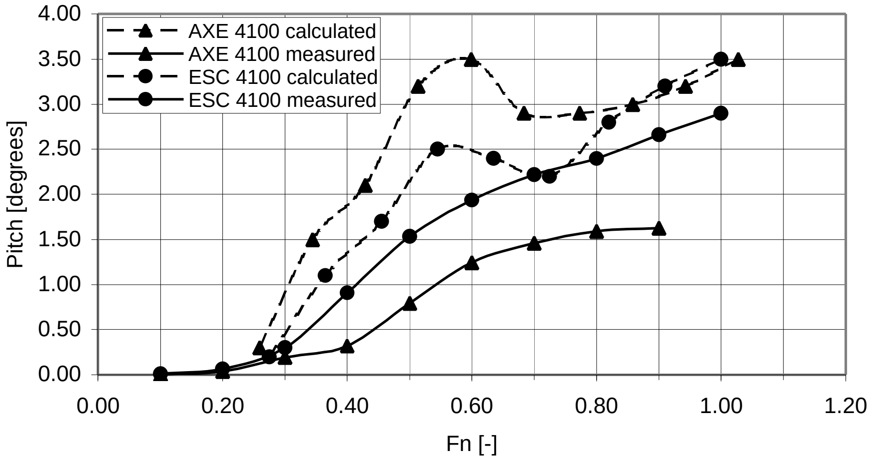


Figure 5. Running trim (pitch) of ESC4100 and AXE4100.

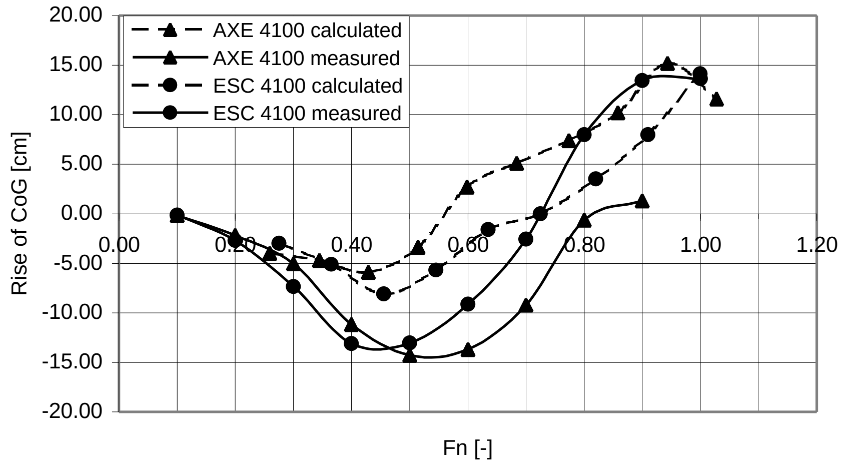
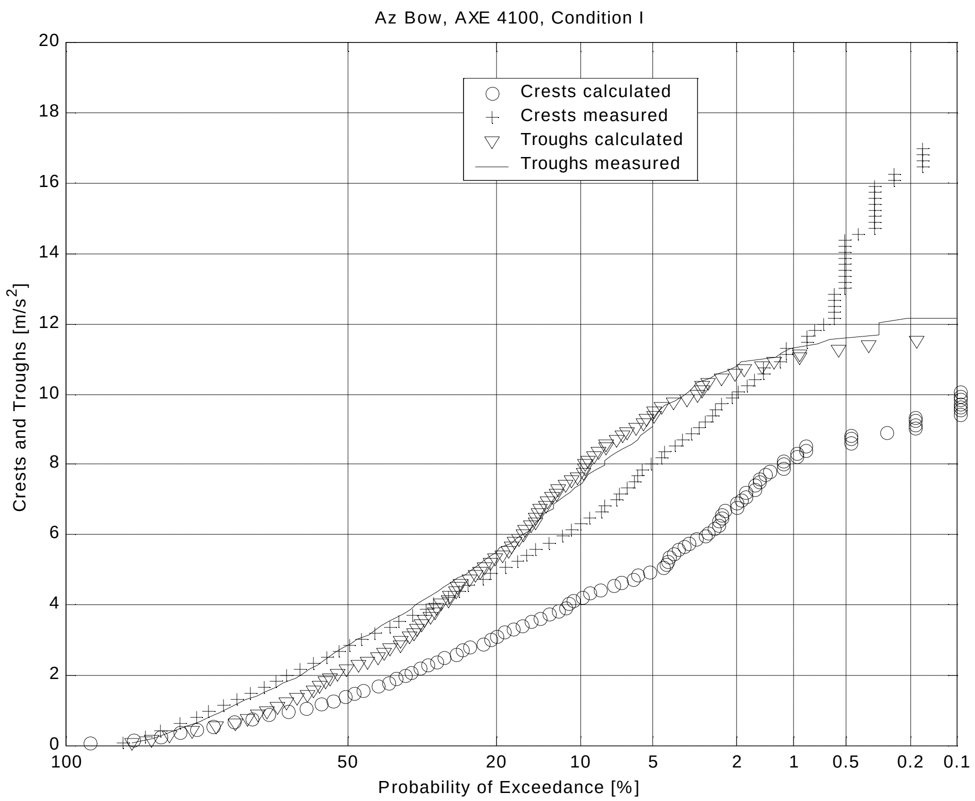


Figure 6. Sinkage of Centre of Gravity of ESC4100 and AXE4100.



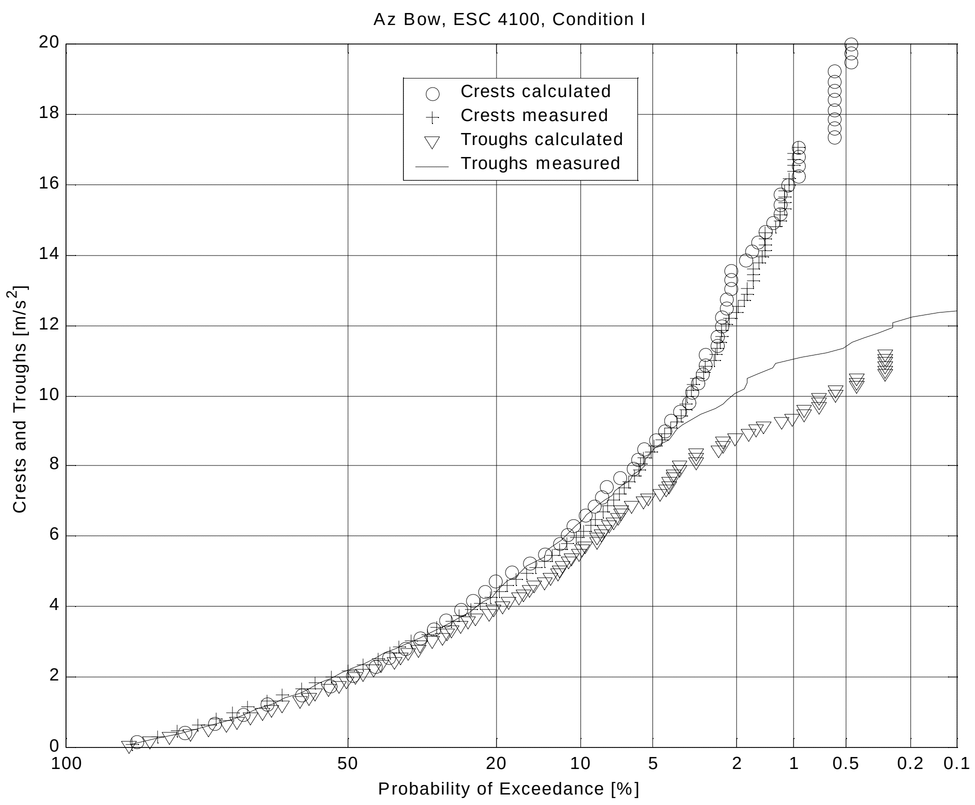
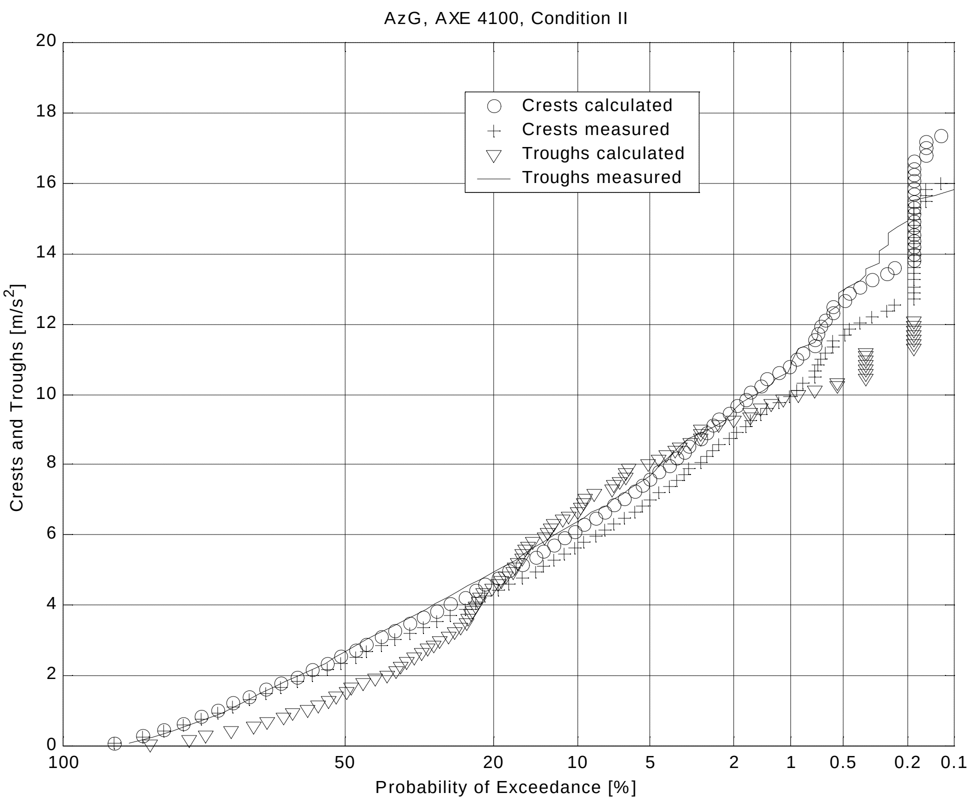


Figure 7. Vertical acceleration bow in head seas for condition #1 (H_s=1.25 m, T_p=6 s).



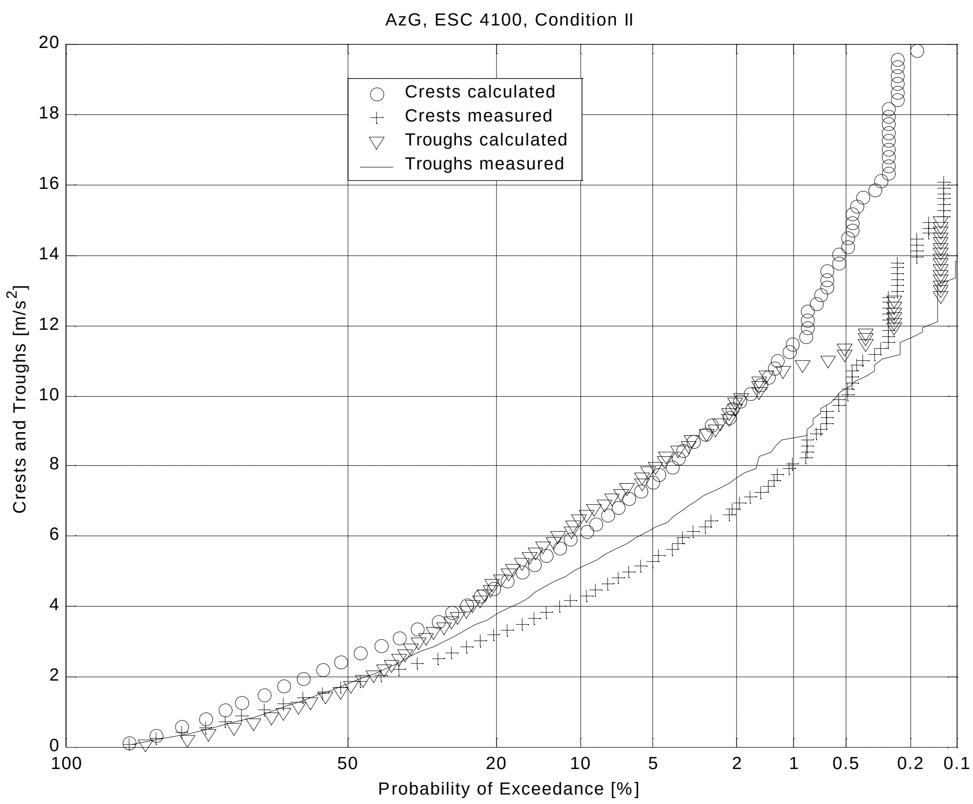


Figure 8. Vertical acceleration bow in head seas for condition #2 (H_s=2.25 m, T_p=8 s).

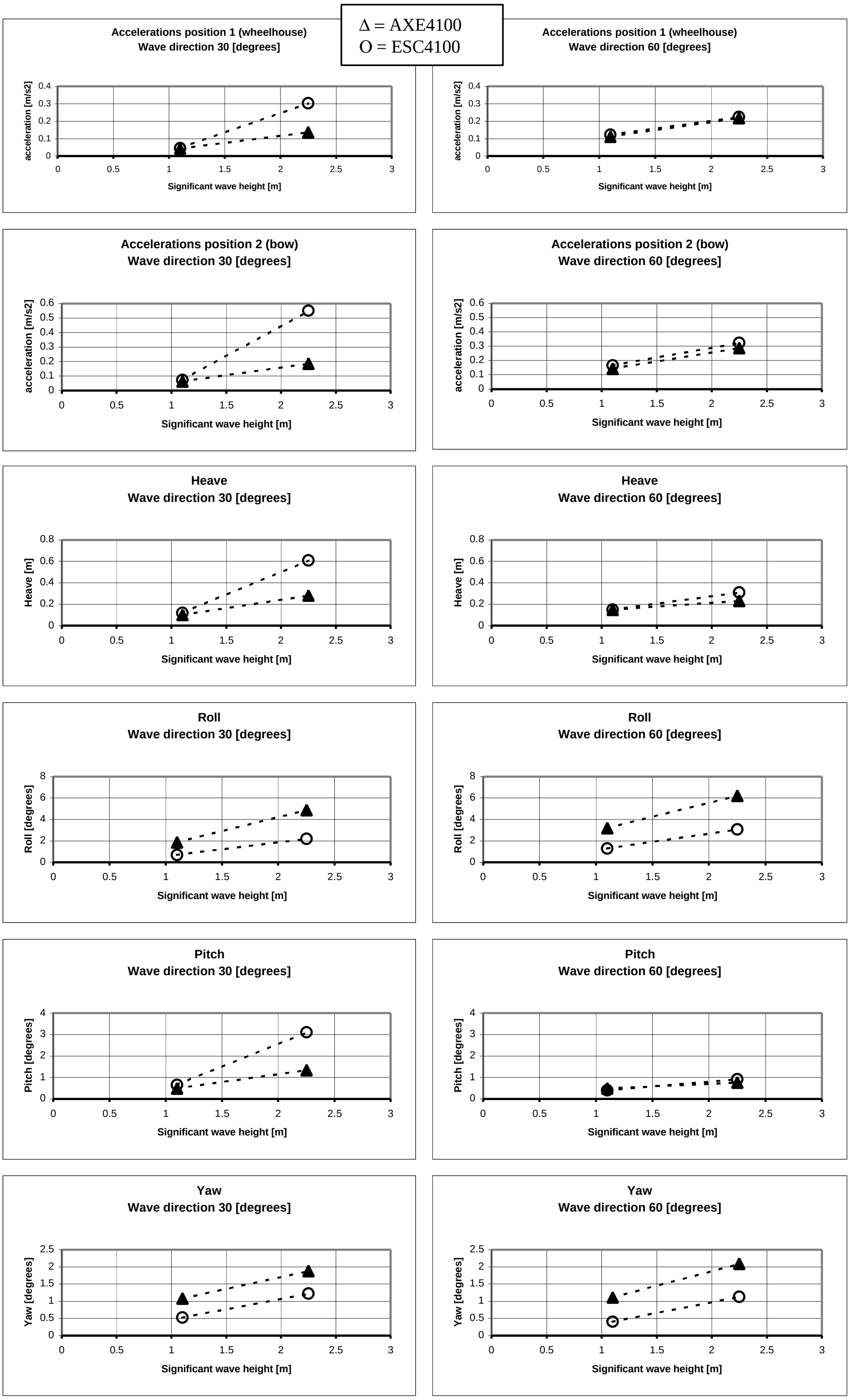


Figure 9. FREDYN results (RMS values) in stern quartering seas (T_p = 5 s).

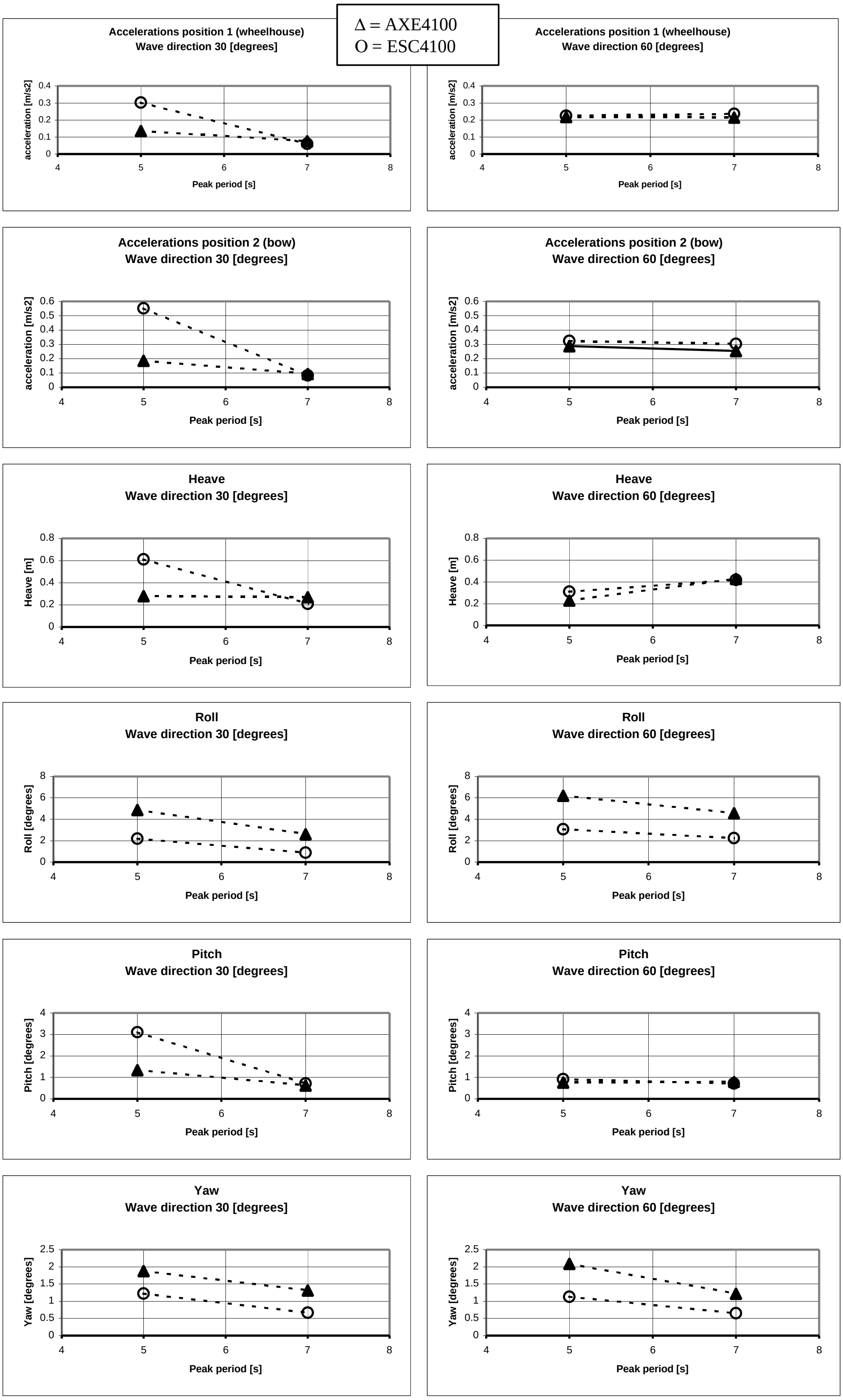


Figure 10. FREDYN results (RMS values) in stern quartering seas ($H_{1/3}$ =2.25 m).