SUPPLEMENT No. 410

Trägårdh Peter:

Model test with M/S ESTONIA. Sea loads on bow visor and yawing behaviour due to heel.

SSPA Maritime Consulting. Report 7524.

Gothenburg 1995.

EX 3(5)

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MARITIME CONSULTING

REPORT

Subject	Report
Model tests with M/S Estonia **Sea loads on bow visor and yawing behaviour due to heel.**	7524
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Order Fax dated 1995-05-18	Code of classification

Summary

Model tests with a self-propelled model of M/S Estonia have been carried out in both the towing tank and the Maritime Dynamics Laboratory (MDL) in order to study the wave induced loads on the bow visor. At the tests in the towing tank the model was free to heave, trim and roll and the model speed was equal to the towing carriage while in MDL the model was completely free to move in all 6 degrees of freedom and controlled by an autopilot.
As an example the maximum expected wave and response during abt 3 hours in irregular bow sea with a significant wave height Hs= 4.3 m at a speed of 14.5 knots, which have been claimed to be the most probable condition preceding the accident, can be derived from these tests. Thus the highest wave would be 8.4 m, the upward vertical force 7.4 MN and opening deck hinge moment 35.4 MNm.

Some tests were carried out in order to study the yawing behaviour at different heel angles. The ship did not yaw as would be expected due to the curved waterline at heel, i.e. to port at a starboard heel. This could be explained by the negative pressures forward of the two propellers running with the same thrust creating steering forces that are larger than and opposite to those created by the unsymmetric curved waterline at heel.

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1. Introduction

Model tests with a model of M/S Estonia have been carried on behalf of Statens Haverikommission (Board of Accident Investigation) in Stockholm. The purpose of the tests was to measure the wave induced loads on the bow visor in different waves and speeds at head and bow seas.
The yawing behaviour caused by the heeling of the ship due to water flooding was also studied.

The test program was decided in co-operation with a SHK representative who also was present at the tests in SSPA Maritime Dynamics Laboratory (MDL). The main object was to get a good statistical basis for estimation of actual loads on the bow visor. The most effective way was to run a long (abt 5 hours full scale time) head sea condition in the towing tank, a reasonable long (abt 3 hours) bow sea condition in MDL and further shorter conditions in both tanks.

2. Model test data

Model tests were carried out in SSPA towing tank on June 19-20 and in MDL on June 28 - July 1. Main data for test conditions (full scale data):

Ship Model			2758-A
Scale			1:35
Length, Lpp		(m)	137.40
Beam		(m)	23.59
Draft			
moulded	forward	(m)	5.17
	aft	(m)	5.61
Displacement		(m^3)	11930
		(tonnes)	12050
Block coefficient		(-)	0.683
LCB		(% aft L/2)	4.85
GM (corr)		(m)	1.17
Rudder	No of rudders		2
	Height	(m)	4.0
	Area, tot/rud	(m^2)	10.85
	- , mov/rud	(m^2)	8.75
	- , tot	(% of L·T)	2.90
Propeller	No of propellers		2
	No of blades	(-)	4
	Diameter	(m)	4.200
	Pitch Ratio	(-)	0.868
	Model No		P1757 (left and right rotating outward)

Photos, body plan and contours of the model is given in figs 1-5. The model was fitted with bilge keels, duck-tail, bow and rudder ice knifes, controllable rudders and a separate bow visor attached to the model with a six-component balance (fig 6).

3. Wave tests in the towing tank

At the tests in the towing tank the model was free to move in heave, roll and pitch. Although self-propelled the model was connected to the carriage with a towing rod including a x-force gauge. The propeller rpm was calibrated to give zero towing force in calm water. Thus the measured force gives some information about the added resistance in head waves. The speed of the model was constant during the test and the same as the carriage.

However the main object of the tests was to measure forces and moments on the bow visor caused by the wave impact. The wave profile was measured both some distance ahead of the model where the waves are undisturbed by the model and the tank walls but also abt 4 m beside the model at the same longitudinal position as the forward perpendicular (FP) thus providing information for calculation of relative motion as the vertical motion at FP was measured. In addition the vertical acceleration at FP was measured.

The following table gives the test program. In order to get desired amount of statistical bases several test runs were carried out in irregular sea. For the analysis the time series of measuring parameters for all runs for each test condition were added together.

Tests in SSPA towing tank on June 19-20 1995

Run 4-5	Irregular head sea	Hs= 4.0 m - Tp= 8.0 s,	10 knots	
6-31	Irregular head sea	Hs= 4.0 m - Tp= 8.0 s,	15 knots	
32-33	Irregular head sea	Hs= 4.0 m - Tp= 8.0 s,	19 knots	
34-35	Irregular head sea	Hs= 5.5 m - Tp= 8.0 s,	10 knots	
36-37	Irregular head sea	Hs= 5.5 m - Tp= 8.0 s,	15 knots	
38-40	Irregular head sea	Hs= 5.5 m - Tp= 8.0 s,	19 knots	
41	Irregular head sea	Hs= 5.5 m - Tp= 8.0 s,	15 knots	
42	Irregular head sea	Hs= 5.5 m - Tp= 8.0 s,	10 knots	
46	Regular head sea	H = 4.0 m - T = 9.3 s,	10 knots	(λ/L= 1.0)
47	Regular head sea	H = 4.0 m - T = 9.3 s,	15 knots	(λ/L= 1.0)
48	Regular head sea	H = 4.0 m - T = 9.3 s,	19 knots	(λ/L= 1.0)
49	Regular head sea	H = 4.0 m - T = 8.0 s,	10 knots	(λ/L= 0.74)
50	Regular head sea	H = 4.0 m - T = 8.0 s,	15 knots	(λ/L= 0.74)
51	Regular head sea	H = 4.0 m - T = 8.0 s,	19 knots	(λ/L= 0.74)

Irregular waves of JONSWAP spectrum.

4. Wave tests in MDL

At the tests in MDL the model was completely free to move in all six degrees of freedom, self-propelled and controlled by an autopilot. An X-Y-positioner (measuring arm) is the only link between the carriage and the model. The deviation in position between model and carriage are fed into a steering computer which controls the carriage to "hunt" the model. The measuring arm also provide measuring signals for calculation of all 6 DoF motions and from this the vertical motion at FP could be calculated.

The propeller rpm was adjusted to give the desired mean speed during the test run.
The wave profile was measured at a position abt 2 m starboard of the model (leeward side), longitudinally adjusted so that the wave meets the FP of the ship at the same time. Thus the relative motion could be calculated as the difference between the wave height and the vertical motion at FP.

The following table gives the test program. In order to get desired amount of statistical bases several test runs were carried out in irregular sea. For the analysis the time series of measuring parameters for all runs for each test condition were added together.

Tests in SSPA Maritime Dynamics Laboratory on June 28-30

Run	7-13	Irregular head sea	Hs= 4.0 m - Tp= 8.0 s,	15 knots
	15	Regular head sea	H = 4.0 m - T = 8.0 s,	15 knots (λ/L= 0.74)
	18	Regular bow sea	H = 4.0 m - T = 8.0 s,	15 knots (λ/L= 0.74)
	20	Regular bow sea	H = 4.0 m - T = 8.0 s,	10 knots (λ/L= 0.74)
	22	Regular bow sea	H = 6.0 m - T = 8.0 s,	15 knots (λ/L= 0.74)
	34-37	Irregular bow sea	Hs= 4.0 m - Tp= 8.0 s,	10 knots
	39-40	Irregular bow sea	Hs= 4.0 m - Tp= 8.0 s,	10 knots
	45-46	Irregular bow sea	Hs= 4.0 m - Tp= 8.0 s,	10 knots
	48-55	Irregular bow sea	Hs= 5.5 m - Tp= 8.0 s,	10 knots
	56-66	Irregular bow sea	Hs= 5.5 m - Tp= 8.0 s,	15 knots
	67-116	Irregular bow sea	Hs= 4.3 m - Tp= 8.3 s,	14.5 knots

Irregular waves of JONSWAP spectrum is used as it is representative for the relatively shallow water of the actual area of the Baltic sea and for a relatively young storm with the energy concentrated around the peak period Tp. It generally means more severe (conservative) response that the more commonly used Pierson-Moskowitz or ITTC spectrum.
It should also be noted that all tests have been run in long-crested sea which generally give more conservative response but also is considered as more representative for a young storm.

5. Manoeuvring tests in MDL

The background for running manoeuvring tests was a theory that the starboard heel angle caused by the water flooding of the ro/ro deck would make the ship yaw to port regardless of the autopilot trying to keep course by compensating with a starboard rudder angle. This yawing was expected to be explained by the unsymmetric curved waterline profile of the hull due to heel.

Due to practical testing reasons the weights used instead of water to heel the ship had to be placed on the port rail thus providing a port heel angle. The following static heel angles were achieved with weights placed on the port rail:

Scale		Heel
model	full	angle
5 kg	214 ton	8.7°
10 kg	428 ton	15.3°
15 kg	643 ton	21.5°
20 kg	857 ton	27.2°
22.5 kg	965 ton	30.3°

Manoeuvring tests at an initial speed of 14.5 knots:

Run no
23: 5 kg at L/2 - autopilot in calm water
24: 10 kg at L/2 - autopilot in calm water
25: 15 kg at L/2 - autopilot in calm water
26: 15 kg at L/2 - zero rudder in calm water
27: 20 kg at L/2 - zero rudder in calm water
29: 15 kg at L/2 - autopilot in bow sea -150°
30: 15 kg at L/2 - zero rudder in bow sea -150°
31: 15 kg aft - zero rudder in calm water
32: 15 kg at L/2 - initial rudder at 30° put to zero in calm water
38: 15 kg at L/2 - zero rudder in calm water - only starboard propeller running
41: 15 kg at L/2 - zero rudder in calm water - only starboard propeller running
42: 15 kg at L/2 - zero rudder in calm water - only port propeller running
43: 0 kg at L/2 - zero rudder in calm water - only port propeller running

From runs 23-25 it could be concluded that there was no problem for the autopilot to maintain a straight course using only moderate rudder angles. Thus it was decided to lock the rudder in a position that provided the most straight course in calm water without heel, i.e. starboard 1.8 deg called zero rudder. Runs 26-27 gave a clear indication that the ship turned the unexpected way, i.e. port heel gives port yaw. The tests in waves with autopilot confirmed the good steering behaviour in calm water and with zero rudder the ship turned to port just as before.
There was no significant change of behaviour if the weights were place as far aft as possible (cf run 26 and 31).

At run 32 the test started with a starboard rudder angle just to initiate a starboard turn. After put to zero rudder the yaw rate decreased and probably it would have turned port if the dimension of the basin had been large enough.
By stopping the port propeller the port yawing was increased (cf runs 26, 38 and 41).
At runs 41-43 the initial speed was reduced to 12 knots, i.e. the approximate steady speed with one propeller running at the same rpm as corresponding to 14.5 knots with both propellers.
By stopping starboard propeller the ship turned the other way (run 42) but not at all as much as with port propeller stopped (cf run 41 and 42).
Time traces from all manoeuvring tests are given in the appendix [1] to this report and as an illustration runs 23-24 are given here (fig 19-20).

6. Results and conclusive remarks

Definitions of co-ordinate system, motions and wave direction are given in fig 11. Note that the height of the wave crest is negative and that negative relative motion means decreasing free-board. Standard statistics of relevant parameters from all tests are given in the appendix to this report [1]. Note that the period Tz is the zero-crossing period of encounter and that amplitudes marked with * means single amplitudes and ** double amplitudes. Time series and Weibull diagrams of relevant parameters and tests are also given in [1] but some examples are included here (fig 12-16).

The Weibull diagram is a special form of showing a statistical distribution and is a straight line with an inclination of 2.0 for a Rayleigh distribution which seems to be the case for the waves. For the forces and especially the moments the inclination is smaller and the highest values fall out of line probably because of too low statistical occurrence.

The measured Z-force has been corrected for the difference in mass of the model visor (2.98 kg corresponding to 127.8 ton in full-scale) and the full-scale visor (53.0 ton) to a nominal value, called Z-force nom. Also the pure dynamic wave load, Z-force dyn, has been calculated. The measured moments have been transformed to the deck hinge of the visor (Yh-moment) which also is corrected for the mass difference.
It should be noted that the weight of the visor is not included in the Z-force.

Time series of relative motion, X and Z-forces and Yh-moment are given for the most probable condition (14.5 knots in bow waves of Hs= 4.3 m and Tp= 8.3 s) in fig 13 . Note the very similar X and Z-forces (fig 13 c and d) with the upwards negative force peaks. From fig 13 e it is obvious that the opening positive deck hinge moment peaks do not occur as frequently as the vertical force peaks while the relative motion (fig 13 b) has the same frequency as the encountering wave.

In the tables below the maximum values from the Weibull diagrams are read. No of encounters have been calculated from ln(-ln(1-P(x))) where P(x) is the probability for a certain value to be exceeded. Hm is the height of the largest following crest and trough.

Towing tank tests - irregular sea

Dir	Hs	Speed	Waves		Rel mot (neg)		Z-force		Yh-moment	
			No	Hm	No	(m)	No	MN	No	MNm
180	4.0	10	357	6.33	301	-5.69	77	-1.8	178	1.8
180	4.0	15	3914	8.19	3018	-7.60	538	-6.2	55	18.2
180	4.0	19	301	7.29	211	-5.70	51	-8.5	14	16.8
180	5.5	10	662	9.55	538	-7.41	119	-6.3	38	18.5
180	5.5	15	459	9.07	392	-6.94	151	-5.9	55	14.2
180	5.5	19	424	9.55	301	-7.84	151	-8.1	45	27.5

Max values recalculated to the same probability level corresponding to 1618 wave encounters meaning Prob= ln(-ln(1-P(x))) =2.0 where (1-P(x))=1/1618 and which have been calculated proportionally with respect to no of encounters of each parameter and extrapolated (interpolated) in the Weibull diagrams:

Dir	Hs	Speed	Waves		Rel mot(neg)		Z-force		Yh-moment	
			Prob	Hm	Prob	(m)	Prob	MN	Prob	MNm
180	4.0	10	2.0	7.02	1.977	-6.02	1.767	-2.5	1.901	1.4
180	4.0	15	2.0	7.68	1.964	-7.38	1.687	-4.6	1.139	12.0
180	4.0	19	2.0	8.19	1.951	-7.20	1.725	-5.9	1.464	28.0
180	5.5	10	2.0	10.05	1.972	-9.55	1.736	-6.2	1.511	22.5
180	5.5	15	2.0	9.55	1.978	-8.95	1.837	-7.0	1.662	21.4
180	5.5	19	2.0	10.31	1.952	-9.42	1.850	-10.0	1.638	39.6

MDL tests - irregular sea

Dir	Hs	Speed	Waves		Rel mot (neg)		Z-force		Yh-moment	
			No	Hm	No	(m)	No	MN	No	MNm
180	4.0	15	363	8.84	301	-7.41	62	-5.0	5	14.9
150	4.0	10	363	8.08	301	-6.68	71	-2.4	45	3.4
150	5.5	10	363	9.55	301	-8.50	71	-7.3	17	31.6
150	5.5	15	363	10.05	251	-8.51	71	-10.8	20	54.8
150	4.3	14.5	1618	8.40	1280	-7.60	301	-7.4	67	35.4

Max values recalculated to the same probability level corresponding to 1618 wave encounters meaning Prob= ln(-ln(1-P(x))) =2.0 and extrapolated in the Weibull diagrams (fig 15-16):

Dir	Hs	Speed	Waves		Rel mot (neg)		Z-force		Yh-moment	
			Prob	Hm	Prob	(m)	Prob	MN	Prob	MNm
180	4.0	15	2.0	8.62	1.974	-6.42	1.727	-3.8	1.133	17.0
150	4.0	10	2.0	8.51	1.974	-7.68	1.750	-2.9	1.668	3.6
150	5.5	10	2.0	12.18	1.974	-9.92	1.750	-7.9	1.465	44.5
150	5.5	15	2.0	11.72	1.949	-9.31	1.750	-11.7	1.502	43.5
150	4.3	14.5	2.0	8.40	1.968	-7.60	1.742	-7.4	1.436	35.4

The maximum expected response (single amplitude) during 1618 wave encounters (abt 3 hours) have been plotted versus ship speed in fig 18. There do not seem to be a clear connection between relative motion/velocity, vertical force on visor and deck hinge moment, which is quite surprising. From the video recordings from the tests it seems likely that high deck hinge moment is in some way connected to a steep high wave hitting the visor high up. This explains why the highest vertical forces do not occur at the highest vertical motion and velocity and that high vertical forces can occur without causing large hinge moments.
Thus the maximum expected upward vertical force during 3 hours would be 7.4 MN and opening deck hinge moment 35.4 MNm for the most probable condition, i.e. 14.5 knots in bow irregular sea Hs= 4.3 m. However this does not occur due to the highest wave (Hm= 8.4 m) but for a wave of 6.5 m height as could be seen in the time series (fig 13-14).

Complete results from the tests in regular waves are given in the appendix and in fig 17 the most interesting results are plotted. Note that the distribution of peak values has not been calculated for the deck hinge moments from the towing tank tests. The reason is that the peak moments from the waves are very small and hardly becomes an opening moment (positive). For the worst case (run 22: 15 knots in bow sea with H= 6.0 m and T= 8.0 s) the opening deck hinge moment was only 2.1 while the closing moment was 3.3 MNm (fig 31d in the Appendix).
As an example time series from one test are given in fig 12.

The results from these model tests are similar to what could be expected in view of tests of bow loads on ro/ro ships carried out on behalf of the Swedish Shipowners' Association [2].

Manoeuvring tests

Generally a ship with a starboard heel angle should turn to port due to the change of the symmetric waterline profile of the hull to a unsymmetric curved waterline. This phenomena is sometimes called 'the banana effect' and is not very strong.
The 'unexpected' turning behaviour at the tests that were carried out here is probably caused by the negative pressures created in front of each forward working propeller. The horizontal components of these pressures acting on the V-formed sections of the aftbody cancel each other due to symmetry at zero heel, but at a starboard heel the component on the port side increases and on the starboard side decreases. The steering effect of this is likely to dominate over 'the banana effect'.

However it should be noted that these tests were carried out without any wind, which probably would have had a larger effect than 'the banana effect' on the ship making it to turn towards the wind as long as the speed was high enough. At zero speed the ship would have drifted with mainly beam wind and sea.

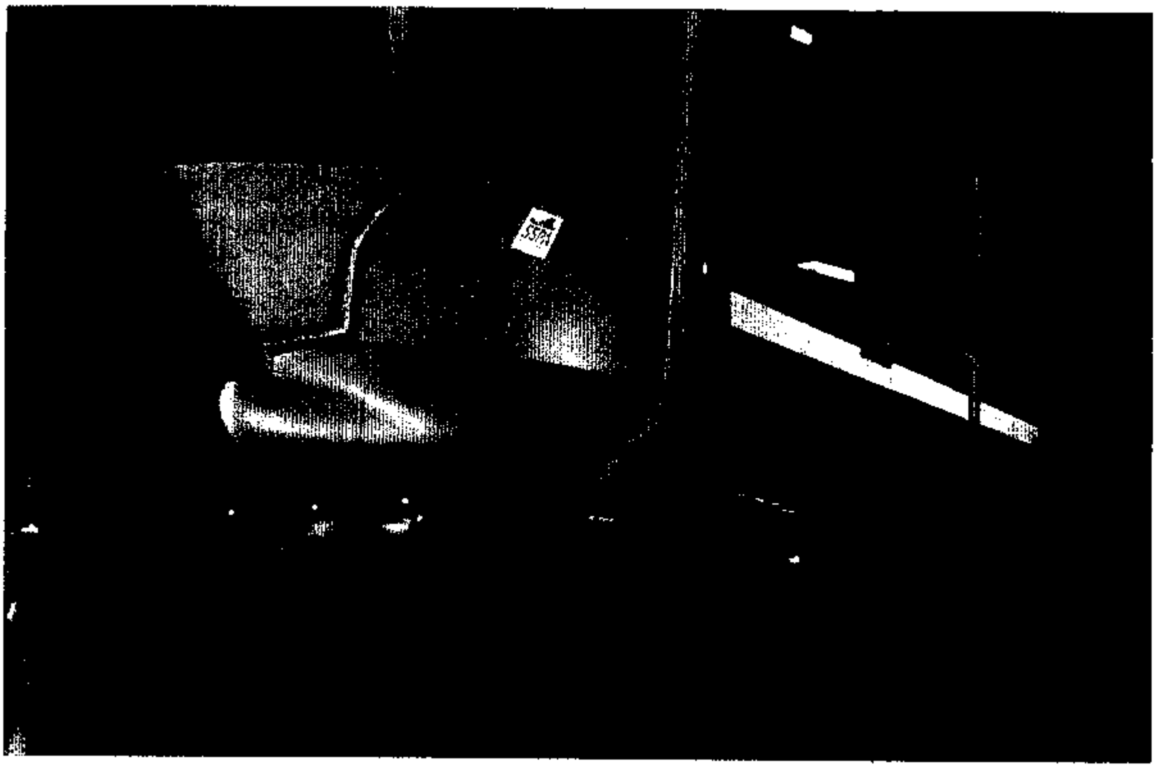
7. References

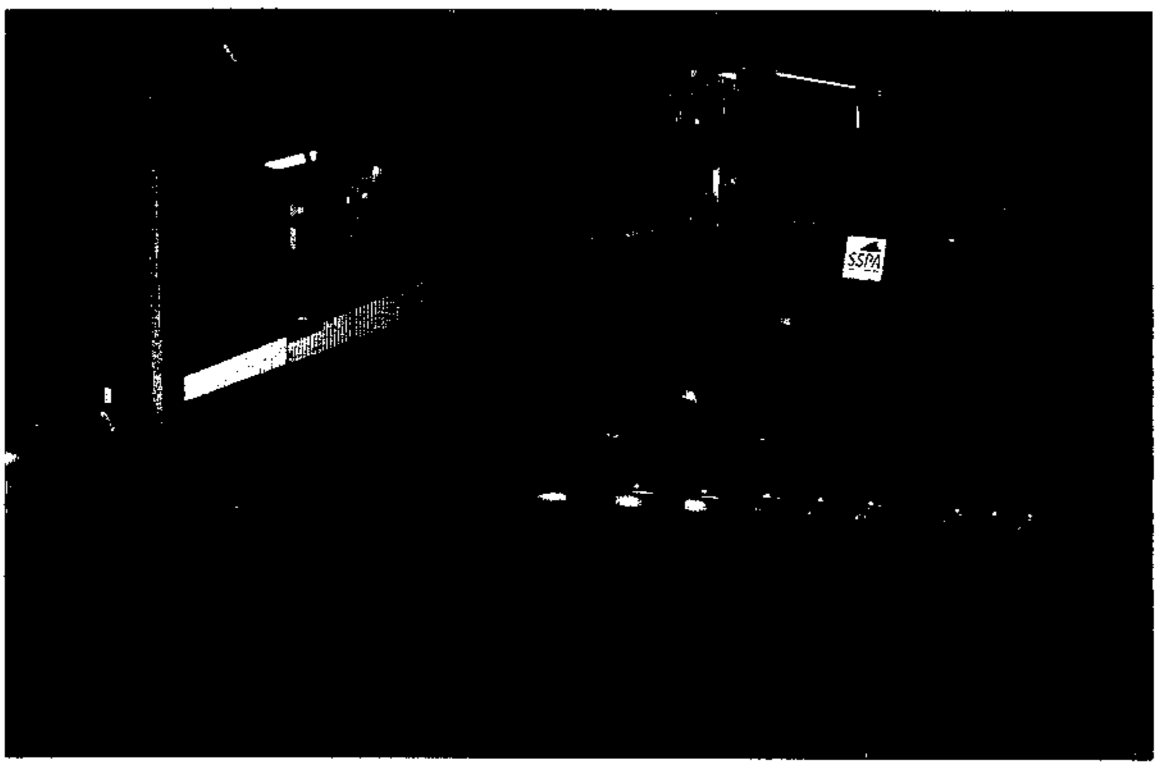
[1] P Trägårdh "Model tests with M/S Estonia - Appendix"
SSPA Report 7524-Appendix, 1995-09-20

[2] J Lundgren "Bow Loads on Ro/Ro Ships - Visor forces on five different bow shapes
Model tests in regular waves and irregular seas"
SSPA Report 7315-1 , Preliminary report from 7 March 1995

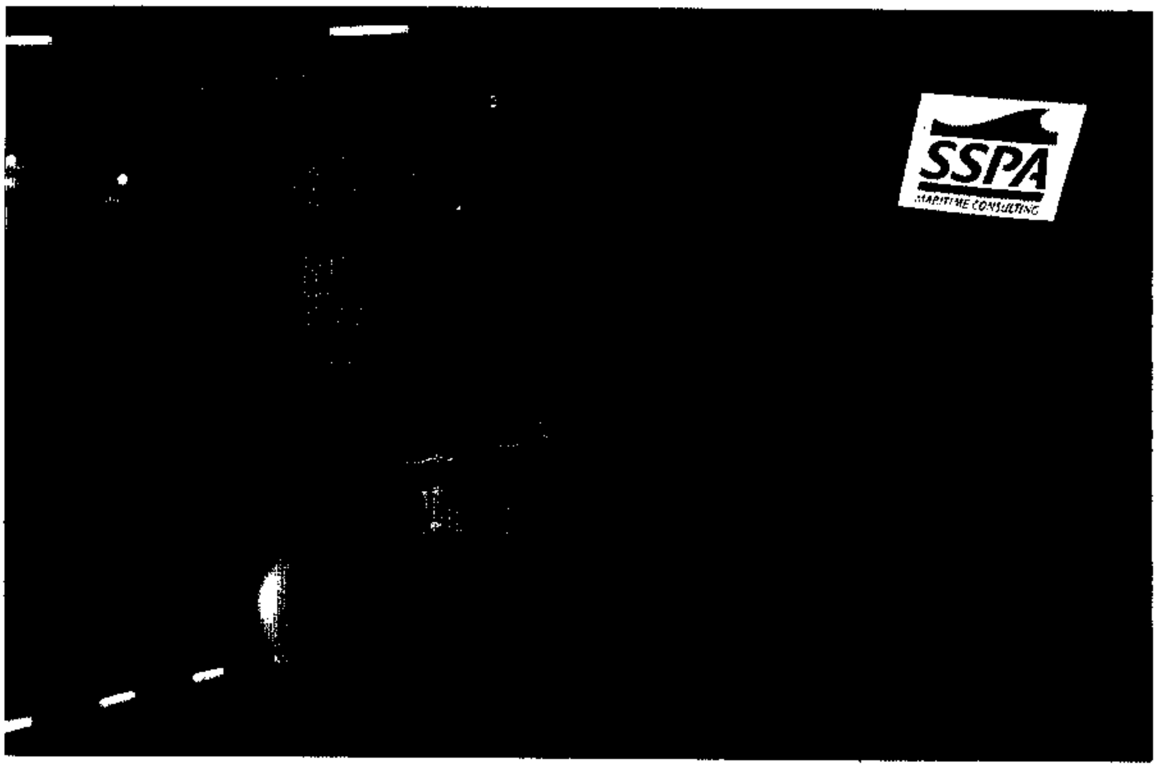
8. Figures

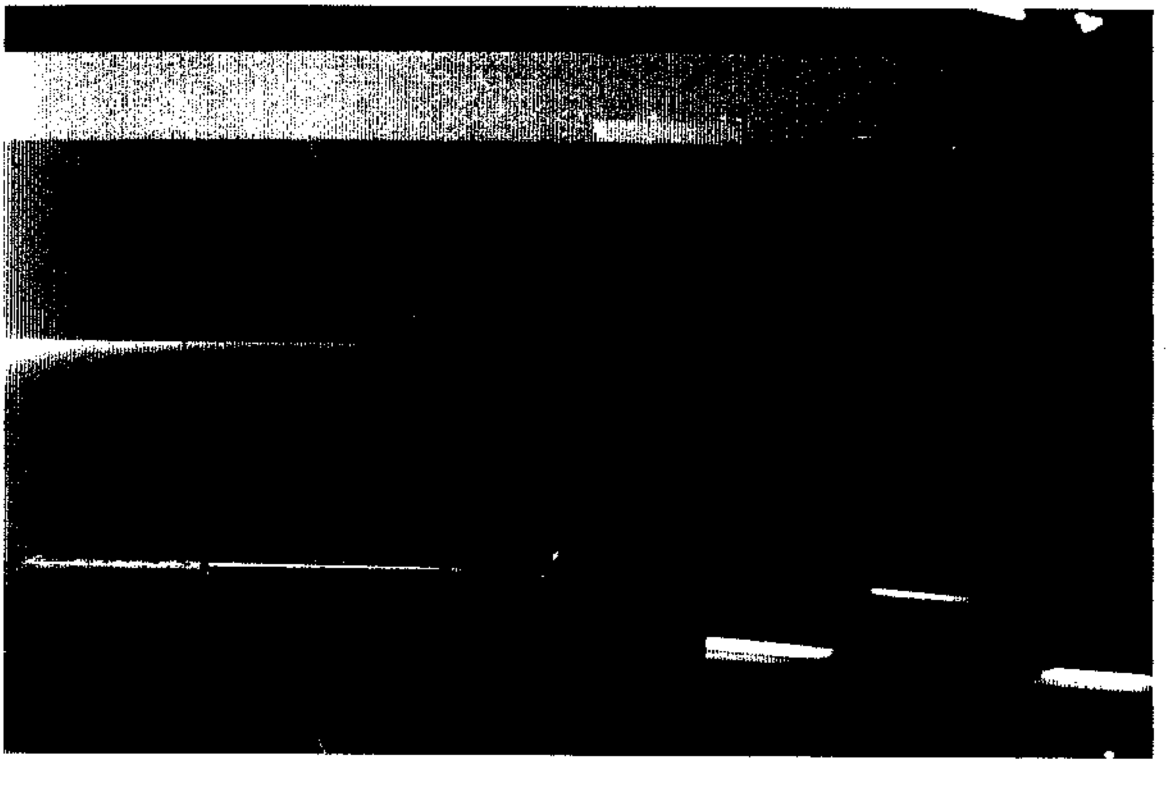
SSPA MARITIME CONSULTING	M/S Estonia SHIP MODEL 2758-A	Fig 1 Report 7524



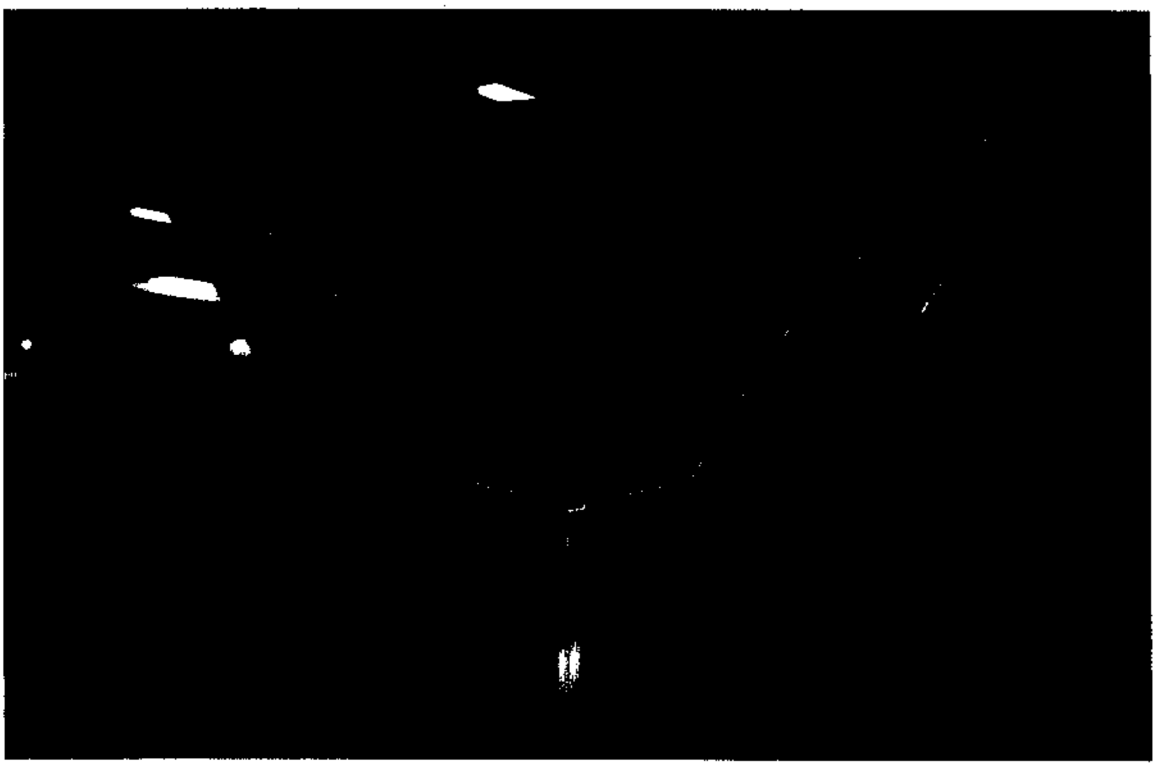


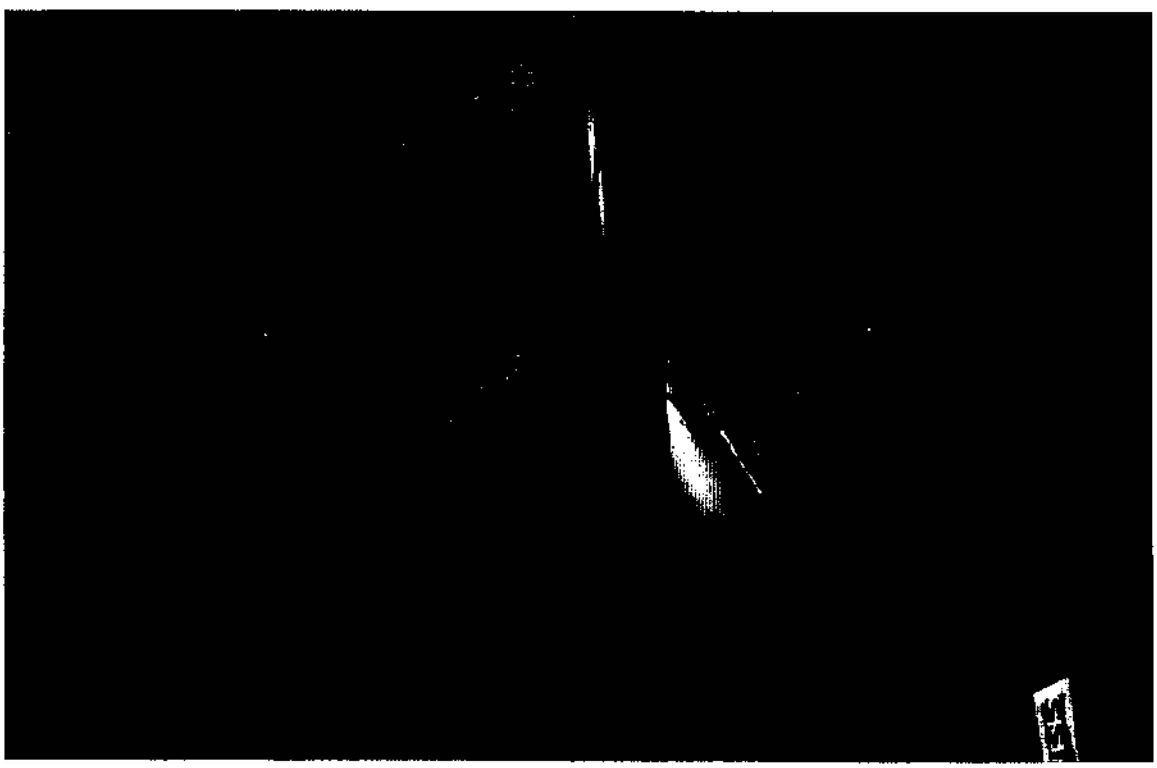
SSPA MARITIME CONSULTING	M/S Estonia SHIP MODEL 2758-A Forward and aft contours	Fig 2 Report 7524



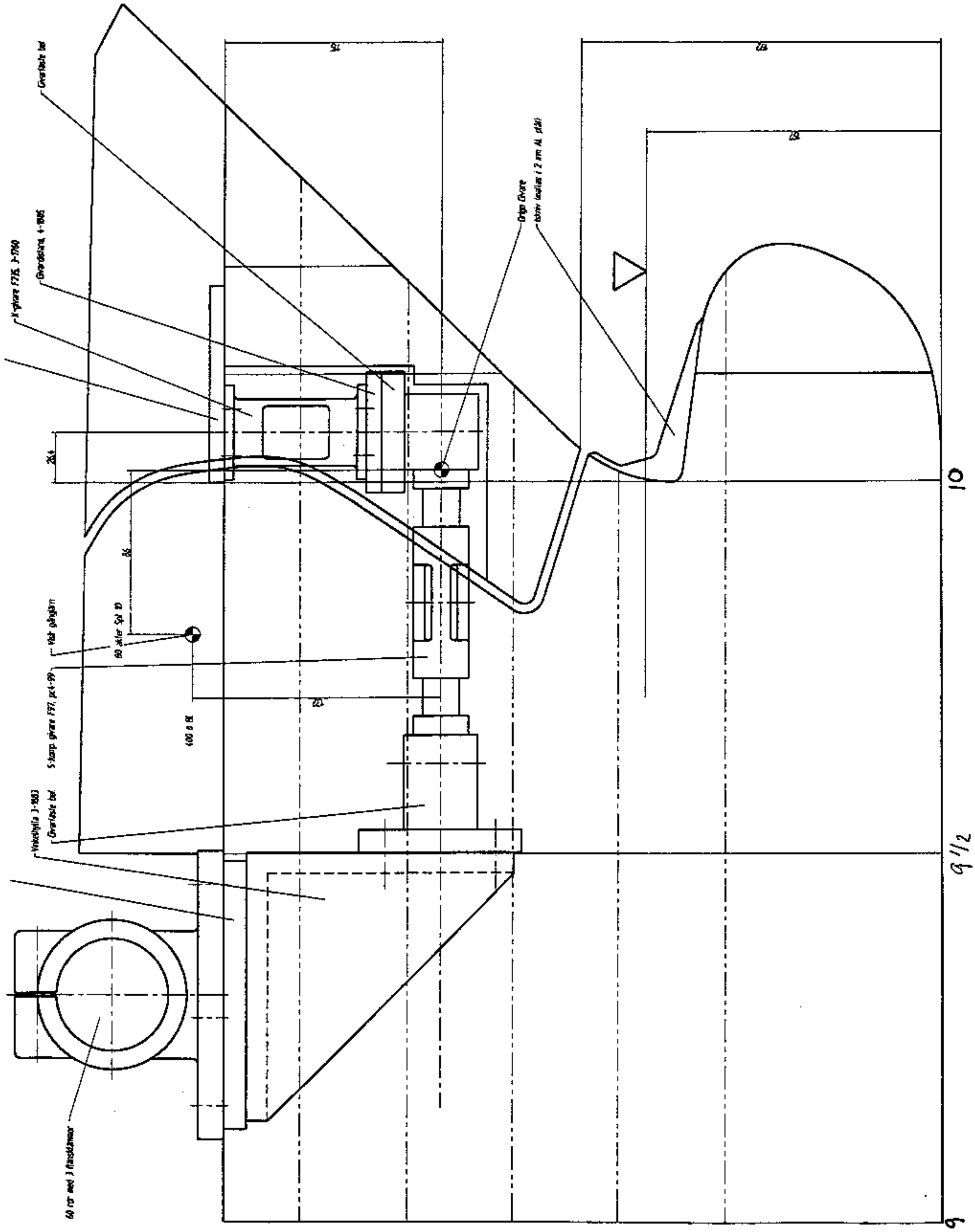


SSPA MARITIME CONSULTING	M/S Estonia SHIP MODEL 2758-A Bow with visor	Fig 3 Report 7524





SSPA MARITIME CONSULTING	M/S Estonia Bow visor Arrangement for 6-comp balance	Fig 4 Report 7524



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M/S Estonia
Ship model 2758-A

BODY PLAN

Fig 5

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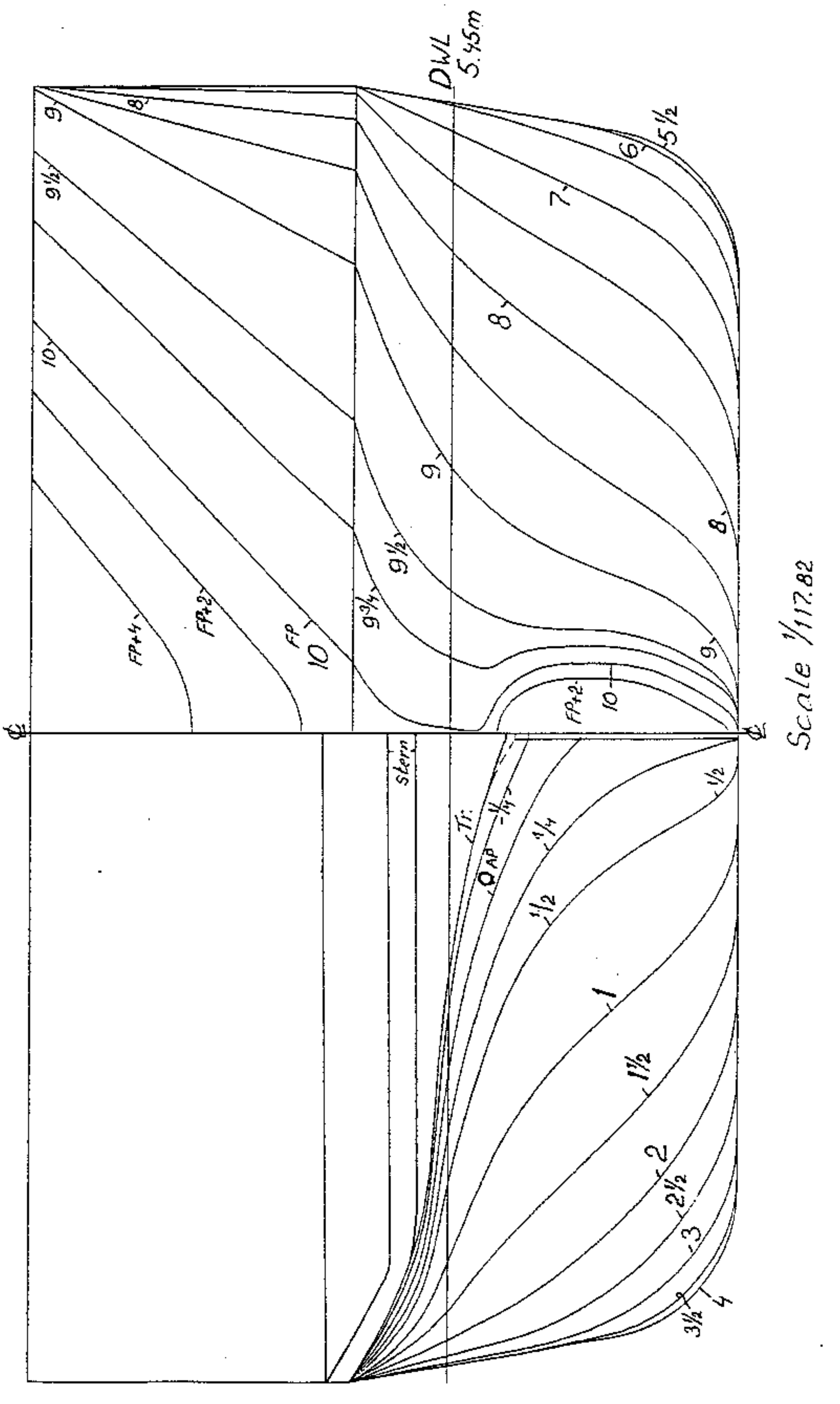
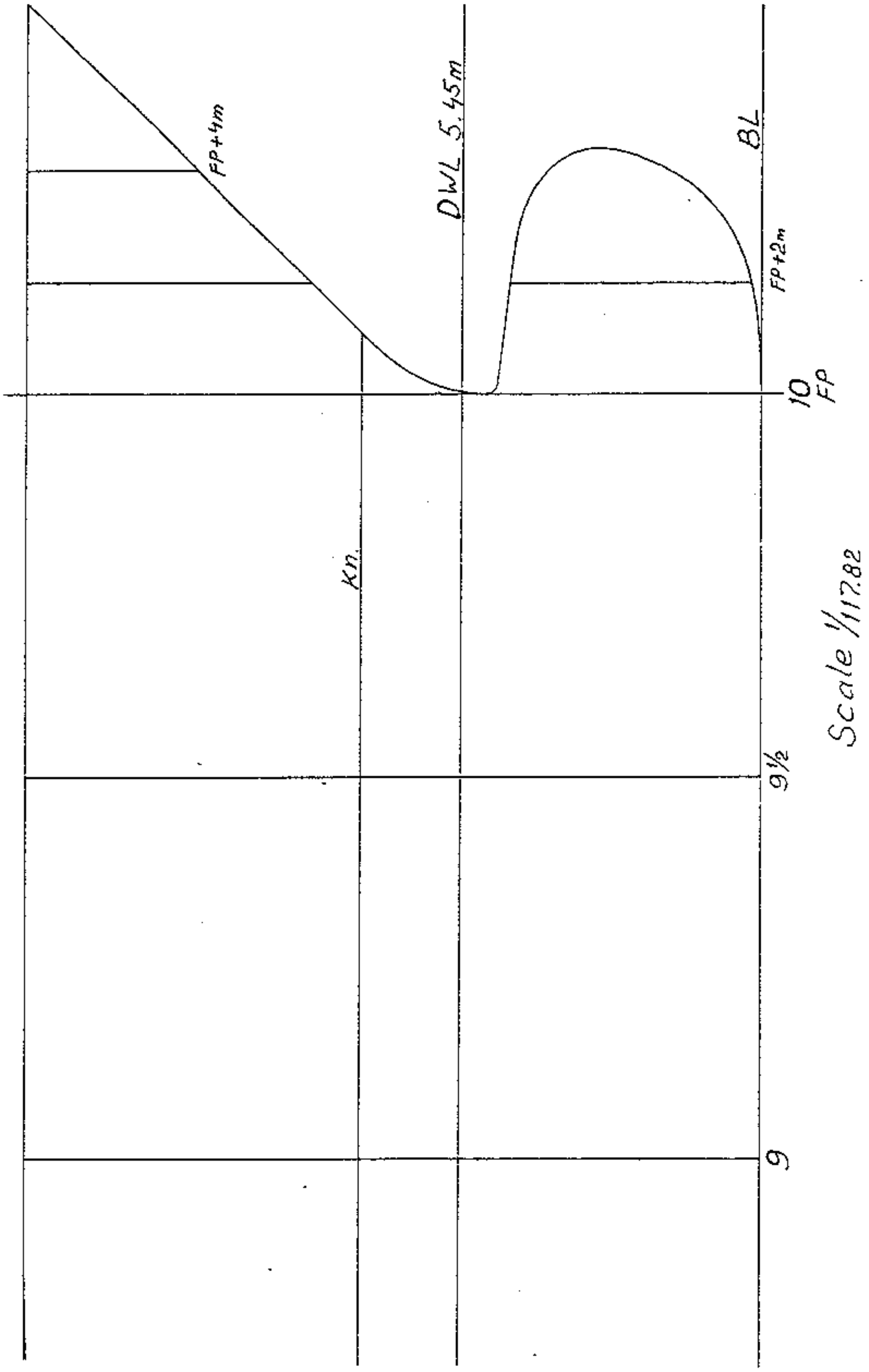


SSPA MARITIME CONSULTING	M/S Estonia Ship model 2758-A CONTOUR forward	Fig 6a Report 7524



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M/S Estonia
Ship model 2758-A

CONTOUR aft

Fig 6b

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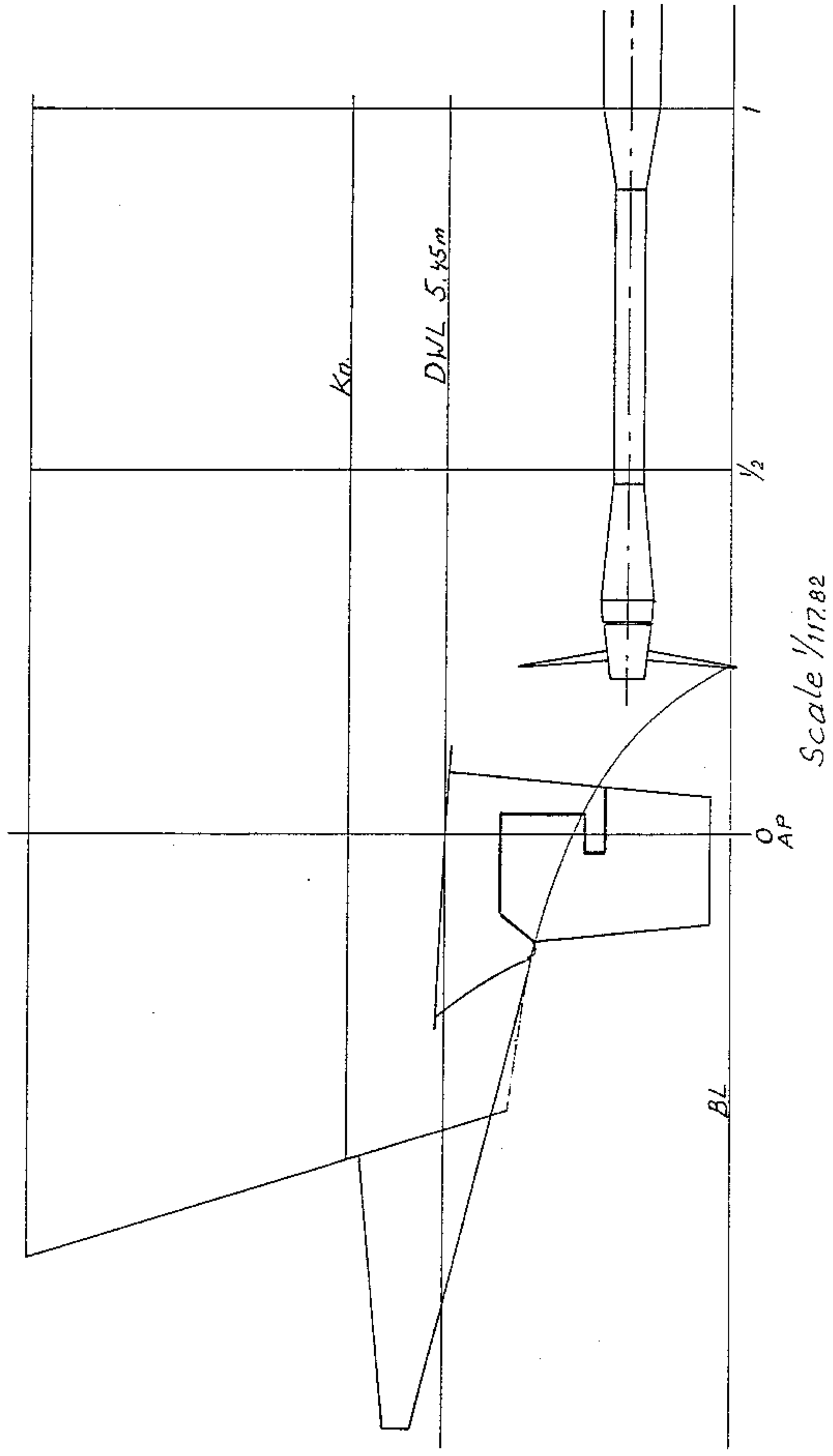
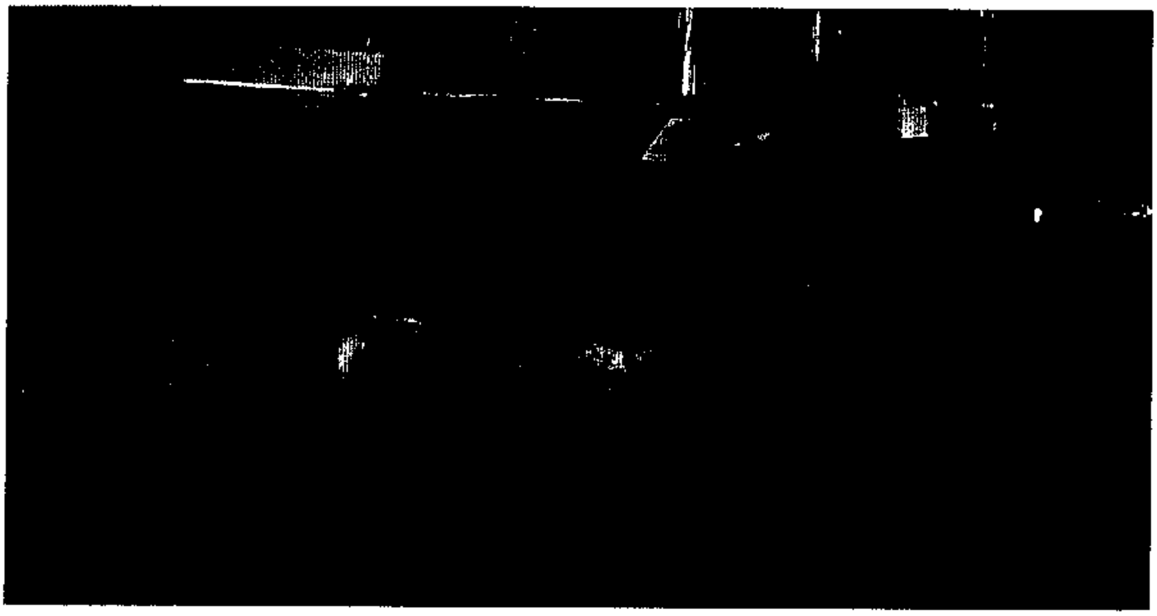
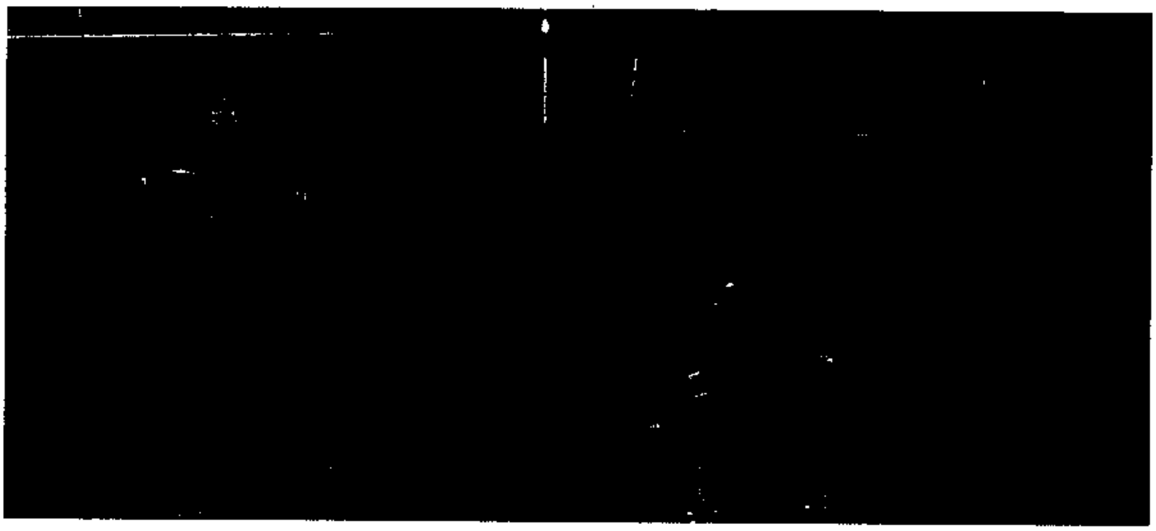
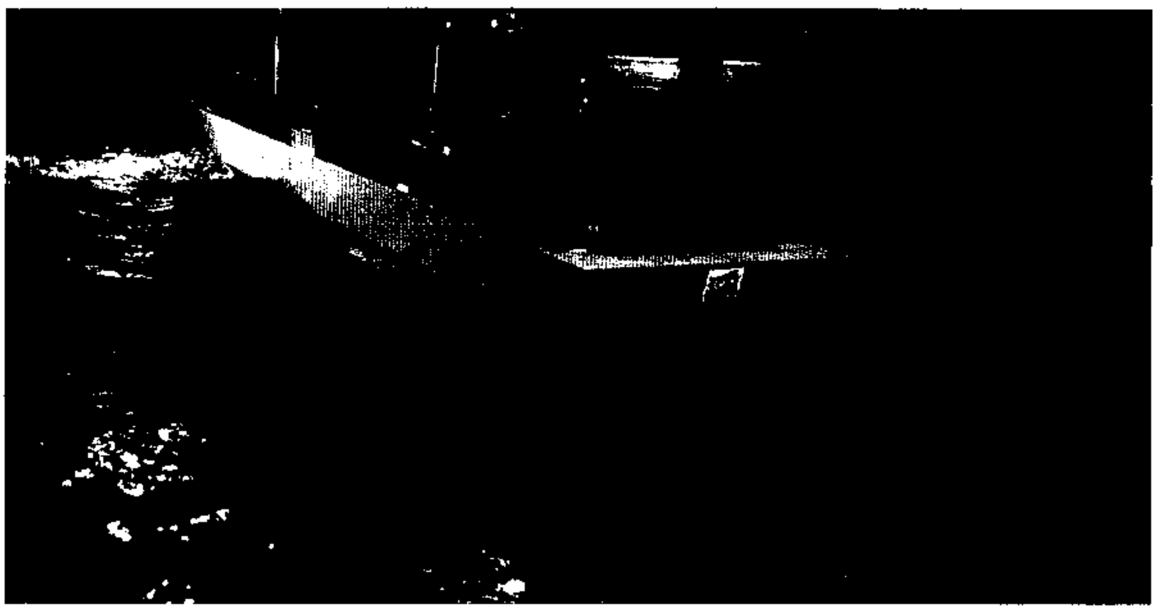


SSPA MARITIME CONSULTING	M/S Estonia Test in towing tank Speed 15.0 knots in head sea Hs= 4.0 m	Fig 7 Report 7524







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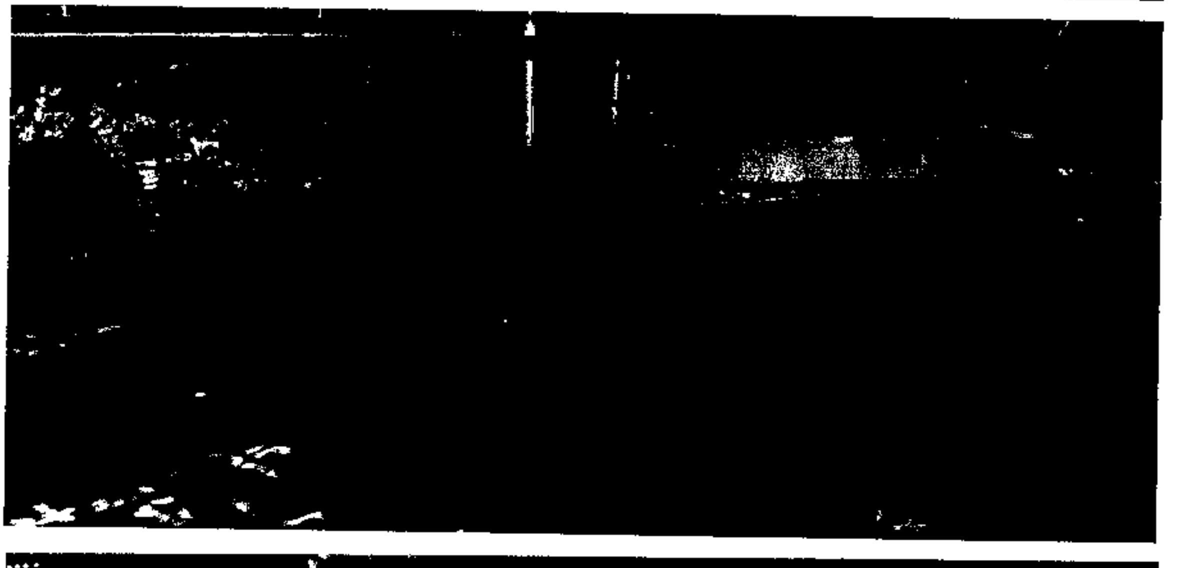
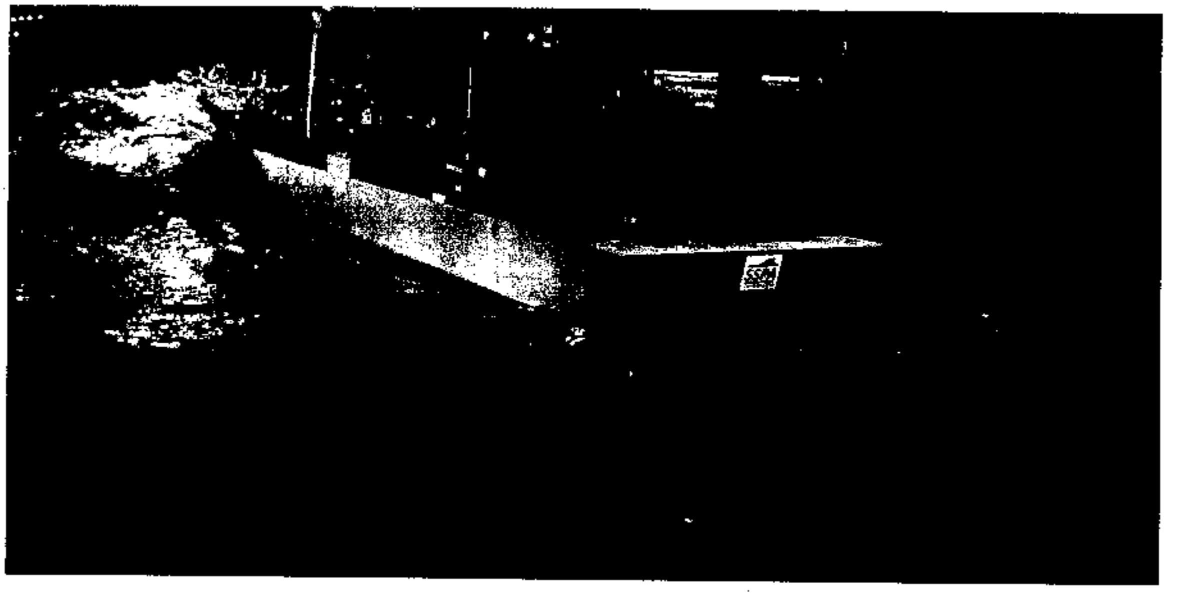
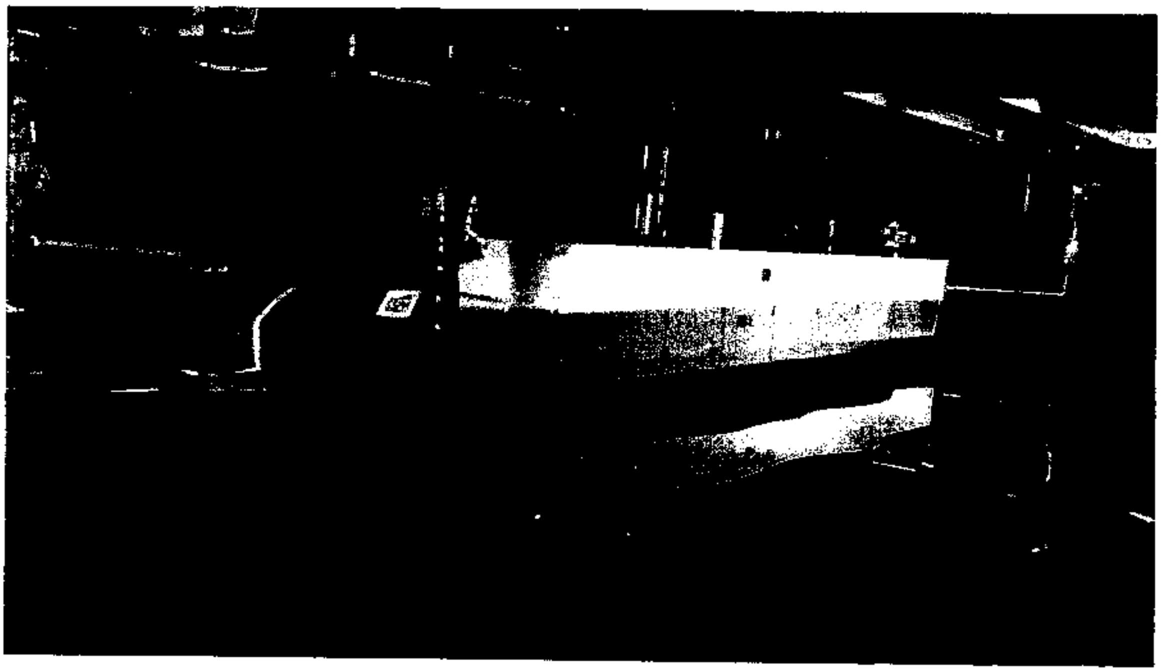
M/S Estonia

Test in towing tank
Speed 15.0 knots in head sea Hs= 4.0 m

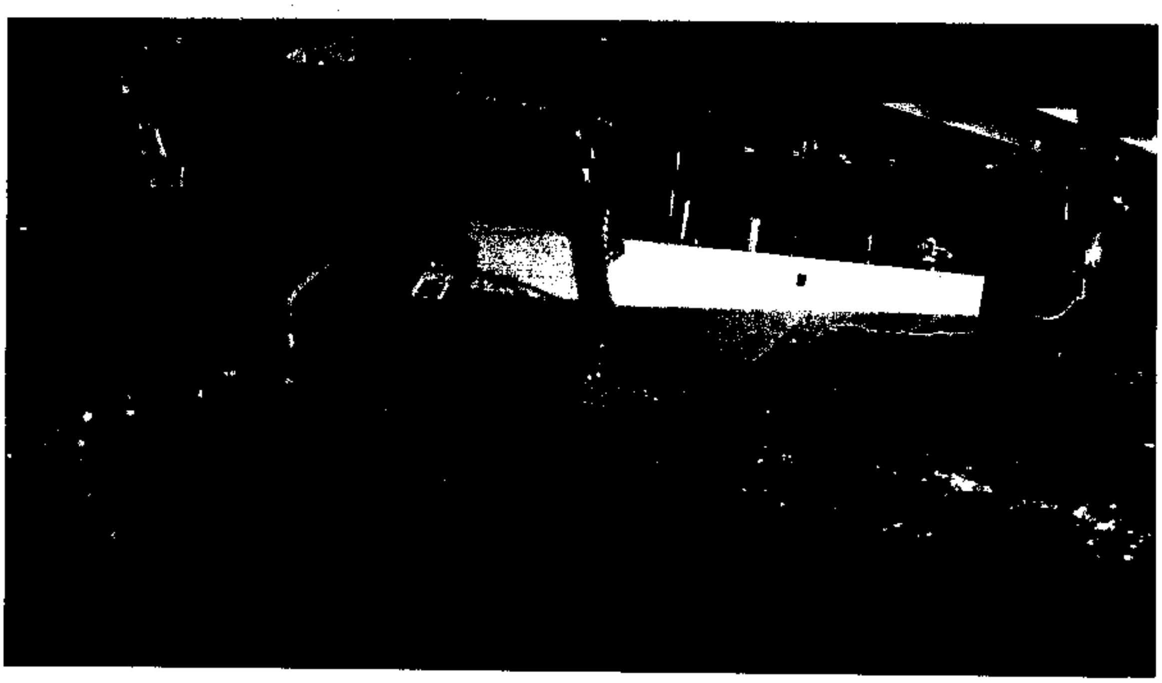
Fig	8
Report	7524



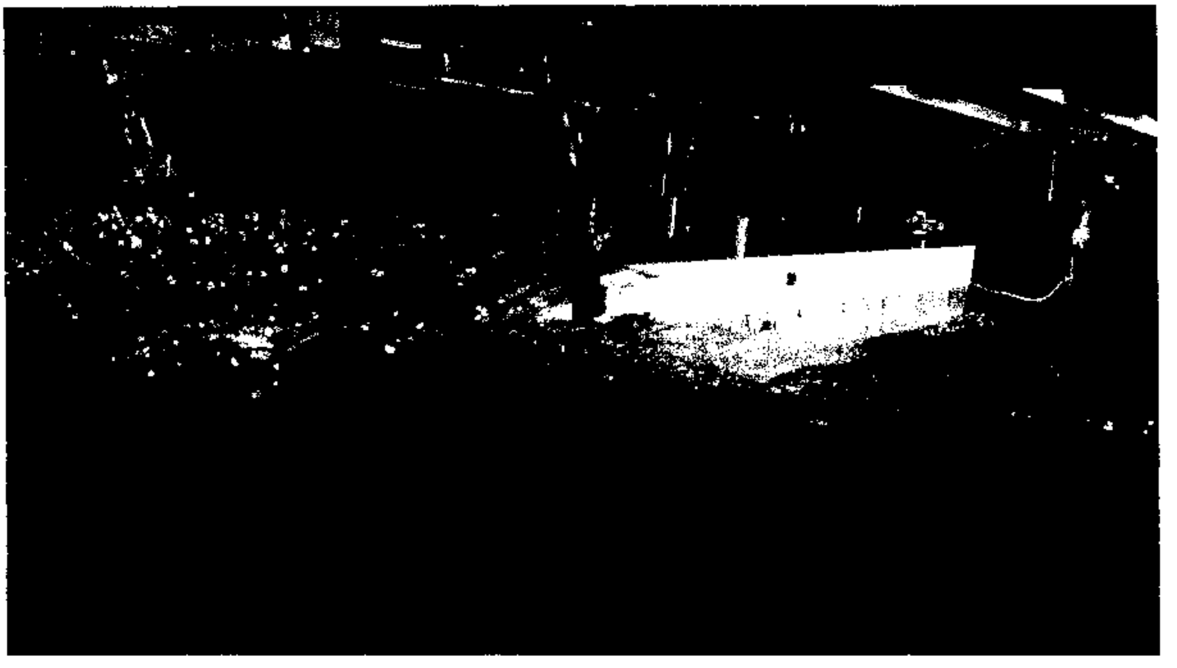




Model at rest



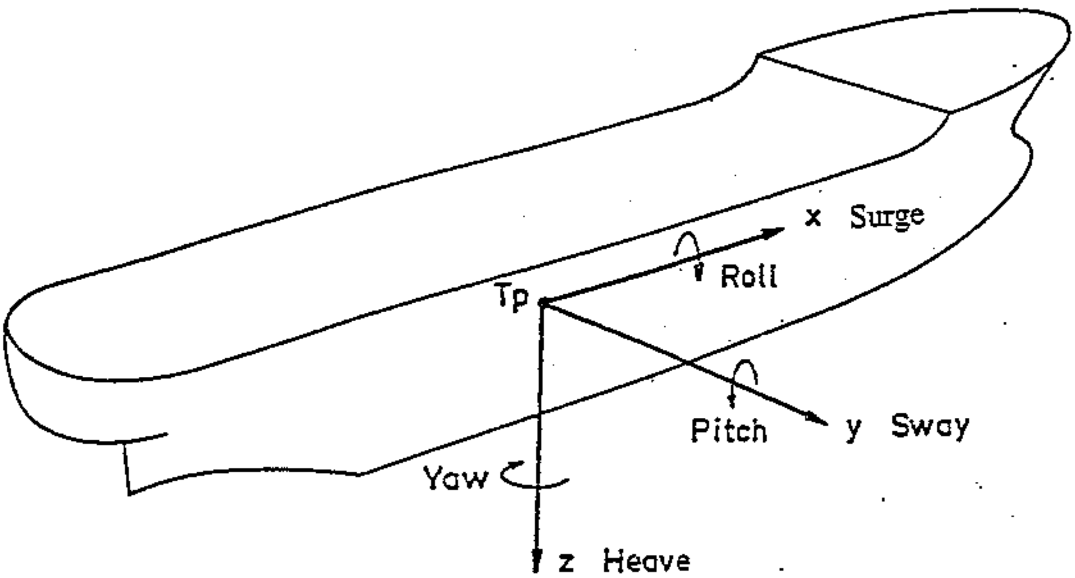
Speed 10.0 knots in bow sea Hs= 5.5 m



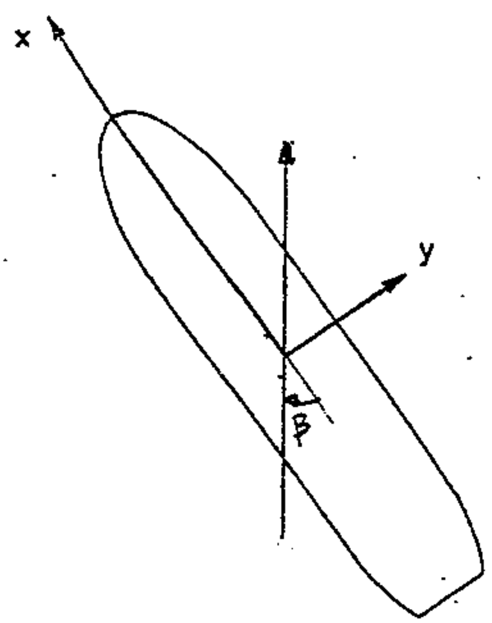
Speed 15.0 knots in bow sea Hs= 5.5 m

Speed 14.3 knots in bow sea Hs= 4.3 m

SSPA MARITIME CONSULTING	M/S Estonia Definitions of motions and wave direction	Fig 11 Report 7524

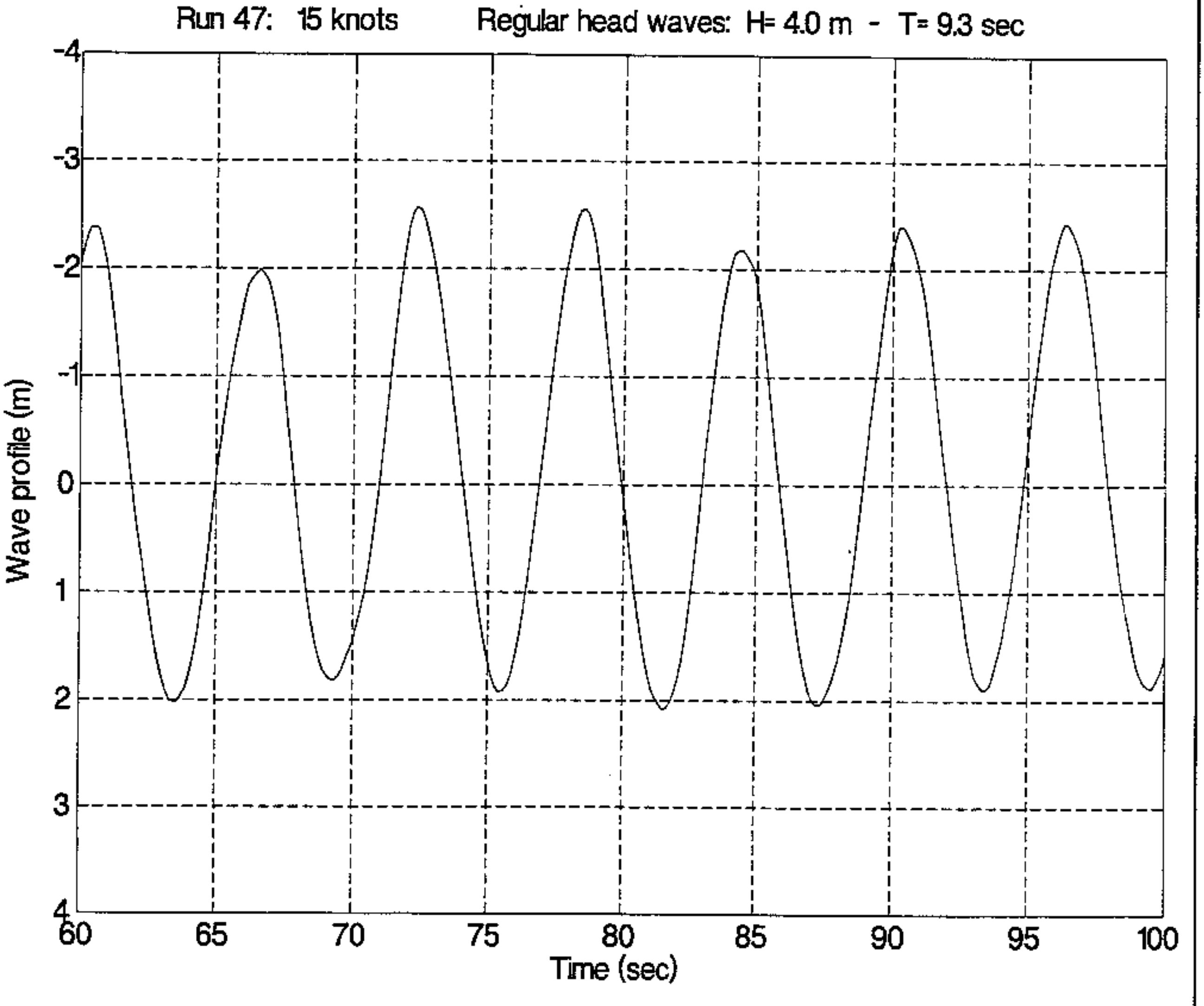


Definition of motions



Definition of wave direction

SSPA MARITIME CONSULTING	M/S Estonia Encountering wave profile Towing tank tests in regular waves Speed 15.0 knots	Fig 12a Report 7524



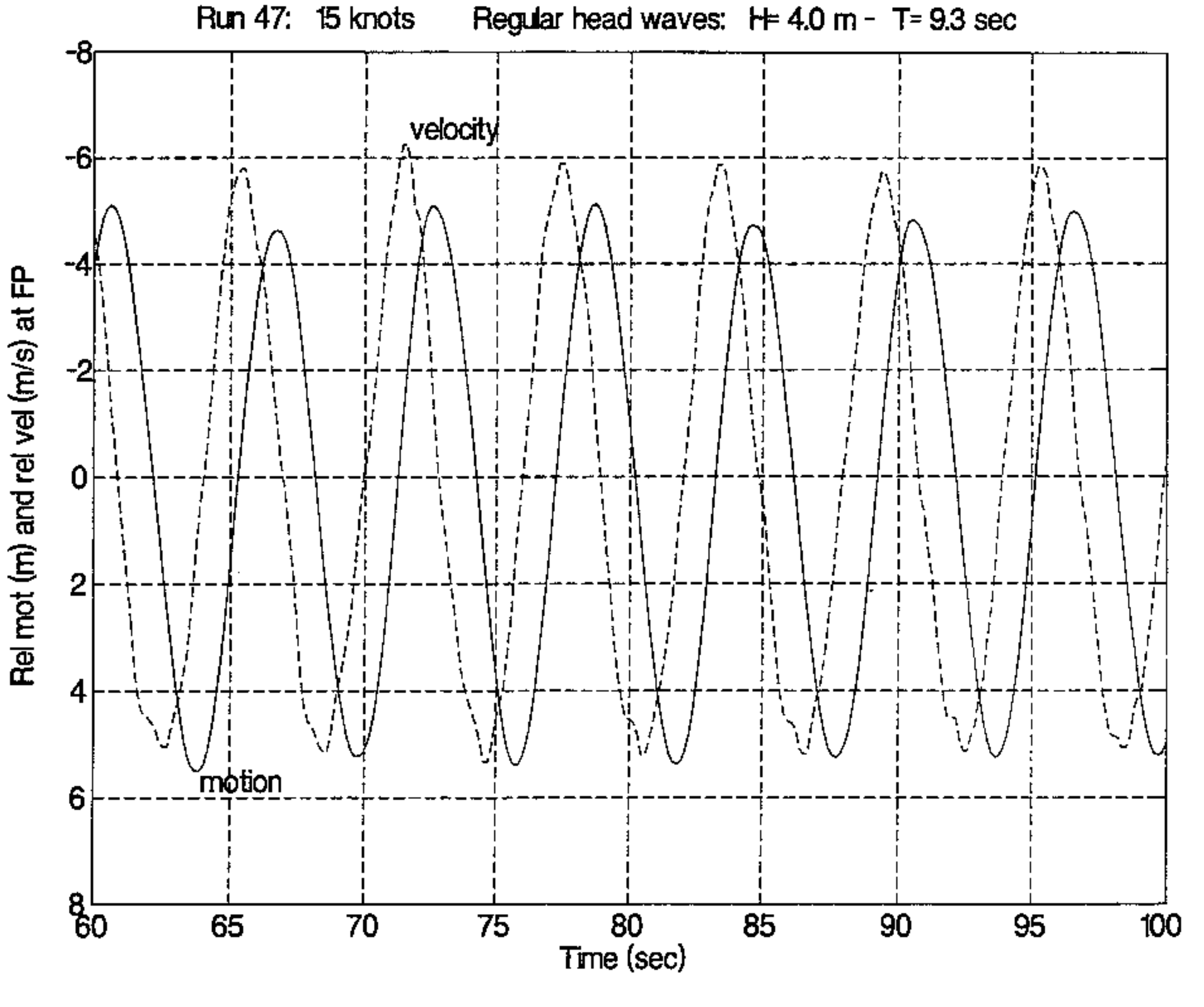
SSPA MARITIME CONSULTING

M/S Estonia

Relative motion and velocity at FP
Towing tank tests in regular waves
Speed 15.0 knots

Fig 12b

Report 7524

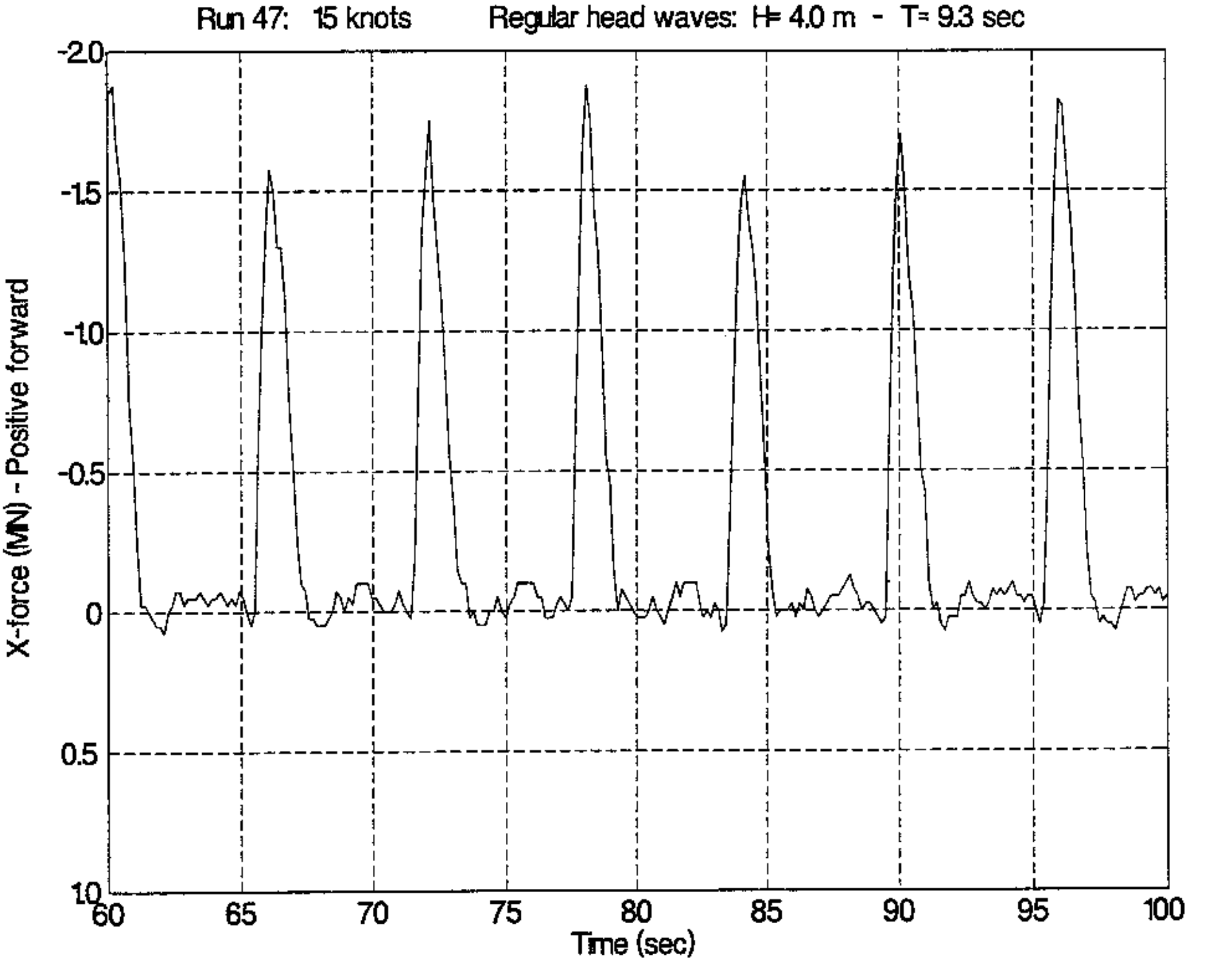


SSPA MARITIME CONSULTING

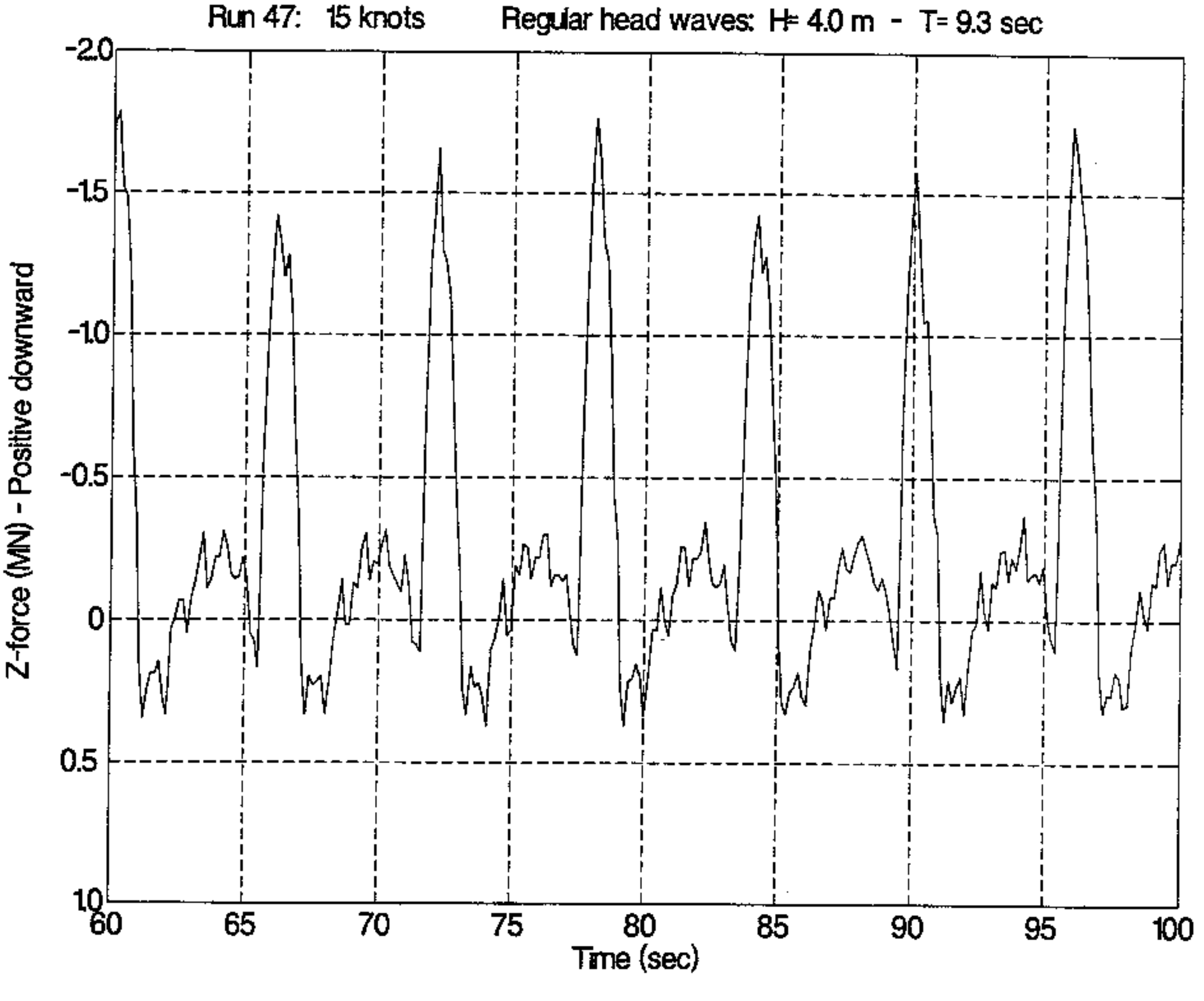
M/S Estonia

Longitudinal (X) force om visor
Towing tank tests in regular waves
Speed 15.0 knots

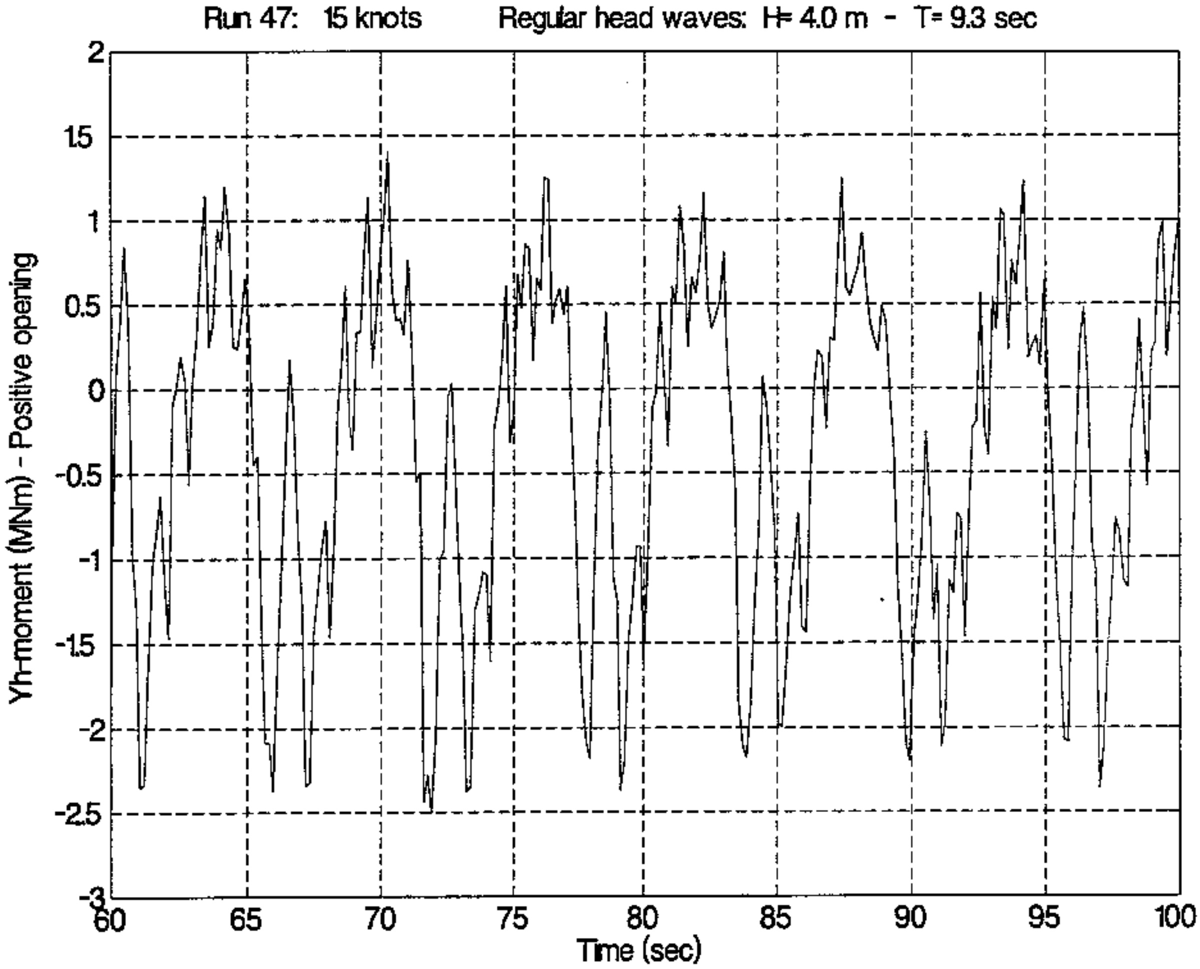
Fig	12c
Report	7524



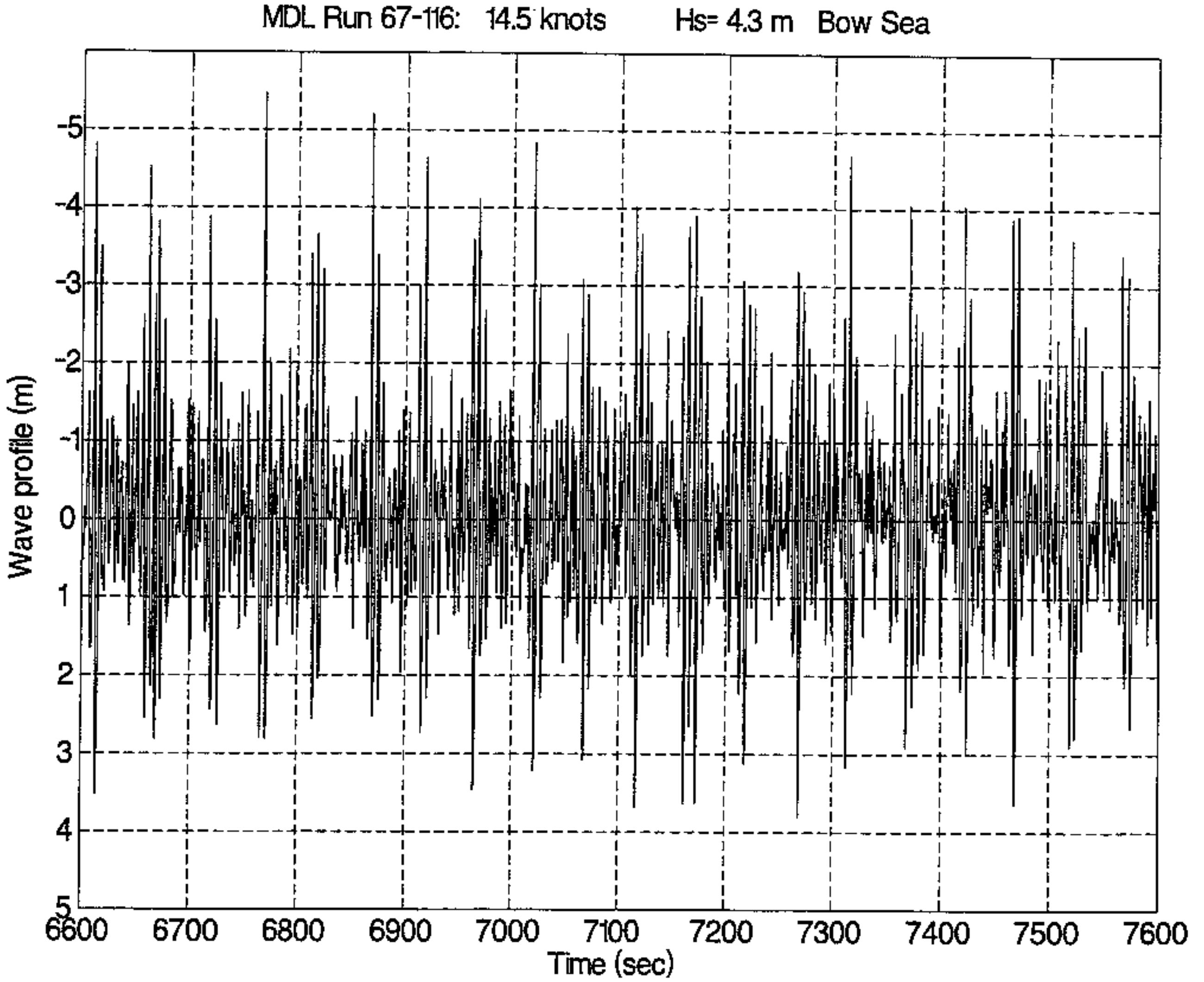
SSPA MARITIME CONSULTING	M/S Estonia Encountering wave profile Towing tank tests in regular waves Speed 15.0 knots	Fig 12d Report 7524



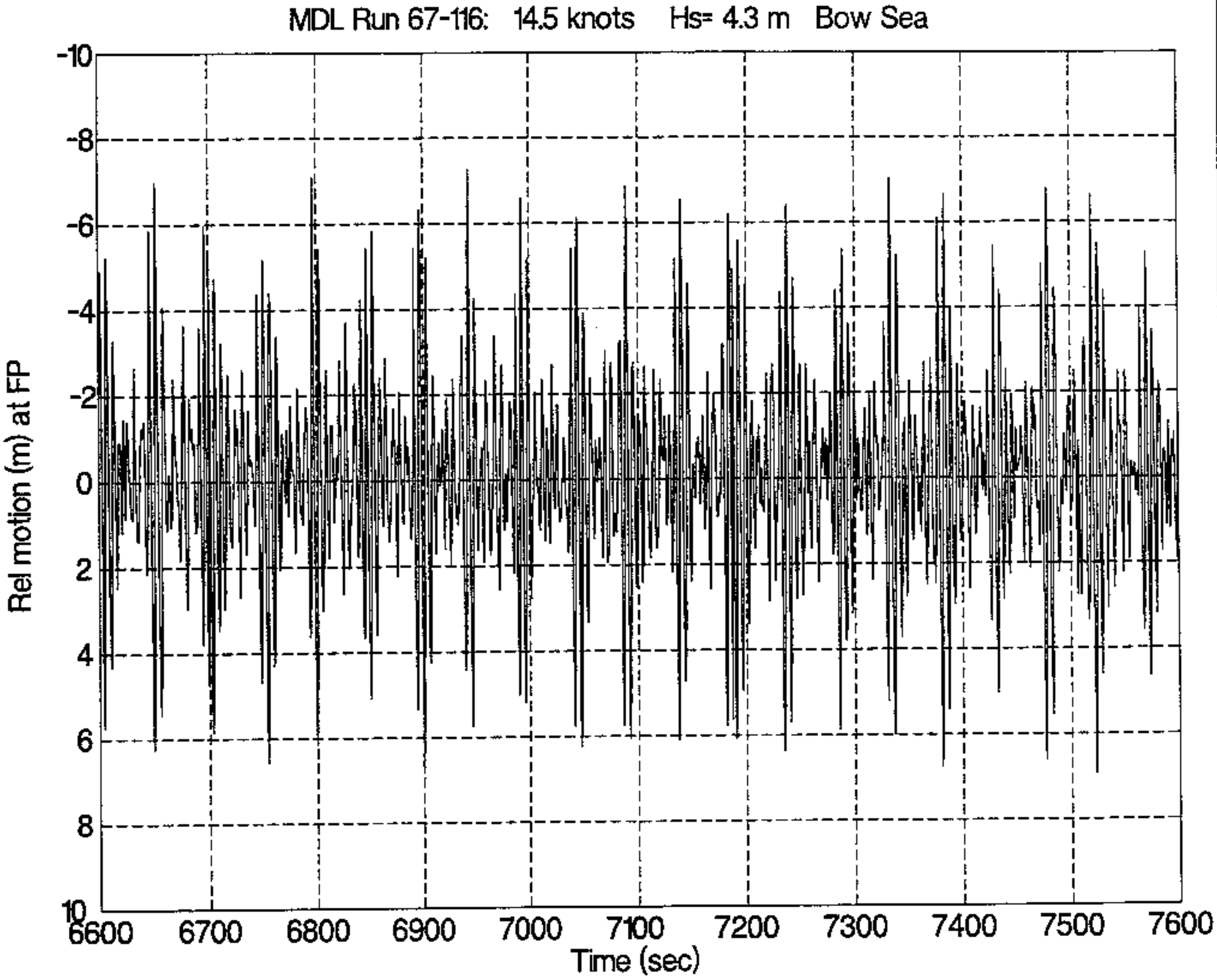
SSPA MARITIME CONSULTING	M/S Estonia Deck hinge (Yh) moment Towing tank tests in regular waves Speed 15.0 knots	Fig 12e Report 7524



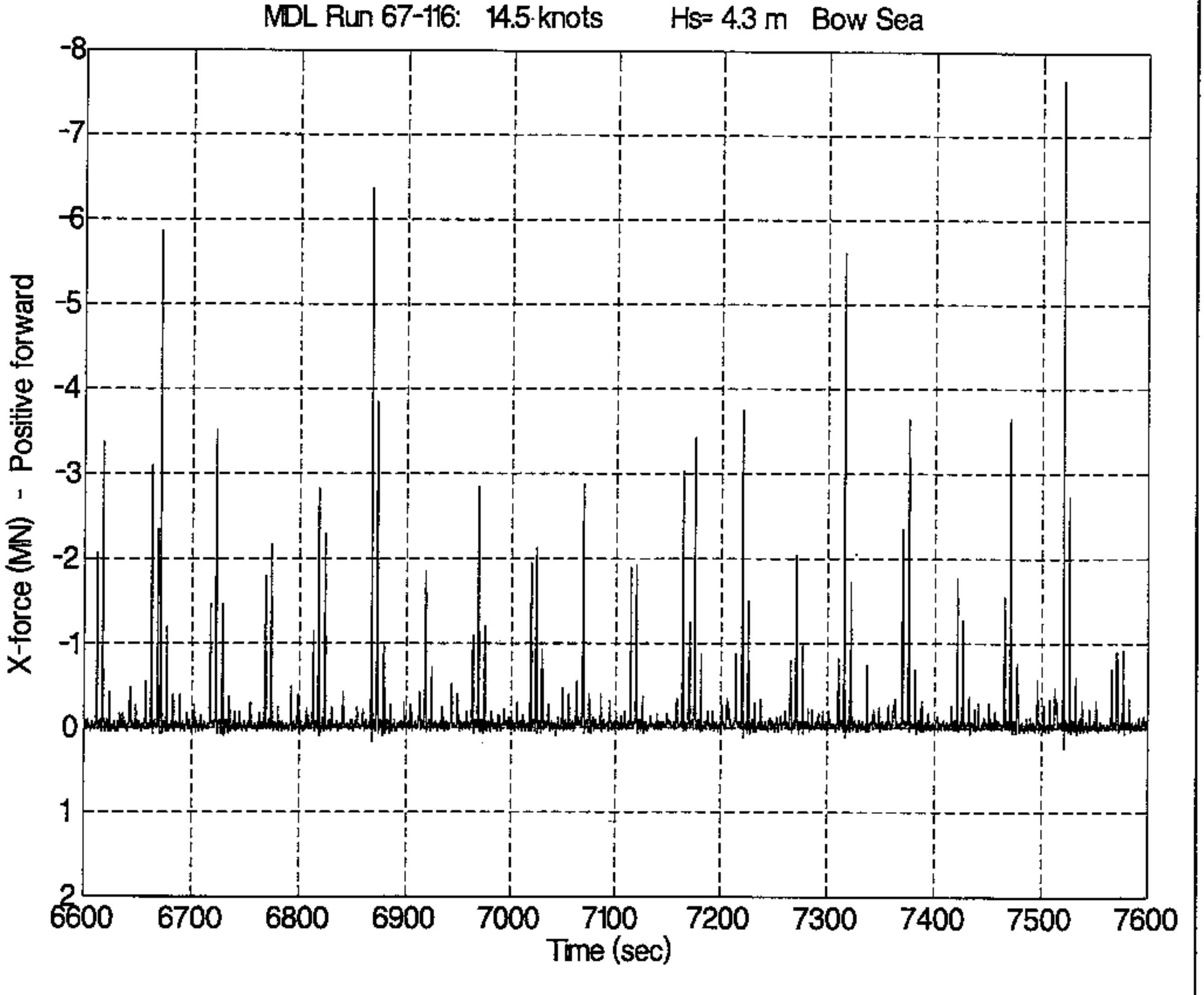
	M/S Estonia Encountering wave profile Sequence in irregular bow sea Hs= 4.3 m Speed 14.5 knots	Fig 13a Report 7524



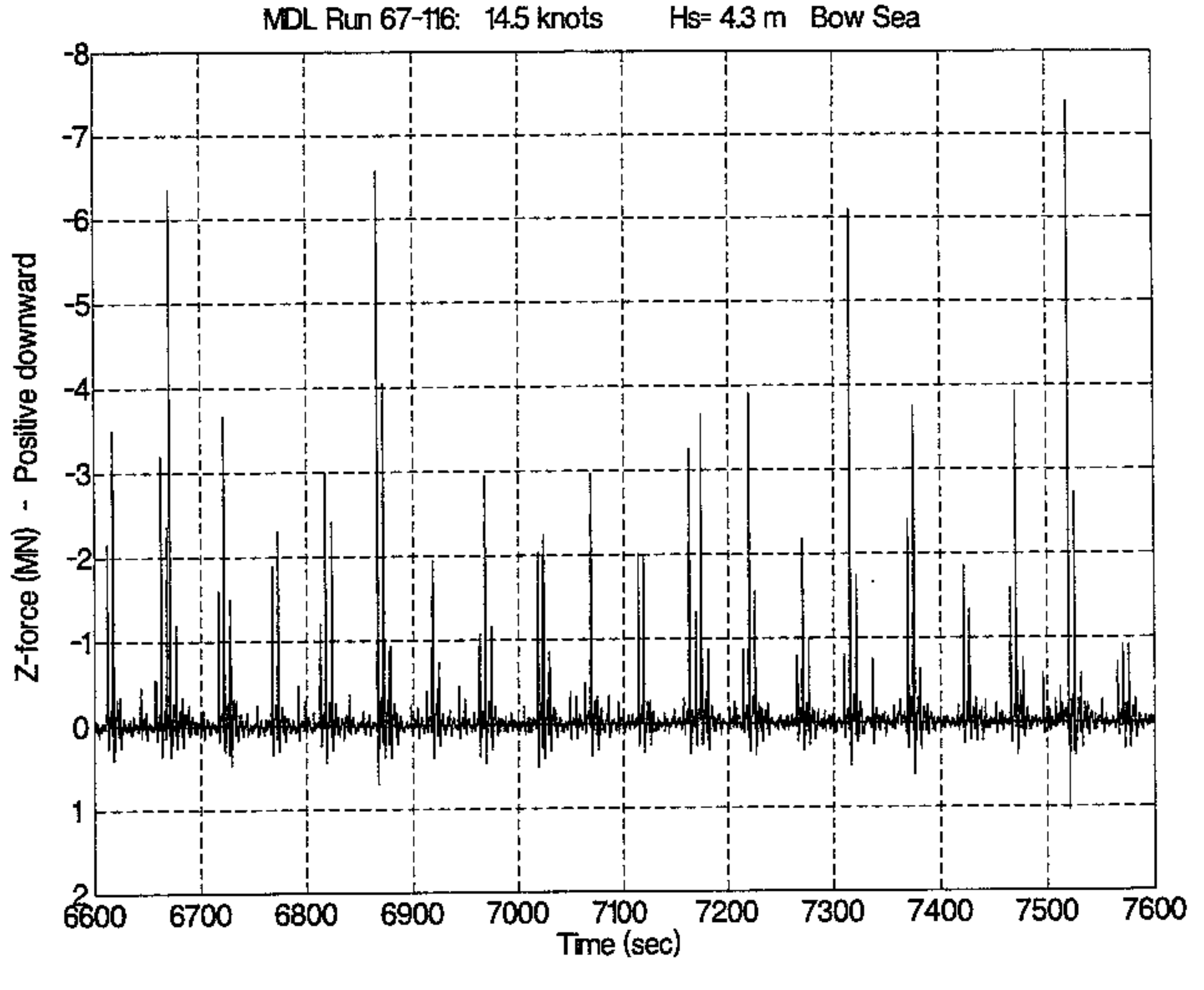
SSPA MARITIME CONSULTING	M/S Estonia Relative motion at FP Sequence in irregular bow sea Hs= 4.3 m Speed 14.5 knots	Fig 13b Report 7524



	M/S Estonia	Fig 13c
SSPA MARITIME CONSULTING	Longitudinal (X) force on visor Sequence in irregular bow sea Hs= 4.3 m Speed 14.5 knots	Report 7524



	M/S Estonia Vertical (Z) force on visor Sequence in irregular bow sea Hs= 4.3 m Speed 14.5 knots	Fig 13d Report 7524

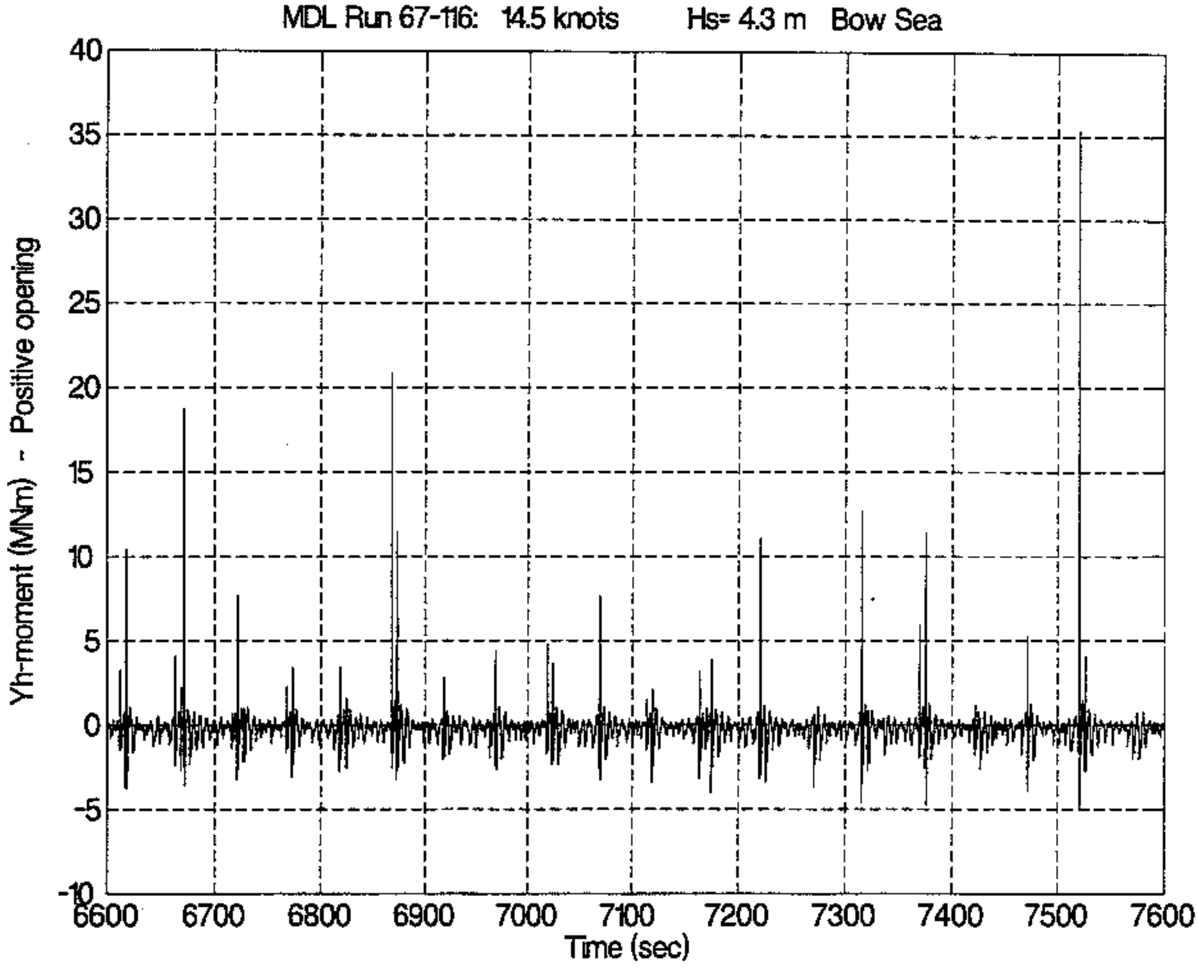


SSPA MARITIME CONSULTING

M/S Estonia

Deck hinge moment (Yh)
Sequence in irregular bow sea Hs= 4.3 m
Speed 14.5 knots

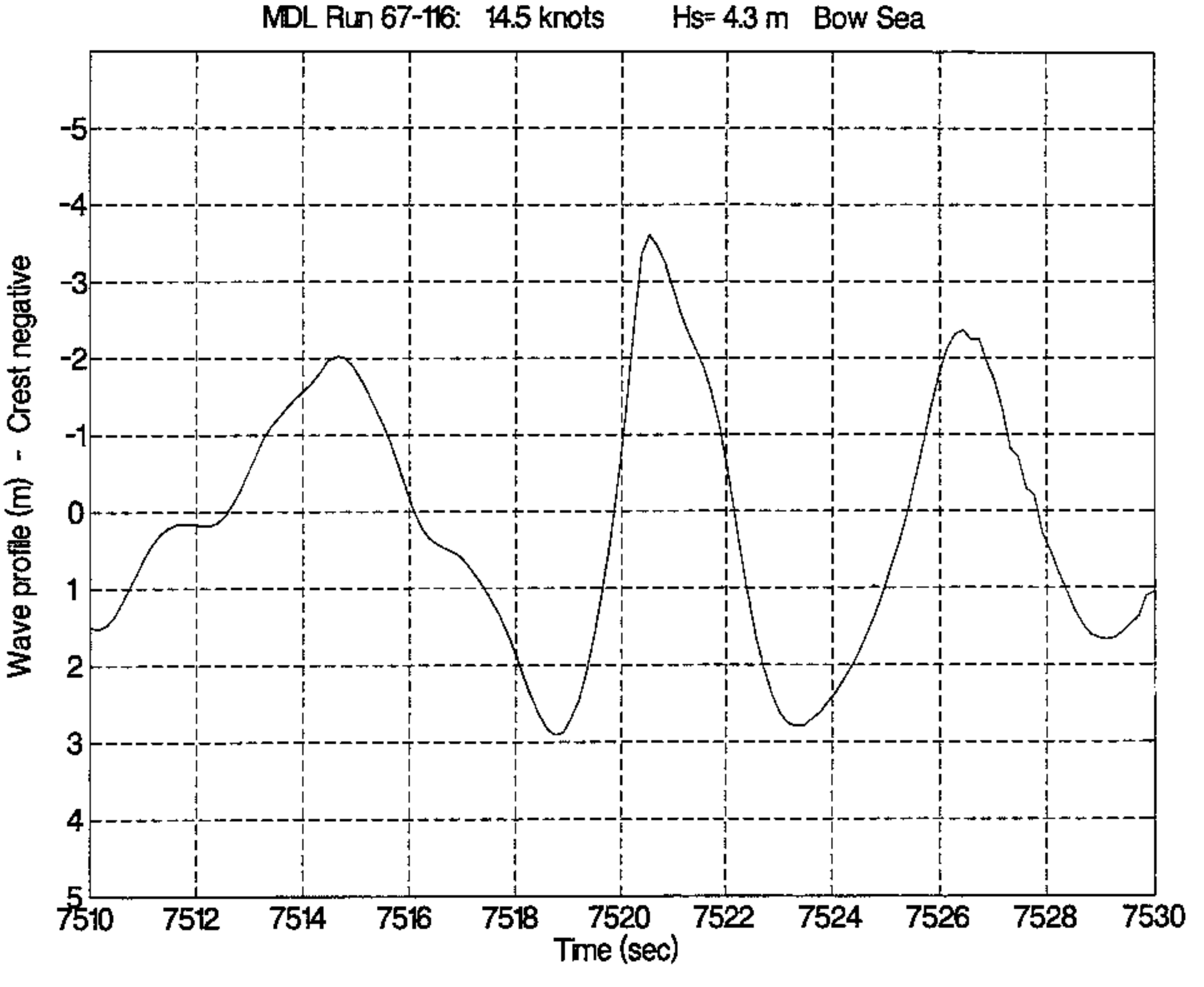
Fig	13e
Report	7524



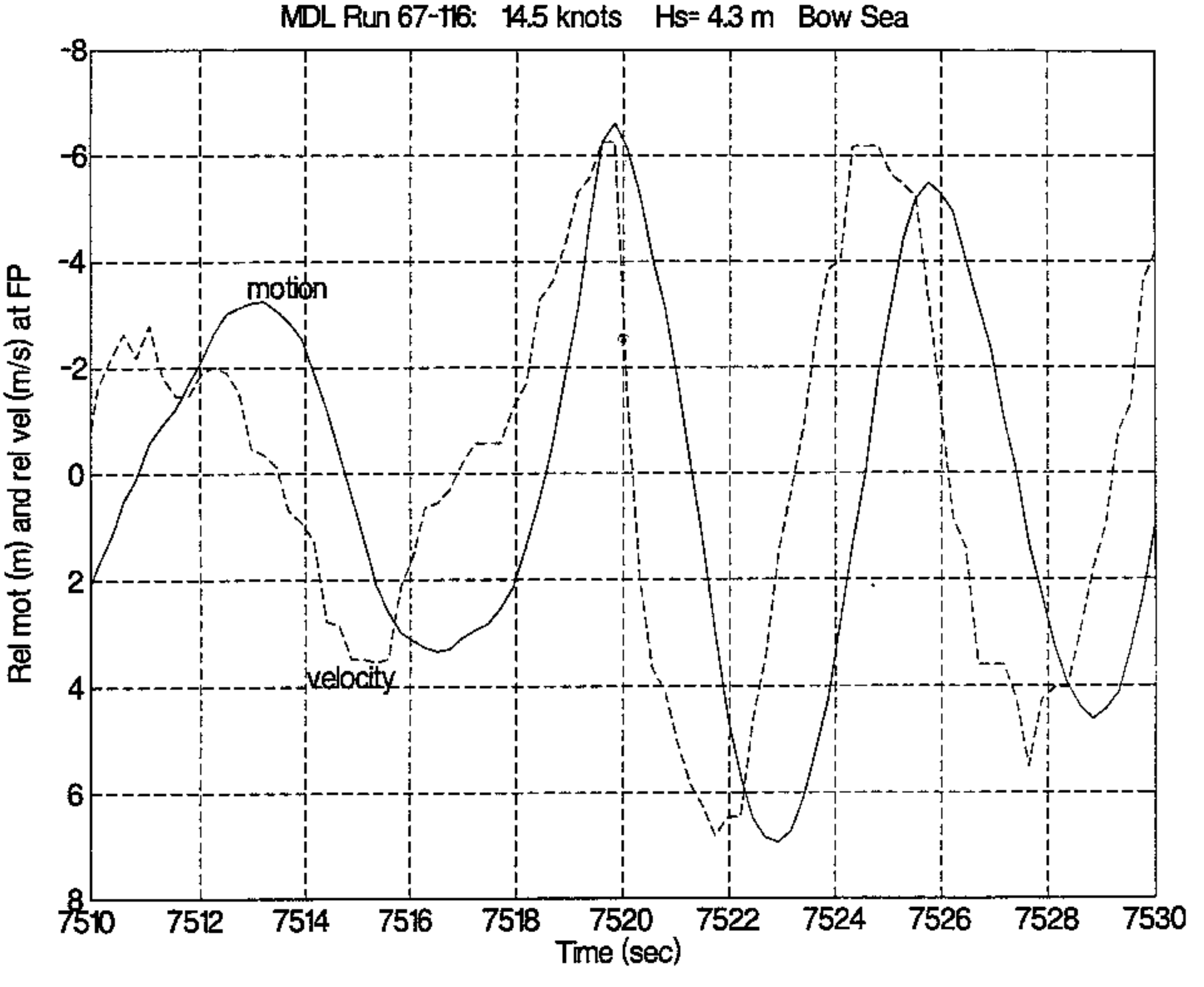
M/S Estonia

Encountering wave profile
Detailed time trace from run 116
Speed 14.5 knots in bow sea Hs= 4.3 m

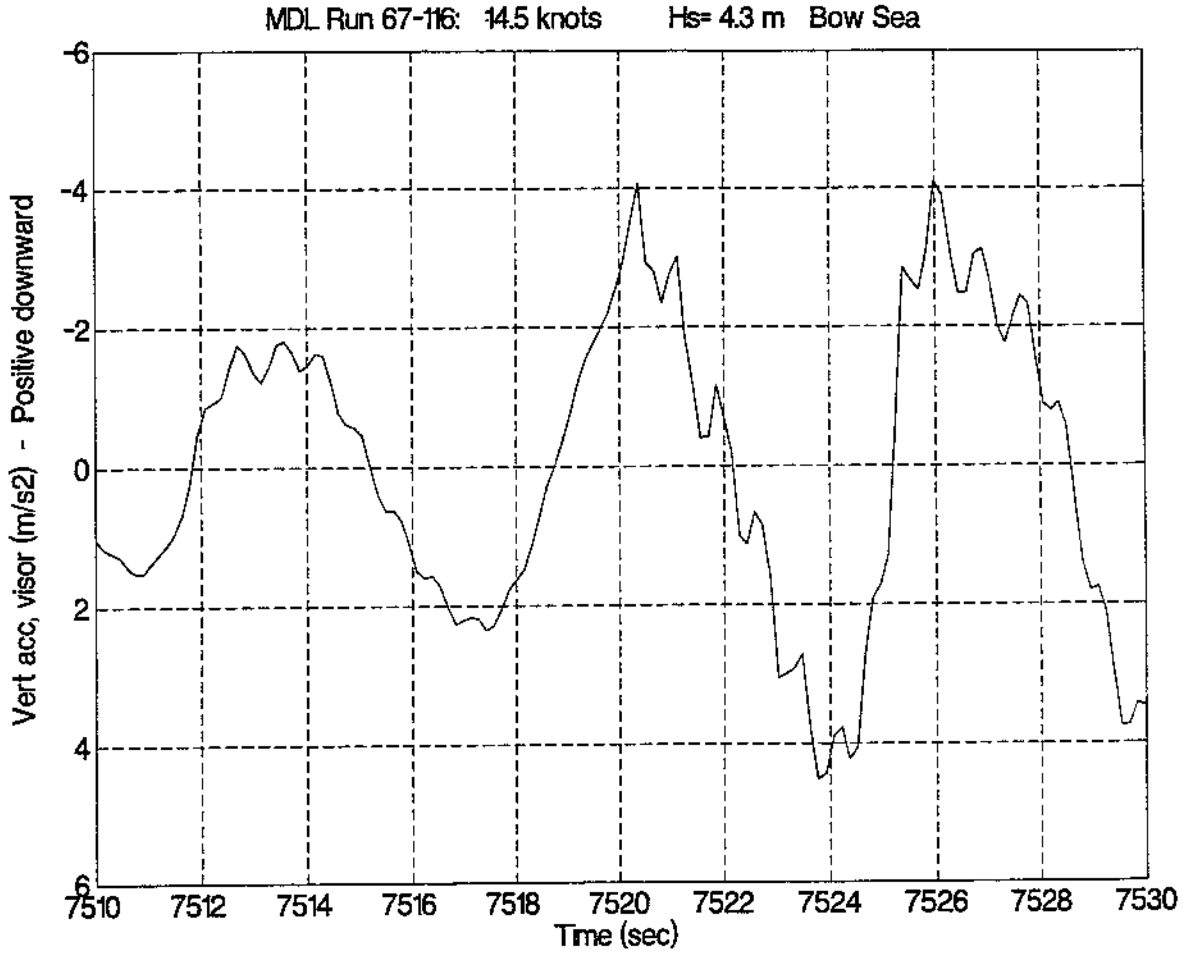
Fig	14a
Report	7524



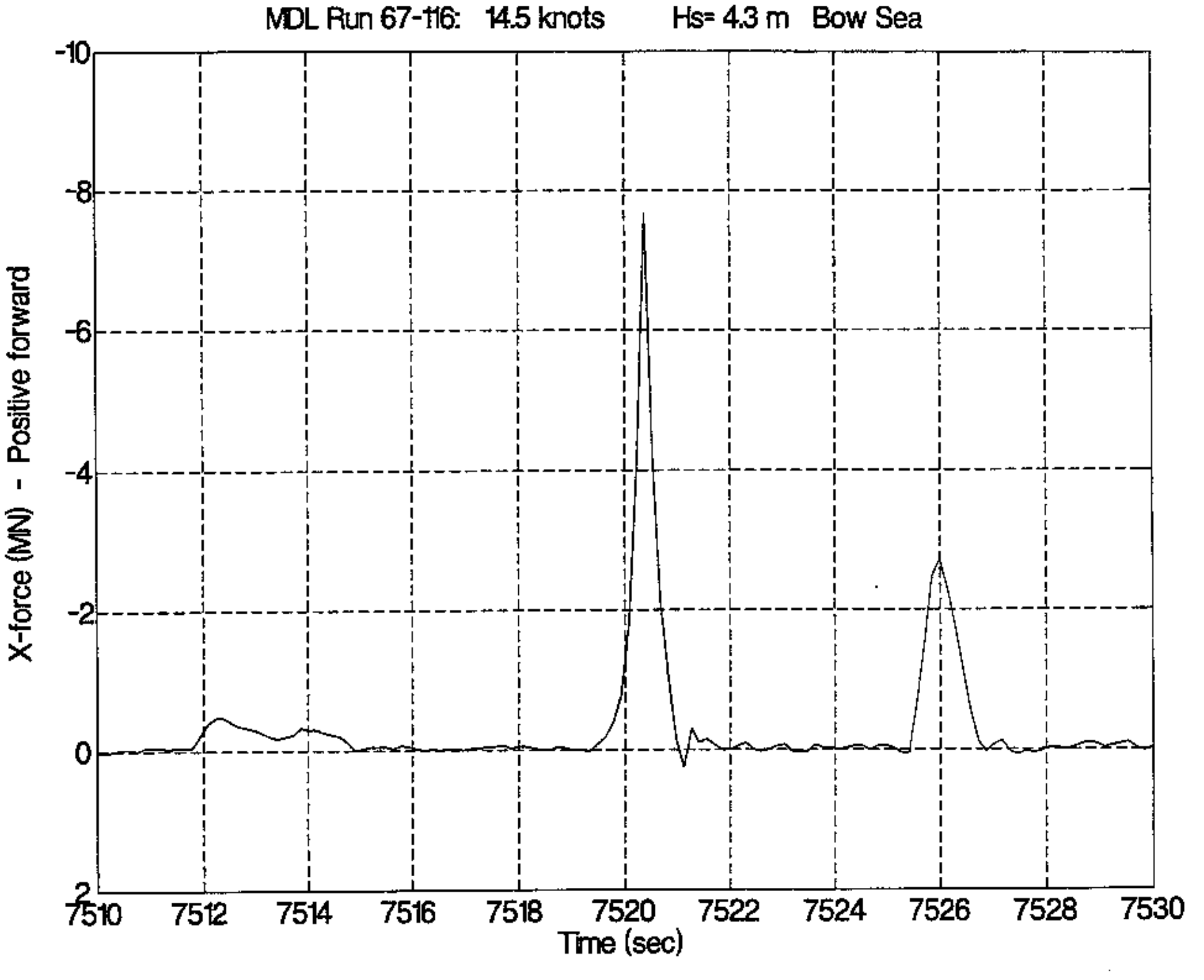
SSPA MARITIME CONSULTING	M/S Estonia Relative motion and velocity at FP Detailed time trace from run 116 Speed 14.5 knots in bow sea Hs= 4.3 m	Fig 14b Report 7524



SSPA MARITIME CONSULTING	M/S Estonia Vertical acceleration of visor Detailed time trace from run 116 Speed 14.5 knots in bow sea Hs= 4.3 m	Fig 14c Report 7524



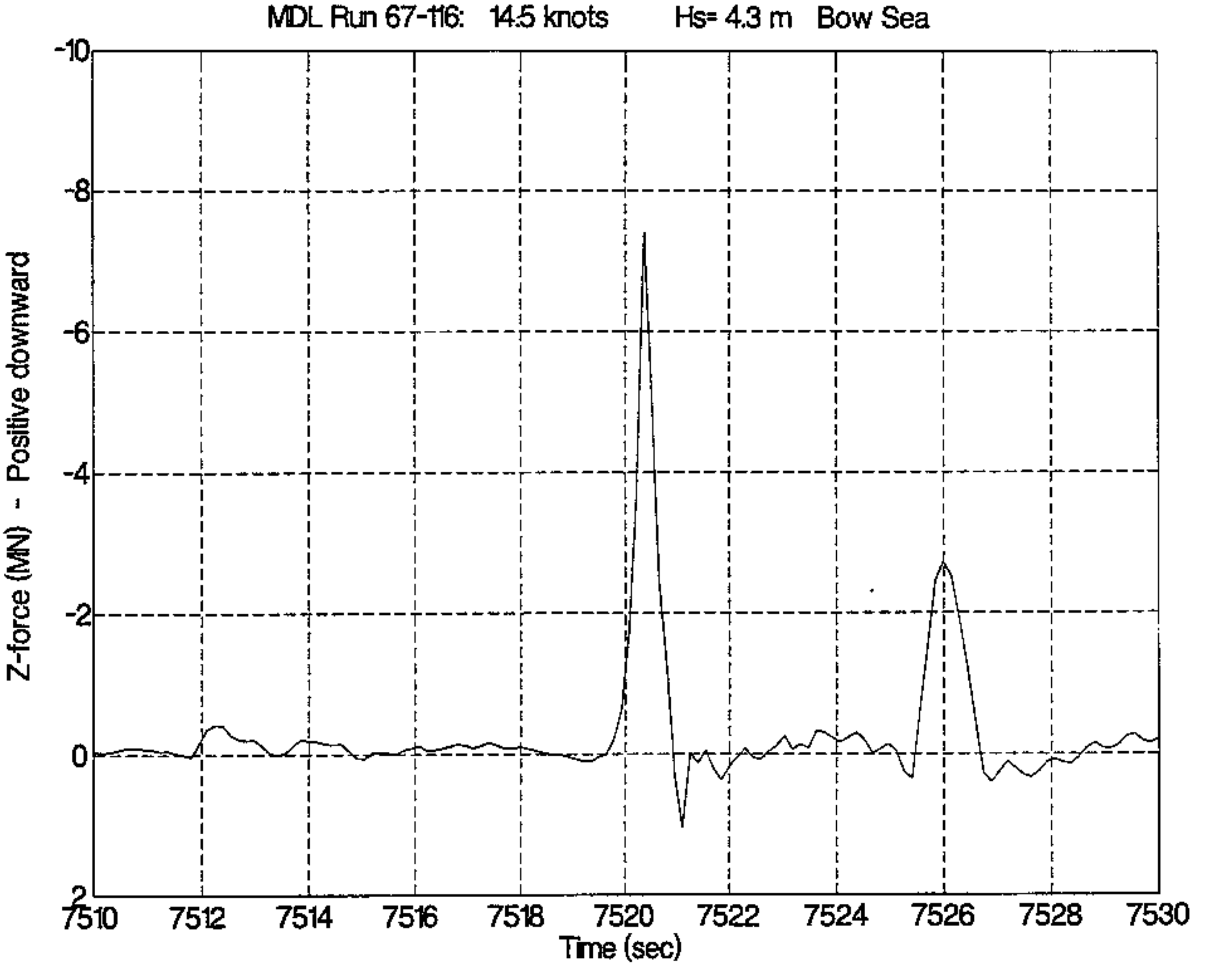
SSPA MARITIME CONSULTING	M/S Estonia Longitudinal (X) force on visor Detailed time trace from run 116 Speed 14.5 knots in bow sea Hs= 4.3 m	Fig 14d Report 7524



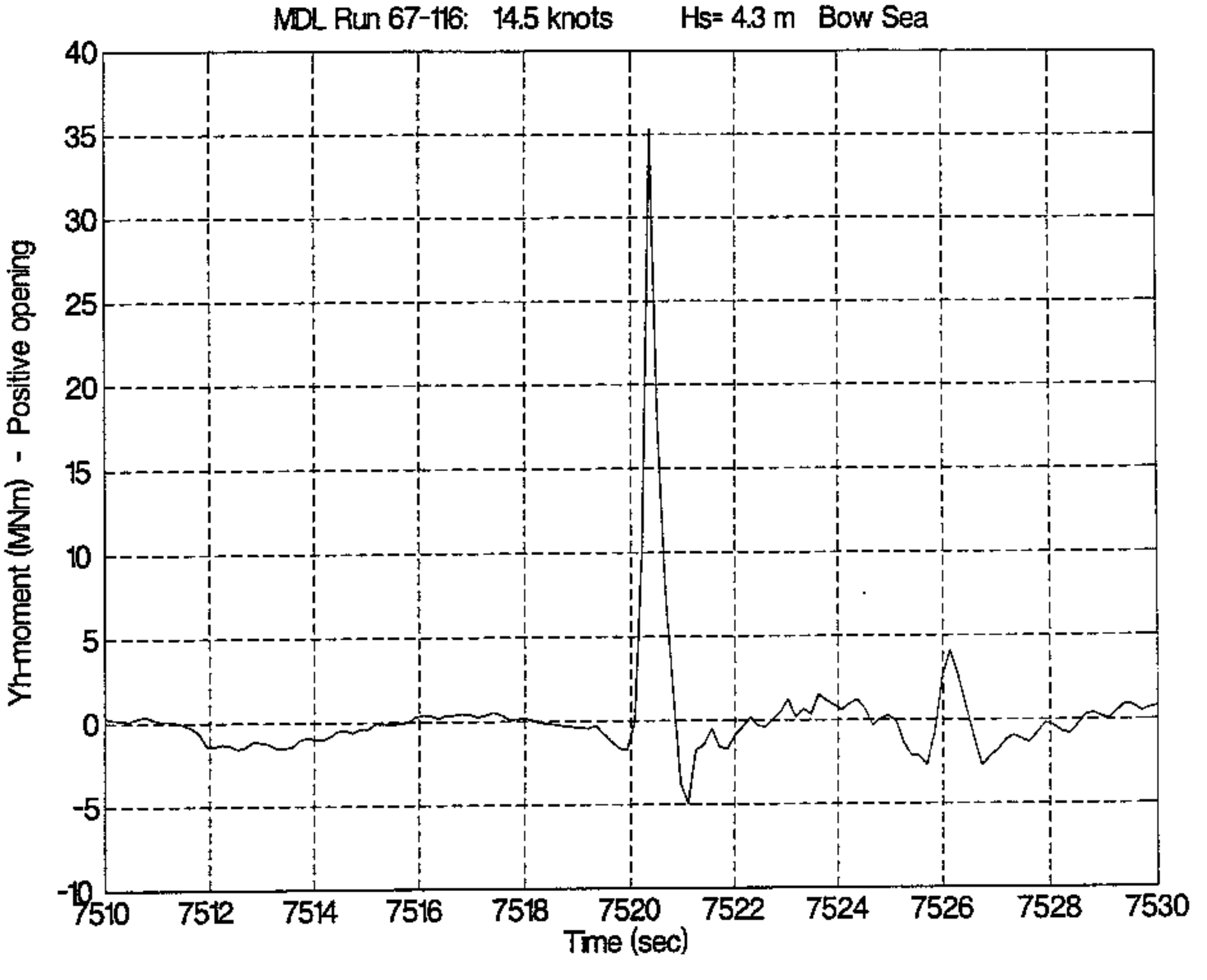
M/S Estonia

Vertical (Z) force on visor
Detailed time trace from run 116
Speed 14.5 knots in bow sea Hs= 4.3 m

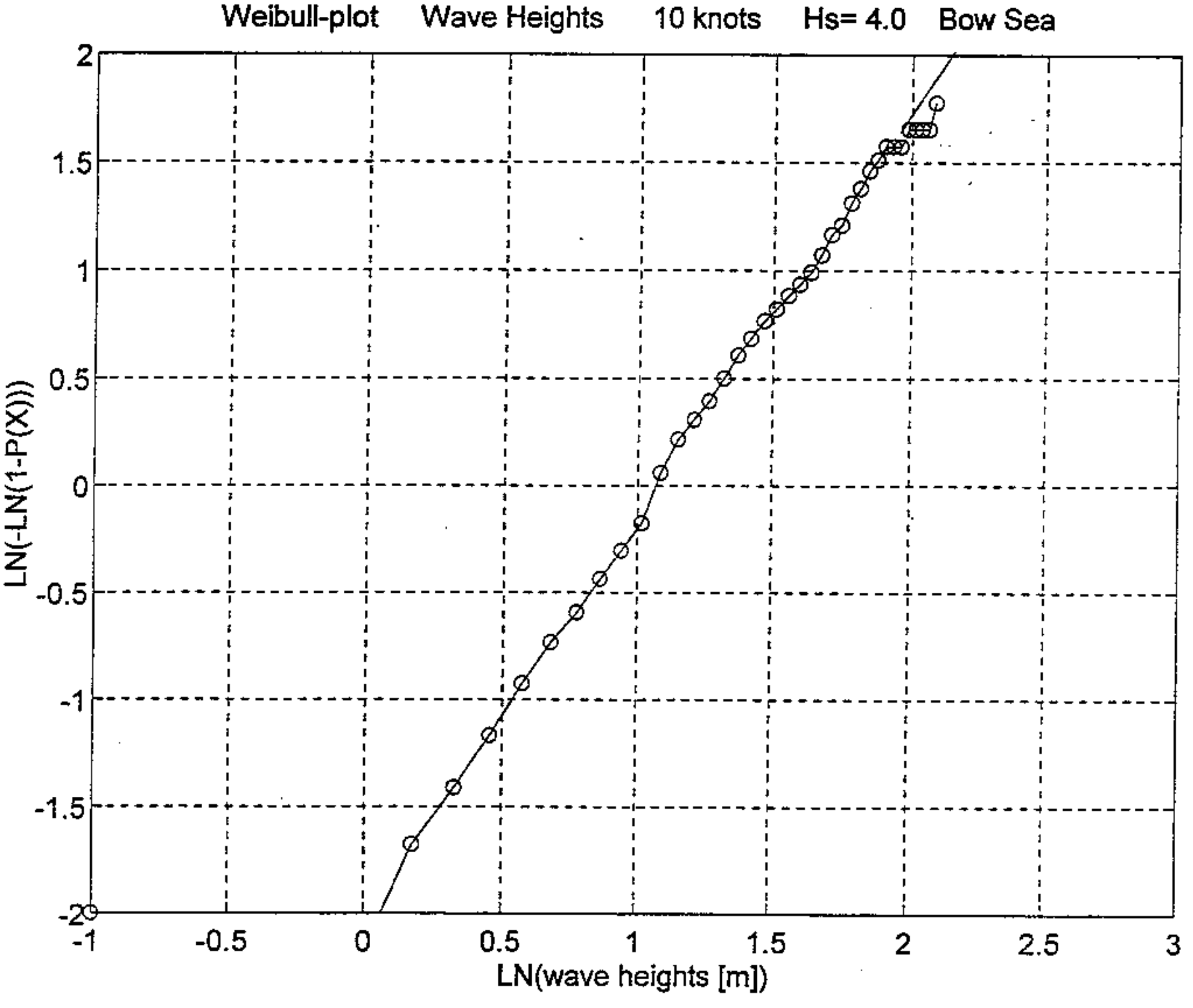
Fig	14e
Report	7524



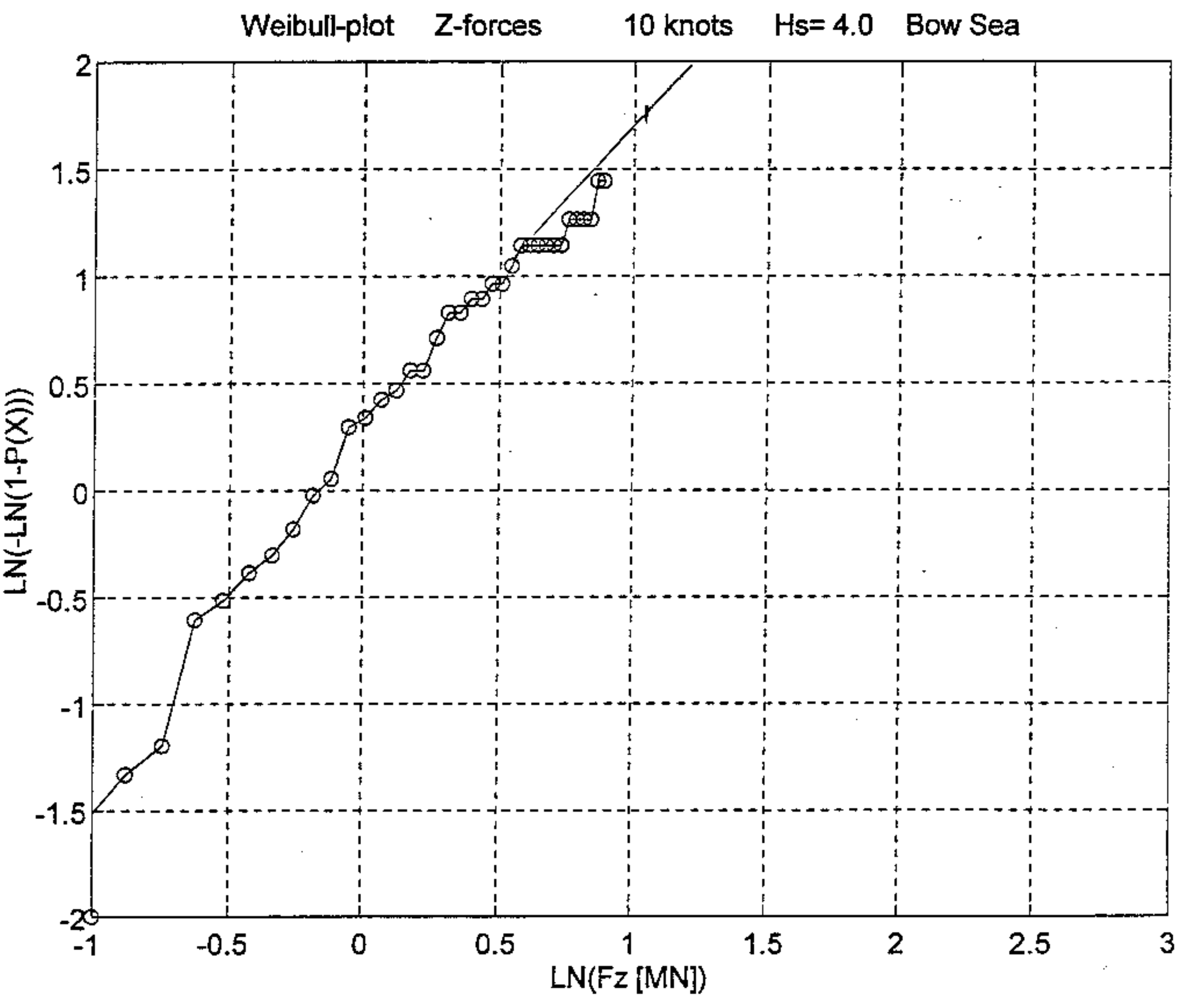
SSPA MARITIME CONSULTING	M/S Estonia Deck hinge moment (Yh) Detailed time trace from run 116 Speed 14.5 knots in bow sea Hs= 4.3 m	Fig 14f Report 7524



SSPA MARITIME CONSULTING	M/S Estonia MDL tests in irregular sea Weibull diagram from run 34-46: Wave height Speed 10 knots in bow sea Hs= 4.0 m	Fig 15a Report 7524



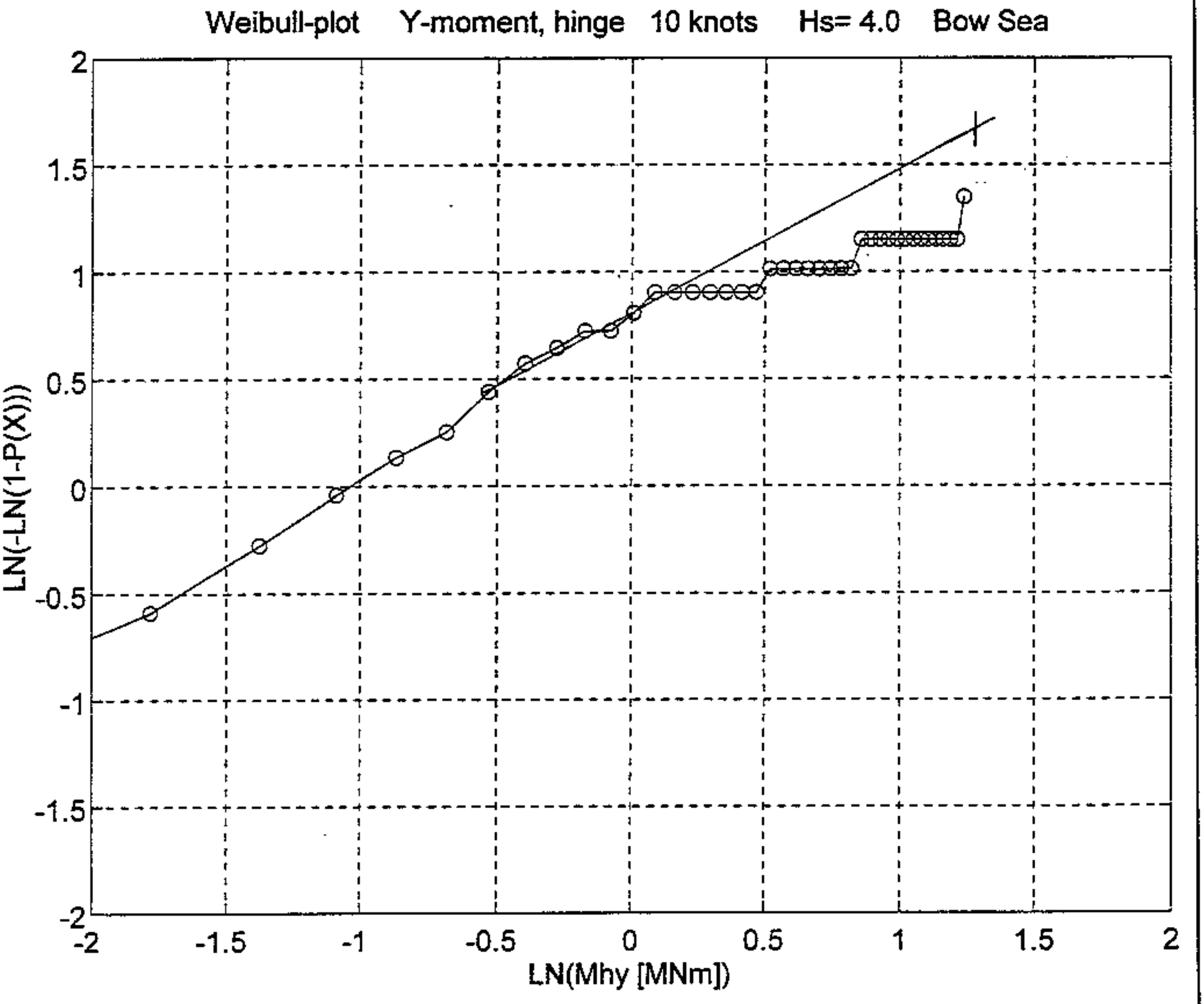
SSPA MARITIME CONSULTING	M/S Estonia MDL tests in irregular sea Weibull diagram from run 34-46: Vertical (Z) force on visor Speed 10 knots in bow sea Hs= 4.0 m	Fig 15b Report 7524



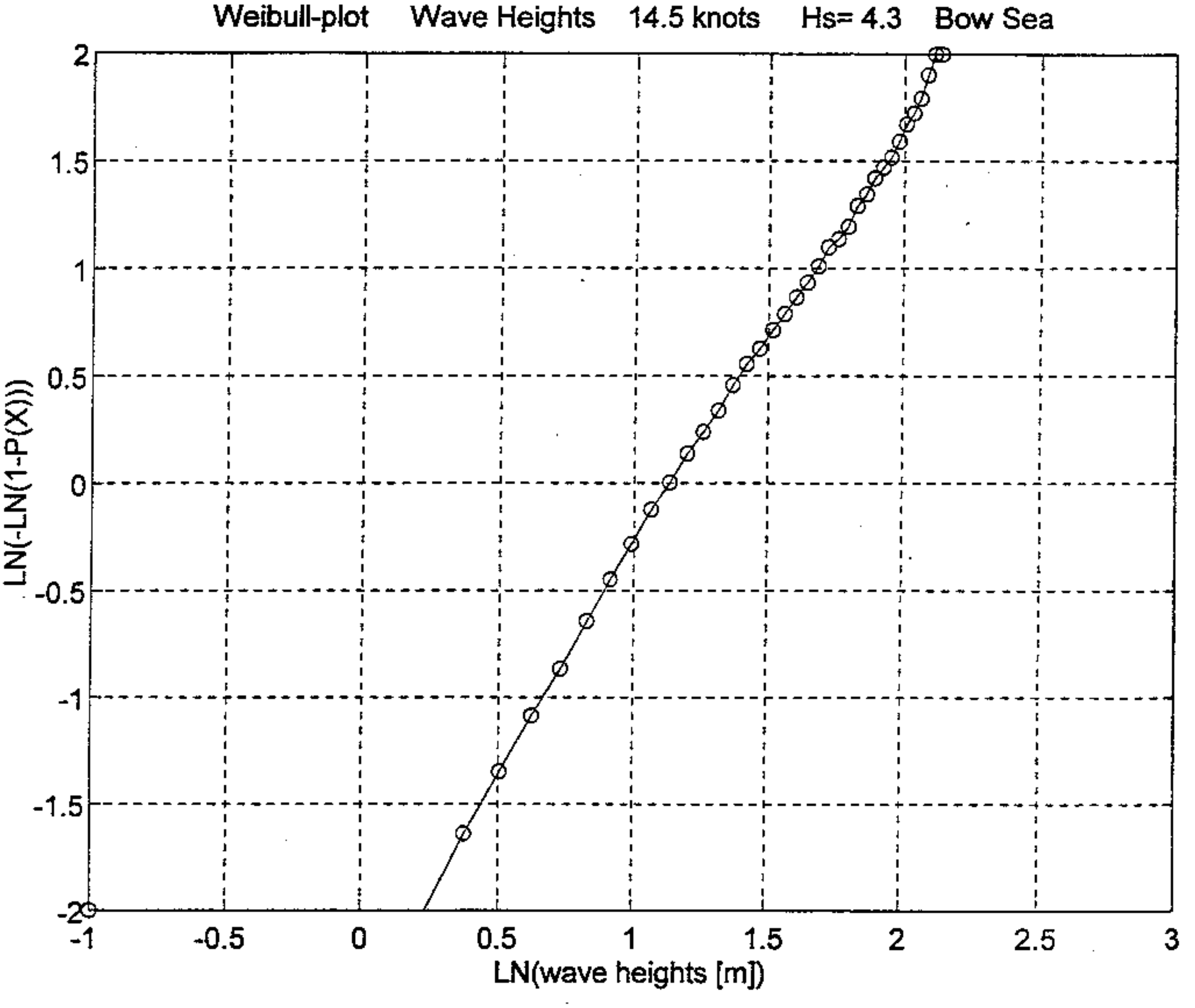
SSPA MARITIME CONSULTING

M/S Estonia
MDL tests in irregular sea
Weibull diagram from run 34-46:
Deck hinge (Yh) moment
Speed 10 knots in bow sea Hs= 4.0 m

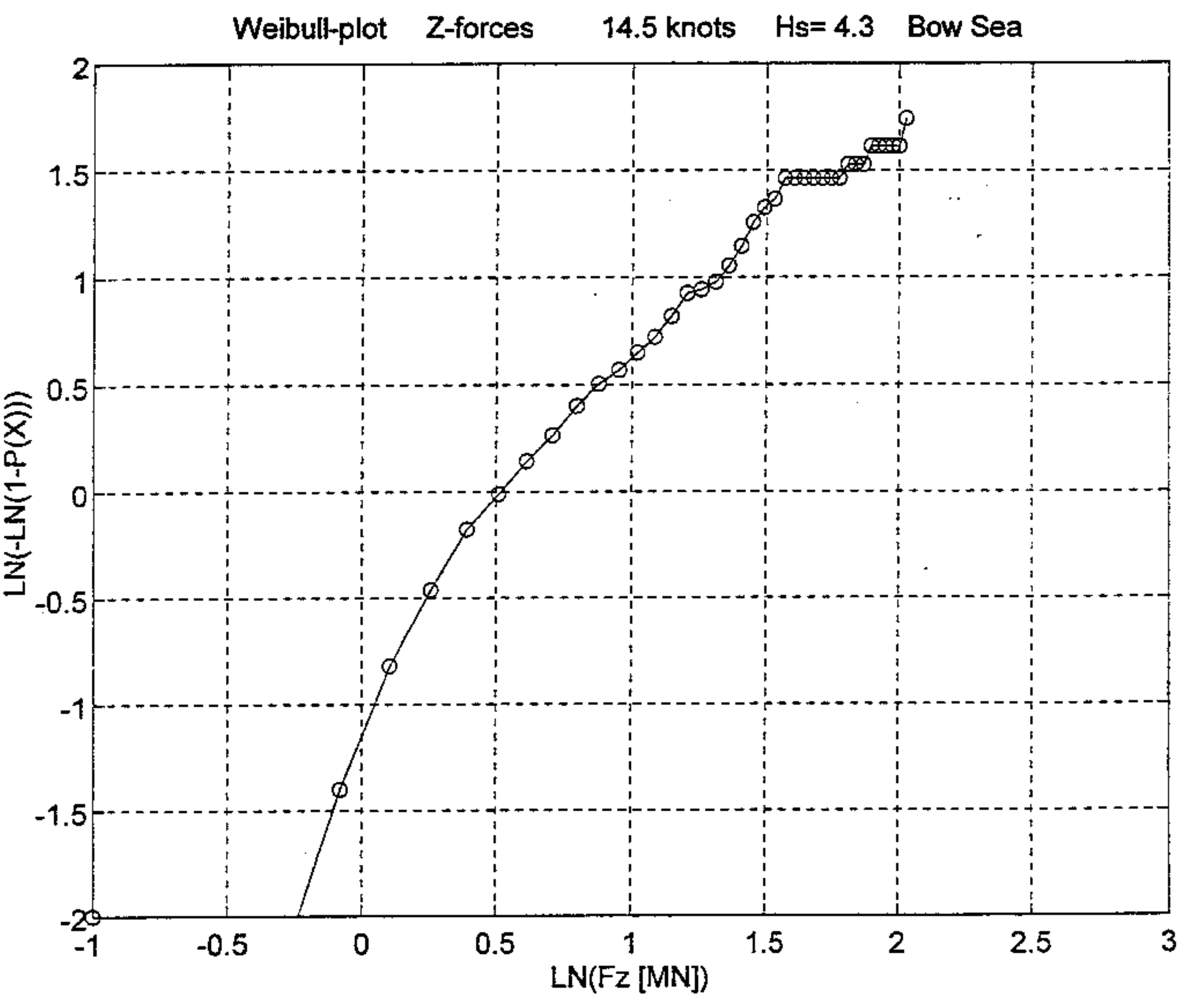
Fig 15c
Report 7524



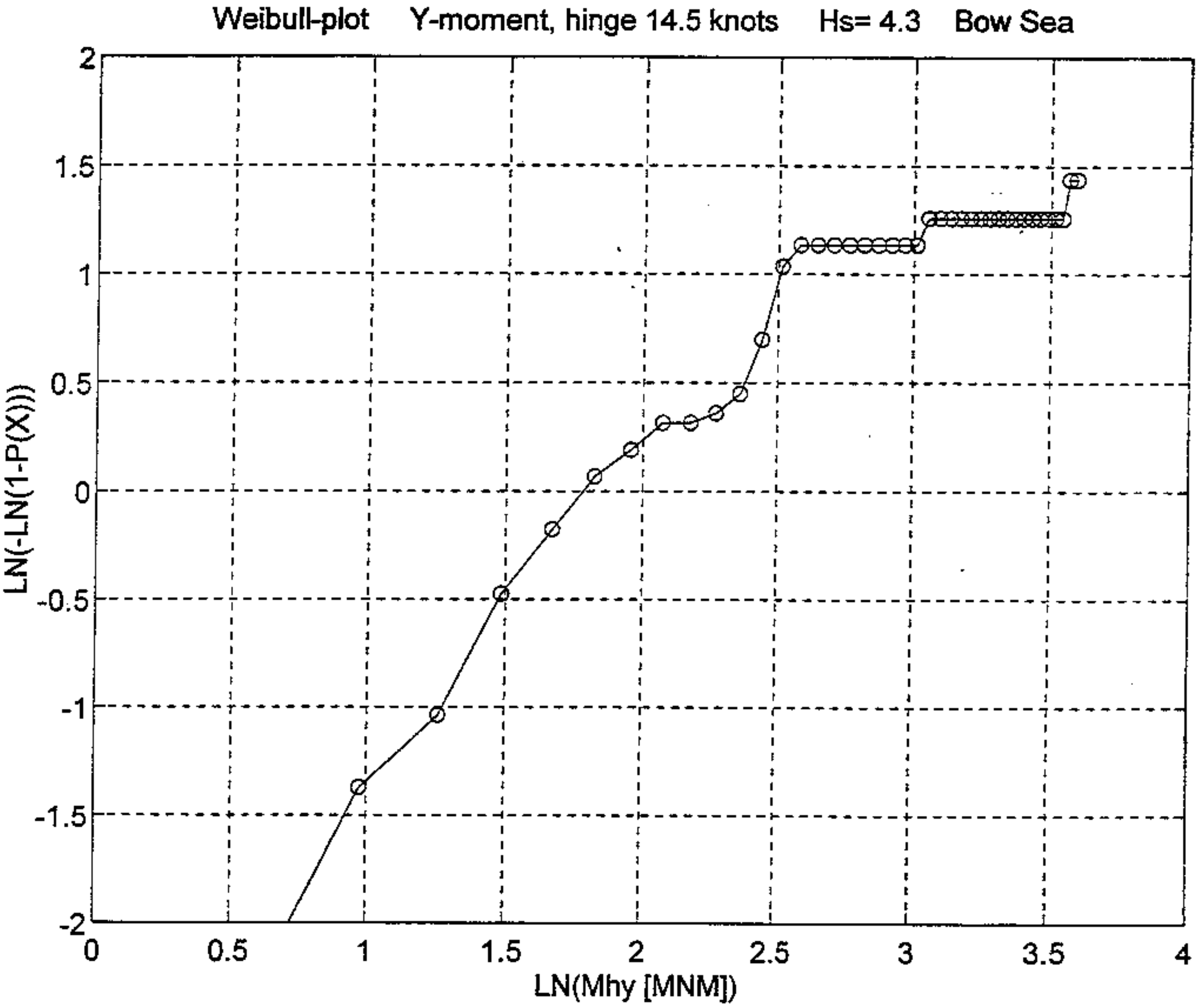
SSPA MARITIME CONSULTING	M/S Estonia MDL tests in irregular sea Weibull diagram from run 67-116: Wave height Speed 14.5 knots in bow sea Hs= 4.3 m	Fig 16a Report 7524



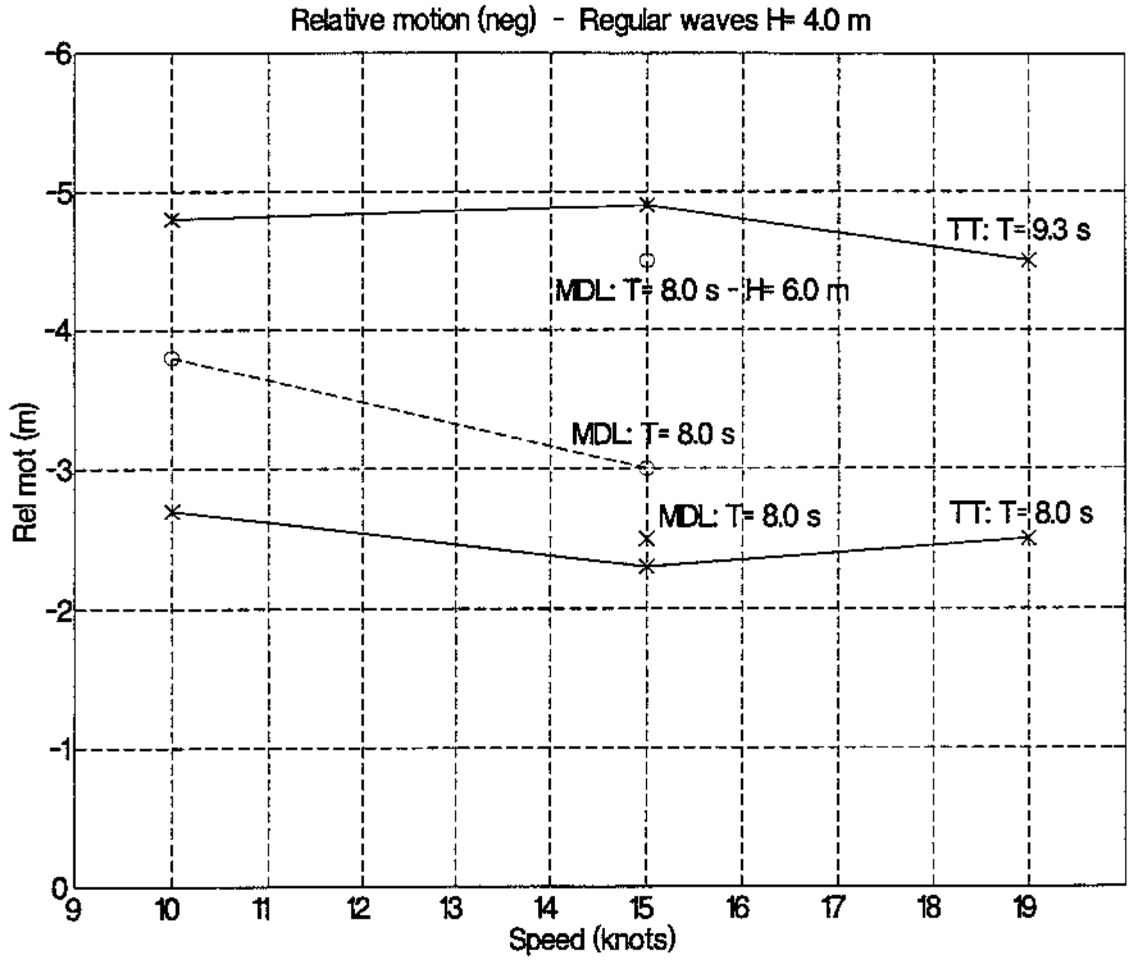
SSPA MARITIME CONSULTING	M/S Estonia MDL tests in irregular sea Weibull diagram from run 67-116: Vertical (Z) force on visor Speed 14.5 knots in bow sea Hs= 4.3 m	Fig 16b Report 7524



SSPA MARITIME CONSULTING	M/S Estonia MDL tests in irregular sea Weibull diagram from run 67-116: Deck hinge (Yh) moment Speed 14.5 knots in bow sea Hs= 4.3 m	Fig 16c Report 7524



SSPA MARITIME CONSULTING	M/S Estonia Relative Motion from model tests in regular waves	Fig 17a Report 7524



TT: towing tank
MDL: Maritime Dynamics Laboratory

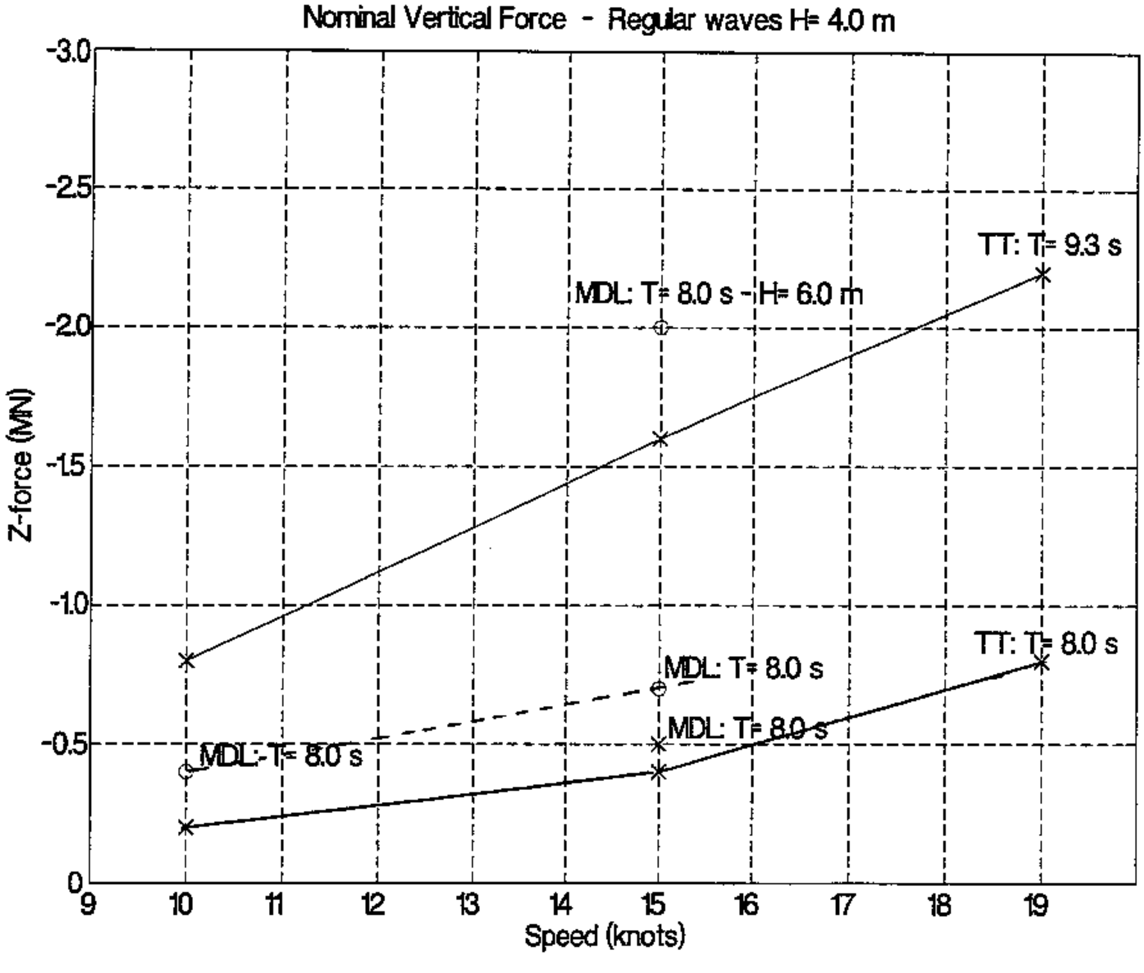
x: head sea
o: bow sea

M/S Estonia

Vertical Force on Visor
from model tests in regular waves

Fig 17b

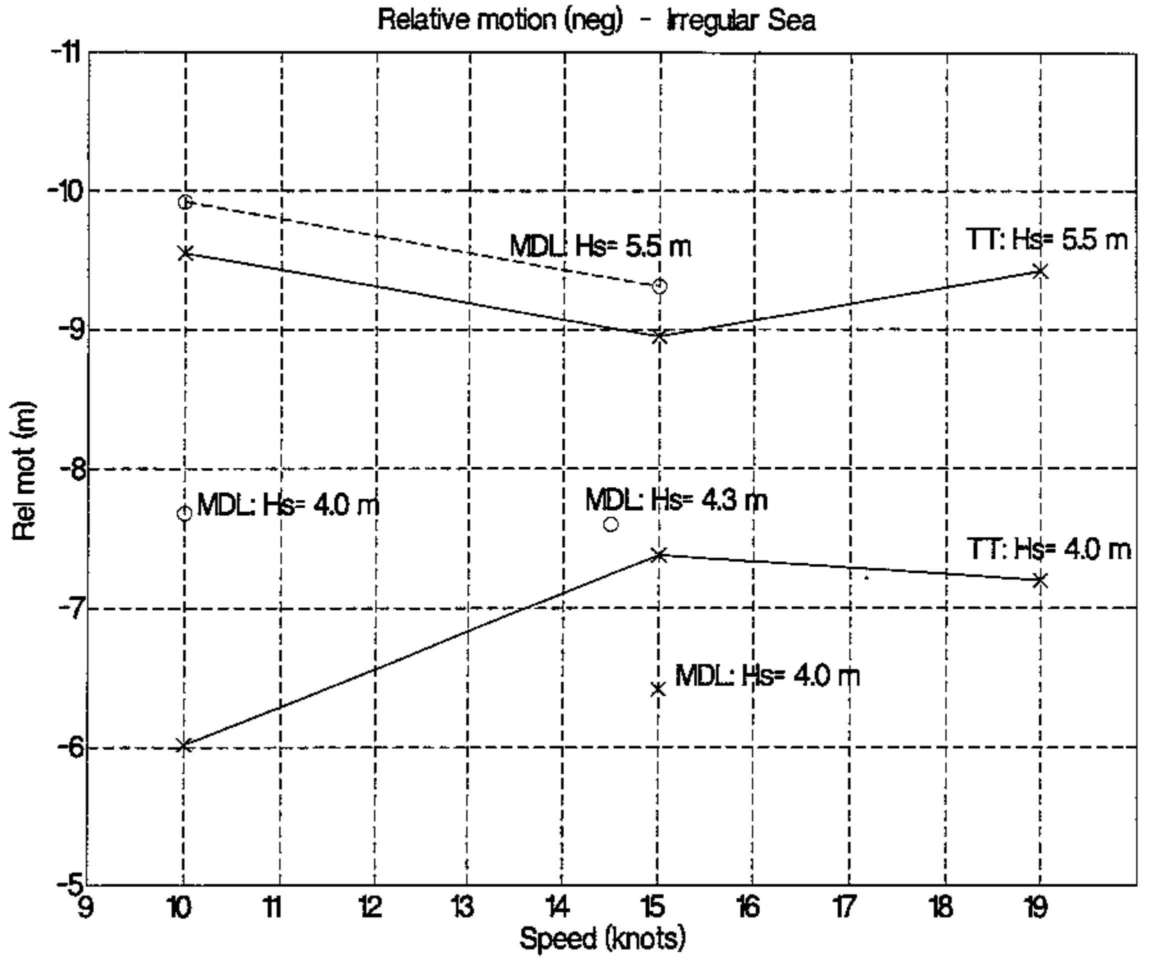
Report 7524



TT: towing tank
MDL: Maritime Dynamics Laboratory

x: head sea
o: bow sea

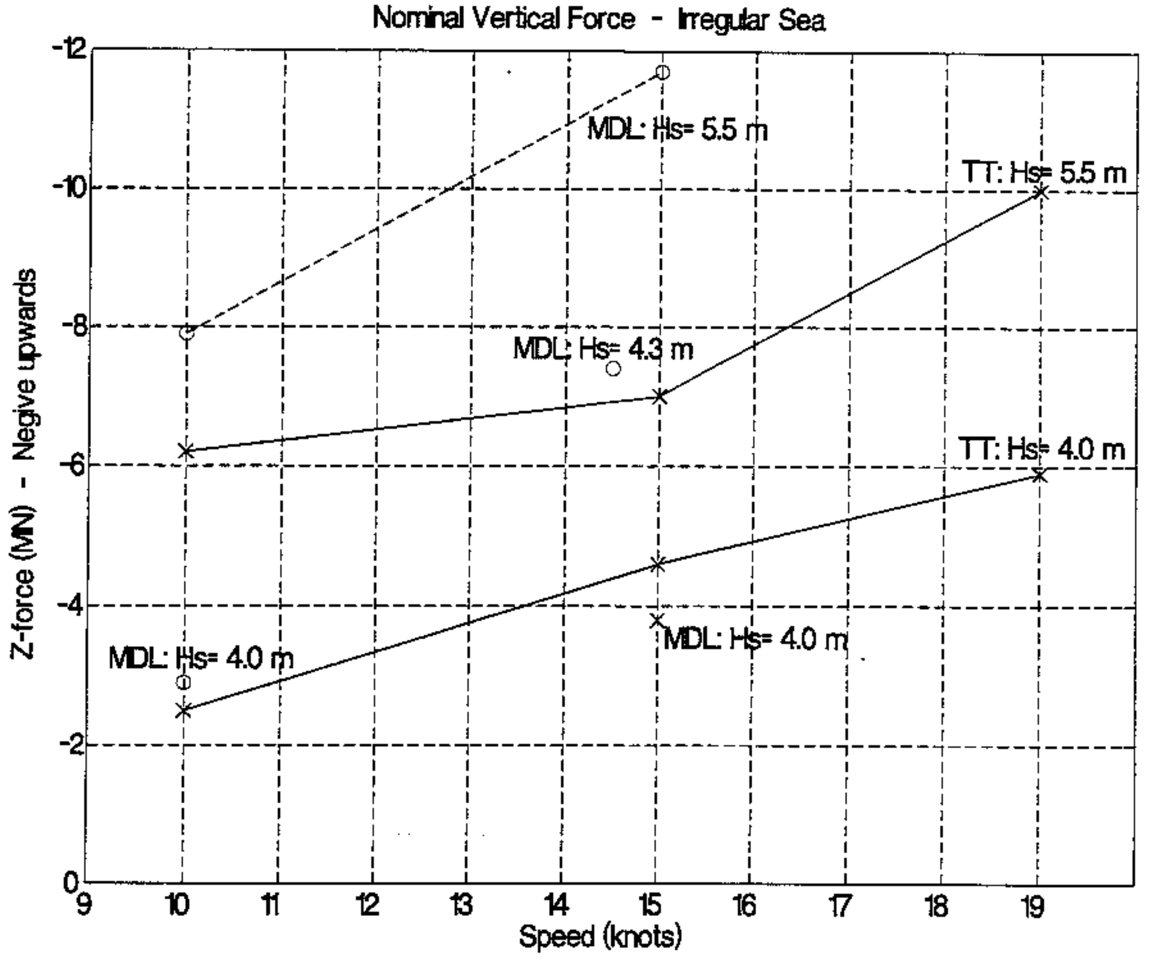
SSPA MARITIME CONSULTING	M/S Estonia Maximum Expected Relative Motion during 3 hours (1618 wave encounters) in irregular sea	Fig 18a Report 7524



TT: towing tank
MDL: Maritime Dynamics Laboratory

x: head sea
o: bow sea

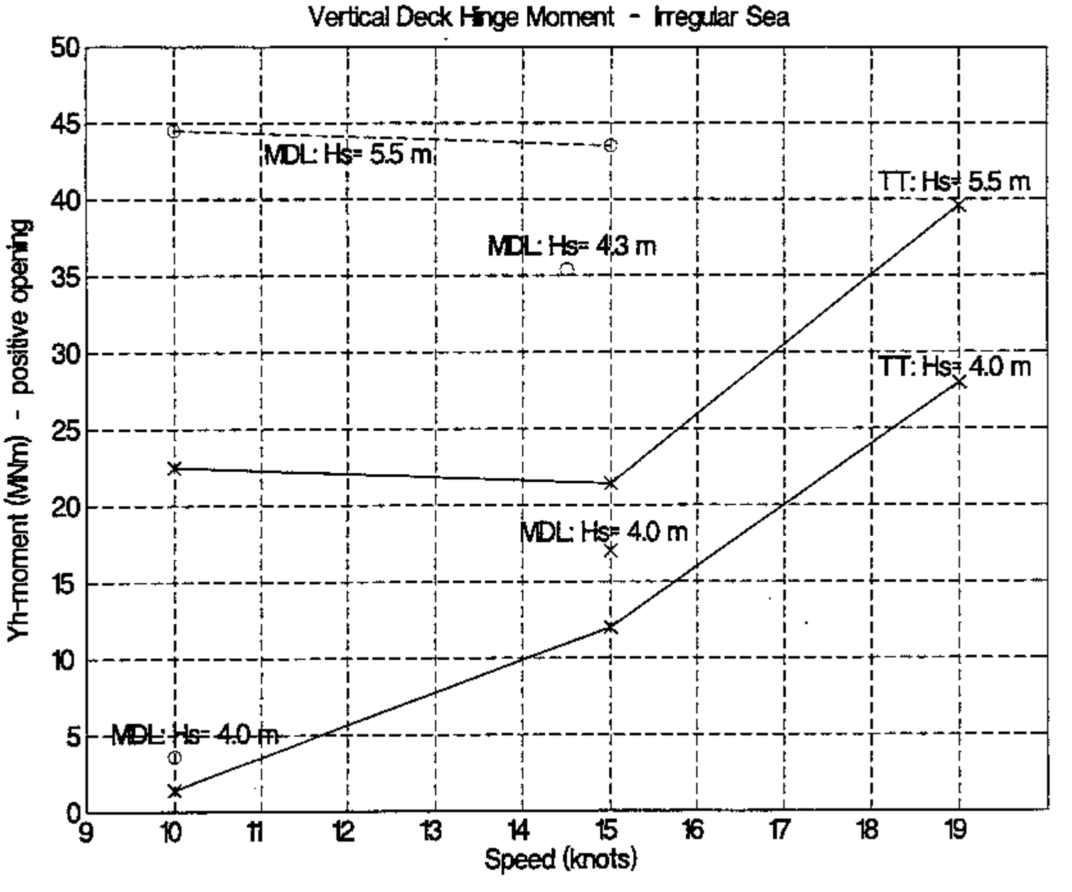
SSPA MARITIME CONSULTING	M/S Estonia Maximum expected Vertical Force on Visor during 3 hours (1618 wave encounters) in irregular sea	Fig 18b Report 7524



TT: towing tank
MDL: Maritime Dynamics Laboratory

x: head sea
o: bow sea

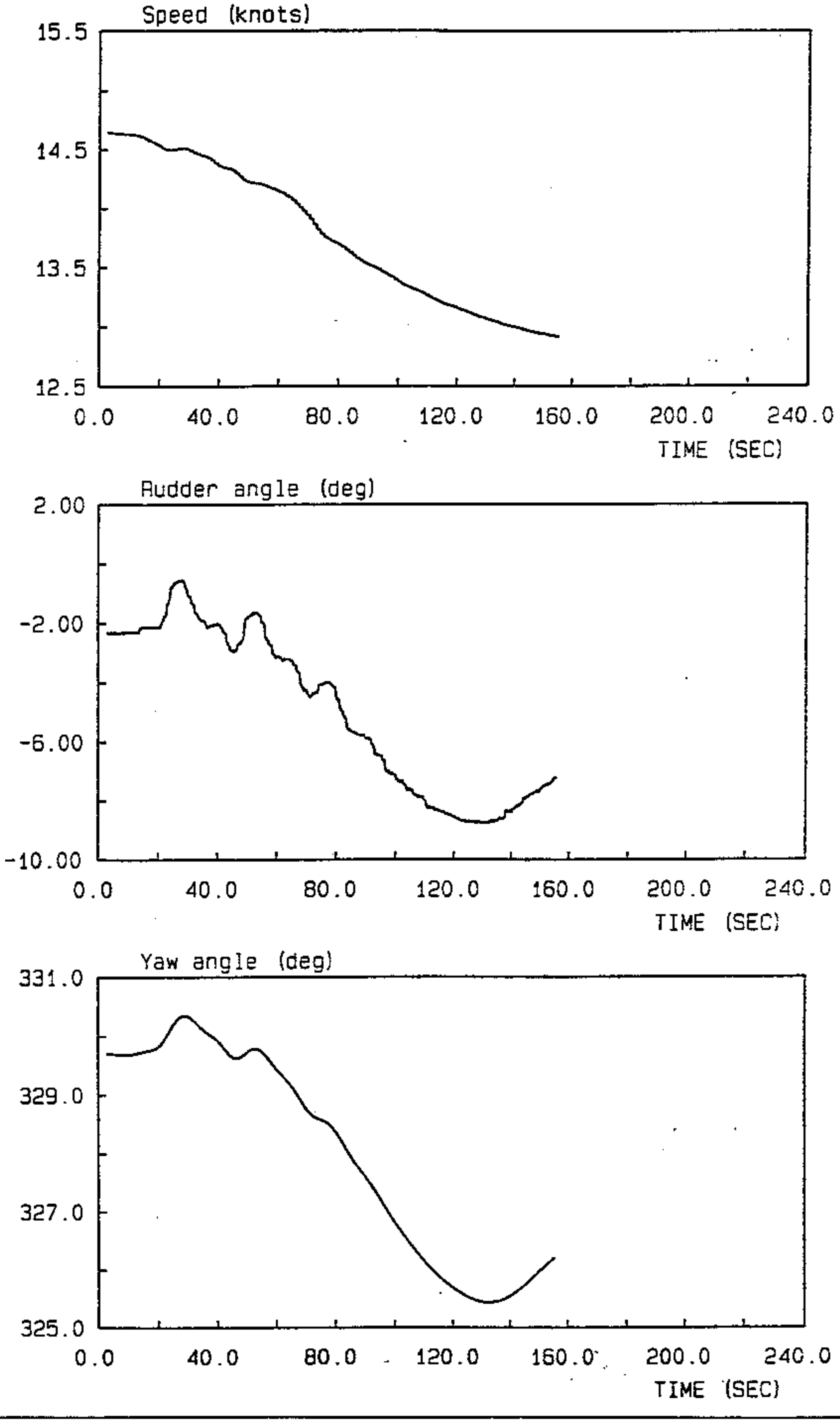
SSPA MARITIME CONSULTING	M/S Estonia Maximum expected Deck Hinge Moment (Yh) during 3 hours (1618 wave encounters) in irregular sea	Fig 18c Report 7524



TT: towing tank
MDL: Maritime Dynamics Laboratory

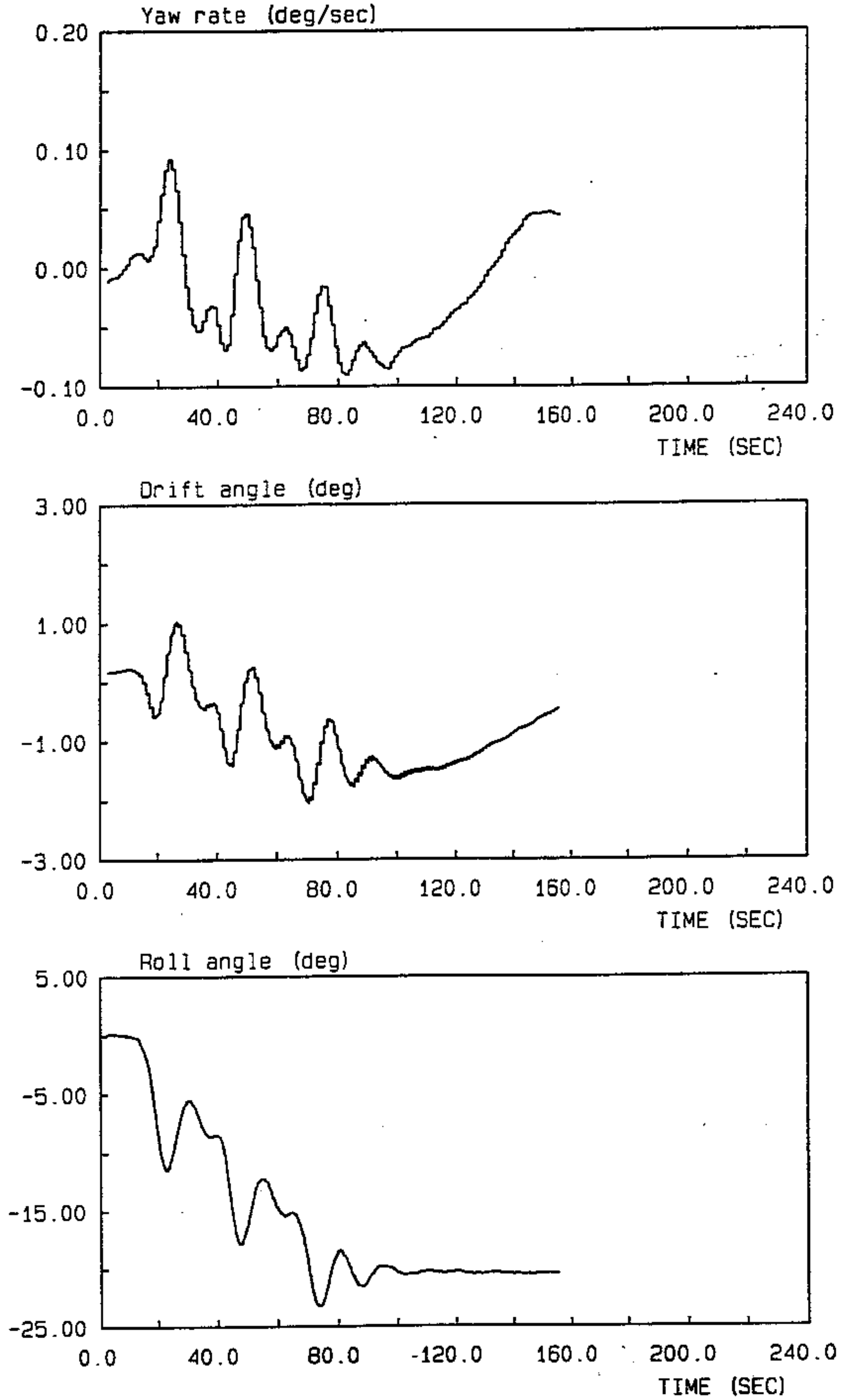
x: head sea
o: bow sea

SSPA MARITIME CONSULTING	M/S Estonia Manoeuvring test in calm water Run 25: Heel angle 21.5 deg Speed 14.5 knots - autopilot	Fig 19a Report 7524

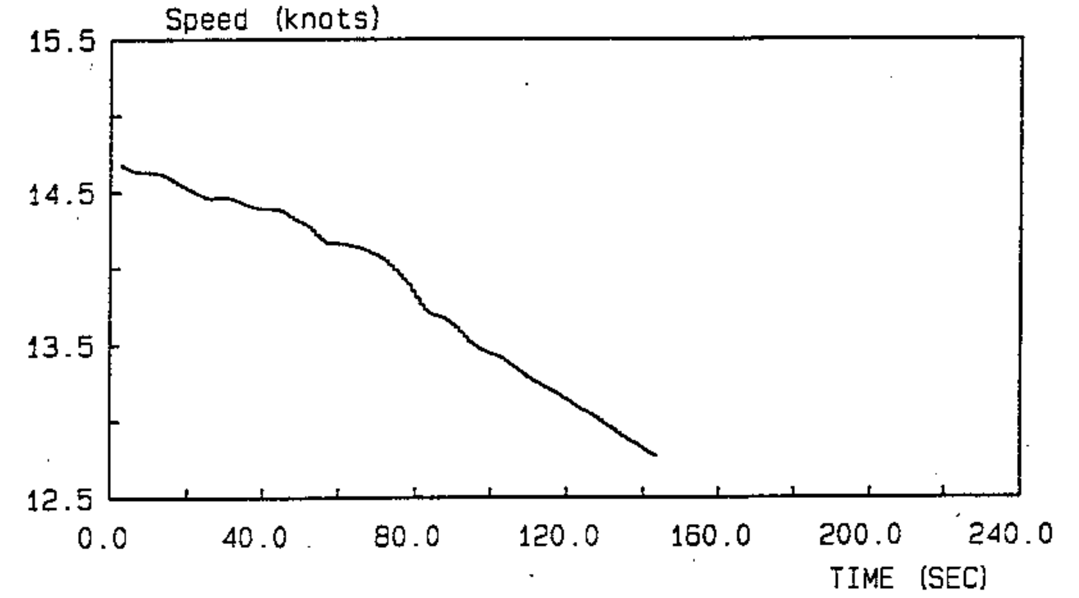


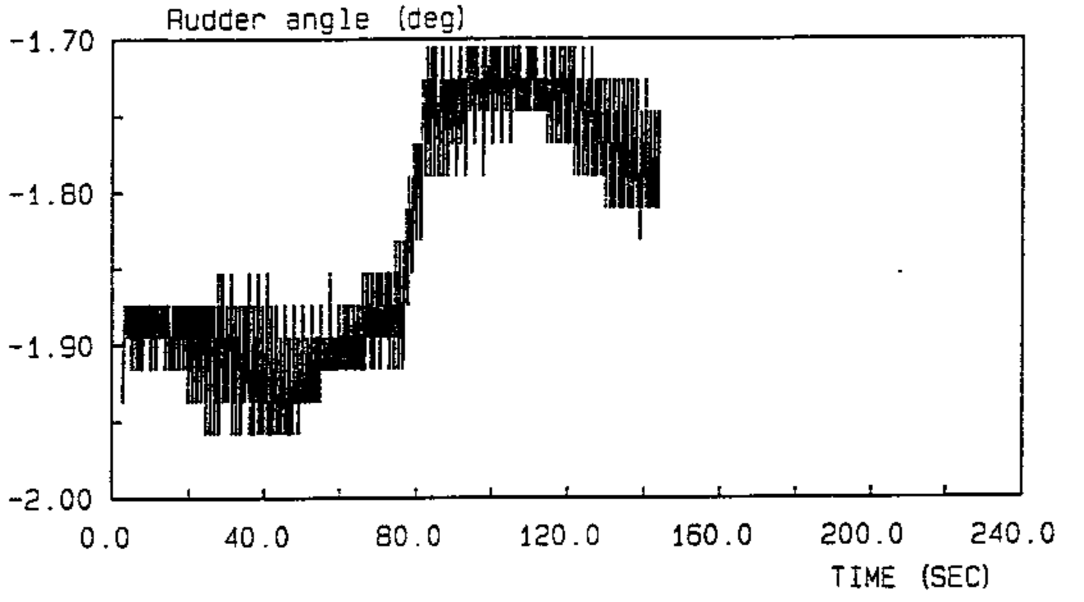
SSPA MARITIME CONSULTING

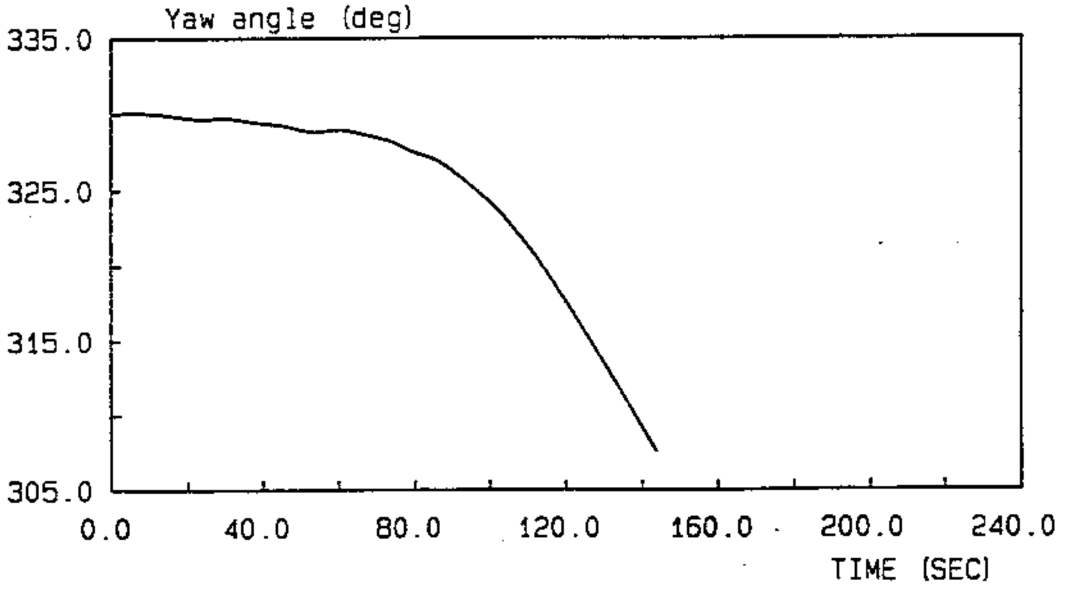
M/S Estonia	Fig 19b
Manoeuvring test in calm water Run 25: Heel angle 21.5 deg Speed 14.5 knots - autopilot	Report 7524



	M/S Estonia	Fig 20a
SSPA MARITIME CONSULTING	Manoeuvring test in calm water Run 26: Heel angle 21.5 deg Speed 14.5 knots - zero rudder	Report 7524







SSPA MARITIME CONSULTING	M/S Estonia Manoeuvring test in calm water Run 26: Heel angle 21.5 deg Speed 14.5 knots - zero rudder	Fig 20b Report 7524