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Sea Trials with Regard to Design and Operational Limits of Fast Pilot Vessel MS VOYAGER

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Abstract

The fast, 28 knots, seagoing 18 metres pilot vessel MS VOYAGER is a new type of tender, which is propelled by two water jets, with a hull being constructed from aluminium and a deckhouse constructed from specially developed composite materials.
In order to assess the actual quality of the design, the vessel was extensively tested in 1994 during normal operating conditions with regard to vibrational conduct, vessel motions and manoeuvring characteristics, as well as actual hull mechanical stress levels. In the present paper a description is given regarding these full scale tests and the resulting data and analysis thereof.
It was found that mechanical vibration levels on board were well below acceptable levels. Transient loading of the vessel's structure, during fast free sailing in adverse weather conditions as well as unwanted collisions during pilotage, resulted in problems related to fatigue of construction members.
Speed and manoeuvring characteristics and the vessel's motions in a seaway are assessed too. Also, ship motions calculations were carried out and compared with the actual vessel motions already monitored, in order to determine the range of reliability of the strip theory method for high vessel speeds. Equipped with this motion feedback, special attention has been given to the effect of lengthening of the vessel on slamming phenomena and acceleration levels.
A number of recommendations are finally made for the following generation of this type of pilot vessel.

Authors' Biographies

Mr. Jakob Pinkster holds a Master's degree in Naval Architecture from the Delft University of Technology. After his graduation in 1979, he was R$\&$D project engineer at Royal Boskalis Westminster Group, R&D project engineer at Damen Shipyards and lecturer at the Polytechnic West Brabant, respectively. Since 1991, he holds the position of Assistant Professor in the Ship Design Section of the Delft University of Technology. He presents lectures for students on ship design and supervises them in their design and graduation work. His particular areas of research interest are ship design and advanced marine vehicles, on which subjects he has published various papers.

Mr. Johan M.J. Journée holds a Master's degree in Naval Architecture from the Delft University of Technology since 1975. In 1958, he started his career as assistant metal worker at the Rotterdam Dockyard Company. Since 1963, he has been employed at the Ship Hydromechanics Laboratory of the Delft University of Technology and at present he is an Associate Professor there. He presents lectures for students on waves, seakeeping, manoeuvring and offshore hydromechanics. His particular areas of research interest are loads on and motions of ships and other floating structures in waves, the behaviour of ships during and after a sudden ingress of water due to a collision and speed loss and fuel consumption of ships in waves. On these subjects he has published a variety of papers.

1 Introduction

Any ship that arrives at or departs from a harbour generally makes use of the services of a pilot who knows the local navigational hazards and has experience with the manoeuvring of vessels. A pilot tender is a vessel that brings these pilots to and from

such ships. This exchange of pilots takes place at sea, often under severe weather conditions. The fast pilot vessel MS VOYAGER, owned by the Rotterdam based Dutch company "Facilitair Bedrijf Loodswezen B.V.", was commissioned in early 1994. This is a new type of pilot tender, which is propelled by two water jets with the hull being constructed from aluminium and a deckhouse from specially developed composite materials.

The general arrangement of MS VOYAGER, with an overall length of about 18 metres, is shown in Figure 1. The vessel is equipped with two diesel engines of 626 kW each and is capable of developing a sustainable service speed of 28 knots, which is more than twice the speed of the company's other pilot vessels. The new vessel and her three man crew have to be capable of simultaneously transporting a total number of 12 pilots anywhere along the treacherous North Sea along the Dutch coast in sea conditions with significant wave heights up to 2.75 metres. In order to meet the owner's demanding specifications, the vessel may well be considered to have been designed in that presently poorly defined zone where defiance of acceptable safety levels may well be a fact; not purposely so, but solely through lack of present understanding of how to design such vessels. The owners, realising this, requested the Department of Marine Technology of the Delft University of Technology therefore to thoroughly test the vessel with regard to her design and operational limits.

MS VOYAGER was consequently tested with regard to vibrational conduct, vessel motions and manoeuvring characteristics as well as actual hull mechanical stress levels. These extensive tests were carried out using full-scale measurement on board of the vessel during normal operating conditions. These conditions included sailing at sea at (full) speed, sometimes in seas up to 2.5 metres significant wave height. Another condition was the actual transfer process of pilots to and from ships, during which the pilot vessel also at times incurred heavy transient loading due to unwanted collisions between the vessels.

The following describes these different sea tests and results thereof for the hydromechanic and hydro-elastic behaviour of the vessel.

2 Hydromechanic Behaviour of the Vessel

During several days a large number of full-scale tests, related to the hydromechanic behaviour of the vessel, have been carried out. Speed trials in calm water have been performed out to determine the relation between the forward ship speed and the number of revolutions of the water jet engines. Among others, the results of these tests are needed for the determination of the magnitude of the speed loss of the ship in a seaway.
Acceleration and stopping tests have been performed to get an impression of the safety of the vessel during pilotage operations. In this connection, also the manoeuvring characteristics of the vessel have been determined. For this, turning circle tests, spiral tests and Kempf zig-zag manoeuvres have been carried out.
Finally, during two days seakeeping tests have been performed to determine the motion and acceleration behaviour of the vessel in a seaway. Special attention has been paid to the vertical acceleration peaks in the passengers' room and forward due to slamming.
A full description of these experiments and the results is given by Ooms and Journée (1994) in a technical report to the contractor.

2.1 Experimental Set-Up

For the calm water tests and the ship motion tests, different test equipment was required. For the speed and trajectory measurements use was made of a Magnavox MX200 Differential GPS receiver with an MX50R correction receiver. The correction signals came from the Hook of Holland reference station at a distance of between 25 and 50 km.
Using DGPS rather than standard GPS resulted in an absolute position accuracy of between 5 and 10 m. The remaining position error is a slow drift phenomenon around the correct position. However, as only relative accuracy was important and several of the tests were short (about 1 minute), the actual accuracy for these tests was estimated to be between 1 and 3 metres. For the longer lasting speed tests, the influence of the absolute error due to the DGPS system decreases rapidly with distance. During the manoeuvring tests a Sperry C14 course gyroscope was used for the instantaneous course registration. Furthermore, a potentiometer was used to measure the water jet angle ("rudder angle").
The waves were measured by the WAVDEL wave buoy of the Delft University of Technology, which was anchored near the measuring area. The acceleration signals were transmitted to the ship, sampled and stored for later processing. This wave buoy measures the total energy supplied by the waves to the buoy, so information on a directional spreading of the waves will not be obtained. The mean wave direction has to be determined visually.
During the ship motion tests a Schaevitz LMP-05 accelerometer was placed next to the fore peak bulkhead to measure the vertical accelerations at the bow in ship-bound co-ordinates. Three identical accelerometers were placed in the accommodation just aft of the helmsman's chair, to measure the accelerations along the x, y and z axes of the ship.
Roll and pitch angles were measured using a Sperry VG14 vertical gyroscope. Each signal was fed through a second order filter with a cut-off frequency of 2 Hz. Because this bandwidth was too low to measure the often short peak accelerations, the signal from the bow accelerometer was also fed through two peak detectors that caught and stored the positive and negative peak values of the bow acceleration in each sample interval.
All signals from filters and peak detectors were then send to a PC with an analogue-

to-digital converter, where they were sampled 8 times per second and subsequently stored for later processing.

2.2 Speed Trials

The speed trials in calm water have been carried out in the North Sea Channel, under weak transverse wind conditions.

Figure 2 shows the measured forward ship speed V as a function of the number of revolutions N of the water-jet engines. At about 15 knots the ship speed starts to increase strongly with the number of revolutions, because of a decrease of the wetted surface of the hull due to the planing behaviour of the vessel.

Figure 2 also shows the same data in irregular waves defined by Beaufort 4 and 6 at various wind and wave directions. The data shown in this figure have been obtained during sea trials when measuring the motions of the vessel, as will be described further on. In head wind and waves a small speed loss was observed, while in following wind and waves there was a slight increase in speed due to the (wind)surfing behaviour of the vessel.

2.3 Acceleration and Stopping Tests

At about 1200 and 1800 rpm of the water jet engines, a range of acceleration and stopping tests have been performed in the North Sea Channel at moderate wind conditions. An example of some of the results of these experiments is given in figure 3 for about 1800 rpm.

During the acceleration test given in figure 3, the ship reached a speed equal to 95% of the obtainable speed of about 15.3 knots after a distance of 90 metres (5 ship lengths) in 18.0 seconds. This means an average acceleration of 0.43 m/s^2 with a maximum value of about 0.75 m/s^2.

Two types of stopping tests have been performed; natural stopping by simply reducing the number of revolutions of the water jet engines and forced stopping by lowering the buckets with causes a reversal of

the direction of the thrust. During the natural stopping test given in figure 3, the ship slowed down to a speed equal to 10% of the initial speed of about 17.7 knots after a distance of 73 metres (4 ship lengths) in 45 seconds. This means an average acceleration of -0.18 m/s^2 with an extreme value of about -0.60 m/s^2.

During the forced stopping test given in figure 3, the ship slowed down from the initial speed of about 17.7 knots to zero speed after a distance of 7 metres (less than half a ship length) in 8.3 seconds. This means an average acceleration of -0.87 m/s^2 with an extreme value of about -2.05 m/s^2.

2.4 Manoeuvring Tests

Turning circle and spiral tests have been performed in coastal sea areas SW of IJmuiden, at N = 1200, 1800 and 2200 rpm with nominal water jet angles d of 6, 12 and 18 degrees to port side as well as to starboard. The observed wave height was about 0.75 metres.

An example of the path of the ship, corrected for current, during one of these turning circles is given in figure 4. Also, the relations between the rate of turn and the water jet angles are given in this figure. From these experiments, it appeared that the turning ability at high speeds of this ship is about 0.7 degrees of turning per second per degree of water jet angle. The figure shows an offset in the water jet angle of about +2.5 degrees. Probably, this offset can be explained by the equal rotational directions of the two water jet engines.

At about 1800 rpm and a water jet angle of 18 degrees, the diameter of the turning circle was less than 50 metres, while the forward ship speed slowed down from 17.0 to 10.8 knots.

Additionally, a range of Kempf zig-zag tests have been carried out which confirmed the excellent manoeuvring characteristics of the vessel, found during the turning circle and spiral tests.

2.5 Seakeeping Tests

During the seakeeping experiments in coastal sea areas SW of IJmuiden, the motions of the centre of gravity of the vessel in 6 degrees of freedom, the vertical motions forward at the fore peak bulkhead, the number of revolutions of the water jet engines, the forward ship speed and the heading have been measured. The water depth varied between 10 and 15 metres. The waves have been measured by the WAVDEL wave buoy, anchored near the sailing area. During two days, these experiments were carried out for a range of headings and number of revolutions of the water jet engines.

During the first measuring day, after a severe storm in the days before, the sea conditions were characterised by Beaufort 6. The significant wave height $H_{1/3}$ decreased from 2.1 to 1.5 metres at the end of the day, while the zero up-crossing wave period T_2 varied between 5.1 and 5.8 seconds. The heading of the waves, influenced by a S to SSW wind with a speed of about 5 m/s, measured ashore, and the refraction of the waves in shallow waters, was estimated to be about 080 degrees. The experiments have been carried out at a wide range of headings of the ship and 600, 1200, 1800 and 2050 rpm of the water jet engines.

During the second day, the stable sea conditions were characterised by Beaufort 4. The significant wave height $H_{1/3}$ varied between 1.0 and 1.1 metres, while the zero up-crossing wave period T_2 was about 4.5 seconds. The heading of the waves, influenced by a S to SSW wind with a speed of about 3 m/s, measured ashore, and the refraction of the waves in shallow waters, was estimated to be about 100 degrees. The experiments have been carried out at a wide range of headings of the ship and 600, 1200, 1800 and 2200 rpm of the water jet engines.

It should be mentioned that a visual observation of the mean wave direction on board of small vessels is rather difficult, because of the low altitude of the observer above the waves.

For the two highest ship speeds, the measured RMS-values of the vertical accelerations amidships and forward during these two days, are given in figure 5. These experimental data have been compared with theoretical data, obtained with the linear frequency domain strip theory ship motions computer code SEAWAY, of which a user's manual is given by Journée (1992) and the underlying theory is described by Journee (1996).

The time-averaged significant wave heights and mean wave periods, during each of the two measuring days, are input for the computations. A constant wave direction has been used and the directional spreading of the waves has not been taken into account; uni-directional long crested waves are supposed here. This choice was more or less justified by visual observations of the waves during the experiments.

At about 1800 rpm, the vessel will start planing. At this ship speed and at lower speeds, a fairly good agreement between experiments and predictions has been found; see figure 5. When judging the predictions, it should be kept in mind that constant wave parameters have been used and that the effect of the S to SSW wind waves during the measuring days has not been accounted for.

At higher speeds the ship is planing and computations, while assuming that the vessel is a displacement ship, would have less sense. But, even then, figure 5 shows that the maximum values of the vertical accelerations were fairly well predicted, especially at Beaufort 4.

Also, the peak values of the vertical accelerations amidships and forward have been measured. Figure 6 shows the

measured peak values forward at the two highest ship speeds in Beaufort 4 and 6. The figure shows extreme negative peak values of about -1g and extreme positive peak values of about +4g. It is obvious that such data can not be obtained with a linear frequency domain computer program.
Figure 7 shows the measured positive and negative peak values of the vertical accelerations during all the experiments as a function of the corresponding RMS-values. The derivatives of these curves, i.e. the values of the tangents to the curves for small RMS-values, are equal to plus or minus $5 \cdot RMS$. This coincides with acceleration thresholds for the linear harmonic motions with a probability of exceedence of $3.7 \cdot 10^{6}$.
Also, figure 7 shows that in rough weather, a small decrease of the RMS-value may result in a considerable reduction in the peak values of the bow accelerations. For instance, a decrease of 10% of the RMS-value may result in a reduction of 20% in the peak acceleration values.

3 Hydroelastic Behaviour of the Vessel

Also, the vessel was consequently tested with regard to vibrational conduct as well as to actual hull mechanical stress levels. These extensive tests were carried out, using full scale measurements on board of the vessel during normal operating conditions, i.e. during sailing at sea at (full) speed, at times in seas up to 2.5 metres significant wave height, as well as during the actual transferal process of pilots to and from ships. During the latter, the pilot vessel also at times incurred heavy transient loading due to unwanted collisions with the (to be) piloted vessel.
A full description of these experiments and the results are given by Pinkster and Hylarides (1994a and 1994b) in two technical reports for the contractor.

3.1 Experimental Set-Up

For the registration of the SB and/or PS water jet revolutions, 2 Honeywell 922AA3XM-ASN-L magnetic pick-ups have been utilised. For the measurement of the vibration accelerations 42 accelerometers were installed, of which 41 single axial accelerometers (makes Sundstrand, Endevco and Bruel & Kjaer) distributed along the ship and 1 Bruel & Kjaer 4322 tri-axial seat-accelerometer for use on helmsman's chair. The measured signals were conditioned, analogue filtered and digitised. In order to protect overshooting of these signals, equal time delay filters (linear phase response) were used.
The same equipment was, more or less, utilised for the mechanical stress measurements. For the measuring of these mechanical stresses in the vessel, 40 Hottinger Baldwin Mess\-technik 3/12OLY13 strain gauges were installed. Furthermore, 3 Endevco 2262-25 accelerometers were used for measuring the accelerations in the fore peak and on the engine foundation.
Vibration levels were monitored at 43 different locations in different directions. Hull stress levels were measured by strain gauges, mounted at 40 different locations in different directions, and monitored. Also, the signals of accelerometers for measuring the ship motions fore and aft were monitored, together with the water jet engine revolutions, measured with the aid of an infrared sensor and markings. A 50-channel recorder was used to store these monitored signals on a time basis.
The location of all monitoring devices and the designation of the signal channels are shown in tables 1 and 2. Figure 1 also shows some of the stress measurement positions used on frame 10.

3.2 Vibration Measurements

In order to assess the comfort and well being of the individuals on the vessel,

extensive vibration measurements were carried out on board under different service conditions. In essence, the vibrational signature of the vessel is to be found resulting from the presence of excitation forces, created by the water jets and/or the main engines as well as the presence of excitation forces due to slamming. This latter force can be regarded as being a transient (impact) excitation force, i.e. zero frequency.
Vibration levels were registered on the water jet, on the engine foundations and the engine itself, on the hull, on the mounting of the superstructure and in the superstructure, eg. the helmsman's chair. Within the choice of measurement locations the vessel's symmetry was taken into consideration.

TNO-CMC at Delft was sub-contracted to install and carry out the vibration measurements according to the specifications of the Delft University of Technology. The installation of the vibration measurement equipment took two days, followed by one day of measuring at sea.
The weather conditions during the measurements, Beaufort 8 with a significant wave height of about 2.5 metres, were considered to be very good as far as expected input levels of external impact forces (slamming) on the ship's structures were concerned. The idea is that a fitting input value should lead to a firm output value and thereby to good (strong) vibrational response signals.
Two types of measurement runs were made.
Firstly, so-called sweeps were carried out, whereby vibrations were monitored while the revolutions of both main engines were slowly increased from minimum number of revolutions to the maximum number. This run was carried out within the outer harbour of IJmuiden.
Secondly, vibrations were monitored for a longer time, while the engines were producing constant (maximum) power and sailing in severe seaway in the vicinity of the entrance to the outer port of IJmuiden.

Three such vibration measurement runs were made. Due to severe slamming in the given sea conditions the vessel's speed was reduced to a maximum of about 18 knots. Each run lasted about 5 minutes and the signals were recorded on a hard disc discretely at a rate of 2000 samples per second. Thereby, vibrations could be clearly registered up to a frequency of 500 Hz. After each run the vessel returned to IJmuiden where the registered data results were investigated on the computer screen. If the results were considered to be clear enough, then a tape backup was made of the data and then the next run was made. In total 45 Gbytes of signal data for all three runs has been backed up on tape.
Using the aforementioned vibration data, table 1 shows the maximum vibration velocity peak values of each of the accelerometers, encountered during any given measurement run for a discrete number (6) of frequency values. These frequency values are repectively 18, 36, 54, 72, 90 and 108 Hz and coincide directly with 0.5^{th}, 1^{st}, 1.5^{th}, 2^{nd}, 2.5^{th} and 3^{rd} engine frequency order. These frequency values also coincide with 1^{st}, 2^{nd}, 3^{rd}, 4^{th}, 5^{th} and 6^{th} order of water jet shaft-frequency values.
For the sake of clarity, the gearbox reduction ratio is 2:1, the main engines are of the V-type with a total of 12 cylinders per engine each producing 626 kW at 2200 rpm and each water jet is fitted with a six bladed impeller.
It may be expected that if any resonance occurs at all, then these should be found at the same frequencies as the excitation frequencies coming from the engines and the water jets. Therefore, the maximum vibration velocity peak values of each of the accelerometers, encountered during any given measurement run for these 6 frequency values, have been filtered from the measured data.

Along with this, the maximum of the maximum vibration velocity peak values per measurement location has been found and is highlighted in table 1 by means of italic bold printing. If these maximum values are found to be within the acceptable values, which are given in the ISO 6954 vibration norm diagram, then no adverse comments are probable with regard to the comfort and well being of people and materials on board of the vessel in the given service scenario.
No extreme values were found for the peak values of the vibration velocities as described above. The highest value obtained was 2.05 mm/s for the topside of the deckhouse aft on starboard side at a frequency of 18 Hz. This coincides with the 1st order of water jet shaft-frequency. According to the ISO 6954 vibration norm diagram, no adverse comments are probable with regard to the comfort and well being values when the velocity level lies below 4 mm/s for this frequency value. Adverse comments are probable when velocity levels are above 9 mm/s and there is a grey zone for velocities between 4 and 9 mm/s.
In conclusion, one may say that this vessel should receive no adverse comments at all with regard to vibration levels. Indeed to gain such good low vibration levels are the dream of many naval architects.

3.3 Hull Mechanical Stress Levels Measurements

About six months after receiving the vessel from the builders, the owners noticed that cracking of certain parts of the aluminium hull was occuring. The cracks were appearing at the second spray rail which forms an integral discontinuity within the main frame structure. This part of the main frame structure and the cracks are described in figure 8.
The Delft University of Technology was asked to investigate this phenomenon and make suggestions to solve this problem. In order to realise this, it was decided to measure the stresses in the hull under different operational conditions. Analyses of these results were expected to lead to the cause of the cracking phenomenon and suggestions should then be made for measures to be taken to solve the problem.
Stress levels were registered in web frames number 10, 11, 13, 14, 15 and 17. Particular attention was taken in the placing of strain gauges on the second spray rail at web frame number 10, since it was difficult to find uncracked material at this location as the cracks had initiated at this exact point. A solution was found by placing 3 of these strain gauges on port side and 2 on starboard side. In order to investigate the stress levels along the frames themselves, web frames 10 and 14 were well fitted with 20 and 12 strain gauges, respectively. Stress levels in the frames along the length of the vessel were investigated with the aid of 2 strain gauges fitted on web frames 11, 13, 15 and 17 each. Within the choice of measurement locations, the vessel's symmetry was taken into consideration. The location of all monitoring devices is shown in table 2, as well as the designation of all 44 signal channels.
Again, TNO-CMC at Delft was sub-contracted to install the necessary equipment and to carry out the hull stress measurements according to the specifications of the Delft University of Technology. The installation of the vibration measurement equipment took 4 days. The actual stress measurements were carried during 2 days; one day for static tests and one day for dynamic tests. The weather conditions during the dynamic tests, Beaufort 8 with a signnificant wave height of about 2.5 metres, were considered to be very good as far as expected input levels of external (slamming) impact forces on the ship's structures were concerned. The idea is that a fitting input value should lead to a firm output value and thereby to good (strong) hull stress level response signals.

Two types of measurement runs were made.
Firstly, so-called pilotage measurements were performed, whereby hull stresses were monitored while the vessel bashed off the quay wall in an attempt to simulate the actual transferring of pilots to and from seagoing vessels. The revolutions of both main engines were somewhat slowed down and the vessel had a reasonable speed during this measurement run, which was carried out within the inner harbour of IJmuiden.
Secondly, so-called sailing measurements were performed, whereby hull stresses were monitored during about 5 minutes, while the engines were producing constant (maximum) power and sailing in severe seaway in the vicinity of the entrance to the outer port of IJmuiden.
Three such sailing measurement runs were made. Due to severe slamming in the given sea conditions the vessel's speed was reduced to a maximum of about 18 knots. Each run lasted about 5 minutes and the signals were recorded on a hard disc discretely at a rate of 2000 samples per second. Thereby, hull stresses could be clearly registered up to a frequency of 200 Hz. After each run the vessel returned to IJmuiden where the registered data results were investigated on the computer screen. If the results were considered to be clear enough, then a tape backup was made of the data and then the next run was made. In total 160 Mbytes of signal data for all three runs has been backed up on tape.
Using the hull stresses as measured during the pilotage simulation and sailing runs, table 1 gives a quantitative description of the extreme value of the hull stress signal that each of the strain gauges showed.
This quantitative description of the stress signal is built up using the following stresses and stress ratios:
TABEL

Figure 8 shows the maximum stress levels measured in the frames during pilotage and sailing conditions. A typical record of the hull stresses, occuring at the second spray rail during slamming, is shown in figure 9.
As may be seen from figure 8, the hull stress levels are well below the 125 N/mm^2 allowable 0.2% yield stress level of the aluminium (AlMg4.5Mn, 5083) material of which the hull is constructed. The maximum stress level encountered was 90 N/mm^2 and this incorporates a safety factor of 1.4.
In general, it may be expected that, if stress values within the hull sufficiently exceed the 125 N/mm^2 value, then cracks or breaking of the material may occur. If however such excessively high stress values are not encountered during measurements under such extreme working conditions of the vessel then one can only conclude that the cracking of the material results from metal fatigue. An investigation into the Wöhler fatigue curve of aluminium in welded condition shows that even at such low stress levels as those encountered during the hull stress measurements presented in this paper fatigue cracking may occur. This is true even though the vessel, after six months service, has had to bear such a short amount of fatigue loading cycles. The more so when one considers the discontinuity of the structure at the position of the second spray rail, where initially the cracks occured. As is well known, in such discontinuities the actual stresses are even higher due to the fact that the stress concentration factor is greater than 1, generally 2-3. This higher stress causes a significant reduction in fatigue life. Also, it should be well noted that no less than three welds have been placed on that small area of material. With regard to this last point, one should also keep in mind that welding aluminium requires much more heat than when welding steel, because of the high thermal conductivity of aluminium. This leads to a large heat affected zone (HAZ) which in turn yields very poor material quality of the aluminium in the vacinity of the welds.

The latter results in even poorer fatigue resistance of the material when compared to similar virgin aluminium material.
Another problem related to the welding of aluminium is the residual stresses in the weld itself, which may be as high as the yield stress of the material itself. Preening of the weld to reduce such residual stresses is recommended.
With regard to the actual amount of stress cycles encountered by the vessel, these are far larger than the number of slams incurred by the vessel alone as can be seen in figure 9 from the measured stresses on a time basis. This is so as the following occurs directly after transient loading of the hull structure; firstly a peak disturbance, i.e stress, in the structure then a damped free oscillation of the frame in the plane of the frame itself. This leads to a larger number of stress cycles than the number of slams alone. Due to these in plane oscillations a rotation point, about which the frame locally oscillates, may be deduced and, as result from this, also a hard spot where the cracking indeed occurs, see figure 10 (problem and mechanism respectively).
Regarding all these unfavourable points related to the material, construction and production method of the 2nd spray rail, it was recommended that the fatigue sensitivity of this construction detail be positively reduced by undertaking the following steps, see also figure 10 (solution): The frame be detached from the 2nd spray rail locally and the web thickness was also increased locally by adding extra plating on both sides (approx. 2 mm thickness). The extra plating was glued to the existing web-plating of the frame. Also the flange on the frames were fully welded instead of intermittently.

4 Lengthening of the Ship

During the hydromechanic experiments, the ship has been tested in sea conditions with wave heights up to 2.0 metres, which results in maximum peak accelerations forward of about 4 g . Since the ship has to operate in sea conditions with wave heights of 2.75 metres, peak accelerations forward up to 6 or 7 times the acceleration of gravity g can be expected, which is too high from an operational point of view. During vibration and stress tests, peak accelerations forward of 6 g were regularly measured in sea conditions with wave heights of 2.5 metres. Lengthening of the ship will reduce the RMS -values of the vertical accelerations. Then, as can be seen in figure 7, the peak accelerations will be reduced much more.

In a study, the ship has been lengthened by increasing the two intervals between the three aftmost ordinates in the lines-plan from 1.51 to 2.71 metres, which means that the ship length at the waterline will be increased from 15.10 to 17.50 metres. The relative position of the fore peak bulkhead, at which the (peak) accelerations have been investigated, has been maintained.

Calculations with the strip theory computer program SEAWAY for head waves and a sea state defined by Beaufort 6, showed a reduction of about 9% of the vertical accelerations forward at 1800 rpm of the water jet engines. Slamming pressures however, are mainly determined by the square of the vertical relative velocity between the ship and the waves. From the computations it appeared that this velocity will be reduced by about 25% in Beaufort 6. Because of the quadratic relation between pressures and velocities, a reduction of the slamming pressures can be expected of about 45%.
This trend for the pressures will be confirmed in figure 7 for the vertical peak accelerations caused by the slamming pressures. The figure shows a very non-linear relation between these peak-values of the accelerations and the RMS -values.

This very non-linear behaviour of the peak accelerations and the resulting peak impact pressures, was one of the reasons for the owner's decision to increase the length of his newly ordered ships by about 2.50 metres.

5 Conclusions

With regard to improved design of the vessel, a number of conclusions are finally made for the following generation of this type of pilot vessel:

- In calm water, the vessel can maintain a speed of about 27 knots at 2200 rpm of the water jet engines. In the higher speed range ($N = 1800$ rpm) and in head wind and waves with a height up to 2.0 metres, the speed loss appeared to be less than about 2 knots. In following wind and waves, an increase of the speed with this same amount has been found, due to the wind and surfing of the ship on the waves.
- The acceleration and natural stopping tests confirm a good behaviour of the ship in this respect. Unexpected forced stopping by reversing the direction of the thrust of the water jets causes large longitudinal accelerations, which can be dangerous for non-seated passengers.
- The ship has excellent manoeuvring characteristics. To maintain a certain heading, a small water jet angle of about 2.5 degrees is required. Probably, this is mainly caused by the similar rotational directions of the two water jet shafts.
- In the high speed range ($N = 2000$ rpm) and maximum allowable operational sea states defined by a significant wave height of 2.75 metres, very high peak accelerations up to $6g$ or $7g$ can be expected.

  A lengthening of the ship by 2.40 metres will considerably reduce these peak accelerations.
- It was found that mechanical vibration levels on board were well below acceptable levels. The highest measured vibration velocity was 3.95 mm/s, but, in the majority of cases, this value was well below 2 mm/s.
- The transient loading of the vessel structure, during fast free sailing in adverse weather conditions and during unwanted collisions during pilotage, although yielding measured stress levels that were significantly below normally well acceptable values, still resulted in problems related the fatigue of some construction members. This was also underlined by the advent of fatigue cracking, discovered around the time of the measurements.

  With regard to an improved structural design of the vessel, a number of recommendations are made for the following generation of this type of pilot vessel:
  - The spray rails should not be an integrated discontinuity in the hull structure; an externally fitted spray rail is therefore recommended.
  - Avoid too many welds being made in a small area.
  - Increase the web frame thickness from 5 to 7 mm, locally in the area of the spray rails.
  - If integrated spray rails are utilised, free the web of the frame locally in the vicinity of the horizontal plating of the spray rail.
  - Pay particular attention to welding in aluminium with regard to the fitting tolerances and the residual welding stresses.
- Up to a speed of about 16 knots ($N = 1800$ rpm), where the ship is not actual planing, linear strip theory computations with the computer program SEAWAY give fairly reliable predictions of the RMS-values of the ship motions and the accelerations in waves.

As a result of these tests related to design and operational limits, the owner has since ordered and received another 3 pilot vessels, which incorporate many of the recommendations as given in this paper. At the end of 1996 the owner again placed an order for yet another 3 similar modified pilot vessels.

6 Acknowledgements

Although the results and views expressed in this paper are entirely those of the authors, accurate design prototype studies of this type are not possible without "real-time design information" from the field itself and the opportunity to make all of the measurements discussed within this paper.
Therefore, the authors are very grateful to Ing. A.C.M. Baaten of the ship owner "Facilitair Bedrijf Loodswezen B.V." at Rotterdam and the crew of MS VOYAGER for their co-operation during this project and to the ship owner for their permission to publish the results of this research.
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A special word of thanks is indebted to Ir. J. Ooms of the Delft University of Technology for his contribution to the preparation, the performance and (last but not least) to the analysis of the hydromechanic experiments.

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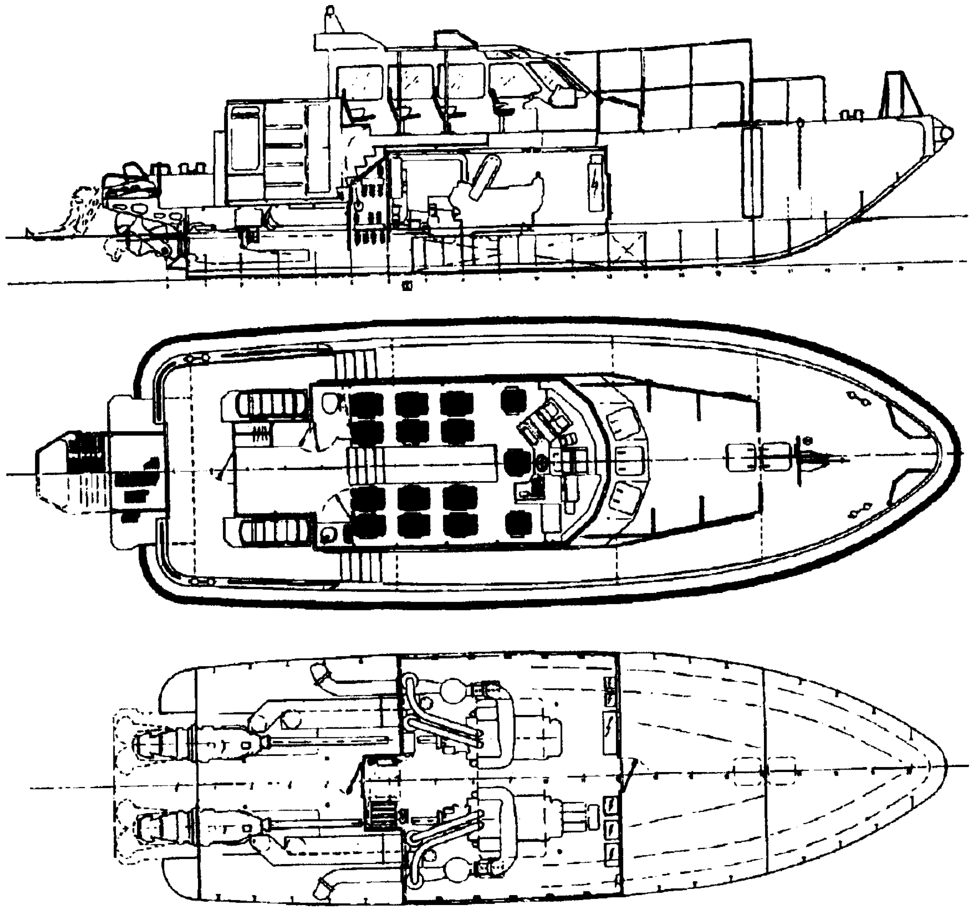
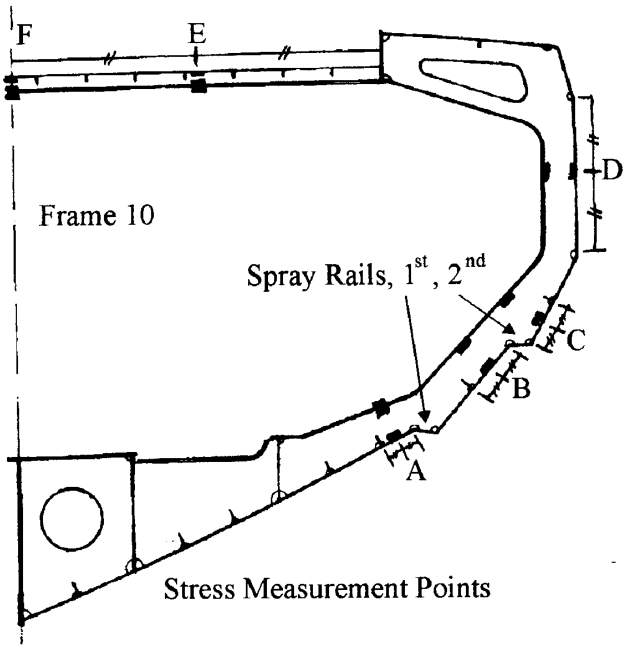
8 Figures





Principal Dimensions

Length o.a.	18.56	m
Length b.p.p.	15.19	m
Breadth o.a.	6.34	m
Breadth moulded	5.49	m
Draught	0.97	m
Depth	2.70	m
Propulsion	2 x 626	kW
Speed	28	kn
Displacement	29.30	ton

Figure 1 General Arrangement MS VOYAGER and Frame Section Number 10

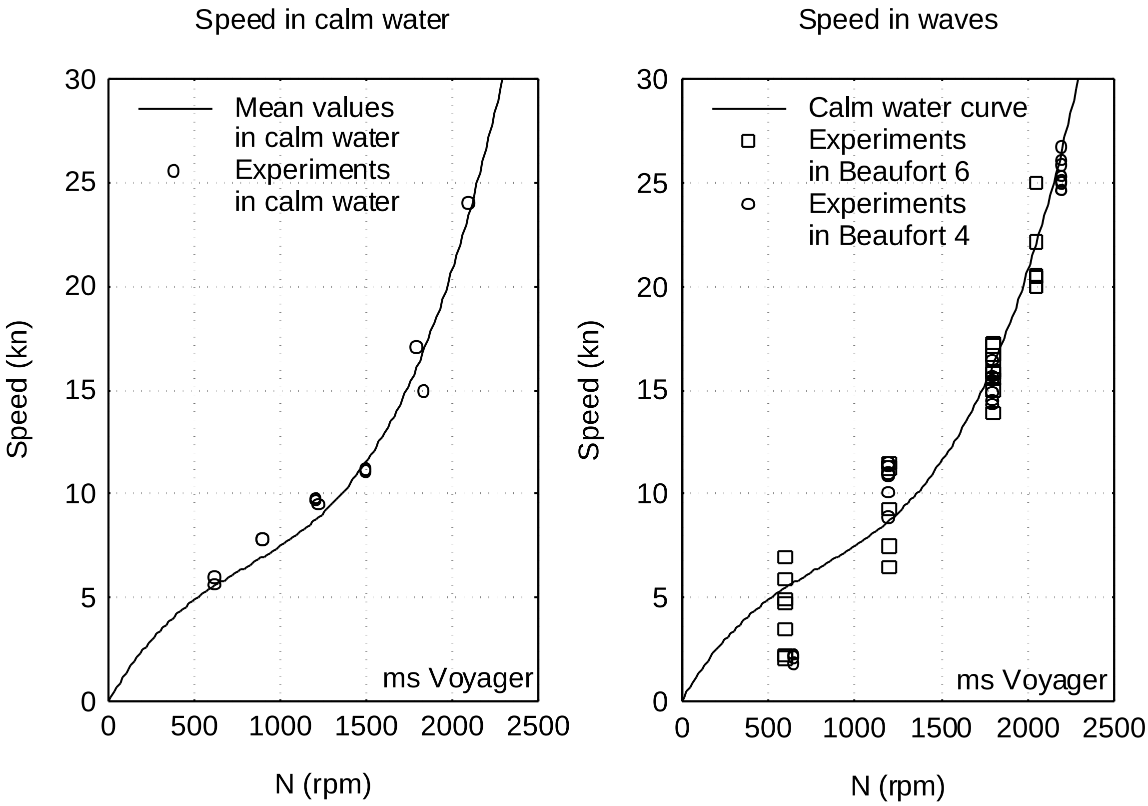


Figure 2 Speed Trials in Calm Water and in Waves

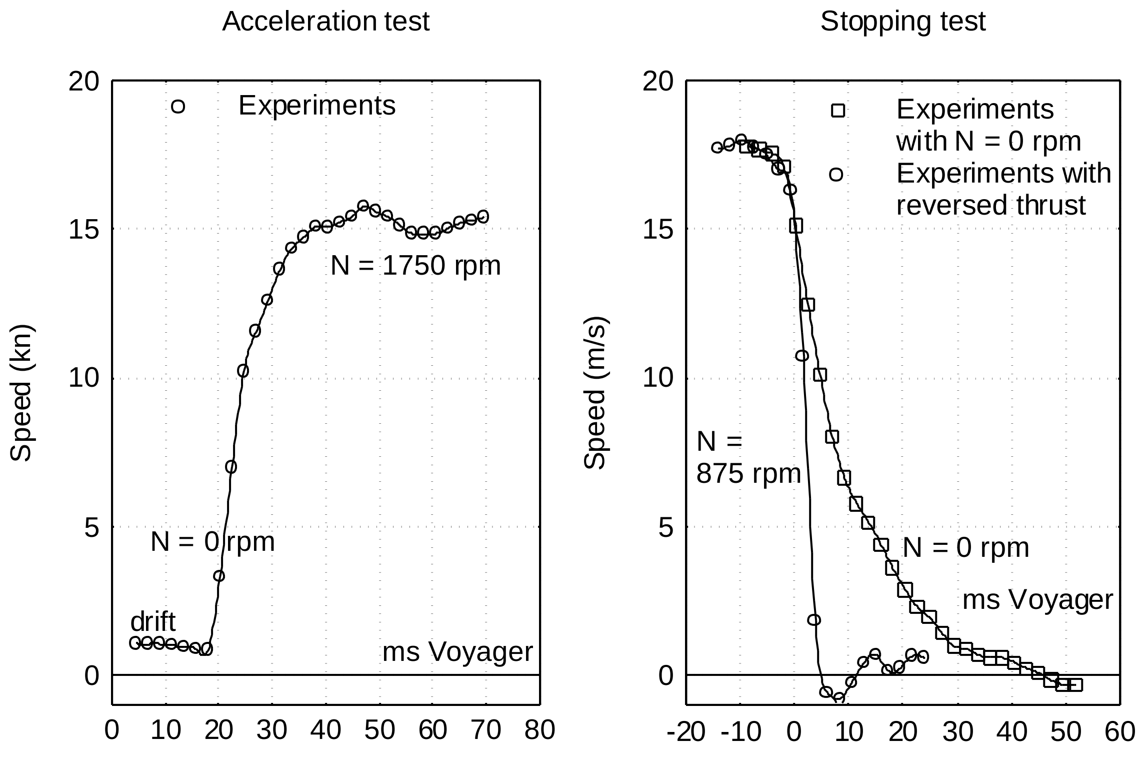


Figure 3 Acceleration and Stopping Tests in Calm Water

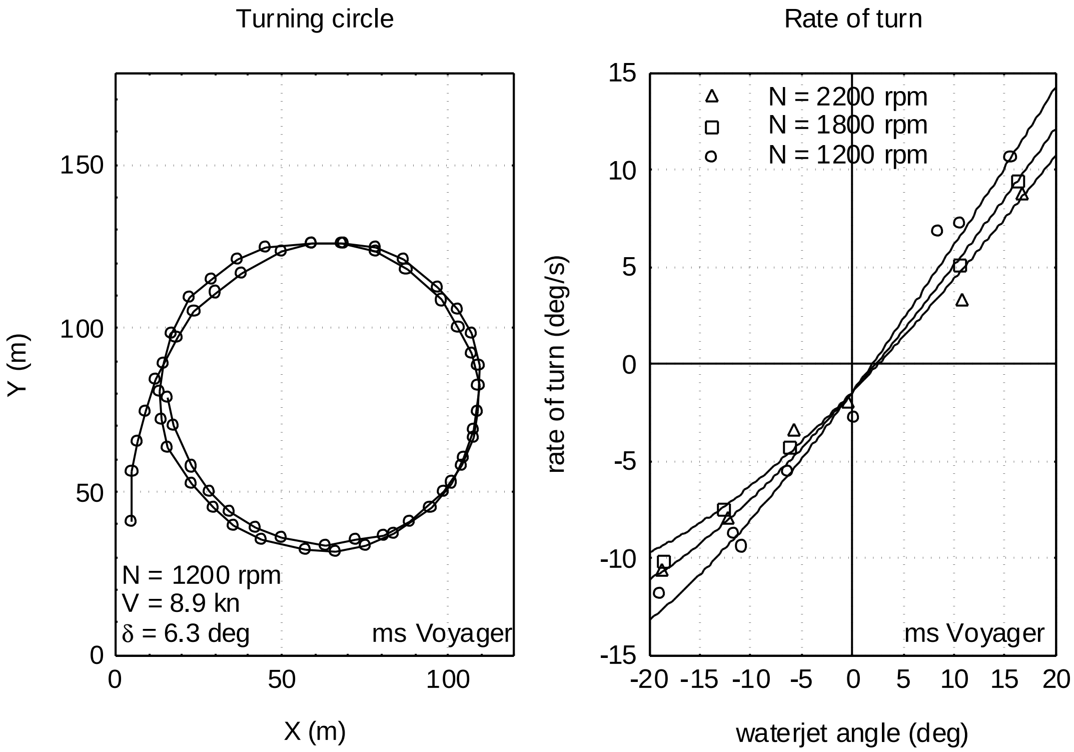


Figure 4 Manoeuvring tests in calm water

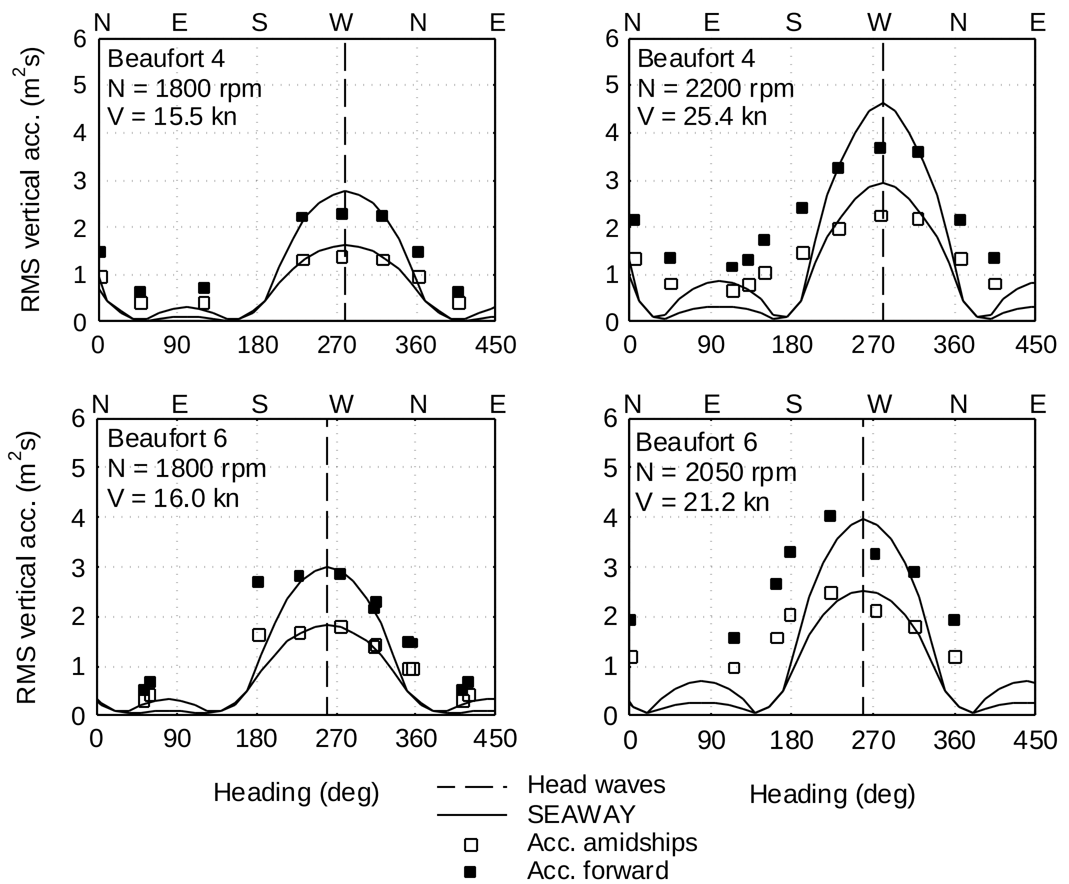


Figure 5 Measured and computed RMS values of vertical accelerations

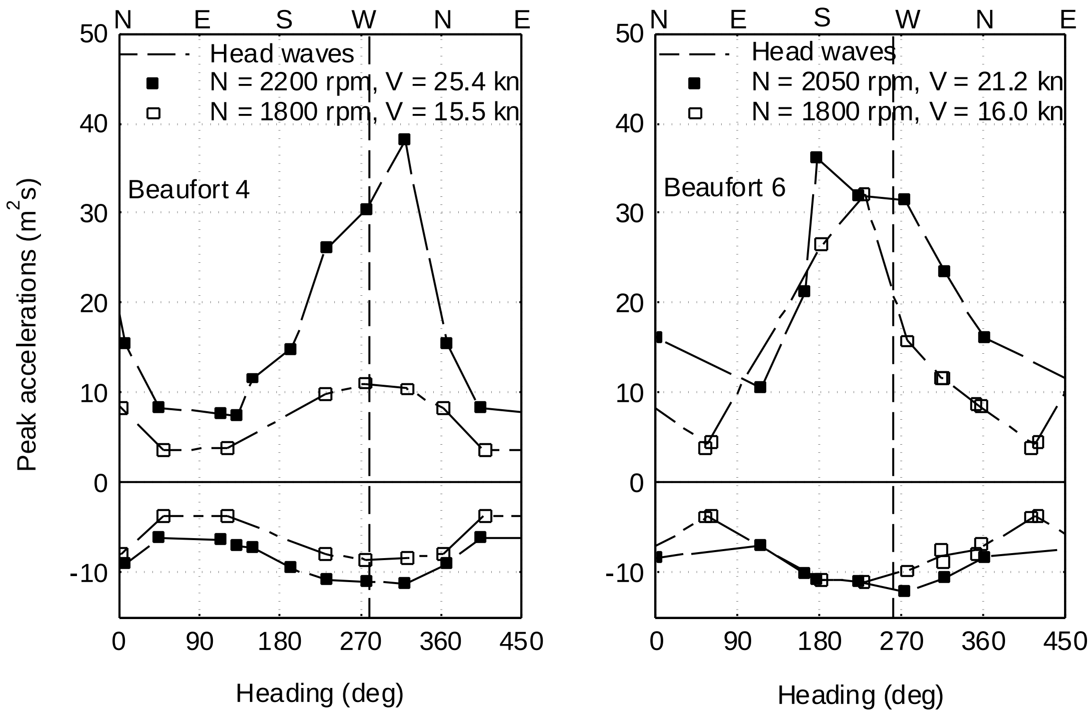


Figure 6 Measured peak values of vertical accelerations forward}

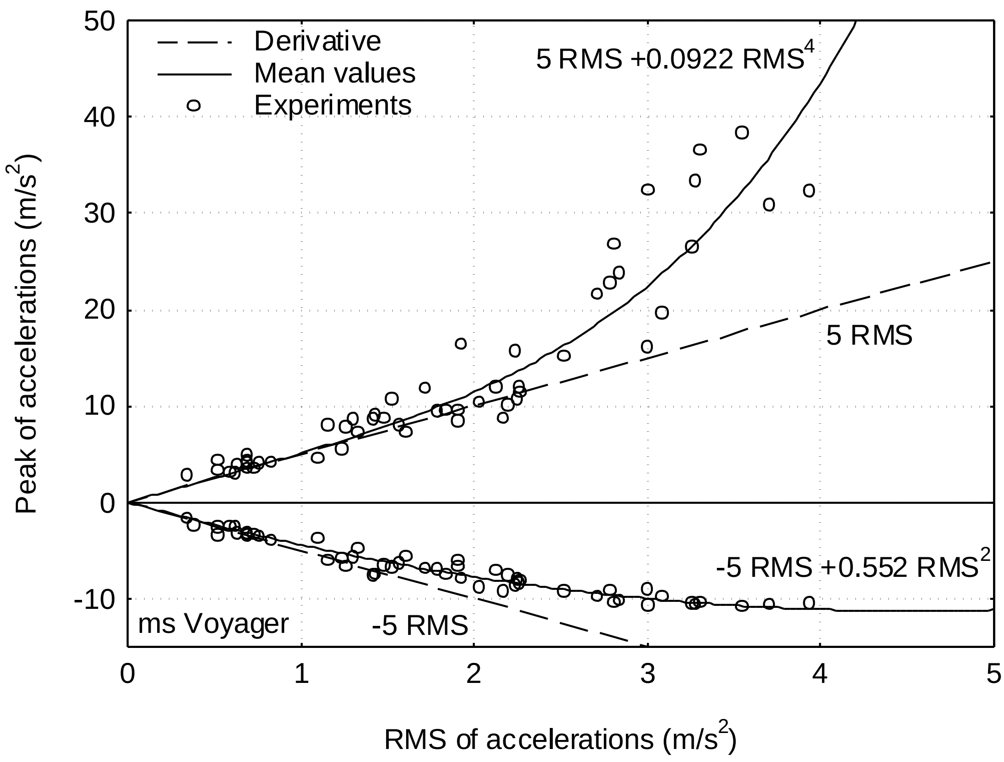


Figure 7 Peak versus RMS values of vertical accelerations forward}

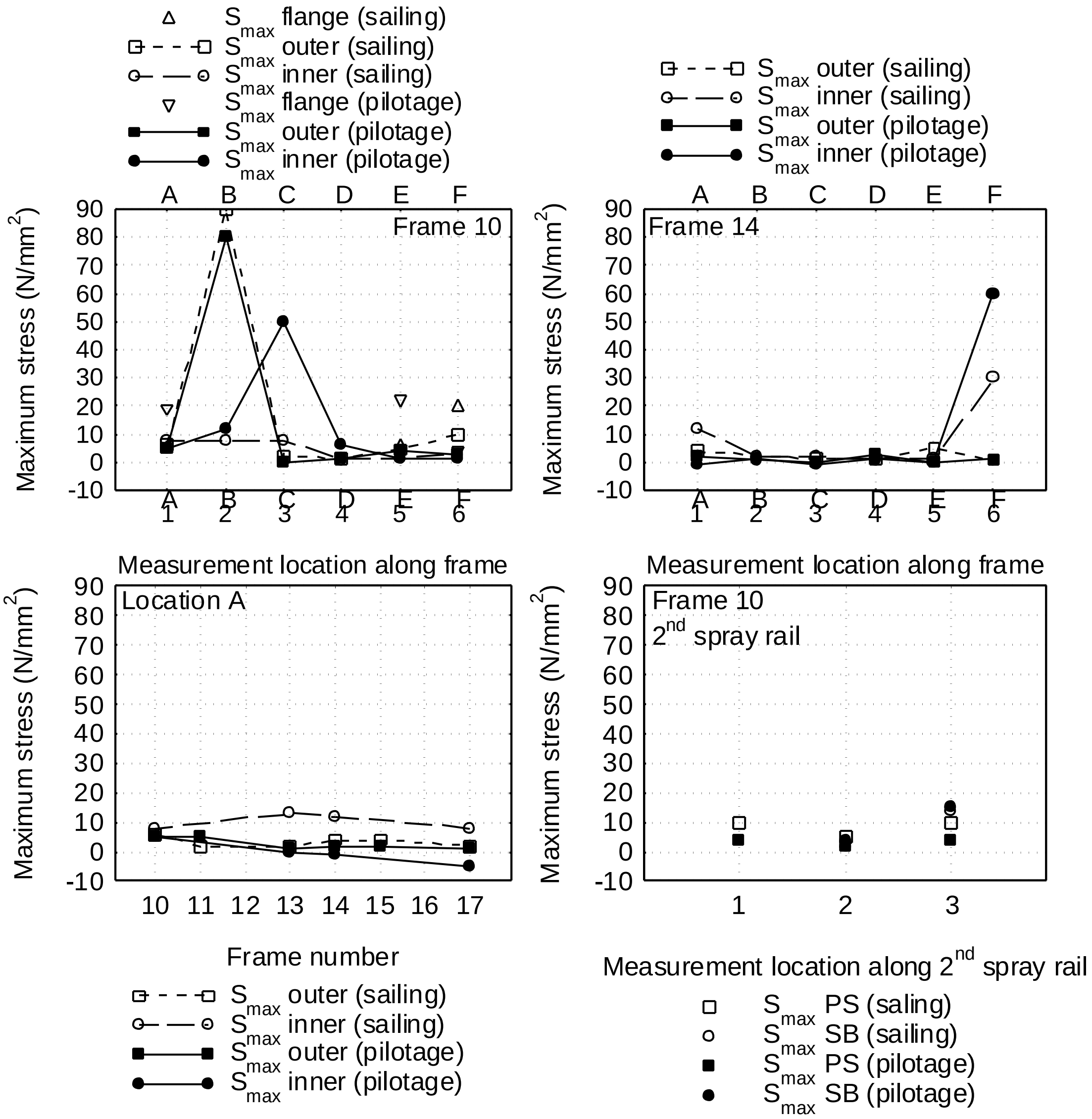


Figure 8 Hull stress levels during pilotage and sailing conditions

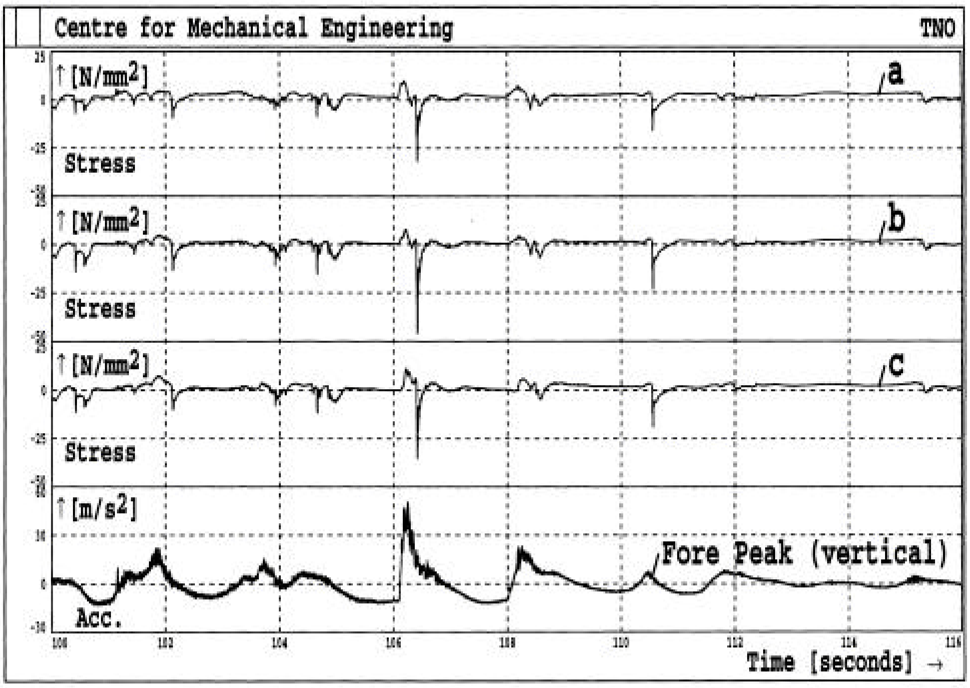


Figure 9 Hull Stress Level Measurement Results for Frame 10 at 2nd Spray Rail PS, in Sailing Condition BF 8, Significant Wave Height 2.5 Metres

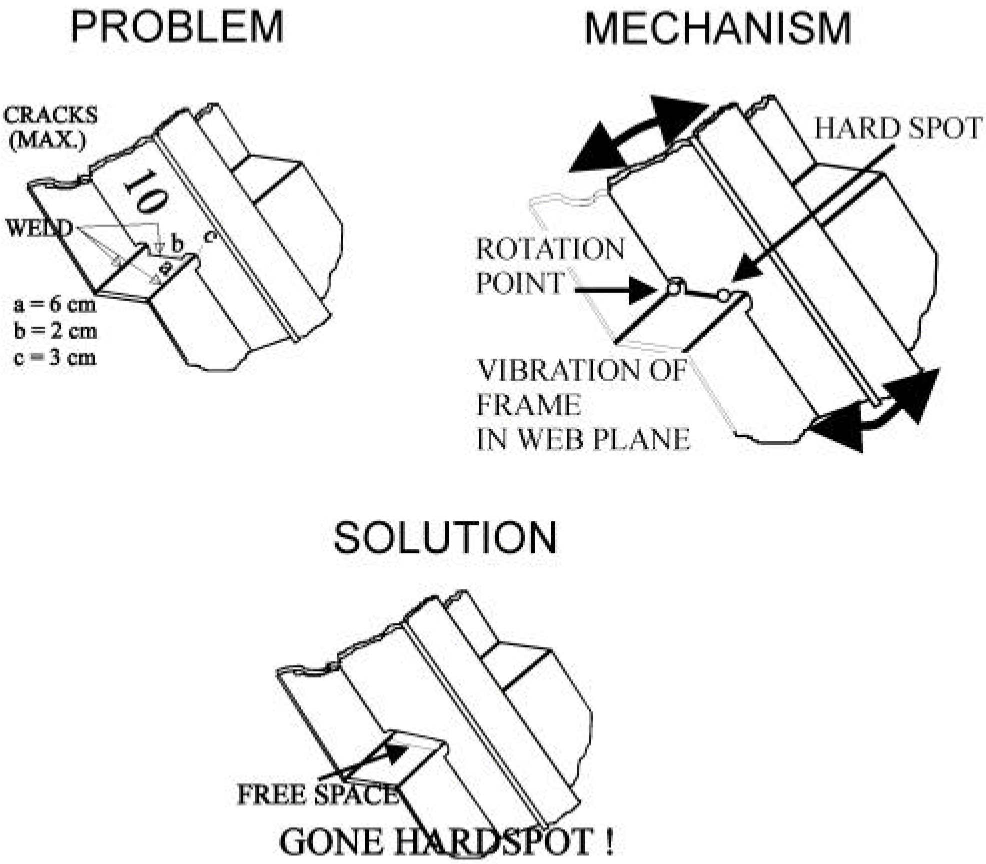


Figure 10 Structural Improvement 2nd Spray Rail

CHANNEL NUMBER	DESCRIPTION MEASURING LOCATION	MEASURED MAXIMUM VIBRATION VELOCITY IN MM/S WHILE SAILING IN A SEVERE SEAWAY																	
		X - DIRECTION[1]						Y - DIRECTION[2]						Z - DIRECTION[3]					
		18 [Hz]	36 [Hz]	54 [Hz]	72 [Hz]	90 [Hz]	108 [Hz]	18 [Hz]	36 [Hz]	54 [Hz]	72 [Hz]	90 [Hz]	108 [Hz]	18 [Hz]	36 [Hz]	54 [Hz]	72 [Hz]	90 [Hz]	108 [Hz]
1	REVOLUTIONS SB WATERJET ENGINE																		
2	REVOLUTIONS PS WATERJET ENGINE																		
3	AFT END MIDSHIPS	0.35	***0.5***	0.2	0.1	0.18	0.1												
4	AFT END MIDSHIPS													***0.75***	0.65	0.6	0.1	0.1	0.2
5	AFT END SB WATERJET	0.9	***1.08***	0.4	0.2	0.2	0.1												
6	AFT END SB WATERJET													0.85	***1.18***	0.4	0.15	0.05	0.05
7	BULWARK AFT MIDSHIPS	0.12	***0.2***	0.2	0.05	0.04	0.09												
8	BULWARK AFT MIDSHIPS													***1.2***	1.1	0.3	0.15	0.1	0.2
9	AFT DECKHOUSE MIDSHIPS	0.17	***0.19***	0.12	0.1	0.6	0.12												
10	AFT DECKHOUSE PS													0.6	***1.9***	0.45	0.08	0.02	0.02
11	AFT SUPPORT DECKHOUSE PS													2.9	1.9	***4.7***	1	0.5	0.3
12	AFT SUPPORT DECKHOUSE MIDSHIPS (BODY)													0.77	***1.38***	0.1	0.05	0.03	0.04
13	TOPSIDE DECKHOUSE AFT SB	0.42	***1.23***	0.43	0.06	0.05	0.03												
14	TOPSIDE DECKHOUSE AFT SB							***2.05***	1.3	0.75	0.1	0.1	0.05						
15	TOPSIDE DECKHOUSE AFT SB													0.5	***1.95***	0.3	0.1	0.1	0.1
16	TOPSIDE DECKHOUSE MIDSHIPS SB	***0.59***	0.42	0.15	0.08	0.02	0.02												
17	TOPSIDE DECKHOUSE MIDSHIPS SB							***3.95***	0.9	0.1	0	0	0						
18	TOPSIDE DECKHOUSE MIDSHIPS SB													0.35	***0.39***	0.22	0.08	0.02	0.02
19	CENTRE SUPPORT DECKHOUSE PS (BODY)													***0.5***	0.26	0.12	0.08	0.08	0.08
20	CENTRE SUPPORT DECKHOUSE PS (DECKHOUSE)													***0.33***	0.24	0.09	0.04	0.04	0.03
21	CENTRE SUPPORT DECKHOUSE PS (BODY)	***0.36***	0.24	0.1	0.12	0.1	0.04												
22	CENTRE SUPPORT DECKHOUSE PS (DECKHOUSE)	***0.43***	0.2	0.1	0.08	0.03	0.02												
23	CENTRE SUPPORT DECKHOUSE PS (BODY)							0.22	***0.46***	0.17	0.03	0.03	0.03						
24	CENTRE SUPPORT DECKHOUSE PS (DECKHOUSE)							0.68	***0.96***	0.27	0.03	0.03	0.02						
25	THRUSTBEARING ENGINE SB (UNDER RUBBER)	0.14	***0.15***	0.08	0	0	0												
26	THRUSTBEARING ENGINE SB (ABOVE RUBBER)	***1.4***	0.8	0.4	0.3	0.2	0.2												
27	THRUSTBEARING ENGINE SB (UNDER RUBBER)													0.49	***0.55***	0.21	0.05	0.03	0.03
28	THRUSTBEARING ENGINE SB (ABOVE RUBBER)													0.7	***0.7***	0.2	0.2	0.3	0.2
29	HELMSMAN'S CHAIR	0.36	***1.46***	0.23	0.05	0.02	0.02												
30	HELMSMAN'S CHAIR							0.5	***3.2***	0.3	0.05	0.05	0						
31	HELMSMAN'S CHAIR													***0.48***	0.3	0.22	0	0	0
32	FORWARD SUPPORT DECKHOUSE PS (BODY)													***1.16***	0.38	0.23	0.08	0.08	0.1
33	FORWARD SUPPORT DECKHOUSE PS (DECKHOUSE)													***1.1***	0.39	0.23	0.03	0.03	0.03
34	DECKHOUSE FORE SB	***0.44***	0.22	0.1	0.06	0.05	0.04												
35	DECKHOUSE FORE SB							***2.45***	1.2	0.02	0	0	0						
36	UPPER DECKHOUSE FORE SB													0.7	***0.95***	0.42	0.08	0.04	0.06
37	ENGINE SUPPORT SB (UNDER RUBBER)													0.35	***0.5***	0.16	0.04	0.04	0.01
38	ENGINE SUPPORT SB (ABOVE RUBBER)													***1.2***	0.7	0.3	0.25	0.25	0.25
39	ENGINE ROOM BULKHEAD FORWARD	***0.3***	0.31	0.14	0.13	0.05	0.05												
40	LOWER SIDE DECKHOUSE FORWARD MIDSHIPS	***0.7***	0.17	0.12	0.03	0.03	0.03												
41	BOTTOM STOREROOM SB													***0.9***	0.64	0.28	0.2	0.32	0.36
42	FORWARD DECK MIDSHIPS ABOVE STOREROOM													0.72	***1.35***	0.18	0.64	0.62	0.76
43	FORE PEAK BULKHEAD MIDSHIPS	0.35	***1.43***	1.26	0.48	0.3	0.61												
44	FOREDECK MIDSHIPS													2.75	***3.9***	0.4	0.25	0.2	0.2
45	FOREHEAD DECK MIDSHIPS	***0.47***	0.33	0.2	0.14	0.06	0.06												
46	FOREHEAD DECK MIDSHIPS													***2.4***	1.3	0.2	0.1	0.1	0

EXPLANATION OF SYMBOLS USED:

KEY TO DIRECTION OF MEASUREMENT : 1 = LONGITUDINAL DIRECTION 2 = LATERAL DIRECTION 3 = VERTICAL DIRECTION

MAXIMUM VALUE PER CHANNEL IN : ***ITALIC BOLD***

TABLE 1 : OVERVIEW OF RESULTS OF VIBRATION MEASURENTS

CHANNEL NUMBER	DESCRIPTION MEASURING LOCATION	FRAME No.	MEASURED STRESSES AND DEDUCED STRESSES AND STRESS RATIOS: Srange [N/mm2] Pilot[1]	Srange Sailing[2]	Srange Pil./Sai.[3]	Smin [N/mm2] Pilot[1]	Smin Sailing[2]	Smin Pil./Sai.[3]	Smax [N/mm2] Pilot[1]	Smax Sailing[2]	Smax Pil./Sai.[3]	κ [–] Pilot[1]	κ Sailing[2]	κ Pil./Sai.[3]	Saver [N/mm2] Pilot[1]	Saver Sailing[2]	Saver Pil./Sai.[3]
1	Revolutions SB engine																
2	Accel. found.PS engine,vert.		6g	overload													
3	Accel. Fore peak,lateral		6g	1.8g	3.3												
4	Accel. Fore peak, vertical		3g	6g	0.5												
5	2nd spray rail Position 2 SB	10	5	6	0.8	-1	-4	0.3	4	2	2.0	-0.3	-2.0	0.1	1.5	-1.0	-1.5
6	2nd spray rail Position 3 SB	10	13	16	0.8	2	-2	-1.0	15	14	1.1	0.1	-0.1	-0.9	8.5	6.0	1.4
7	A inner	10	40	26	1.5	-35	-18	1.9	5	8	0.6	-7.0	-2.3	3.1	-15.0	-5.0	3.0
8	A outer	10	3	8	0.4	2	-2	-1.0	5	6	0.8	0.4	-0.3	-1.2	3.5	2.0	1.8
9	A flange	10	21	7	3.0	-2	-2	1.0	19	5	3.8	-0.1	-0.4	0.3	8.5	1.5	5.7
10	B inner	10	16	17	0.9	-4	-9	0.4	12	8	1.5	-0.3	-1.1	0.3	4.0	-0.5	-8.0
11	B outer	10	140	170	0.8	-60	-80	0.8	80	90	0.9	-0.8	-0.9	0.8	10.0	5.0	2.0
12	C outer	10	0.7	2	0.4	-0.3	0	#####	0.4	2	0.2	-0.8	0.0	#####	0.1	1.0	0.1
13	C inner	10	65	13	5.0	-15	-5	3.0	50	8	6.3	-0.3	-0.6	0.5	17.5	1.5	11.7
14	D outer	10	2	2.6	0.8	-0.5	-1	0.5	1.5	1.6	0.9	-0.3	-0.6	0.5	0.5	0.3	1.7
15	D inner	10	8	6	1.3	-2	-5	0.4	6	1	6.0	-0.3	-5.0	0.1	2.0	-2.0	-1.0
16	E upper	10	2.4	2.7	0.9	-0.8	-1.2	0.7	1.6	1.5	1.1	-0.5	-0.8	0.6	0.4	0.2	2.7
17	E under	10	7	8.5	0.8	-3	-4	0.8	4	4.5	0.9	-0.8	-0.9	0.8	0.5	0.3	2.0
18	E flange	10	27	12	2.3	-5	-6	0.8	22	6	3.7	-0.2	-1.0	0.2	8.5	0.0	#####
19	F upper	10	2	5	0.4	-0.8	-2	0.4	1.2	3	0.4	-0.7	-0.7	1.0	0.2	0.5	0.4
20	F under	10	6	17	0.4	-3	-7	0.4	3	10	0.3	-1.0	-0.7	1.4	0.0	1.5	0.0
21	F flange	10	9	30	0.3	-5	-10	0.5	4	20	0.2	-1.3	-0.5	2.5	-0.5	5.0	-0.1
22	2nd spray rail Position 1 PS	10	19	40	0.5	-15	-30	0.5	4	10	0.4	-3.8	-3.0	1.3	-5.5	-10.0	0.6
23	2nd spray rail Position 2 PS	10	22	50	0.4	-20	-45	0.4	2	5	0.4	-10.0	-9.0	1.1	-9.0	-20.0	0.5
24	2nd spray rail Position 3 PS	10	7	45	0.2	-3	-35	0.1	4	10	0.4	-0.8	-3.5	0.2	0.5	-12.5	0.0
25	A inner	11				failed	failed		failed	failed							
26	A outer	11	6	5	1.2	-1	-3	0.3	5	2	2.5	-0.2	-1.5	0.1	2.0	-0.5	-4.0
27	A inner	13	4	16	0.3	-4.5	-3	1.5	-0.5	13	0.0	9.0	-0.2	-39.0	-2.5	5.0	-0.5
28	A outer	13	2	7	0.3	-1	-5	0.2	1	2	0.5	-1.0	-2.5	0.4	0.0	-1.5	0.0
29	A inner	14	4	16	0.3	-5	-4	1.3	-1	12	-0.1	5.0	-0.3	-15.0	-3.0	4.0	-0.8
30	A outer	14	3	10	0.3	-1	-6	0.2	2	4	0.5	-0.5	-1.5	0.3	0.5	-1.0	-0.5
31	B inner	14	2	8	0.3	-1	-6	0.2	1	2	0.5	-1.0	-3.0	0.3	0.0	-2.0	0.0
32	B outer	14				highfr.int.	highfr.int.		highfr.int.	highfr.int.							
33	C inner	14	3	7	0.4	-4	-5	0.8	-1	2	-0.5	4.0	-2.5	-1.6	-2.5	-1.5	1.7
34	C outer	14	0.6	2.3	0.3	-0.5	-1.2	0.4	0.1	1.1	0.1	-5.0	-1.1	4.6	-0.2	-0.1	4.0
35	D inner	14	1.6	2	0.8	-0.6	-1	0.6	1	1	1.0	-0.6	-1.0	0.6	0.2	0.0	#####
36	D outer	14	3	4	0.8	0	-3	0.0	3	1	3.0	0.0	-3.0	0.0	1.5	-1.0	-1.5
37	E upper	14	4	2	2.0	-4.2	-1	4.2	-0.2	1	-0.2	21.0	-1.0	-21.0	-2.2	0.0	#####
38	E under	14	11.4	7	1.6	-11.2	-2	5.6	0.2	5	0.0	-56.0	-0.4	140.0	-5.5	1.5	-3.7
39	F upper	14	110	90	1.2	-50	-60	0.8	60	30	2.0	-0.8	-2.0	0.4	5.0	-15.0	-0.3
40	F under	14	3	7	0.4	-2	-6	0.3	1	1	1.0	-2.0	-6.0	0.3	-0.5	-2.5	0.2
41	A inner	15				failed	failed		failed	failed							
42	A outer	15	7	12	0.6	-5	-8	0.6	2	4	0.5	-2.5	-2.0	1.3	-1.5	-2.0	0.8
43	A inner	17	35	12	2.9	-40	-4	10.0	-5	8	-0.6	8.0	-0.5	-16.0	-22.5	2.0	-11.3
44	A outer	17	13	7	1.9	-12	-5	2.4	1	2	0.5	-12.0	-2.5	4.8	-5.5	-1.5	3.7

EXPLANATION OF SYMBOLS USED:

Srange= Smax - Smin [N/mm2] Smin = minimum stress [N/mm2] Smax = maximum stress [N/mm2] k = Smin /Smax [-]

Saver = (Smin + Smax)/2 [N/mm2] 1 = Pilotage 2 = Sailing in heavy seas 3 = Pilotage/Sailing in heavy seas

highfr.int = high frequency interference Failed = Signal failure g = gravity acceleration (i.e 6g = acceleration of approx. 60 m/s2)

A flange= Top of flange, position A (fig.1) A inner = webplating near flange, posit. A (fig.1) A outer= webplating near hull, posit. A (fig.1)

2nd spray rail Positions 1,2 and 3 = stress measured perpendicular to cracks a, b and c repectively on plane of spray rail and frame surfaces (see fig. 10)

TABLE 2: OVERVIEW OF RESULTS OF STRESS MEASUREMENTS