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EXPERIMENTAL MEASUREMENTS OF THE SEAKEEPING CHARACTERISTICS OF FAST DISPLACEMENT CATAMARANS IN OBLIQUE WAVES

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CONTENTS

NOMENCLATURE

Demihull	One of the hulls which make up the catamaran
LCG	Longitudinal centre of gravity
TF	Transfer function
RMS	Route mean square
Fn	Froude Number, $\left[u / \sqrt{gL}\right]$
Rn	Reynolds Number, $\left[uL / \nu\right]$
u	Velocity [ms^{-1}]
L, L_{BP}	Demihull length between perpendiculars [m]
A, WSA	Static wetted surface area [m^2]
B	Demihull maximum beam [m]
T	Demihull draught [m]
S	Separation between catamaran demihull centrelines [m]
∇	Volume of displacement (demihull) [m^3]
Δ	Mass displacement in freshwater (demihull) [kg]
C_B	Block coefficient (demihull)
C_P	Prismatic coefficient (demihull)
C_M	Midship section area coefficient (demihull)
$L / \nabla^{1/3}$	Length : Displacement ratio (demihull)
λ	Wavelength [m]
ζ	Wave amplitude [m]
ω, ω_0	Wave circular frequency [$rads^{-1}$]
ω_e	Wave encounter circular frequency [$rads^{-1}$]
μ	Ship heading [rad] (0=following seas, π=head seas)
TF (ω_e)	Transfer function spectrum
g	Acceleration due to gravity [9.80665 ms^{-2}]
ρ	Density of fresh water [1000 kg/m^3]
ν	Kinematic viscosity of fresh water [1.141 x 10^{-6} m^2s^{-1} at 15°C]

1. INTRODUCTION

The applications of high speed commercial catamarans has increased significantly over the past few years. Progress has been made in developing techniques for the power prediction of semi-displacement catamarans, e.g. Ref. 1. At the same time there has been a need to develop techniques for the prediction of the seakeeping performance of such vessels, particularly at higher operational speeds. Earlier research, Ref. 2, has investigated the characteristics of fast displacement catamarans in head seas. The aim of the research described in this report has been to establish a better understanding of the motion characteristics of catamarans in oblique seas. This has been carried out through a programme of experimental and theoretical work.

Model tests on catamarans in waves have been carried out in regular head seas in the Southampton Institute Test Tank, Refs. 2 and 3, in regular head and oblique seas in the Ocean Basin/Manoeuvring Tank at DERA Haslar and in irregular seas in Southampton Water.

This report describes the model tests in head and oblique waves at DERA Haslar. A description of the theoretical work is given in Ref. 4.

2. DESCRIPTION OF MODELS

Two hullforms were tested, designated models 5b and 5s. Details of the principal particulars of the models are given in Table 1 and their body plans are given in Fig. 1. Model 5b is the same form as that used in earlier investigations of calm water resistance and head sea tests, Refs. 1 and 2. It is of round bilge/transom stern form and based on the NPL Series. Model 5s is based on the Series 64 form. It also is of round bilge/transom stern form but has a distinctly different prismatic coefficient and hull shape.

It should be noted that, due to an increase in hull mass during construction the models as tested were heavier than the original design displacement. The design principal particulars and those as tested are both shown in Table 1, noting that in the test condition length/displacement ratio, $L/\nabla^{1/3}$, has decreased from 8.5 to 8.3 and breadth/draught ratio, B/T, from 2.0 to 1.9.

The models have a waterline length of 4.5m, a test displacement (FW) of 324kg and are constructed in GRP. They are free running, propelled by gas fuelled internal combustion engines, radio controlled, and instrumented to record pitch, roll and vertical accelerations at LCG and 7.5% aft of FP. Radii of inertia of the models in pitch, yaw and roll are given in Table 2. Further details of the construction, equipment and layout of the models is given in Appendix A.

3. FACILITIES AND TESTS

3.1 General

The model tests were carried out in the Ocean Basin at DERA Haslar. The basin has a length of 120m, breadth of 60m and water depth of 5.5m. Regular and irregular waves can be generated at various wave heights and frequencies.

For each test run, the model engines were firstly started, then waves started, data acquisition started and the model released at the required heading. The correct heading was maintained manually by the radio control operator. This heading was maintained as long as possible in order to capture sufficient wave encounters before turning out of the run. The lowest number of wave encounters occurred at a heading of 120^0, when the number of full encounters (at the lowest wave frequency) was seven. A schematic view of the tank and model tracks at various headings is shown in Fig. 2.

3.2 Instrumentation and Measurements

Pitch and roll were measured using a pitch/roll gyro mounted in the port hull. Accelerations were measured using piezoresistive accelerometers; these were mounted in both hulls at the LCG for Model 5b and in both hulls at the LCG and at 7.5% aft of FP for Model 5s. The wave system encountered during each run was measured by a wave probe mounted in the tank. Its approximate position is shown in Fig. 2. The waves were measured over a time of 60 secs, and mean values of frequency and wave height calculated for each run. The wavemaker was found to produce waves of the requested frequency, but wave amplitude tended to be larger than that set.

All measurement signals on the model were acquired using an on-board laptop computer via an analogue to digital converter. The system enabled analysis and checking of the results of each run to be carried out during the experiments.

3.3 Test Conditions

The models were tested in head seas (180°) and oblique seas at headings of 150° and 120°, Fig. 2. Hull separation to length ratios (S/L) of 0.2 and 0.4 were tested at each heading over an encounter frequency range of 3 rads/s to 13 rads/s.

The wavemaker set wave height for each set frequency was based on a nominal wave slope of 2°. The range of frequencies tested at each heading is given in Tables 3 and 4, and the log of actual recorded wave frequencies and heights for all the tests is given in Tables 5 and 6. It should be noted that for both models at a heading of 120°, tests were not carried out at frequencies less than 0.4 Hz since there would not have been an adequate number of wave encounters. For Model 5b at S/L = 0.4 tests at the highest and lowest frequencies were curtailed by the time limitations of the test programme.

The tests were carried out at mean calm water speeds of 4.35 m/s for S/L = 0.2 and 4.45 m/s for S/L = 0.4. These speeds were derived for both models from measured times over a measured distance in the basin. The nominal Froude numbers for these speeds are Fn = 0.65 for S/L = 0.2 and Fn = 0.67 for S/L = 0.4.

Experiments at higher speeds in the Haslar Basin had been proposed in the original research programme. However, experience in the Basin indicated that speeds greater than about 4.5 m/s would have led to an inadequate number of wave encounters in oblique seas, together with the possibility of collisions with the walls and wavemakers when coming out of oblique test runs.

Some supplementary tests were carried out using Model 5s with S/L = 0.4. Two runs were carried out in head seas with reduced wave height for given frequency, two runs were carried out at a wave frequency of 0.475 Hz in an attempt to capture better the resonant frequency and two runs were carried out in beam seas (90^o) at slow (engine idle) speed. Further details of the test conditions are given in Table 6b.

4. REDUCTION AND PRESENTATION OF DATA

RMS values of the measured motions and wave frequency were used to calculate the transfer functions. The values were taken from the records where regular motions had been established and, at the lower frequencies, using a minimum of seven encounters. At the higher frequencies many more waves were encountered. An example of a record is shown in Fig. 3.

Pitch and roll were derived as direct calibrated measurements from potentiometers coupled to the pitch/roll gyro. Roll was also estimated using the difference of the heave measurements port and starboard and was found to correlate well with the direct measurements. Heave was derived from double integration of the mean of the accelerations at LCG for each hull. Accelerations at LCG and forward were obtained directly from the calibrated measurements.

Transfer functions were calculated as follows:

$$\text{Pitch TF} = \frac{\text{Pitch Amplitude RMS [rad]}}{\text{Wave Amplitude RMS [m]}} \times \frac{g[ms^{-2}]}{\omega_o^2\,[rads^{-1}]} \qquad (1)$$

$$\text{Heave TF} = \frac{\text{Heave Amplitude RMS}}{\text{Wave Amplitude RMS}} \qquad (2)$$

$$\text{Roll TF} = \frac{\text{Roll Amplitude RMS [rad]}}{\text{Wave Amplitude RMS [m]}} \times \frac{g[ms^{-2}]}{\omega_o^2[rads^{-1}]} \qquad (3)$$

$$\text{Accel. TF} = \frac{\text{Accel. Amplitude RMS [ms}^{-2}]}{\text{Wave Amplitude RMS [m]}} \times \frac{1}{\omega_e^2\ [\text{rads}^{-1}]} \qquad (4)$$

where encounter frequency ω_e is related to wave frequency ω_o by the following equation, where u is the ship speed and μ the ship heading, with $\mu = 0$ for the following sea case and $\mu = 180^\circ$ for the head sea case:

$$\omega_e = \omega_o - \cos\mu \,.\, \frac{\omega_o^2 u}{g} \qquad (5)$$

5. DISCUSSION OF RESULTS

5.1 Model 5b

The results for Model 5b are shown in Figs 4 to 9. These show the transfer functions for pitch, heave and roll to a base of encounter frequency for the three headings and two hull separations.

The pitch transfer function, Figs 4 and 5, shows a small reduction when going from a heading of 180° to 150°, but a significant reduction when going from 150° to 120°. This trend is similar for both spacings, although greater for the wider spacing, S/L = 0.4.

The heave transfer function, Figs 6 and 7, shows a much greater reduction for S/L = 0.4 than for S/L = 0.2 when going from 150° to 120°.

The roll transfer function, Figs 8 and 9, as expected shows a marked increase when going from 150° to 120°. Its value at a heading of 120° and S/L = 0.2 is of the order of 18% higher than that for S/L = 0.4, whilst at 150° and S/L = 0.2 is of the order of 12% lower than that for S/L = 0.4.

It should be noted that, due to the way the heave and acceleration transfer functions have been defined, Equations 2 and 4, the acceleration transfer function at LCG will be identical to that for heave, Figs 6 and 7, and therefore has not been plotted. Accelerations forward were not measured for Model 5b.

5.2 Model 5s

The results for Model 5s are shown in Figs 10 to 19. These show the transfer functions for pitch, heave, roll and forward acceleration to a base of encounter frequency for the three headings and two hull separations, together with speed loss to a base of encounter frequency for S/L = 0.4.

The pitch transfer function, Figs 10 and 11, shows relatively small reductions when going from a heading of 180° to 150°, but a significant reduction when going from 150° to 120°. This trend is similar for both spacings although, like Model 5b, the reduction is greater for the larger spacing, S/L = 0.4.

The results for the heave transfer function, Figs 12 and 13, show similar trends to those for Model 5b. Namely, when going from a heading of 150° to 120° there is a greater reduction in transfer function for S/L = 0.4 than for S/L = 0.2.

The roll transfer function, Figs 14 and 15, shows a marked increase when going from 150° to 120°. Its value at a heading of 120° and S/L = 0.2 is of the order of 19% higher than that for S/L = 0.4. This is similar to Model 5b. At 150° the transfer function at S/L = 0.2 shows little change from that for S/L = 0.4.

Transfer functions for accelerations forward for Model 5s are shown in Figs 16 and 17. At S/L = 0.2 there is little change in forward acceleration with change in heading whereas at S/L = 0.4 there is a marked decrease when going from 150° to 120°.

The results of the extra runs at reduced wave height for given frequency in head seas, for model 5s at S/L = 0.4, are shown in Figs. 11, 13 and 17. It is noted that the reduced wave height has had little influence on the transfer function, indicating a linearity of response with wave height. The roll results from the low speed tests in beam seas are shown in Fig. 15, noting that there is an increase in transfer function as expected.

5.3 Comparison between Models 5b and 5s

Inspection of the results for Model 5b in Figs 4 to 9 and Model 5s in Figs 10 to 17 indicate that, in the main, the difference in performance between the two hull shapes is not large. However, roll response, Figs 8 and 9, 14 and 15 does show a significant difference in that at S/L = 0.2 the roll transfer function for model 5s is 19% higher at a heading of 120° and 14% higher at 150°, and at S/L = 0.4 model 5s is 18% higher at 120° and about the same at 150°.

5.4 Speed Loss

Speed loss in regular waves for both models is shown in Figs 18 to 21. This has been derived from Equation 5, where ω_o is the measured wave frequency, ω_e the actual measured encounter frequency and using nominal values of heading μ, whence speed is derived as follows:

$$u = \frac{g}{\omega_o^2} \cdot \frac{\omega_o - \omega_e}{\cos\mu} \qquad (6)$$

The curves in Figs 18 to 21 show a maximum decrease in speed at about the resonant frequency. It should be noted that estimates of speed would be affected by deviations from the nominal heading which were not recorded. For this reason the results are indicative rather than definitive. The results at 120° are most dependent on deviations from the set heading. Except for Model 5s at S/L = 0.4, the results showed a large amount of scatter at this heading and have not been presented. Typically, the speed loss for Model 5b, Figs 18 and 19 is of the order of 4% to 8% of the calm water speed. For Model 5s, Figs 20 and 21, the speed loss for S/L = 0.2 is about 8% whilst for S/L = 0.4 is about 7% at headings of 120° and 150°, increasing to about 10% at 180. These speed reductions correspond to increases in resistance of the order of 10% to 20%. They are in broad agreement with the added resistance recorded in the head sea tests, Refs 2 and 3, for S/L = 0.2 although the smaller speed loss for S/L = 0.4 (Refs 2 and 3) was not recorded.

5.5 Comparison with the 1.6m Model Data

Comparisons with the 1.6m model results in head seas, Refs 2 and 3, indicate broad agreement in most cases, although the 4.5m models exhibit larger heave transfer functions than those for the 1.6m models. There were several differences in the experiments: the 4.5m model was self propelled whilst the 1.6m model was towed and its two post moved only in heave and was not free to pitch; the Southampton Institute tank used for the 1.6m model may have had some wall effects; the wave probe on the towing carriage was much closer to the model and may have been influenced by the model. It is, however, not clear at present how these may account for the discrepancies in heave response.

6. CONCLUSIONS

- The results of oblique sea tests in regular waves with two catamaran models are presented. The tests were carried out at three headings (180°, 150° and 120°) and at two Separation/Length ratios (S/L = 0.2 and 0.4).

- In the main, motions and accelerations decrease slightly when going from 180° (head seas) to 150° and significantly when going from 150° to 120°, this trend generally being similar for both hull spacings.

- The results indicate that the difference in seakeeping performance between the two hull shapes (NPL and Series 64) is not large.

- The head and oblique sea tests in the Model Basin were carried out at one speed. The influence of speed and length/displacement ratio on seakeeping performance in head seas has been determined separately in earlier complementary tests forming part of the same overall research programme, Refs 2 and 3.

ACKNOWLEDGEMENTS

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	DESIGN		AS TESTED	
Model	**5b**	**5s**	**5b**	**5s**
L/B	11.0	12.8	11.0	12.8
B/T	2.0	2.0	1.9	1.9
$L/\nabla^{1/3}$	8.5	8.5	8.3	8.3
C_B	0.397	0.537	0.400	0.540
Cp	0.693	0.633	0.698	0.637
Cm	0.573	0.848	0.573	0.848
A/L^2	0.1078	0.1095	0.1131	0.1149
LCB [%x]	-6.4%	-6.4%	-6.4%	-6.4%

Notes: Model 5b is based on the NPL Series form.
Model 5s is based on the Series 64 form.

Table 1: Principal Particulars of Models (demihulls)

S/L	Pitch K_{yy}	Yaw K_{zz}	Roll K_{xx}
0.2	0.26L	0.28L	0.11L
0.4	0.26L	0.32L	0.20L

Table 2: Radii of Inertia for Models 5b and 5s
(4.5m models in catamaran configurations)

fw	S/L=0.2			S/L=0.4		
	Headings [deg]			Headings [deg]		
Hz	180	150	120	180	150	120
0.30	●	●				
0.35	●	●		●	●	
0.40	●	●	●	●	●	
0.45	●	●	●	●	●	●
0.50	●	●	●	●	●	●
0.55	●	●	●		●	●
0.60	●	●	●		●	●
0.65	●	●	●			●
0.70	●	●	●			

Table 3: Summary of Tests - Model 5b

fw	S/L=0.2			S/L=0.4		
	Headings [deg]			Headings [deg]		
Hz	180	150	120	180	150	120
0.30	●	●		●	●	
0.35	●	●		●	●	
0.40	●	●	●	●	●	●
0.45	●	●	●	●	●	●
0.50	●	●	●	●	●	●
0.55	●	●	●	●	●	●
0.60	●	●	●	●	●	●
0.65	●	●	●	●	●	●
0.70	●	●	●	●	●	●

Table 4: Summary of Tests - Model 5s

Heading	Wave f Hz	Waveheight m	Wavelength m
180	0.296	0.205	17.84
180	0.35	0.147	12.741
180	0.4	0.128	9.754
180	0.449	0.091	7.751
180	0.5	0.073	6.243
180	0.55	0.063	5.155
180	0.6	0.055	4.335
180	0.648	0.041	3.722
180	0.7	0.039	3.185
150	0.294	0.207	18.008
150	0.35	0.146	12.741
150	0.4	0.123	9.754
150	0.451	0.092	7.685
150	0.5	0.074	6.243
150	0.55	0.064	5.155
150	0.6	0.054	4.335
150	0.648	0.043	3.722
150	0.7	0.041	3.185
120	0.4	0.126	9.754
120	0.449	0.086	7.751
120	0.5	0.073	6.243
120	0.55	0.064	5.155
120	0.597	0.053	4.377
120	0.651	0.043	3.689
120	0.7	0.04	3.185

Table 5a: Wavemaker Data: Model 5b, S/L=0.2

Heading	Wave f Hz	Waveheight m	Wavelength m
180	0.35	0.145	12.741
180	0.4	0.127	9.754
180	0.451	0.083	7.685
180	0.5	0.074	6.243
150	0.35	0.146	12.741
150	0.4	0.128	9.754
150	0.449	0.083	7.751
150	0.5	0.075	6.242
150	0.55	0.062	5.155
150	0.6	0.053	4.335
120	0.449	0.084	7.751
120	0.5	0.076	6.243
120	0.55	0.065	5.155
120	0.6	0.054	4.335
120	0.647	0.045	3.721

Table 5b: Wavemaker Data: Model 5b, S/L=0.4

Heading	Wave f Hz	Waveheight m	Wavelength m
180	0.60	0.060	4.336
180	0.55	0.075	5.162
180	0.50	0.085	6.244
180	0.45	0.098	7.708
180	0.40	0.119	9.717
180	0.35	0.147	12.751
180	0.30	0.166	17.344
180	0.65	0.052	3.688
180	0.70	0.049	3.182
150	0.40	0.125	9.796
150	0.50	0.089	6.244
150	0.45	0.098	7.708
150	0.35	0.150	12.751
150	0.30	0.176	17.344
150	0.55	0.074	5.183
150	0.60	0.061	4.336
150	0.65	0.055	3.688
150	0.70	0.050	3.182
120	0.60	0.061	4.336
120	0.55	0.075	5.162
120	0.50	0.085	6.244
120	0.45	0.098	7.709
120	0.40	0.124	9.756
120	0.65	0.056	3.703
120	0.70	0.049	3.182
120	0.60	0.062	4.336

Table 6a: Wavemaker Data: Model 5s, S/L=0.2

Heading	Wave f Hz	Waveheight m	Wavelength m
180	0.60	0.065	4.336
180	0.55	0.077	5.162
180	0.50	0.086	6.244
180	0.45	0.100	7.709
180	0.40	0.122	9.796
180	0.35	0.149	12.751
180	0.30	0.171	17.344
180	0.65	0.055	3.703
180	0.70	0.050	3.182
150	0.40	0.127	9.796
150	0.50	0.090	6.244
150	0.45	0.104	7.709
150	0.35	0.152	12.751
150	0.30	0.172	17.344
150	0.55	0.077	5.162
150	0.60	0.061	4.336
150	0.65	0.055	3.703
150	0.70	0.050	3.182
120	0.60	0.061	4.336
120	0.55	0.075	5.162
120	0.50	0.085	6.244
120	0.45	0.098	7.708
120	0.40	0.124	9.796
120	0.65	0.056	3.703
120	0.70	0.049	3.182
180	0.45	0.062	7.709
180	0.50	0.051	6.244
180	0.475	0.098	6.929
150	0.475	0.099	6.929
90	0.40	0.123	9.756
90	0.50	0.087	6.244

Table 6b: Wavemaker Data: Model 5s, S/L=0.4

APPENDIX A: DETAILS OF MODELS

Principal Dimensions - As Tested:

	Model 5b	Model 5s
LOA	4.8m	4.8m
LBP (=LWL)	4.5m	4.5m
B	0.409m	0.352m
D	0.550m	0.550m
T	0.220m	0.189m
C_B	0.400	0.540
∇m^3 (per hull)	0.162	0.162

Construction:

The hulls were constructed from GRP. Each hull has a wooden gunwale glassed in and is fitted with three 6mm plywood bulkheads. Platforms carrying the engines, shaft bearings and rudder bearings were made of 18mm plywood and glassed into the hulls.

The two cross beams joining/separating the hulls were of continuous section aluminium alloy mast material (kindly provided free of charge by Kemps Masts). These spars were bolted to each hull via a GRP fitting which was glassed to the hull and an adjacent bulkhead. This set-up allowed adjustment of the separation of the hulls, and removal of the spars for transportation of the models to test sites.

The GRP hulls were constructed outside the University and fitted out in the University Engineering Faculty Workshops.

The models were weighed prior to testing, including fuel and necessary ballast, leading to an all-up weight of 324kg.

Pitch, Roll and Yaw Inertias:

Model 5b was swung in its test condition in pitch and roll to obtain the relevant radii of gyration. The radius of gyration in yaw was estimated from the inertia in pitch assuming the demi-hull inertias in pitch and yaw to be the same. Model 5s was swung in pitch and a similar value to that for Model 5b was obtained. This would be expected since the construction and layouts for both models were effectively identical. For this reason, the values for roll and yaw inertia for Model 5s are assumed to be also the same as those for Model 5b. A summary of the radii of gyration for both models is given in Table 2.

Engines, Transmission and Propellers:

Engines: One per hull. Honda GX160QX4.
Maximum power output: 4.1kW @ 3600 rpm.
Continuous power output: 3.5 kW @ 3600 rpm.
Capable of operation on petrol or propane gas (gas used when operating under cover in the Haslar Model Basin).

Shafting: Stainless steel 19mm (3/4") diameter.

Propellers: Brass. Diameter 152mm, Pitch 178mm. One right handed, one left handed. Propellers, shafting, brass stern tubes and stuffing boxes supplied by Norris Marine Equipment Ltd.

Gear Ratios: Transmission from engine to shaft is achieved using a pulley-belt system. Vee belts and pulleys are used with three gear ratios as follows:

Ratio	Engine Pulley Diameter	Prop. Shaft Pulley Diameter
1:2.5	80mm	200mm
1:1.695	118mm	200mm
1:1	200mm	200mm

All tests to date (January 1999) have been carried out using the mid gear ratio (1:1.695), leading to a speed in calm water of the order of 4.40 m/s (Fn=0.67) at full engine throttle setting.

An outline drawing of the transmission arrangement is shown in Fig. 22. The electric clutch shown was not successful, due mainly to misalignment problems. It was subsequently removed at an early stage of model commissioning and replaced with a direct drive fitting.

Electrical Power/Remote Control:

Electrical power for instrumentation and data acquisition equipment is provided by a 12v battery.

Power for all on-board radio controlled equipment is provided by a 6v battery.

The following operations are controlled by radio: Rudder winches; Throttle servos; Engine hold; Engine off, together with channels for data acquisition trigger etc as required.

The rudder winches (one in each hull) are controlled simultaneously from a single rudder control signal. Similarly, the throttle servos (one in each hull) are controlled simultaneously.

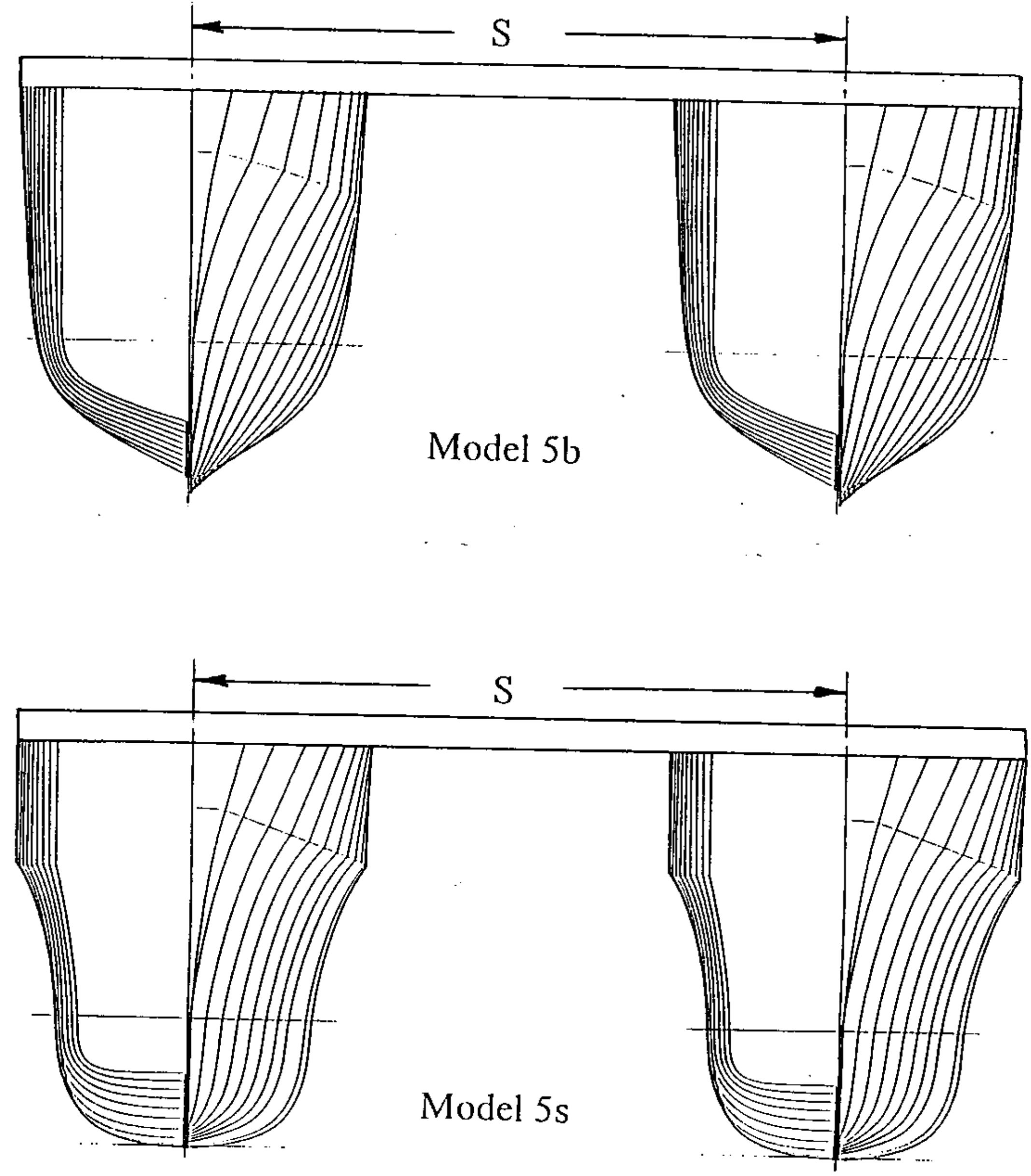
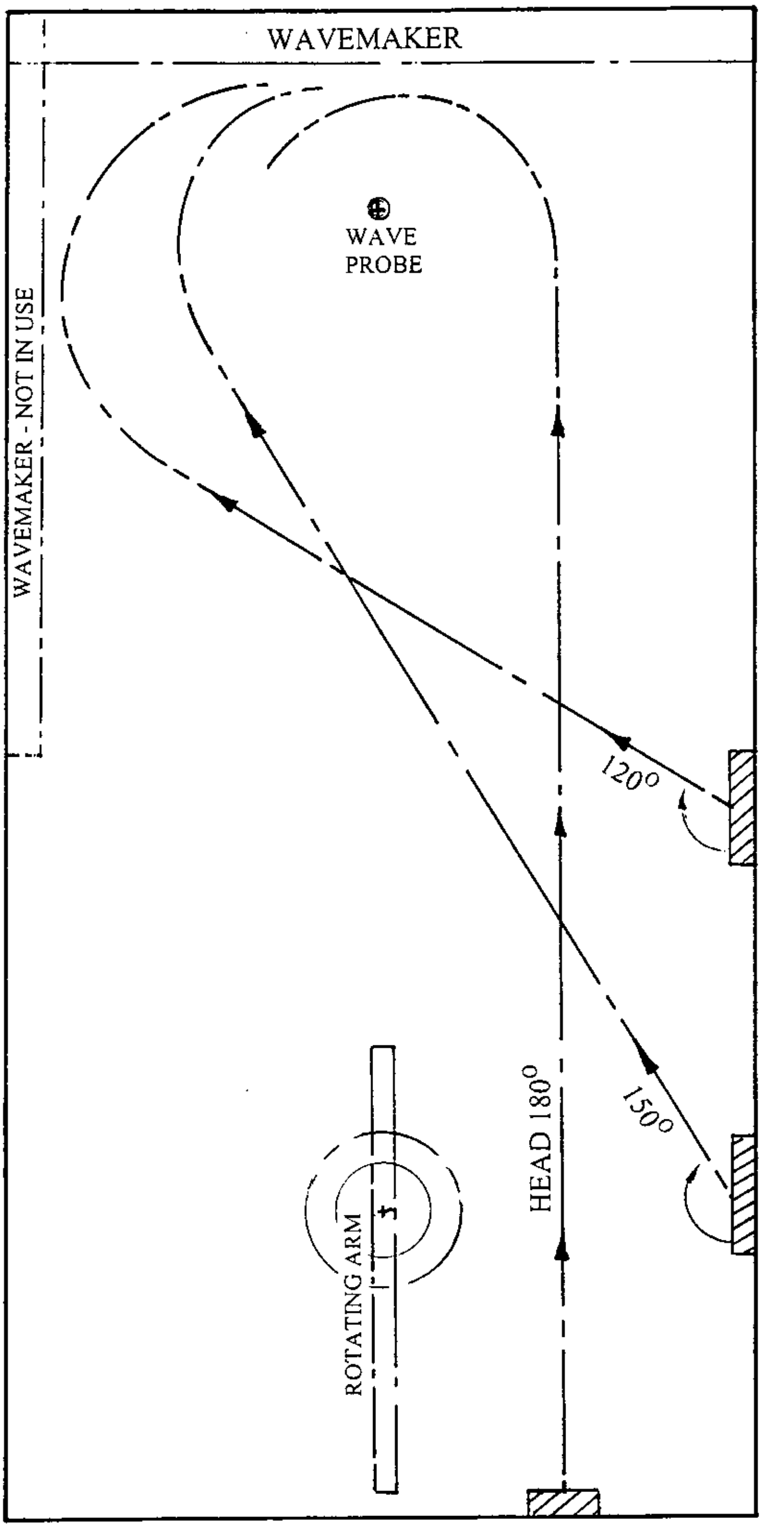
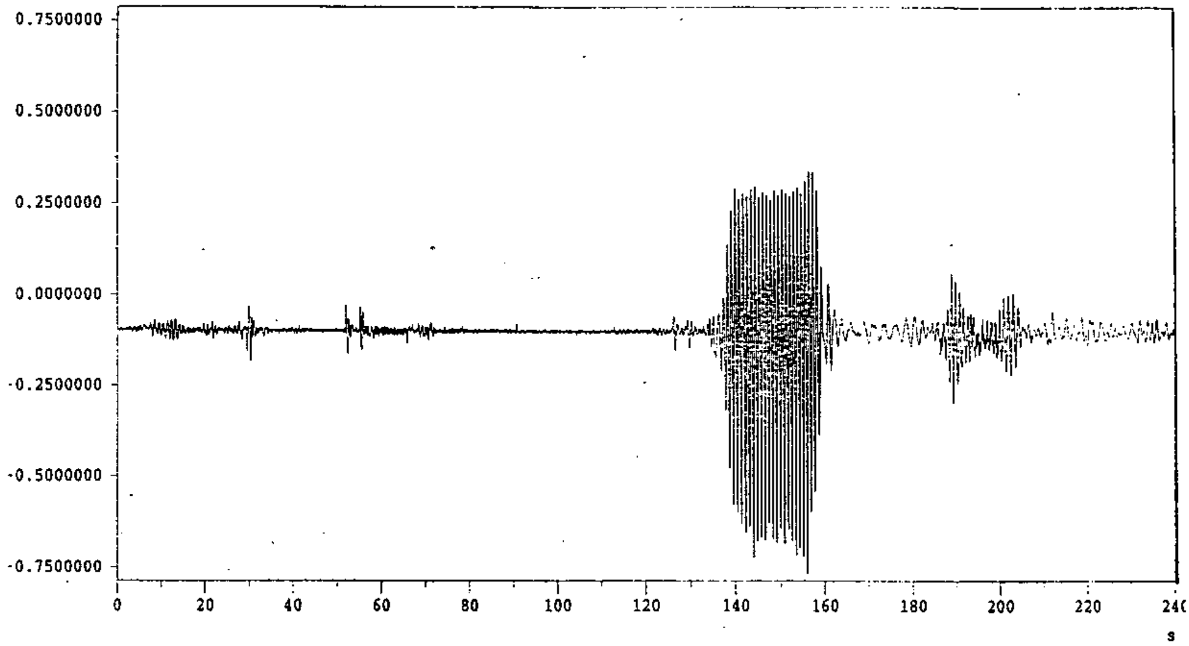


Fig 1: Body plans of models.

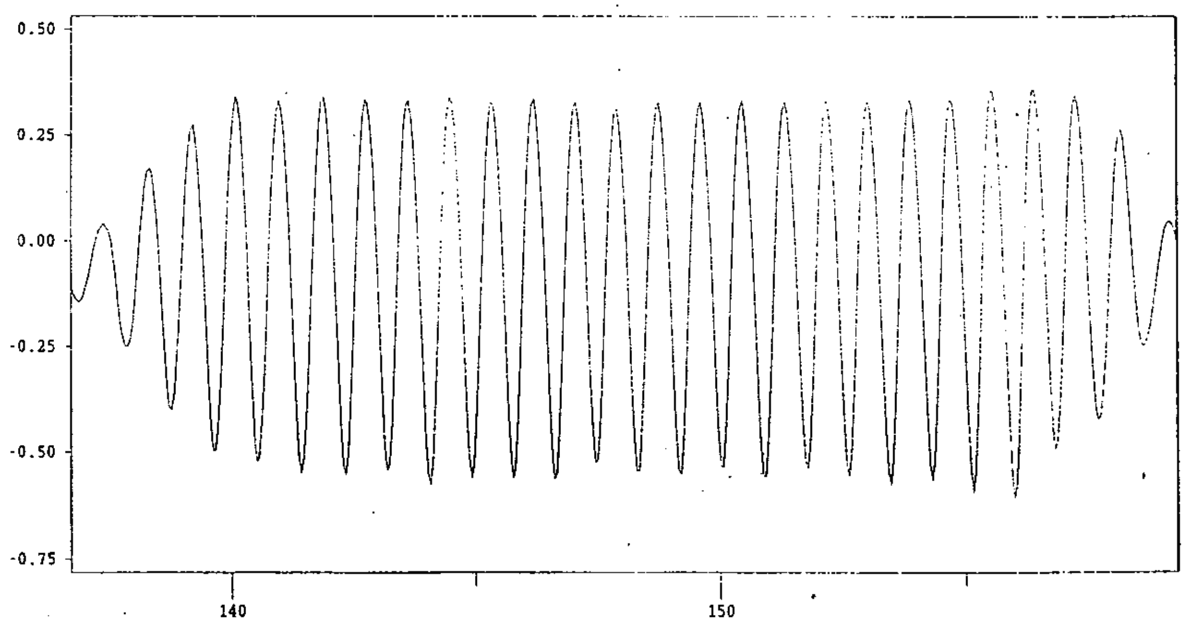


DERA HASLAR OCEAN BASIN: 120m x 60m

Fig 2: Schematic layout of basin and headings of test runs.



(a) Overall measured record.



(b) Portion of measured record used in analysis.

Fig 3: Example of measured Record.

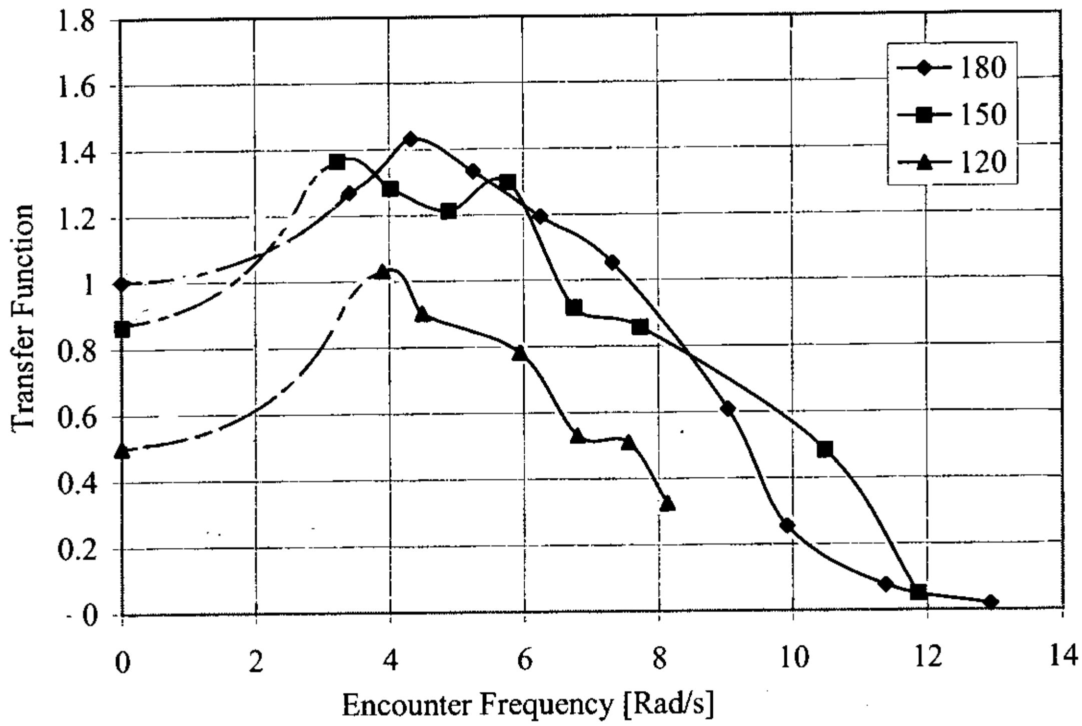


Fig 4:Model 5b Pitch S/L=0.2

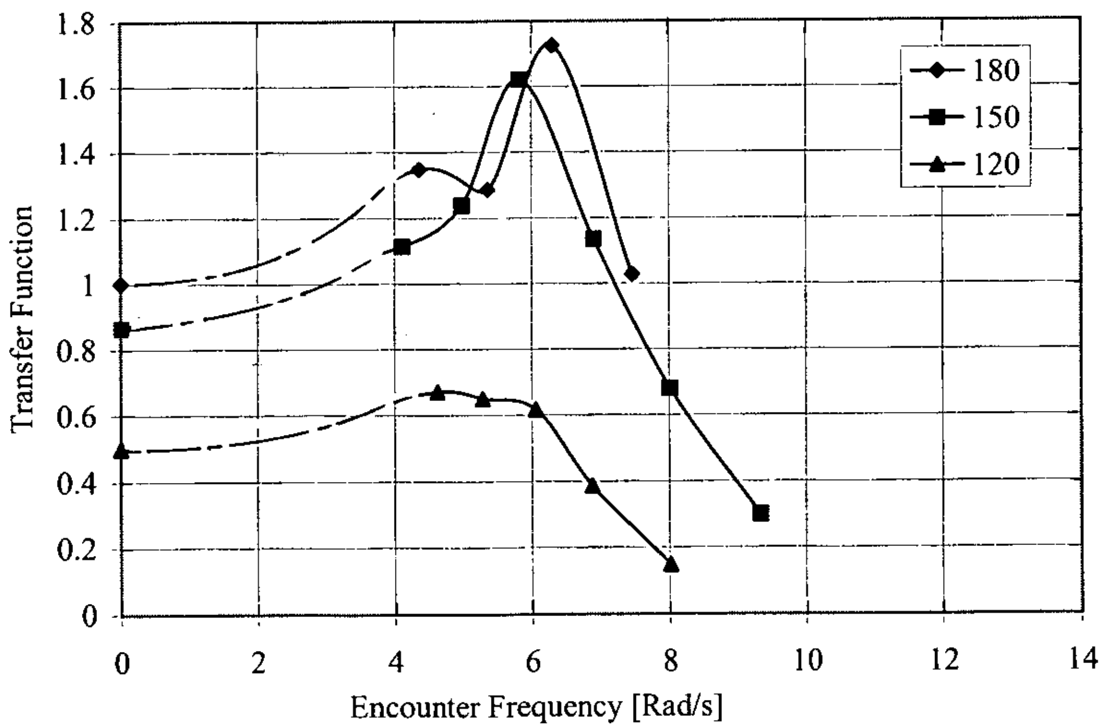


Fig 5:Model 5b Pitch S/L=0.4

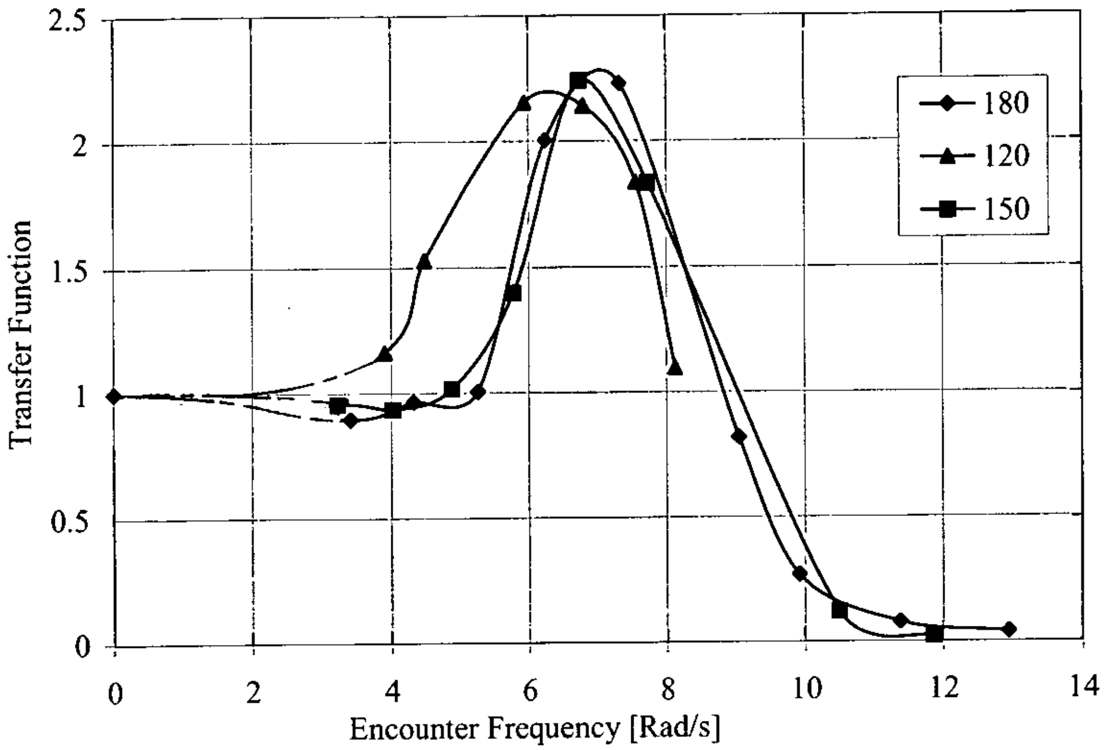


Fig 6:Model 5b Heave S/L=0.2

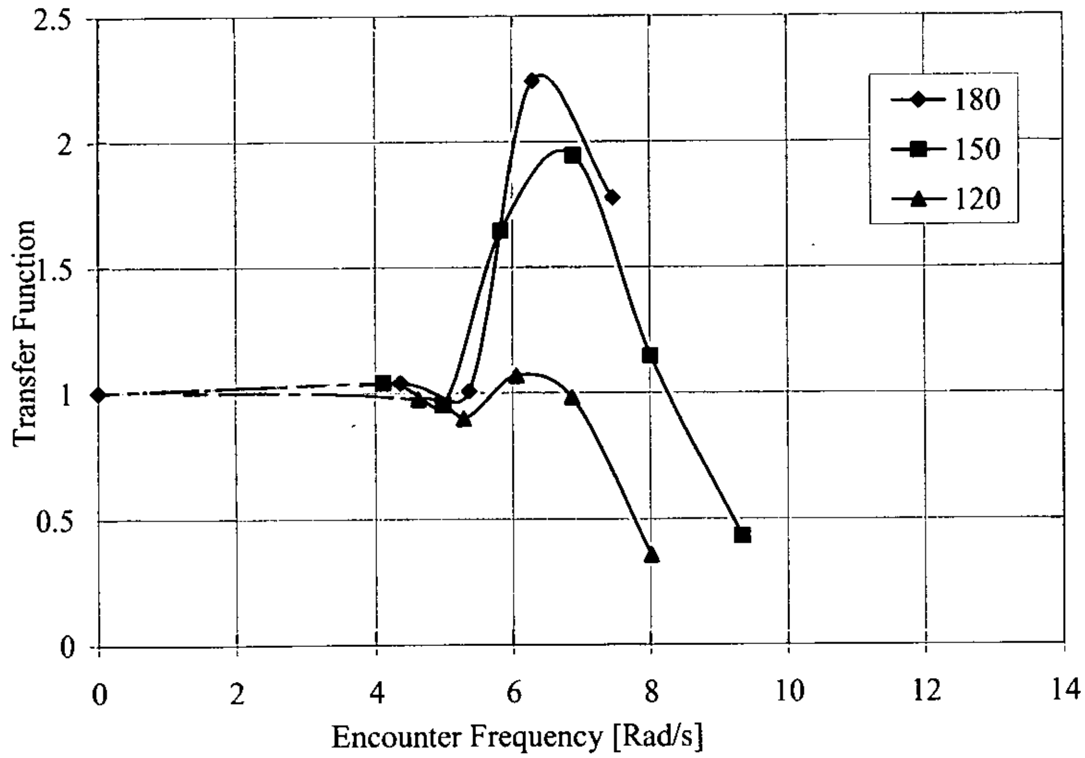


Fig 7:Model 5b Heave S/L=0.4

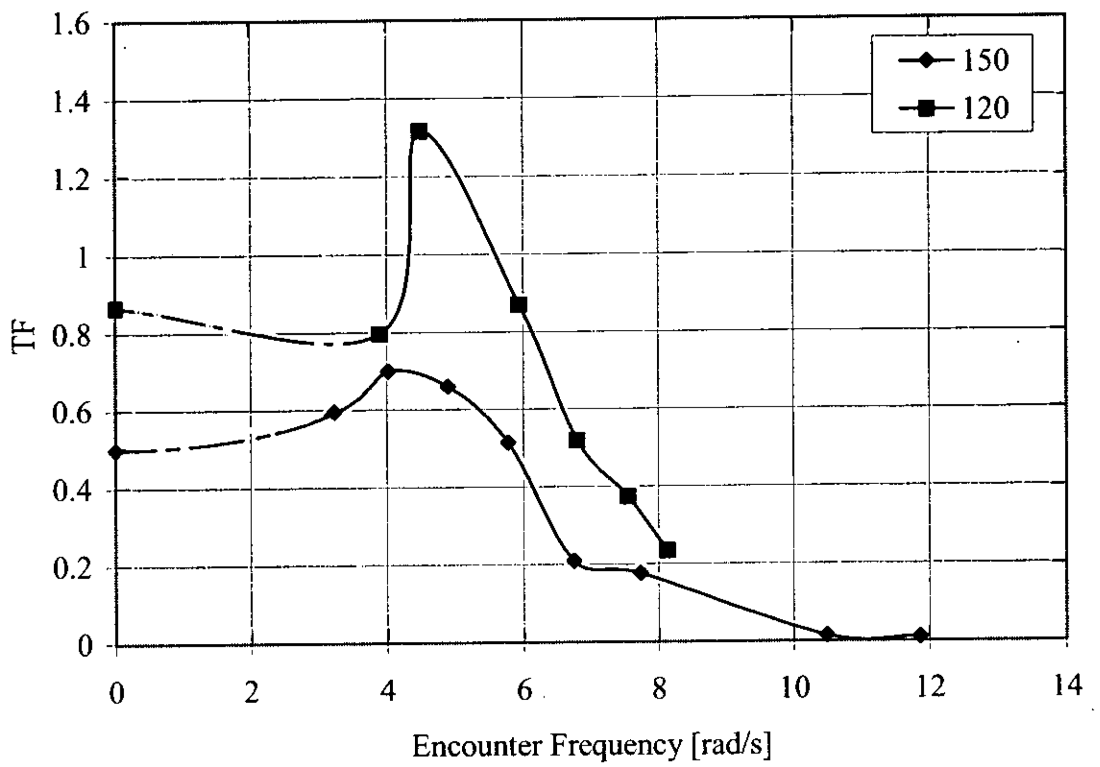


Fig 8: Model 5b Roll S/L=0.2

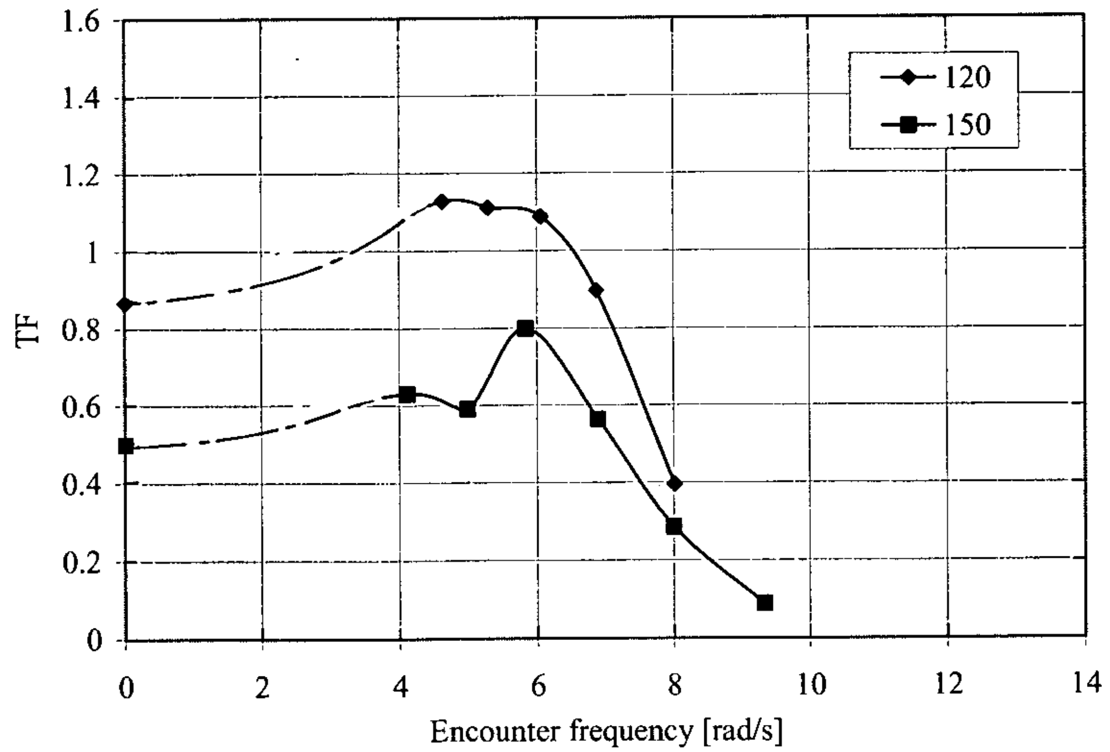


Fig 9: Model 5b Roll S/L=0.4

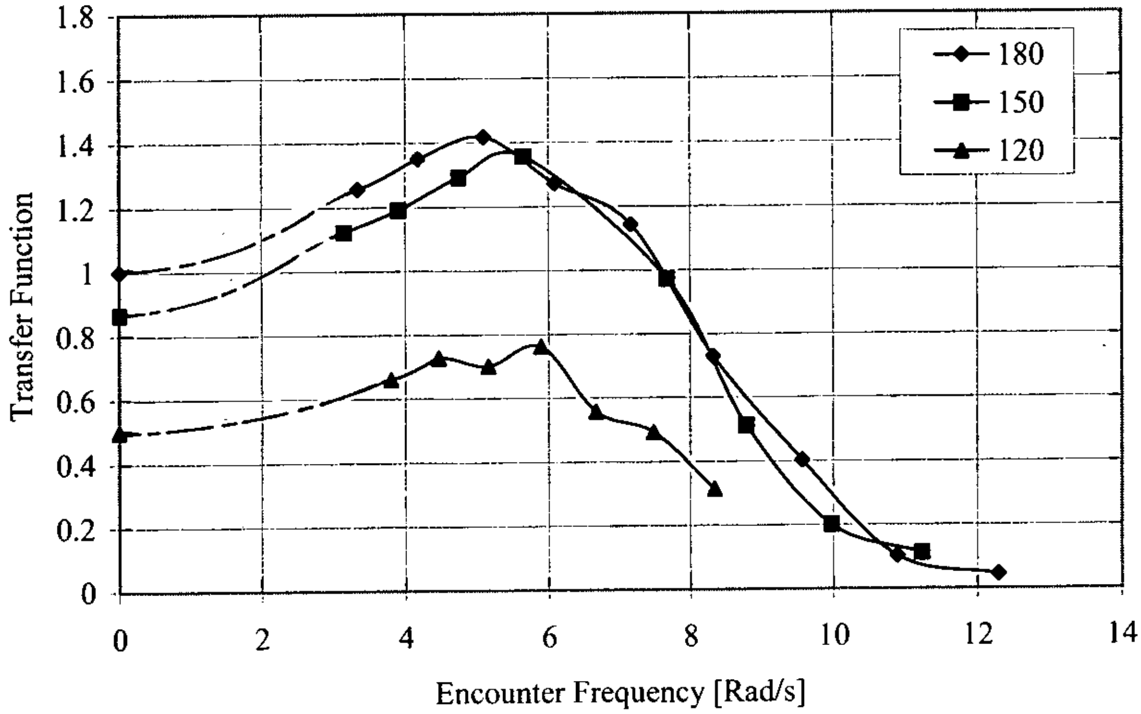


Fig 10: Model 5s Pitch S/L=0.2

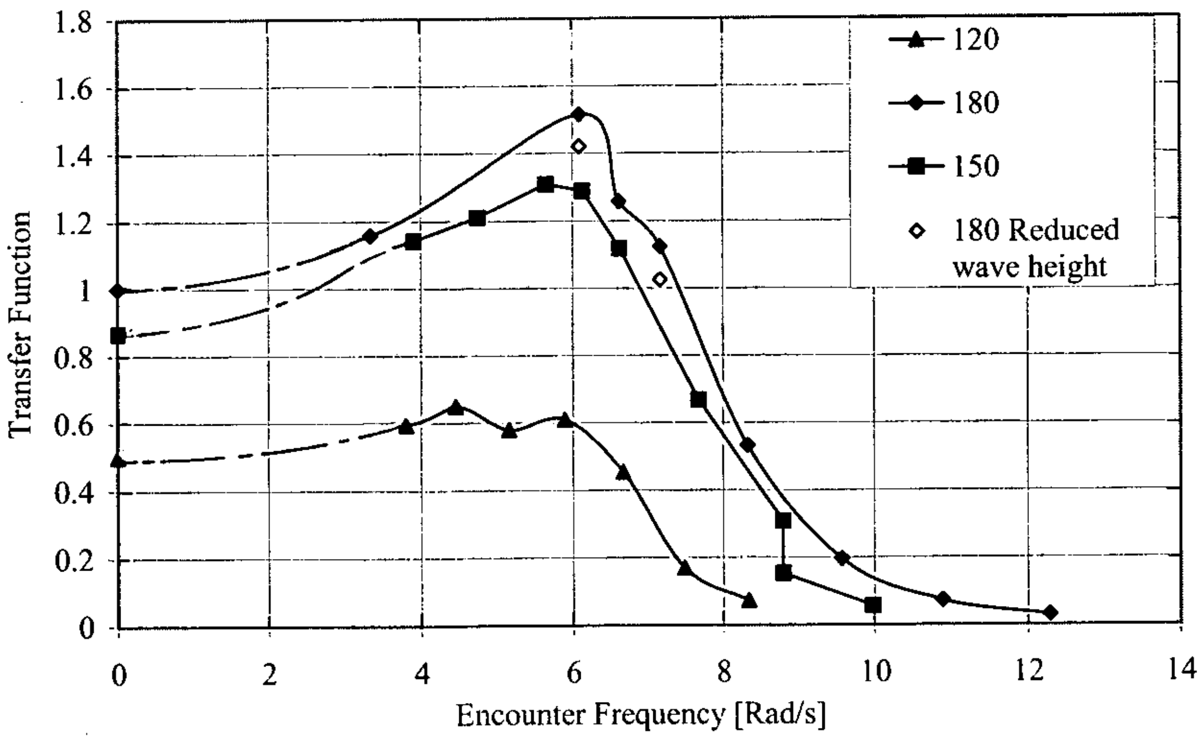


Fig 11: Model 5s Pitch S/L=0.4

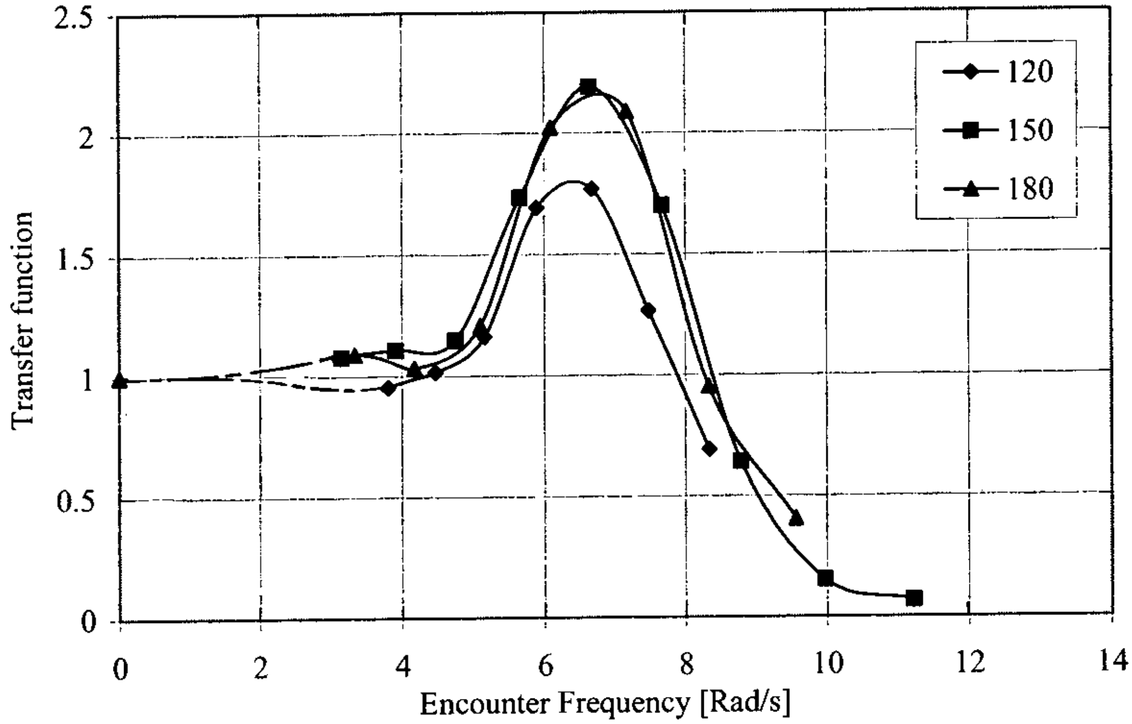


Fig 12: Model 5s Heave s/l=0.2

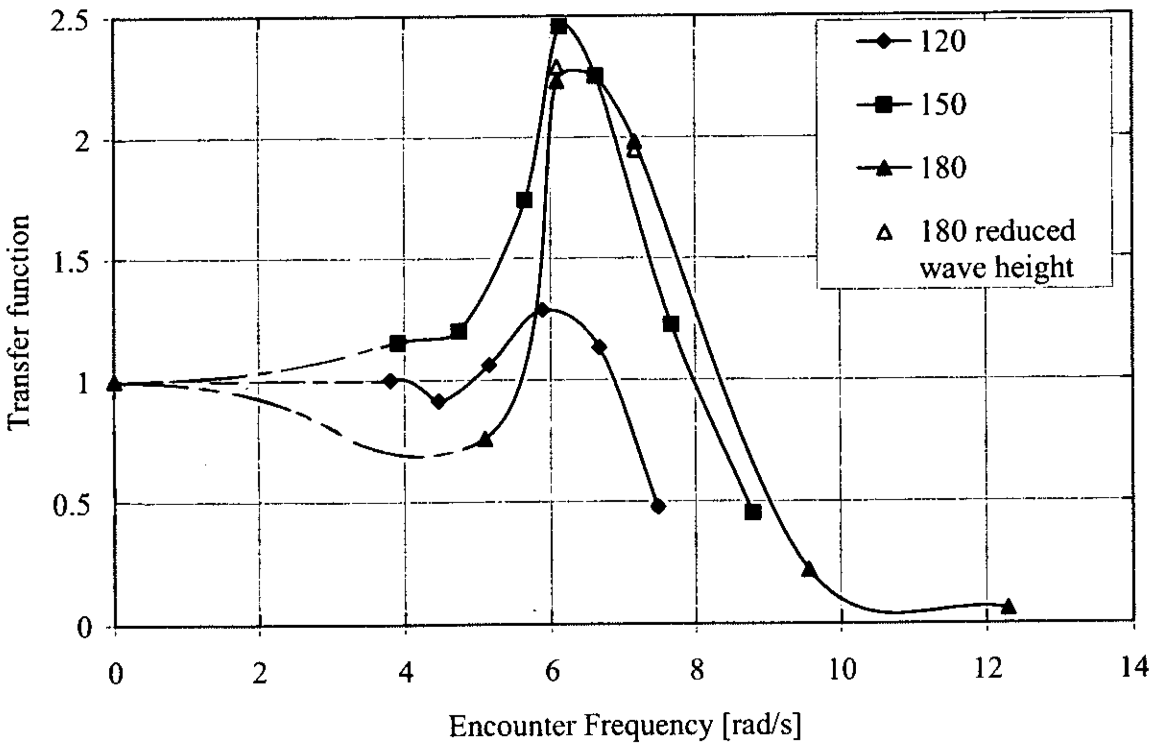


Fig 13: Model 5s Heave S/L=0.4

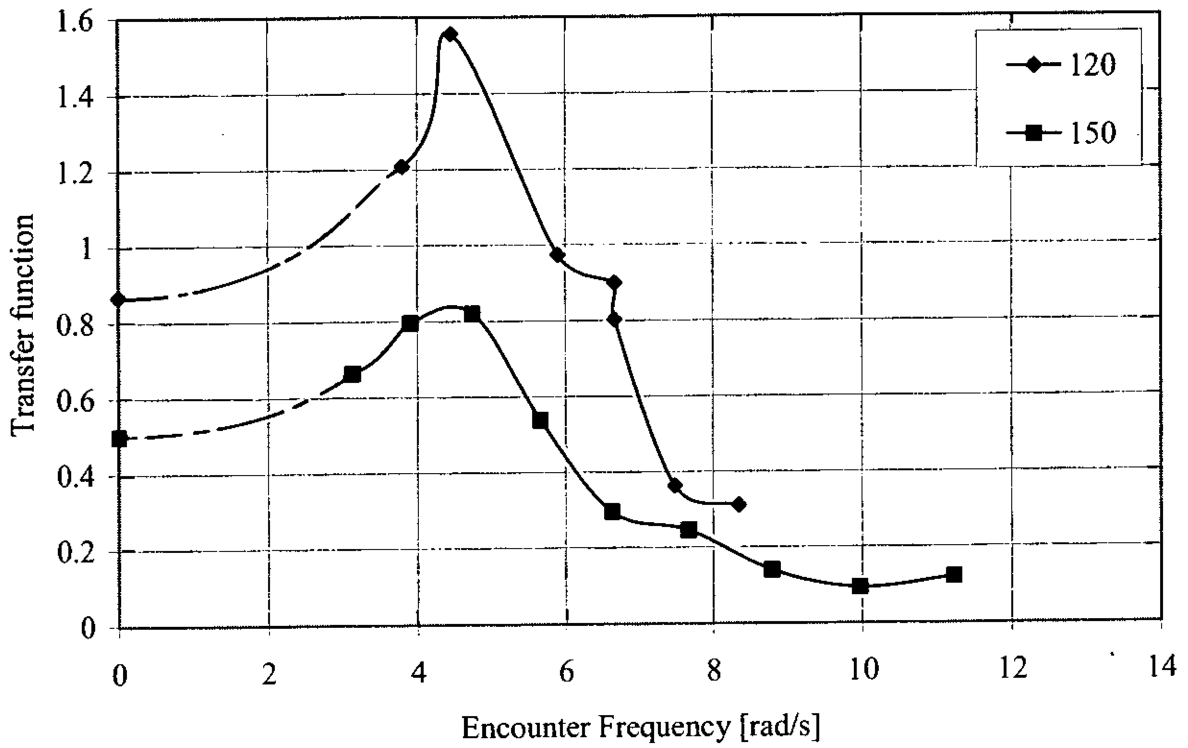


Fig 14: Model 5s Roll S/L=0.2

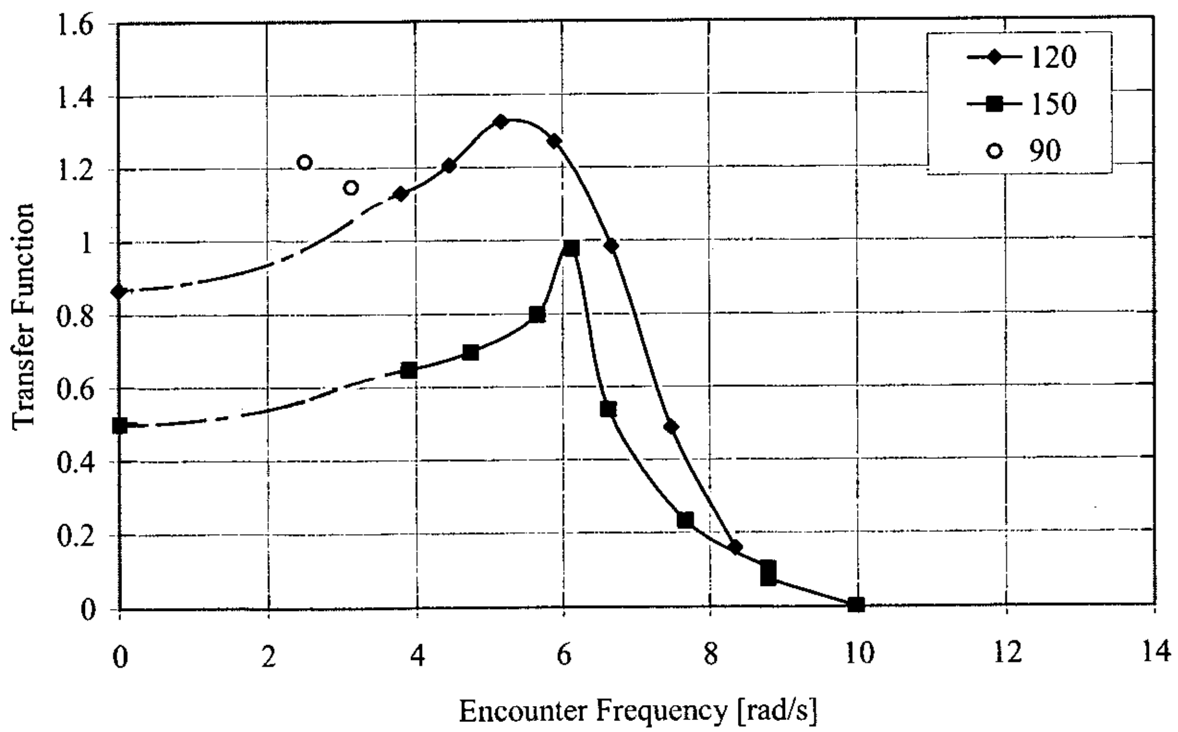


Fig 15: Model 5s Roll S/L=0.4

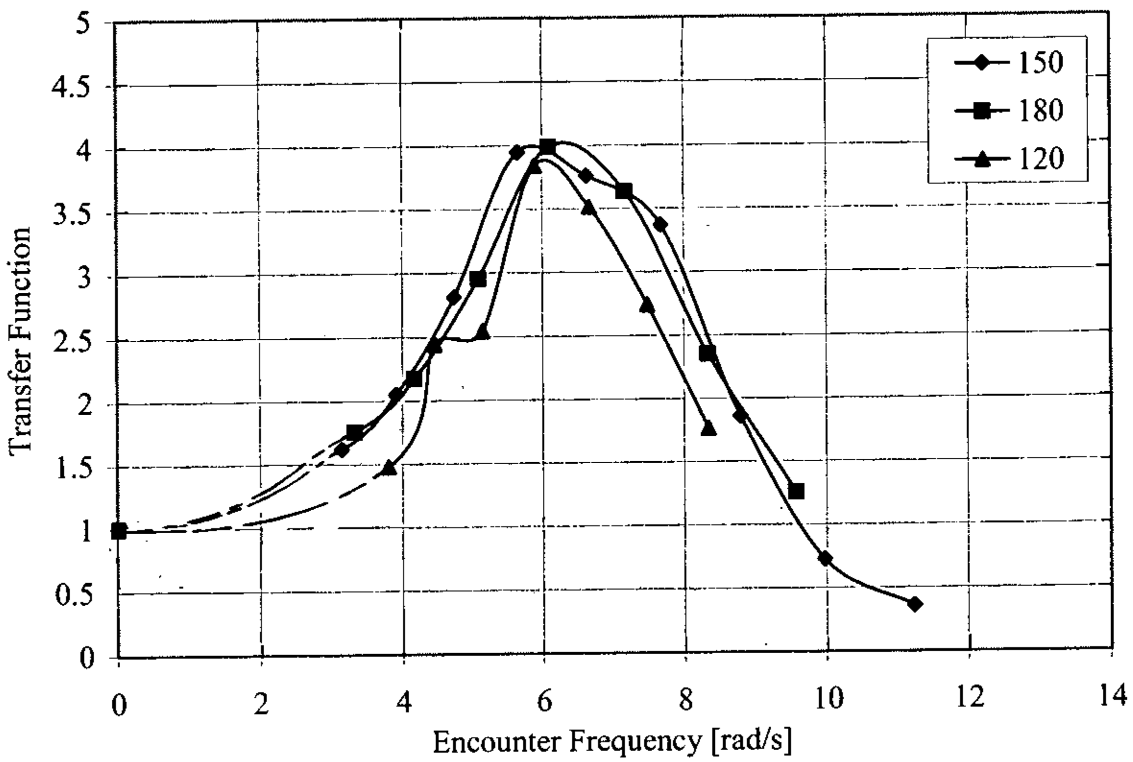


Fig 16: Model 5s FWD accelerations s/l=0.2

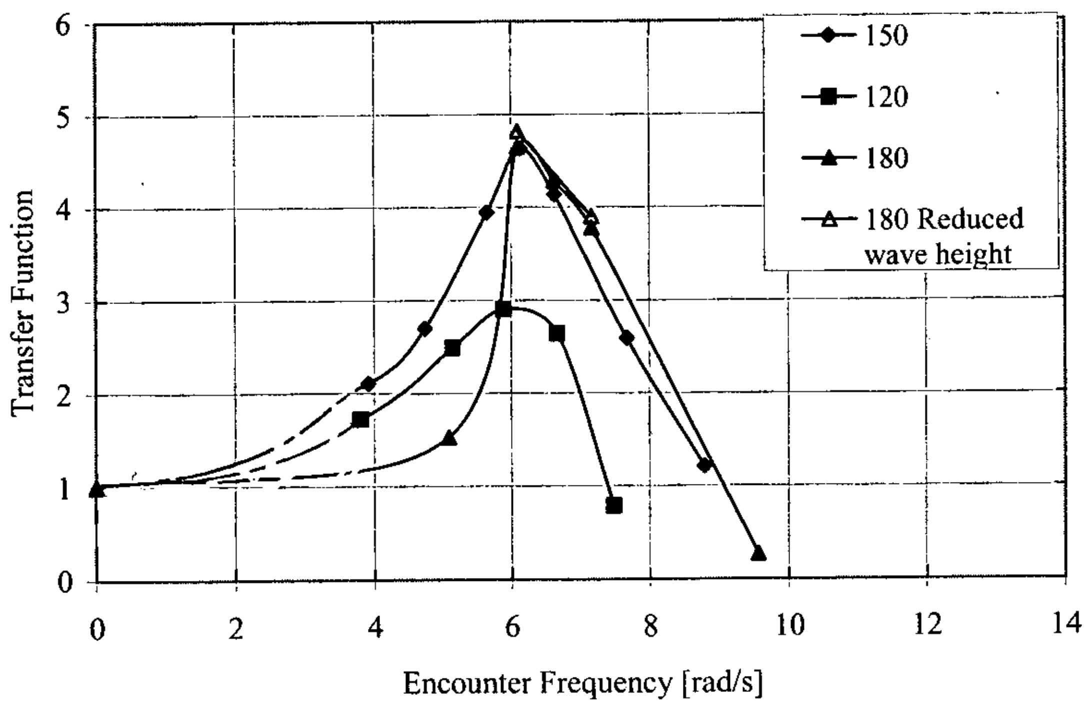
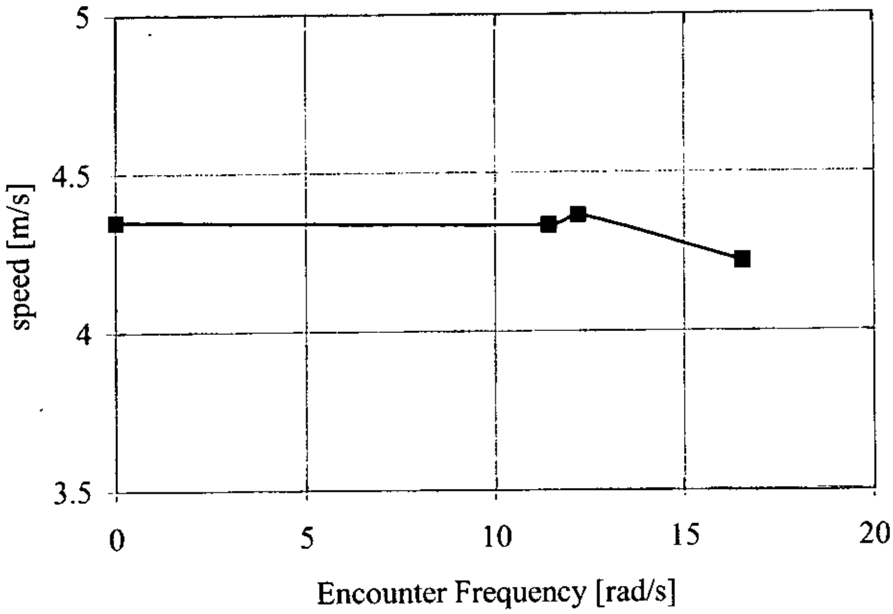
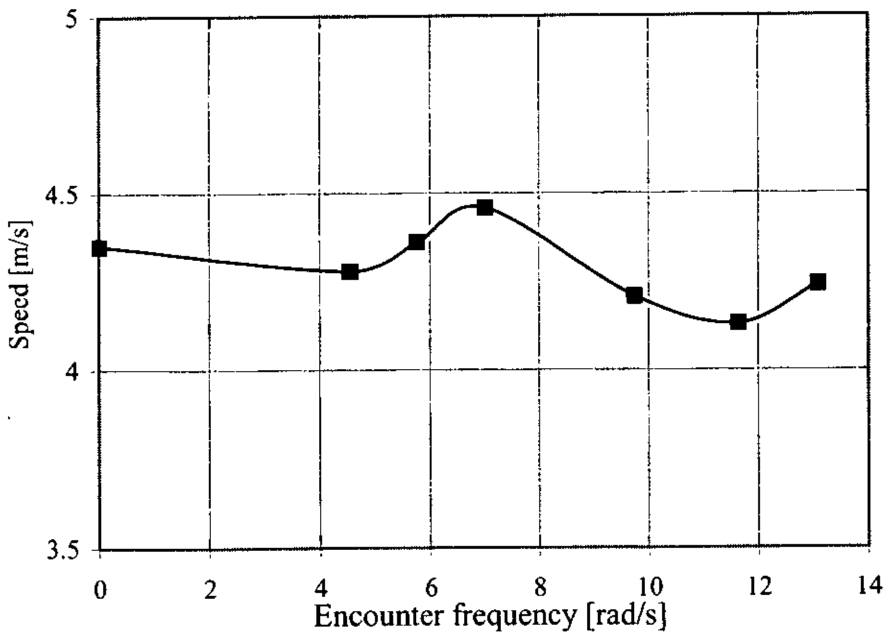


Fig 17: Model 5s FWD accelerations s/l=0.4

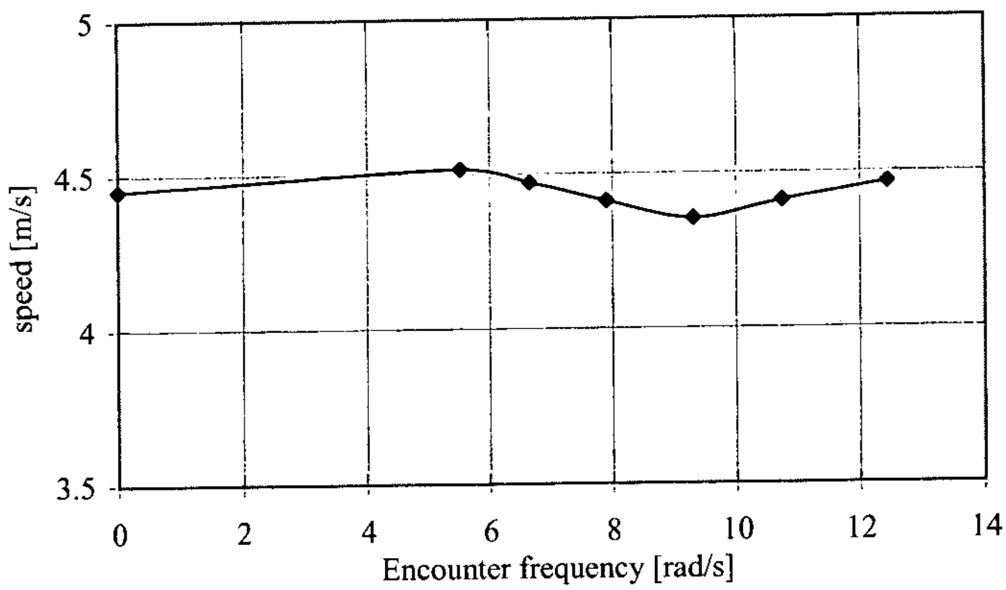


Speed loss with encounter frequency 5b S/L=0.2 150

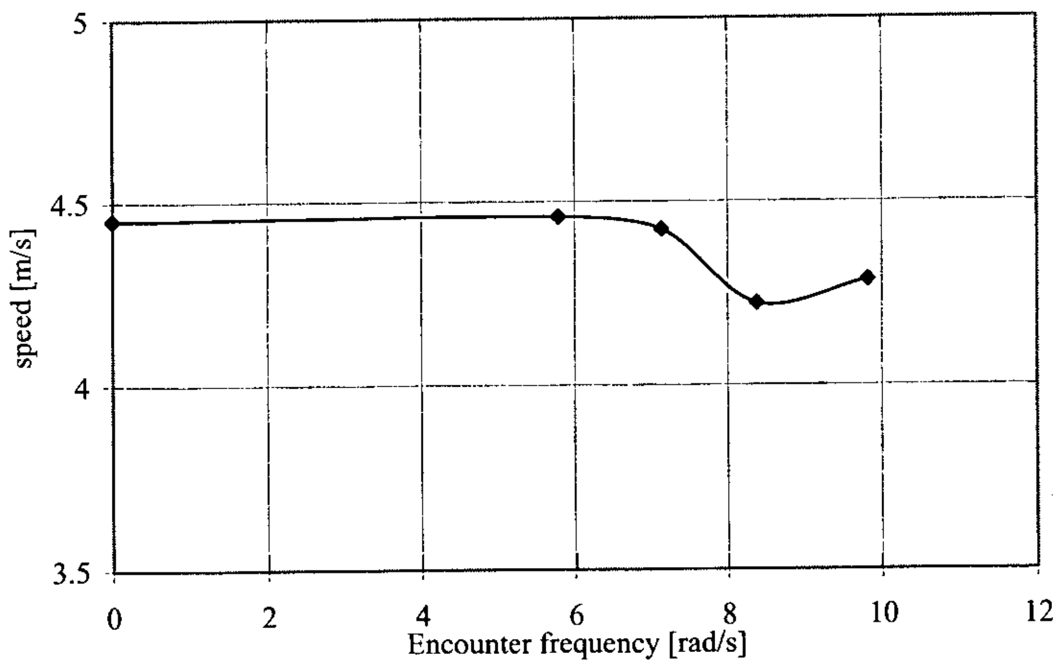


Speed loss with encounter frequency 5b S/L=0.2 180

Fig 18: Speed with encounter frequency 5b, S/L=0.2

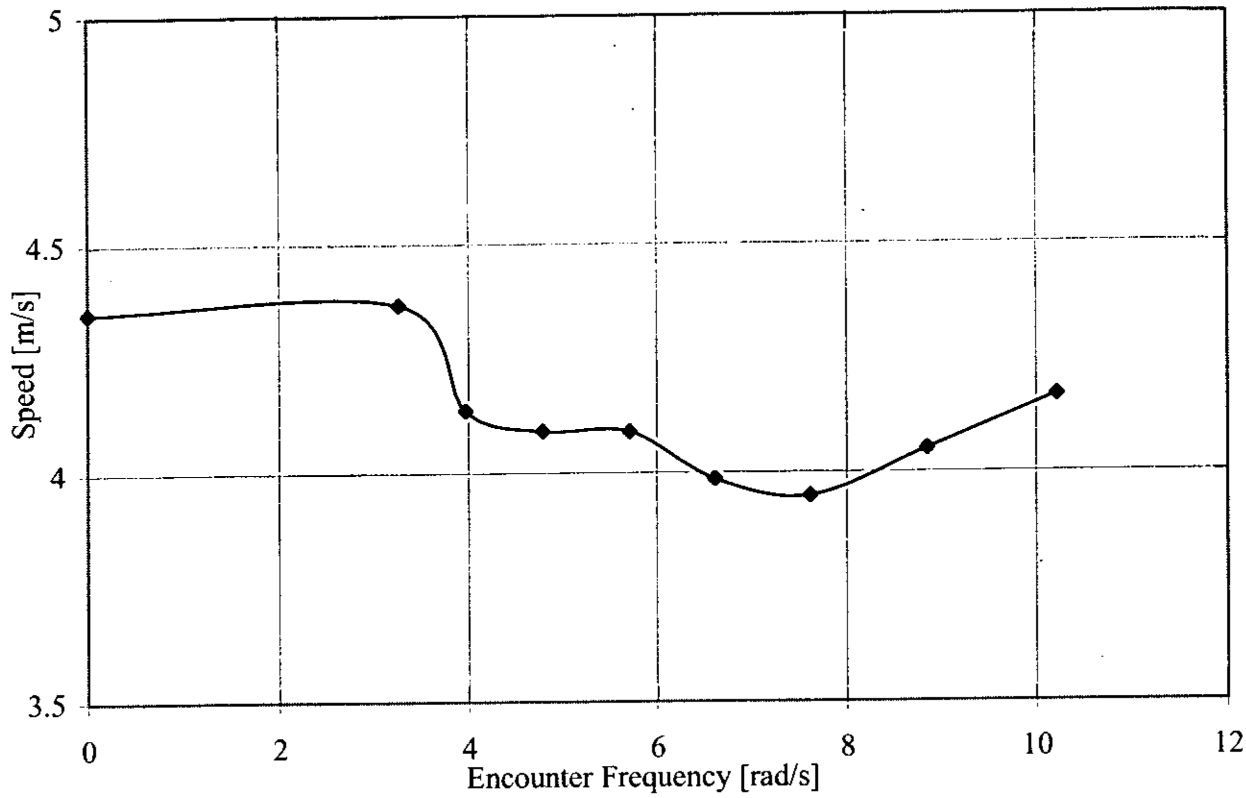


Speed loss with encounter frequency 5b S/L=0.4 150

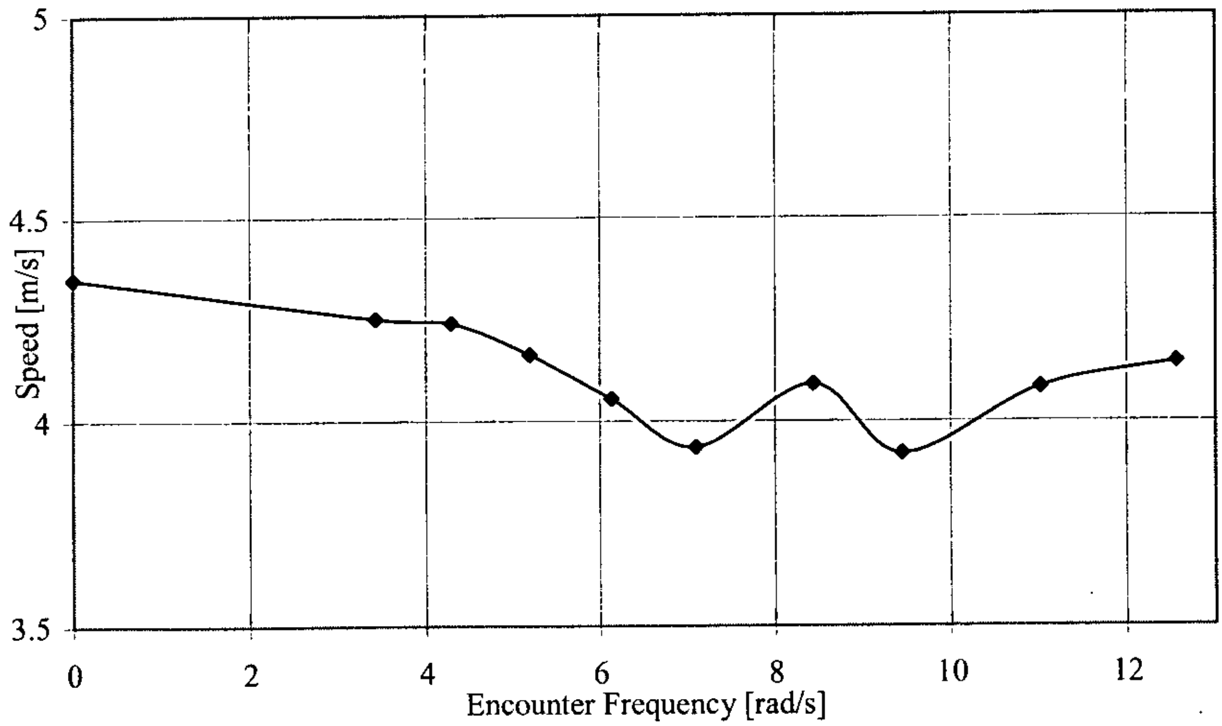


Speed loss with encounter frequency 5b S/L=0.4 180

Fig 19: Speed with encounter frequency 5b, S/L=0.4

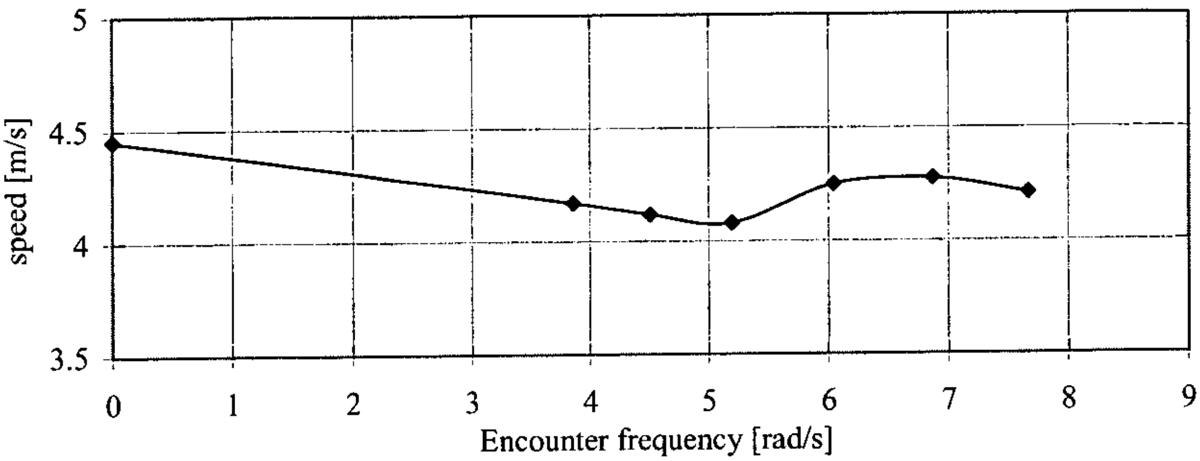


Speed loss with encounter frequency 5s S/L=0.2 150

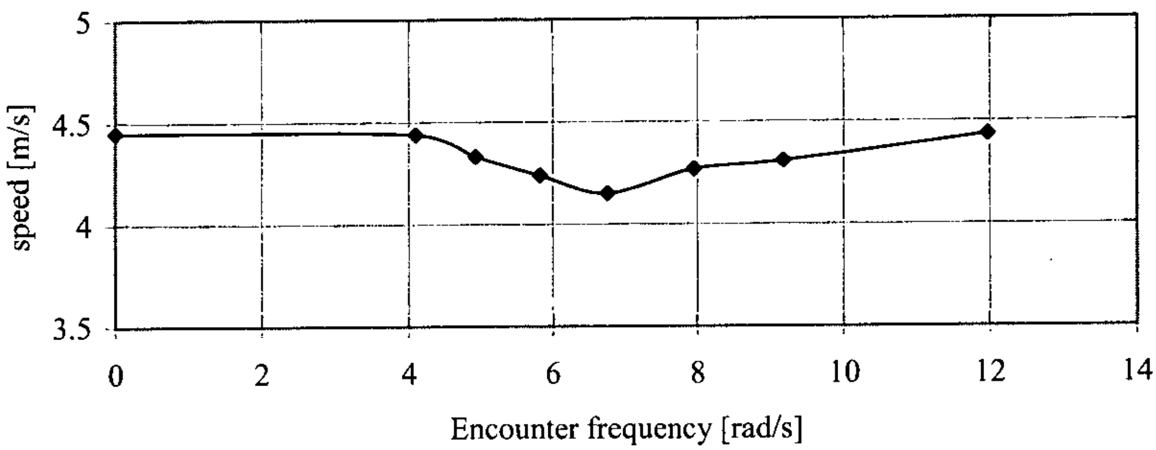


Speed loss with encounter frequency 5s S/L=0.2 180

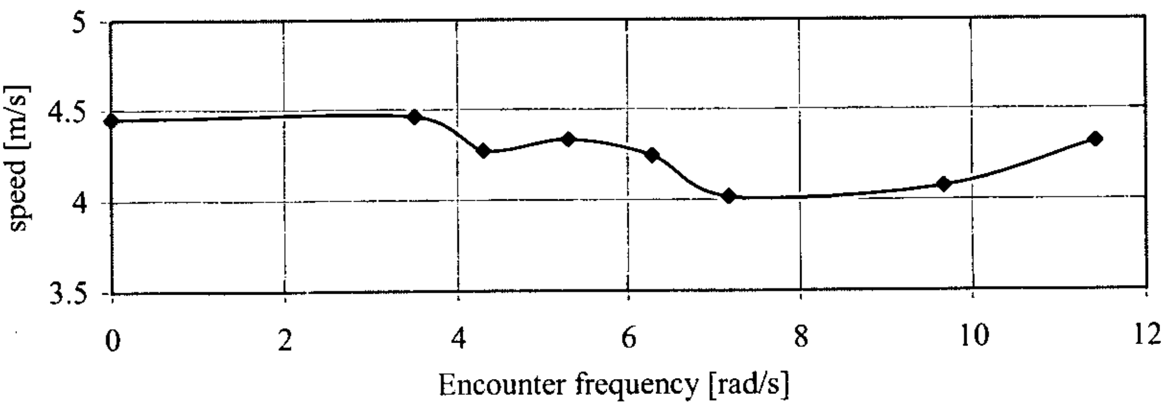
Fig 20: Speed with encounter frequency 5s, S/L=0.2



Speed loss with encounter frequency 5s S/L=0.4 120



Speed loss with encounter frequency 5s S/L=0.4 150



Speed loss with encounter frequency 5s S/L=0.4 180

Fig 21: Speed with encounter frequency 5s, S/L=0.4

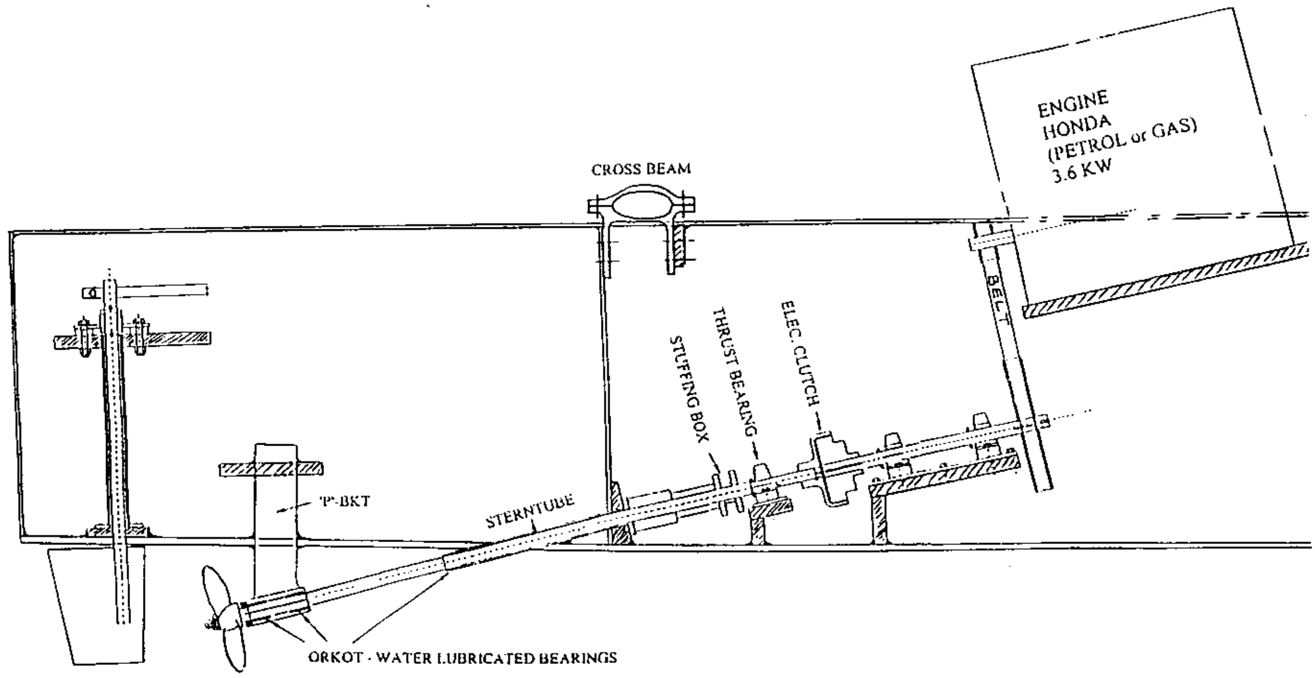


Fig 22: Outline of transmission and rudder arrangements.