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Motions, Resistance and Propulsion of a Ship in Regular Head Waves

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Summary

Extensive tests have been carried out at the Ship Hydromechanics Laboratory of the Delft University of Technology to measure motions, resistance and propulsion in longitudinal regular waves of a model of a fast cargo ship, m.s. S.A. van der Stel. The tests have been carried out for full load condition as well as for light load condition and the results of these experiments are compared with those of a theoretical approach. Gerritsma and Beukelman (1972) have published the first results of this research program. For the sake of completeness their results have been included here again.

1 Introduction

Gerritsma and Beukelman (1972) have introduced a new method to calculate the added resistance of a ship in longitudinal waves. They have assumed that added resistance varies linearly as the squared wave height at a constant wavelength and a constant forward speed. In their report the added resistance has been calculated by determining the radiated energy of the damping waves. In neglecting the surge motion, heave and pitch motions have been calculated by using the strip theory. Added mass and damping for the ship cross sections have been calculated by using a close-fit procedure to describe accurately the form of the cross sections. To support their theory, experiments have been carried out with a towed model of a fast cargo ship in full load condition. In regular longitudinal waves with varying wave amplitude, the frequency characteristics of heave and pitch motions and the average added resistance due to waves have been measured for different speeds. They have shown a satisfactory agreement between calculated and measured values.
In continuation of these tests, a measuring program has been set up with the aim of gaining more insight into motion, resistance and propulsion properties in waves of this ship in full load condition as well as in light load condition. Not only heave and pitch motions are observed now, but also the vertical motions of the fore part of the model, relative to the water surface, in order to determine the dynamical rise of the water surface near the bow. The measured heave and pitch characteristics and the average added resistance are compared with results of calculations like those used by Gerritsma and Beukelman (1972). These

calculations have been made with a computer program named TRIAL. An earlier version of this program has been described by Beukelman and Bijlsma (1976). Added mass and damping for the ship cross sections have now been calculated by using a Lewis conformal transformation.
Extensive propulsion tests have been carried out in still water as well as in regular waves with a self-propelled free-running model. These tests are similar to the tests carried out by Gerritsma, Van den Bosch and Beukelman (1961) with a model of a combined passenger and cargo ship. They have shown that the mean increase of thrust, torque and revolutions of the propeller, just like added resistance, for a constant speed and wavelength vary as the squared wave amplitude.

2 Specifications of Model and Experiments

Fast cargo ship m.s. "S.A. van der Stel" was designed for lifting and transporting cargo items in excess of 100 tons, with an additional accommodation for 12 passengers. The vessel was designed and built for South African Marine Corporation Ltd. in Cape Town, South Africa. She was launched at 26 February 1966 at Verolme Shipyards in Heusden, the Netherlands. The ship, with a length of 152.50 meter, has a service speed of 19.5 knots.

m.s. S.A. van der Stel

The experiments have been carried out with a model (1:50) of this vessel, of which two loading conditions have been considered: full load condition and light load condition. The main particulars of the model in both loading, conditions are given in Table I and Figure 2 shows the body plan of this model.
Four speeds are considered, Fn = 0.15, 0.20, 0.25 and 0.30, while the service speed of the ship corresponds with Fn = 0.26. The model and wave conditions are shown in Table II and Table III. Figure 3 shows a schematic diagram of the measuring system. The regular waves have been measured by means of a two-wire conductive wave probe at a distance of about 3.50 m in front of the centre of gravity of the model. Heave and pitch motions have been measured by two low-friction potentiometers above and at the centre of gravity. Wave amplitude and heave and pitch characteristics have been obtained by a phase locked loop servo system; see Buitenhek and Ooms (1976). At Station 20 in full load condition and Station 18 in light load condition the vertical absolute and relative motions have been

measured too. A low-friction potentiometer and the relative motion have measured the absolute motion by a conductive wave probe, consisting of two NACA-profiles fixed on both sides of the model. An ultra-violet recorder has recorded both motions. In full load condition the mean resistance in still water as well as in regular waves has been measured by means of a towing force caused by known dead weights. In light load condition this towing force has been generated by a torque motor (see Figure 2) and measured by means of a strain gauge dynamometer of which the output has been Integrated over a certain time or a full number of wave periods.

Propulsion tests have been carried out in still water and regular waves, while overload tests in still water have been carried out too. In the propulsion tests the number of revolutions of the propeller has been kept constant by electronically control and therefore the rpm are not affected by cyclic load variations due to wave action. Thrust and torque have been measured by means of strain gauge dynamometers of which a mean value can be found by integrating the output of the dynamometers. In the overload tests in still water the propeller loading can increase by a towing force backwards on the model caused by dead weights. The rpm of the propeller and the model speed have been measured with the aid of phototransistors and electronic counters.

3 Analysis and Presentation of the Test Results

The discussion of the test results has been divided into parts: vertical motions and resistance in regular waves and propulsion in still water and regular waves. The vertical motions are divided into heave and pitch motions and relative motions forwards. The theoretical foundations of these phenomena have been presented by Gerritsma and Beukelman (1972) and Gerritsma et. al. (1961) and are not discussed again here.

3.1 Heave and Pitch Motions

For a range of wave length - ship length ratios, as summarised in Table III, the measured heave and pitch amplitudes in relation to the wave amplitudes are given in Figures 4, 5, 8 and 9 for both loading conditions and four Froude numbers. The experiments show the good linearity of the motions, even in cases of extreme shipping of water on the fore deck and emerging of the fore foot from the water. No significant differences appear in the measured motion amplitudes between the self-propelled model and the towed model without freedom to surge in the full load condition and with freedom to surge in the ballast condition.

In the same way the measured phase lag between heave and pitch motions and wave motions are presented in Figures 6, 7, 10 and 11. The experiments show that the phase lag is not depending on the wave amplitude. No difference has been measured between a self-propelled and a towed model.

In Figures 12, 13 and 14 the mean non-dimensional heave and pitch amplitudes obtained by least square method and the mean phase differences are compared with theoretical values calculated by the program TRIAL, mentioned before. The predicted resonance values of the heave amplitude in Figure 12 are too high. For ship length to wavelength ratios above 1.0 there is a fair agreement between calculation and experiment. Good agreement is shown in Figures 13 and 14 for the pitch amplitude as well as for the phase lag of both motions, with respect to the wave motion at G.

3.2 Absolute and relative motions forward

At Station 20 in full load condition and Station 18 in ballast condition, the sinkage of the model due to the speed has been measured in still water. This is shown in Figures 16 and 17 and will be discussed later.
The bow waves generated by the model running in still water and sinkage of the model cause a static swell-up, which decreases the geometrical freeboard to an effective freeboard. Figure 15 shows the relative displacements at the Stations mentioned before, obtained in two ways. The wave pattern against the hull has been obtained photographically and the static swell-up has been measured from these pictures. On the other hand the relative displacement has been measured electronically by a conductive wave probe on a little distance from the hull.
Tasaki (1963) gives an empirical formula to estimate the static swell-up at the bow:

$$\Delta f = 0.75 \cdot B \cdot \frac{L}{L_e} \cdot Fn^2$$

in which:

L	Length of the waterline
B	Breadth
L_e	Entrance length on the water plane
Fn	Froude number

For the static swell-up measured at the top of the bow wave between Station 19 and 20 there is a good agreement between Tasaki's formula and the measurements.
In order to examine whether absolute and relative motions in regular waves are symmetric or asymmetric with respect to the still water value the maximum and minimum values of these motions in regular waves are measured too. Figure 16 and 17 show these measurements plotted on a base of wave amplitudes.
The amplitudes of these motions are also calculated from the measured heave, pitch and wave motions:

$$V_{x_b} = z - x_b \cdot q$$

$$S_{x_b} = z_{x_b} - z + x_b \cdot q$$

in which V_{x_b} is the vertical absolute motion and S_{x_b} is the vertical relative motion; for the other symbols: see Figure 1.

In Figures 18 and 19 the derivatives of the measured extreme values in Figures 16 and 17 to the wave amplitude, obtained by the least squares method, are plotted against these calculated non-dimensional amplitudes of the motions. For the absolute motions the plotted values are situated on a 45 degrees line. These motions are symmetric with respect to the still water value because the mean values are zero. The measuring systems for heave and pitch motions and absolute motions are independent, so the Figures also underline the reliability of the measuring system. Figure 20 shows the fair agreement between the calculated and measured amplitudes of the absolute motions. For the relative motions the plotted values in Figures 18 and 19 are not situated on a 45 degrees line. The amplitude of the measured relative motion is increased by a dynamical swell-up. When the bow immerses the water surface will rise and when it emerges the water surface will fall.

In Figure 21 the measured dynamic swell-up is shown in percentages of the relative motion calculated from the heave, pitch and wave motion.
Tasaki (1963) carried out forced oscillation tests with a towed ship model in still water to measure the relative displacement of the water surface to the bow of the model. From the results of these experiments he obtained an empirical formula to estimate the dynamical swell-up at the bow:

$$\frac{\Delta S_a}{S_a} = \frac{C_b - 0.45}{3} \cdot \sqrt{\frac{L}{g}} \cdot w_e$$

with as restriction for the block coefficient:

$$0.60 < C_b < 0.80 .$$

This formula shows a linear relation between dynamic swell-up and the frequency of encounter, which is not proved by these experiments. The estimated dynamical swell-up can not be compared with the experiments, because the block coefficient of the model is 0.564.
As shown in Figure 21 there is a remarkable difference in dynamic swell-up at Station 20 and at Station 18. Van Sluys and Tan (1972) have showed this too for two models of compact frigates.
More investigations will be necessary to estimate a good value for the dynamical swell-up.

3.3 Added Resistance in Regular Waves

The added resistance in regular waves is determined by subtracting the still water resistance from the measured total resistance at the speed concerned.
By Gerritsma and Beukelman (1972), the assumption is discussed that added resistance varies as the squared wave amplitude. Figures 22 and 23 show the added resistance as a function of the squared wave amplitude. Except in cases of extreme unrealistic motions at resonance, conditions in high regular waves a very good linearity is shown here. Figure 22 shows too that the influence of surge on added resistance in head waves is negligible. In Figure 24 the non-dimensional values of the measured added resistance are compared with calculations, carried out in away as has been done by Gerritsma and Beukelman.
In full load condition there is a very good agreement, except in short waves at higher speeds where the diffraction resistance is underestimated. In ballast condition the calculated peak values are somewhat larger than the measurements.

3.4 Propulsion in Still Water and Regular Waves

Propulsion tests and overload tests have been carried out in still water with the self-propelled model. The measured rpm, thrust and torque are shown in Figures 25, 26 and 27 on a base of the sum of still water resistance at the speed concerned and overload force.
Propulsion tests with a free-running model have also been carried out in regular waves at different wavelengths and wave heights. During these tests, the rpm has been kept constant by electronically control. The measured thrust and torque of the propeller are mean values over a large number of wave periods. As shown in Figures 25, 26 and 27 there are no significant differences between these measurements and overload tests in still water even in

cases of extreme emerging of the propeller. This means that the propulsive efficiency is the same in both cases. In the near future a separate report on this subject will be published.
As shown before, added resistance varies as the squared wave amplitude. The Figures show the linearity between added rpm, thrust and torque and added resistance. So the added rpm, added thrust and added torque vary also as the squared wave amplitude.

4 Conclusions

From the analysis of the experiments and calculations the following conclusions may be drawn:

1. The influence of surge and propulsion on the vertical motions and added resistance in regular waves may be neglected.
2. At a constant wave length and a constant forward speed it is shown that:
   - Heave and pitch motions and absolute and relative motions forward vary linearly as the wave amplitude, even in extreme wave conditions.
   - Phase differences between heave and pitch motions and wave motions are constant for varying wave amplitudes.
   - Added resistance varies quadratic with the wave amplitude.
   - Added rpm, thrust and torque vary quadratic with the wave amplitude.
3. The calculated heave and pitch characteristics and added resistance are in good agreement with the measurements, although the calculated heave amplitude in the range of resonance and the peak values of the added resistance in the ballast condition are somewhat too high.
4. For calculating shipping water and slamming phenomena more attention must be paid to the static and dynamical swell-up.
5. The propulsive efficiency is not influenced by the wave motion but only by a decreasing propeller loading.

5 Acknowledgements

The author wishes to thank prof. ir. J. Gerritsma and Mr. W. Beukelman for the attention paid to the following-up of their experiments.
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Last but not least the preparation of all the graphs by Mr. P.W. de Heer is gratefully acknowledged.

6 References

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W. Beukelman and E.F. Bijlsma, *Description of a Program to Calculate the Behaviour of a Ship in a Seaway (named TRIAL)*, Report 383-M, Delft Ship Hydromechanics Laboratory, 1973.

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7 Tables

		Full Load Condition	Ballast Condition
L_{pp}	m	3.050	3.050
B	m	0.456	0.456
T at even keel	m	0.183	0.104
∇	m^3	0.1434	0.0725
C_b		0.564	0.503
L_{CB}/L_{pp}	%	-1.10	+0.39
k_{yy}/L_{pp}	%	21.88	26.04

Model Scale: 1:50

Table 1 Main Particulars of the Model

	Towed Model without Freedom for Surge	Towed Model with Freedom for Surge	Self-Propelled Model
Motions	F	B	F B
Added Resistance	F	F B	

F means: Tests have been carried out for full load condition.
B means: Tests have been carried out for ballast condition.
The propulsion tests have been carried out with a self-propelled model.

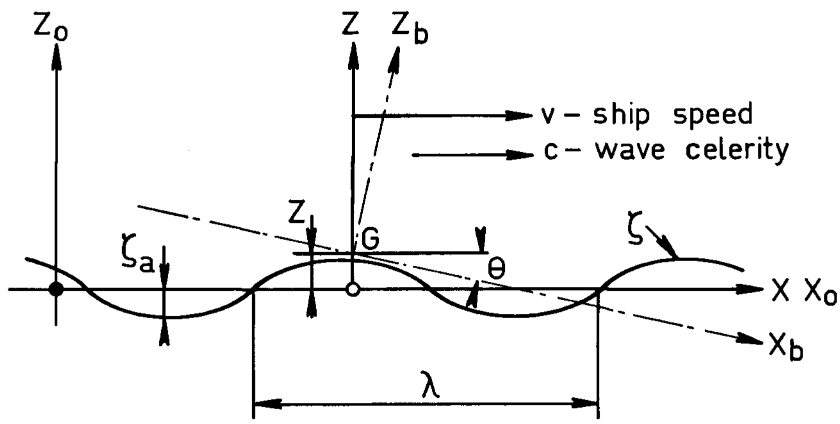
Table 2 Model Conditions

z_w/L_{pp} l/L_{pp}	1/50	1/40	1/30
0.60	*		
0.80	*	*	*
1.00	*	*	*
1.20	*	8	*
1.40	*	*	*
1.60	*		
1.95	*		

* means: Tests are carried out for 4 Froude numbers: 0.15, 0.20, 0.25 and 0.30.
For $Fn = 0.15$ only wave height $z_w/L_{pp} = 1/50$ has been considered.

Table 3 Wave Conditions

8 Figures



wave – $\zeta = \zeta_a \cos(k x_o \cos\mu - \omega t)$ in $x_o \; y_o \; z_o$

$\zeta = \zeta_a \cos(\omega_e t)$ in $x \; y \; z$, $x=0$

heave – $z = z_a \cos(\omega_e t + \varepsilon_{z\zeta})$

pitch – $\theta = \theta_a \cos(\omega_e t + \varepsilon_{\theta\zeta})$

$$\omega_e = \omega - \frac{\omega^2}{g} V \cos\mu$$

Figure 1 Symbols and Definitions

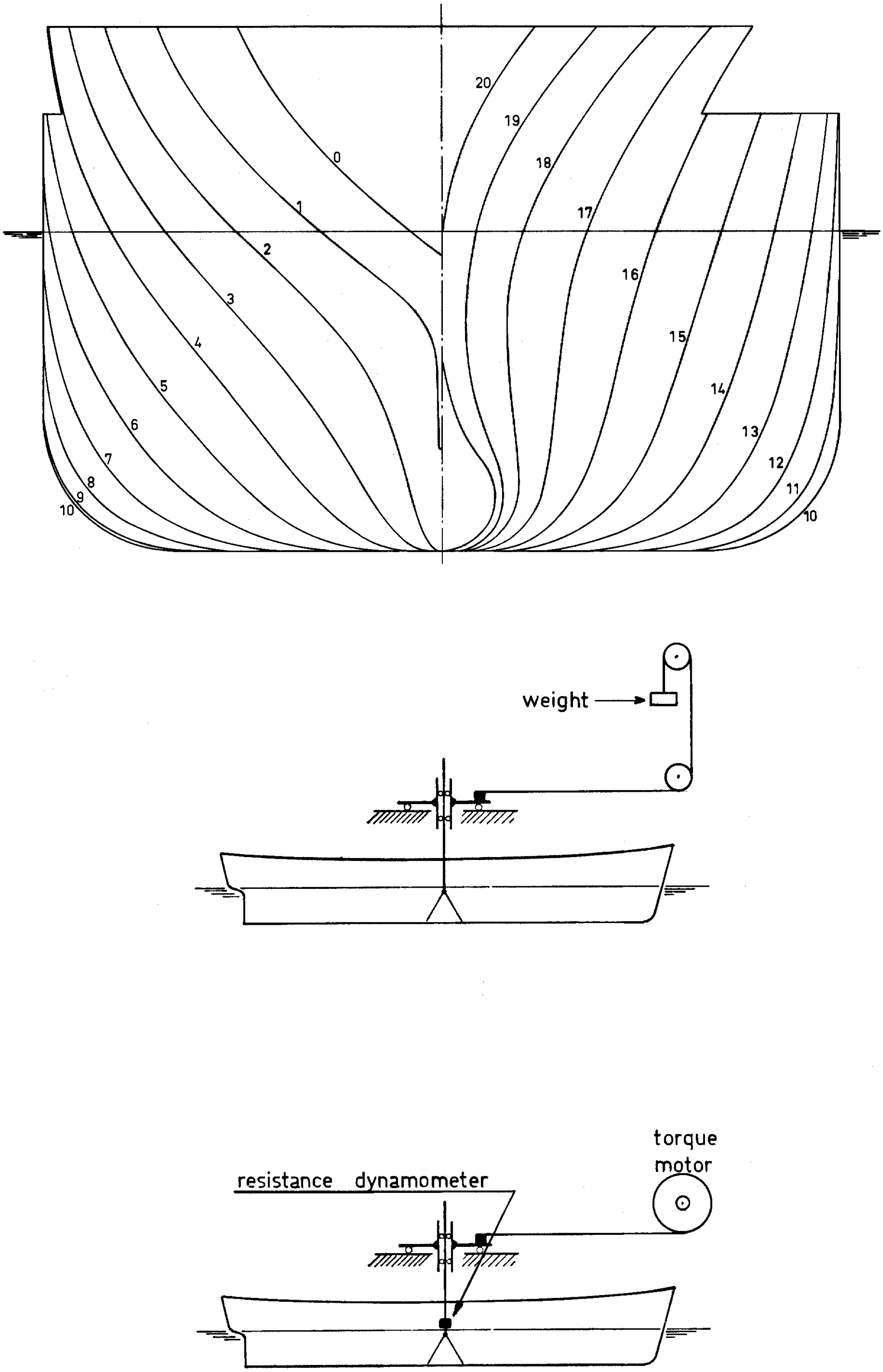
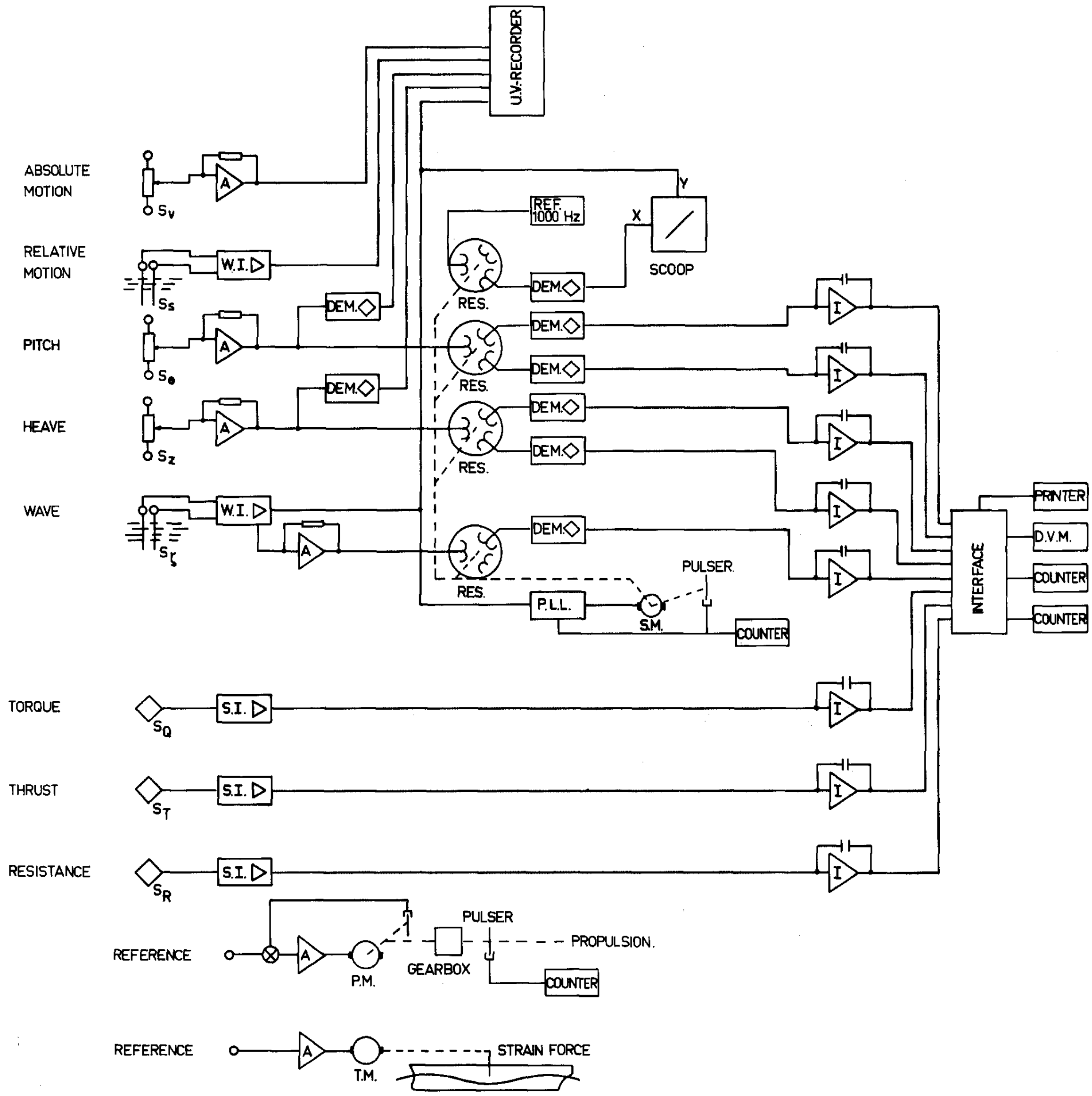


Figure 2 Body Plan and Arrangement for Resistance Tests



SENSORS:

S_{pp}: PIEZOELECTRIC PRESSURE TRANSDUCER
S_{ps}: SEMICONDUCTOR PRESSURE TRANSDUCER
S_v : POTENTIOMETER DISPLACEMENT TRANSDUCER
S_s : CONDUCTANCE WAVE HEIGHT TRANSDUCER
S_Q : TORQUE
S_T : THRUST
S_R : RESISTANCE DYNAMOMETER.

W.I. : WAVE INDICATOR.
DEM. : DEMODULATOR.
S.I. : STRAINGAGE INDICATOR.
REF. : REFERENCE SOURCE.
RES. : RESOLVER.
P.L.L. : PHASE LOCKED LOOP SYSTEM.
T.M. : TORQUE MOTOR.
S.M. : STEPPER MOTOR.
P.M. : PROPULSION MOTOR.
I : INTEGRATOR
A : AMPLIFLIER.
D.V.M. : DIGITAL VOLTMETER.

Figure 3 Scheme of Measuring System

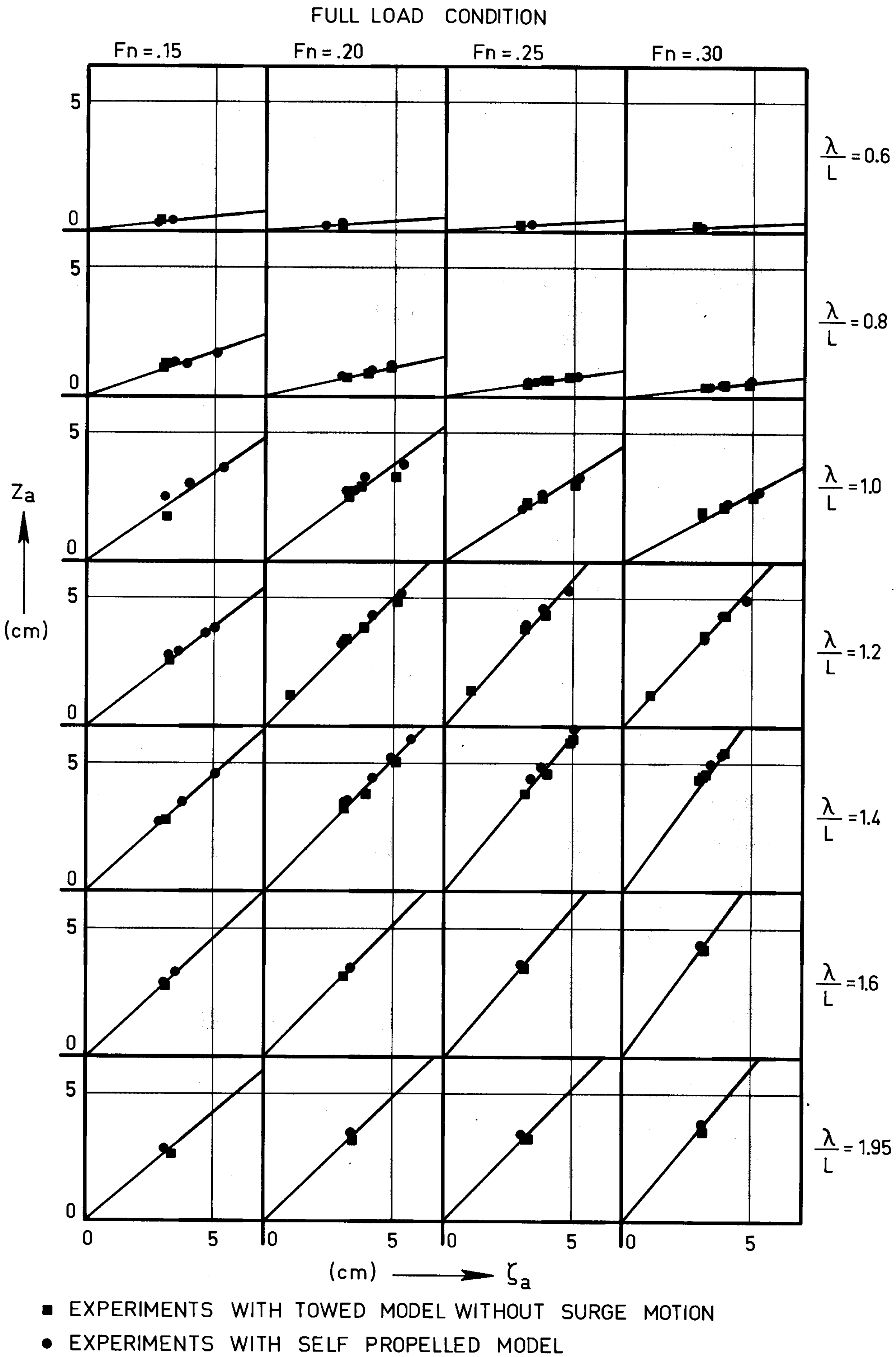


Figure 4 Relation between Heave and wave Amplitude
(Full Load Condition)

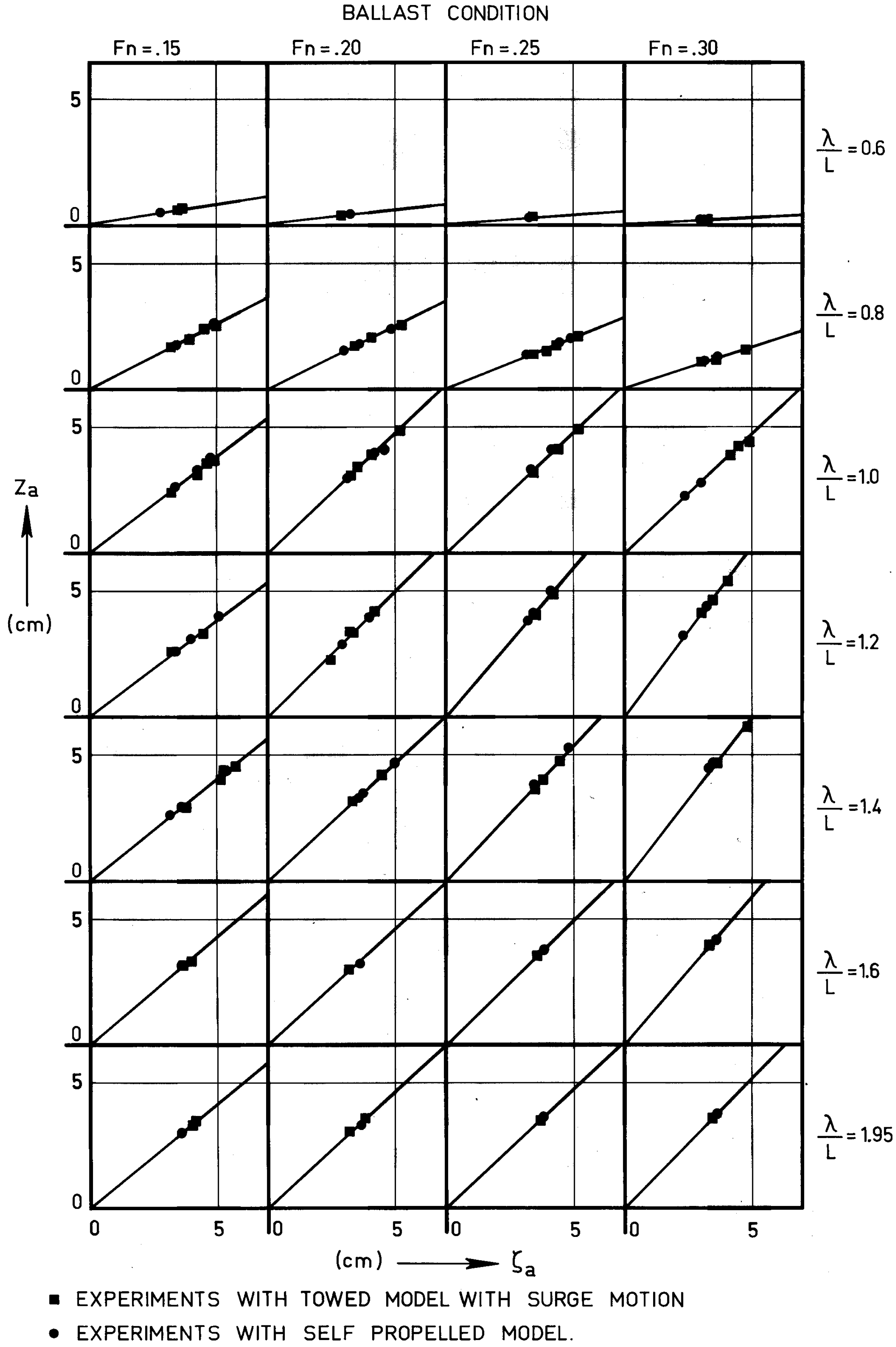


Figure 5 Relation between Heave and Wave Amplitude
(Ballast Condition)

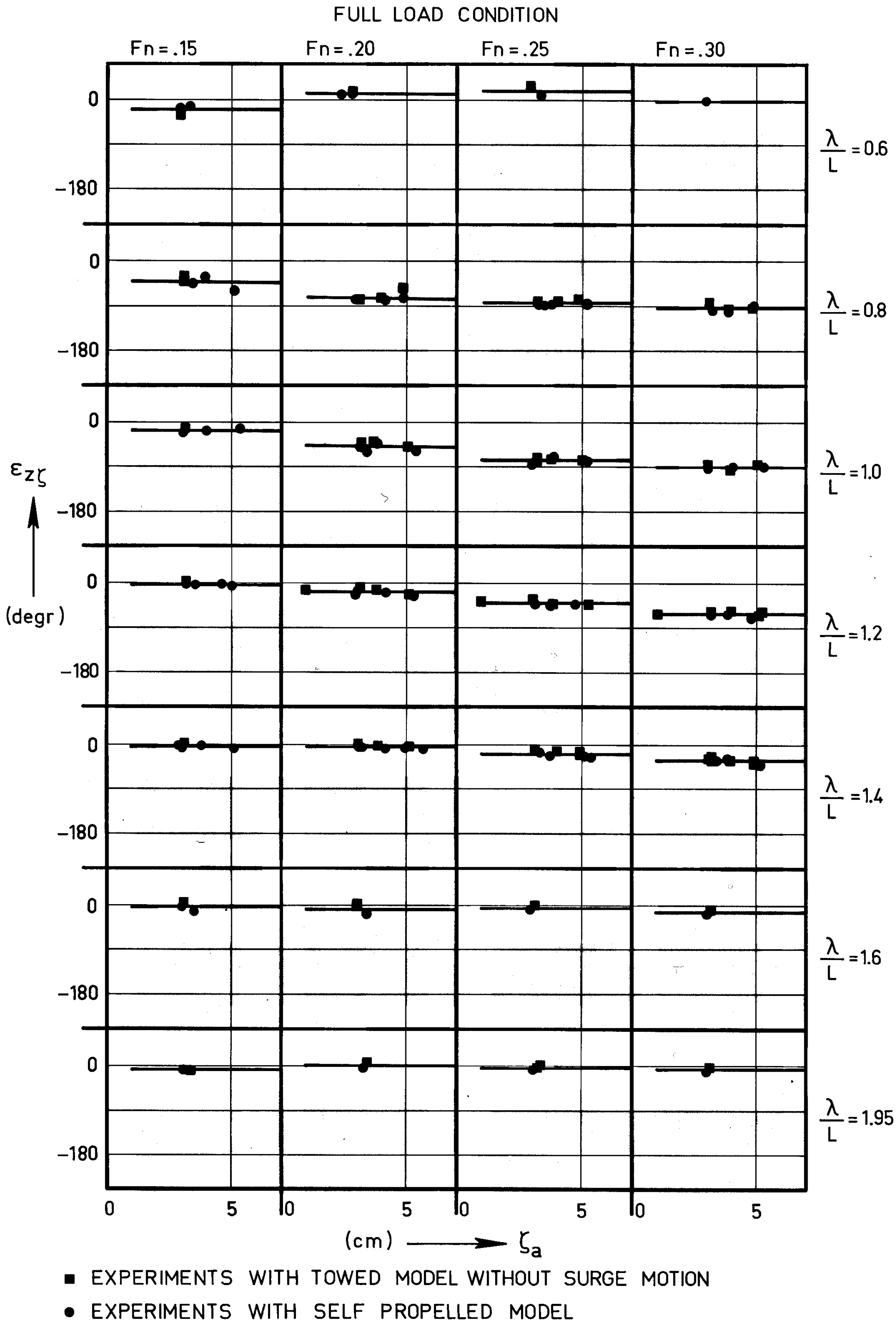


Figure 6 Relation between Phase Lag of Heave and Wave and Wave Amplitude
(Full Load Condition)

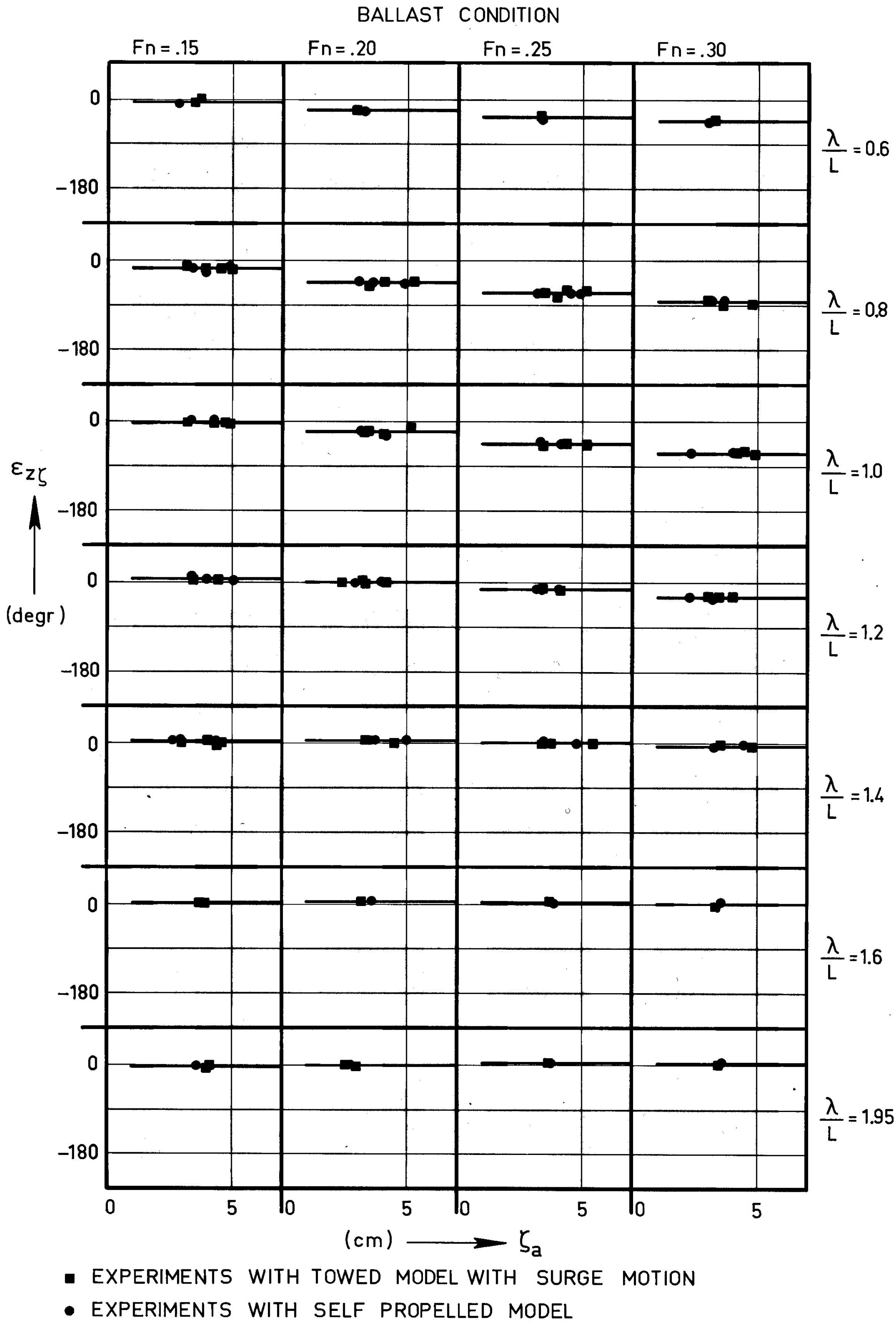


Figure 7 Relation between Phase Lag of Heave and Wave and Wave Amplitude (Ballast Condition)

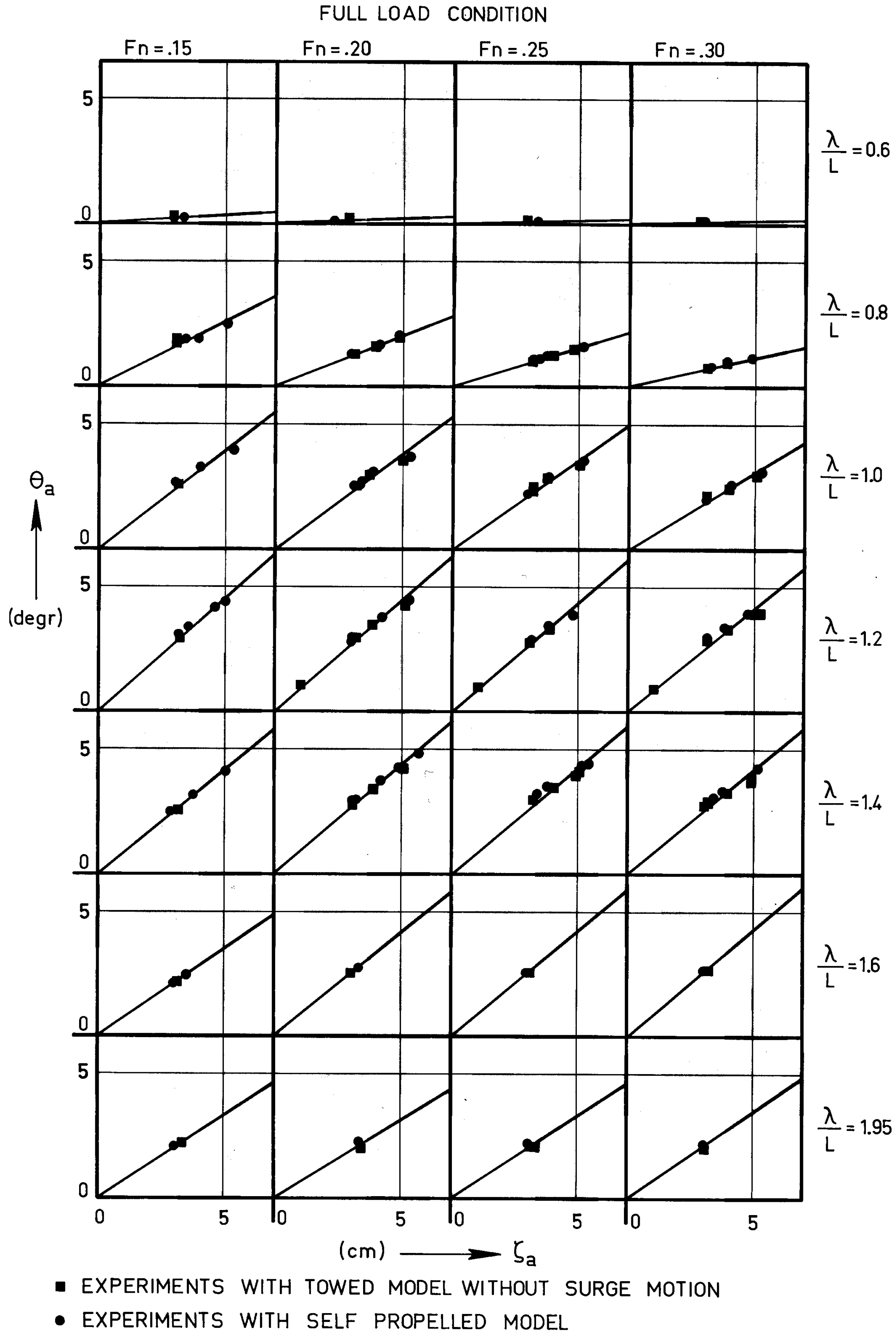


Figure 8 Relation between Pitch and Wave Amplitude
(Full Load Condition)

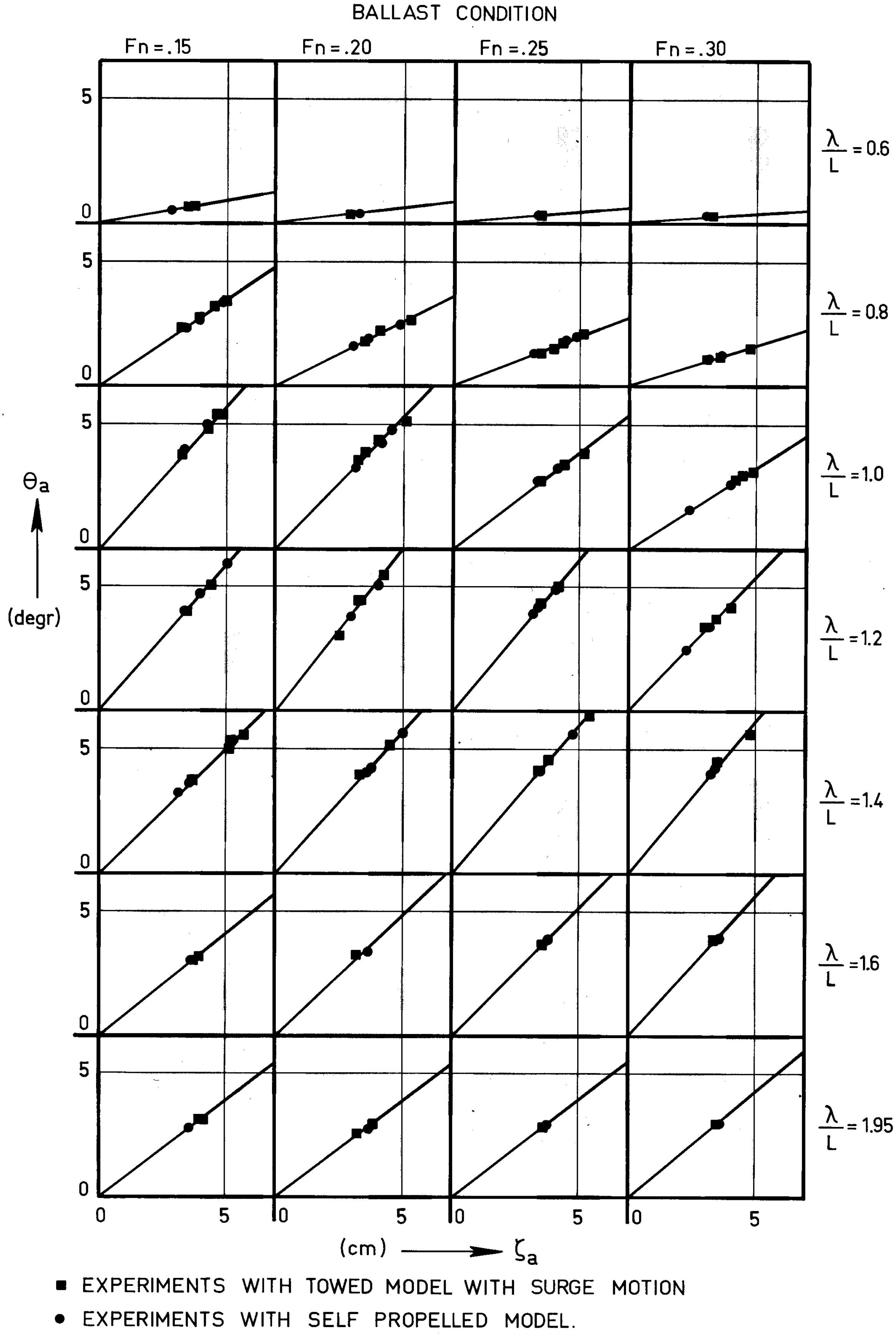


Figure 9 Relation between Pitch and Wave Amplitude
(Ballast Condition)

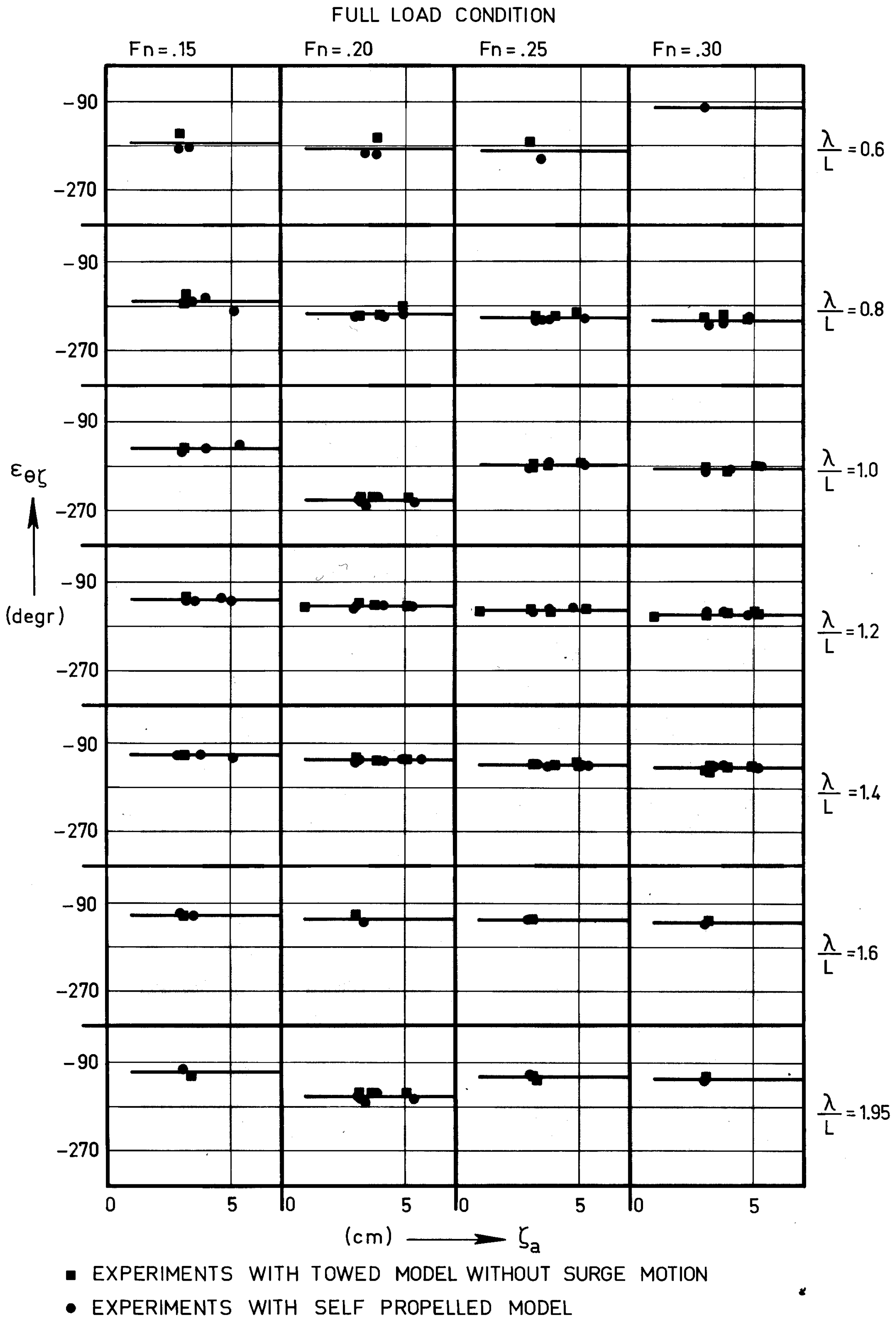


Figure 10 Relation between Phase Lag of Pitch and Wave and Wave Amplitude
(Full Load Condition)

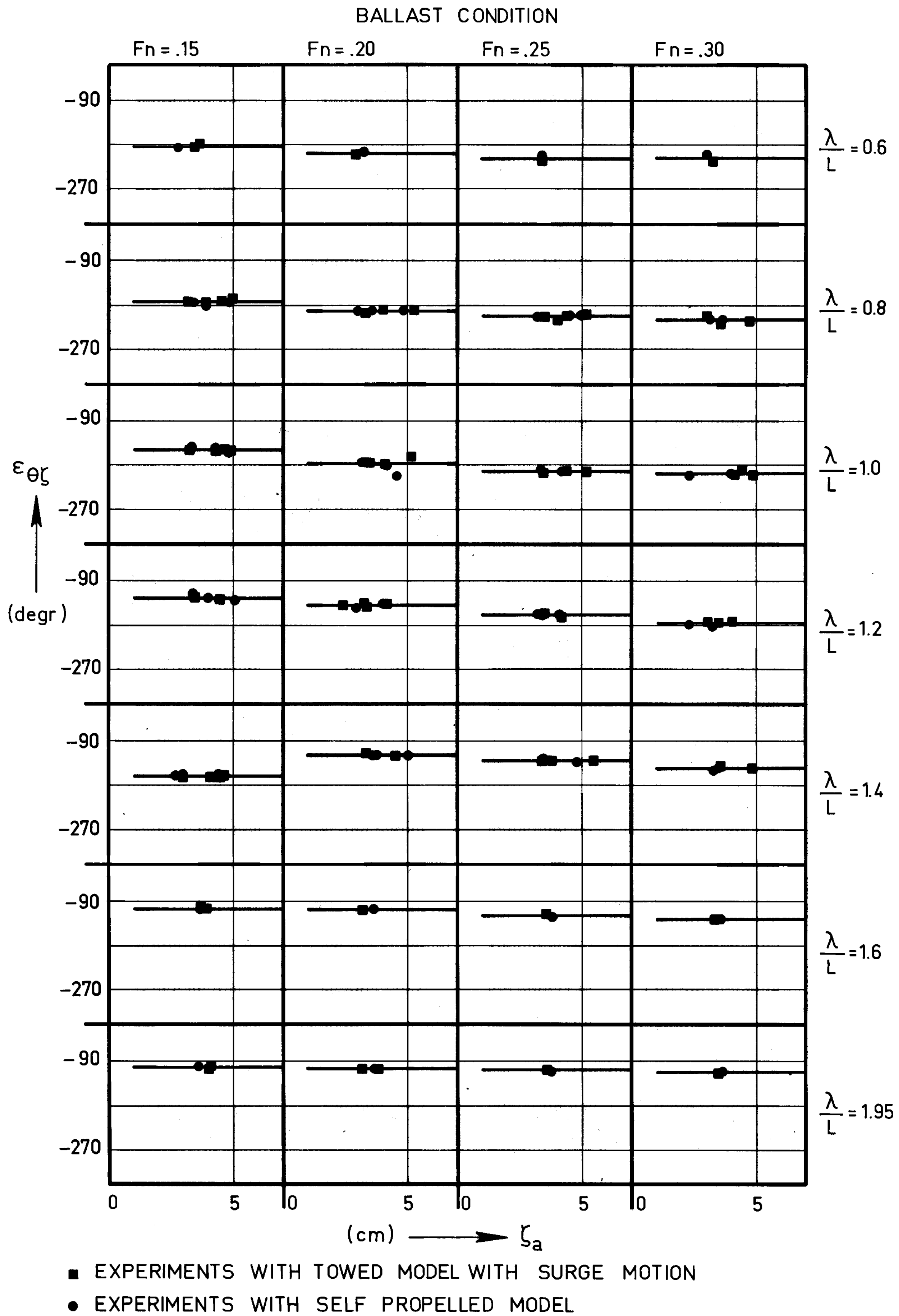


Figure 11 Relation between Phase Lag of Heave and Wave and Wave Amplitude (Ballast Condition)

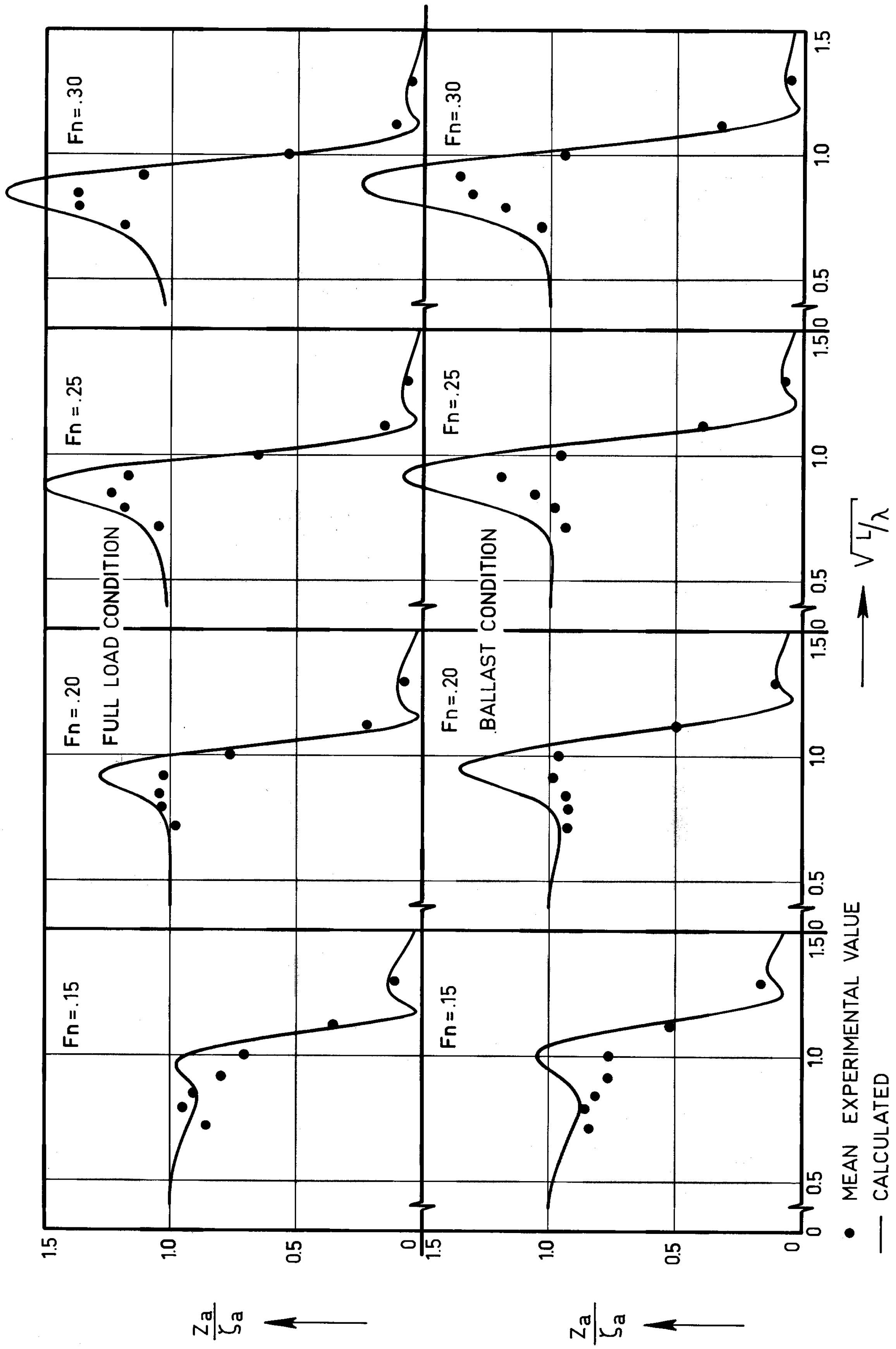


Figure 12 Measured and Calculated Heave Amplitude Characteristics in Regular Waves

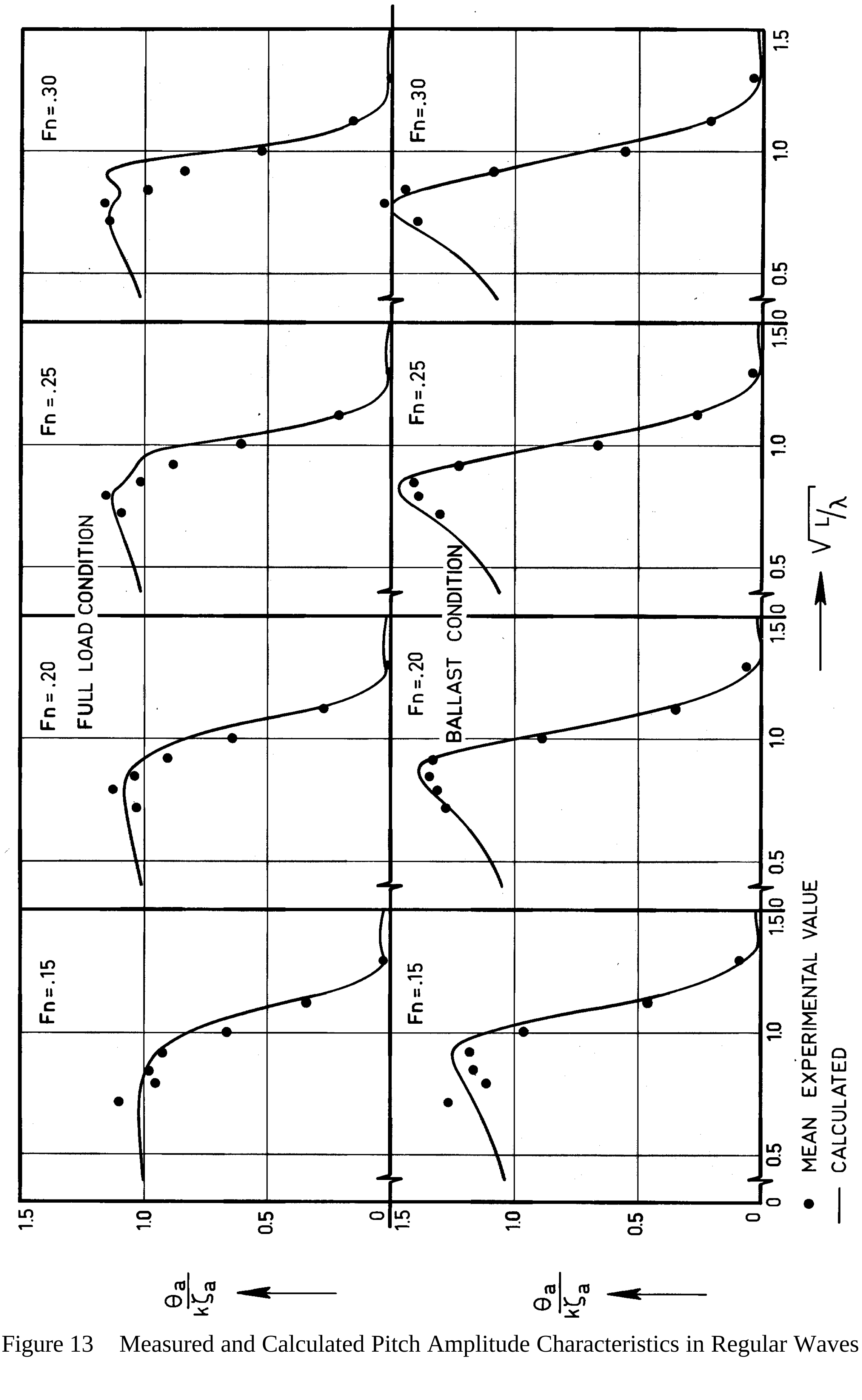


Figure 13 Measured and Calculated Pitch Amplitude Characteristics in Regular Waves

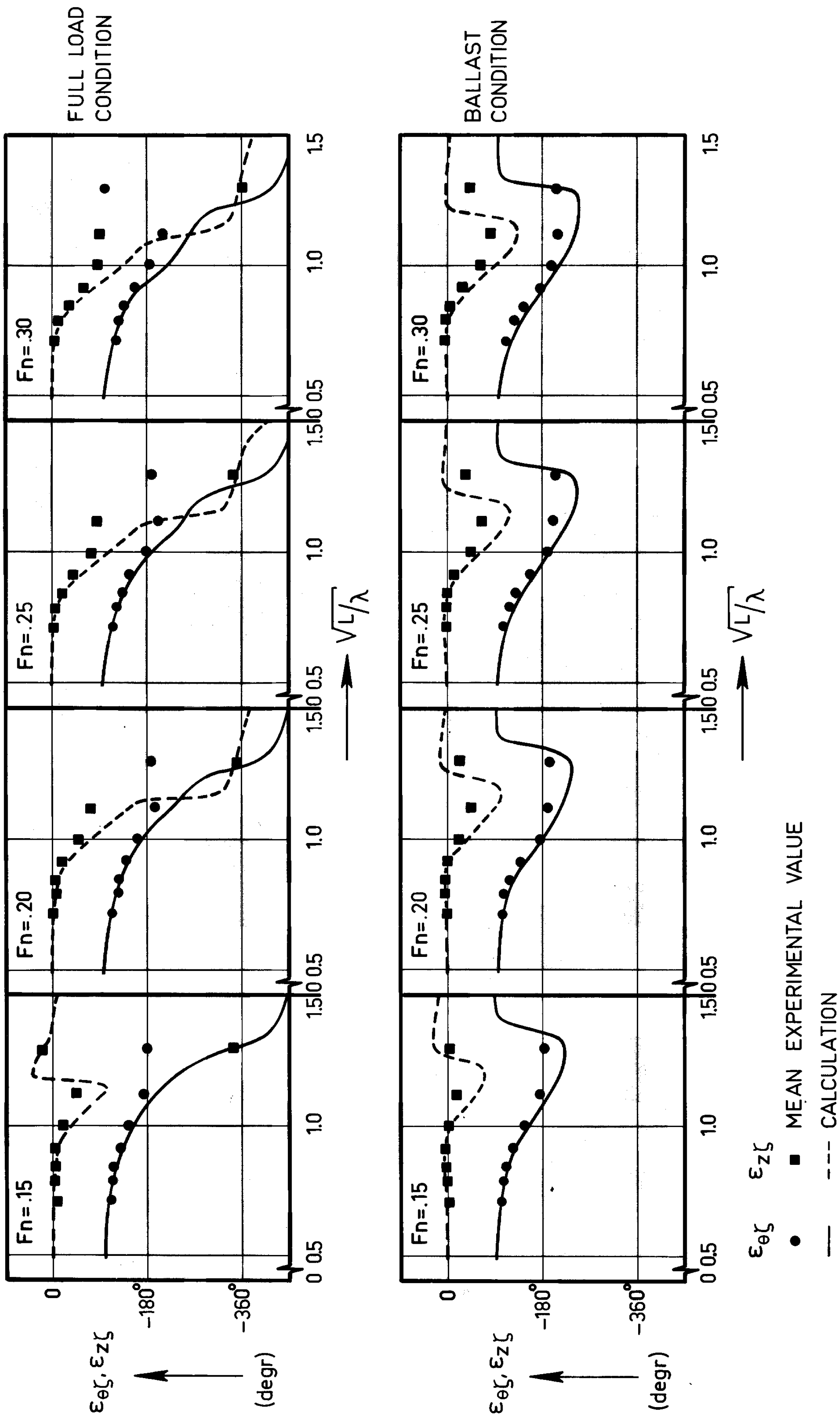


Figure 14 Measured and Calculated Phase Characteristics for Heave and Pitch in Regular Waves

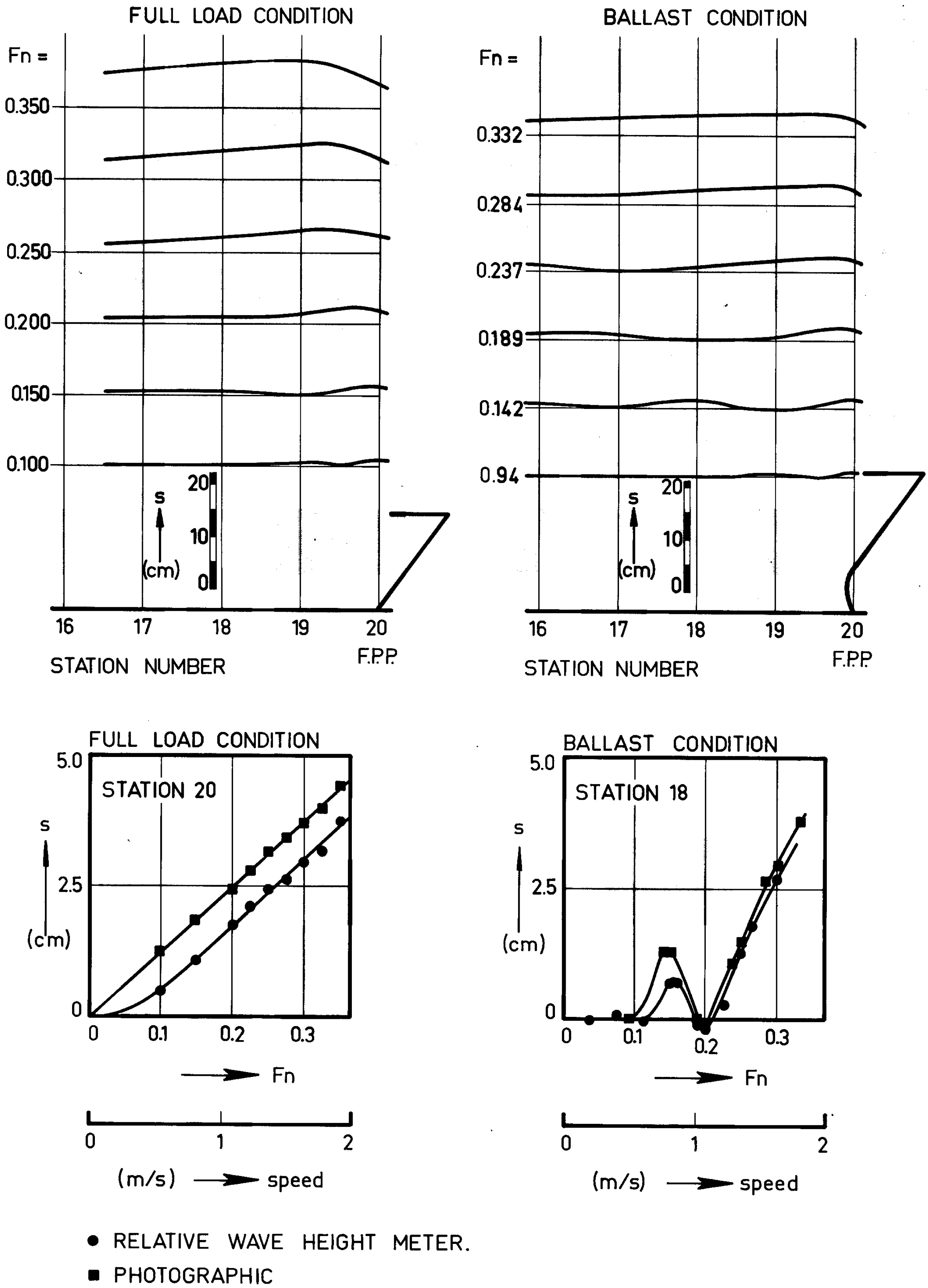


Figure 15 Relative Displacement of the Model for Different froude Numbers

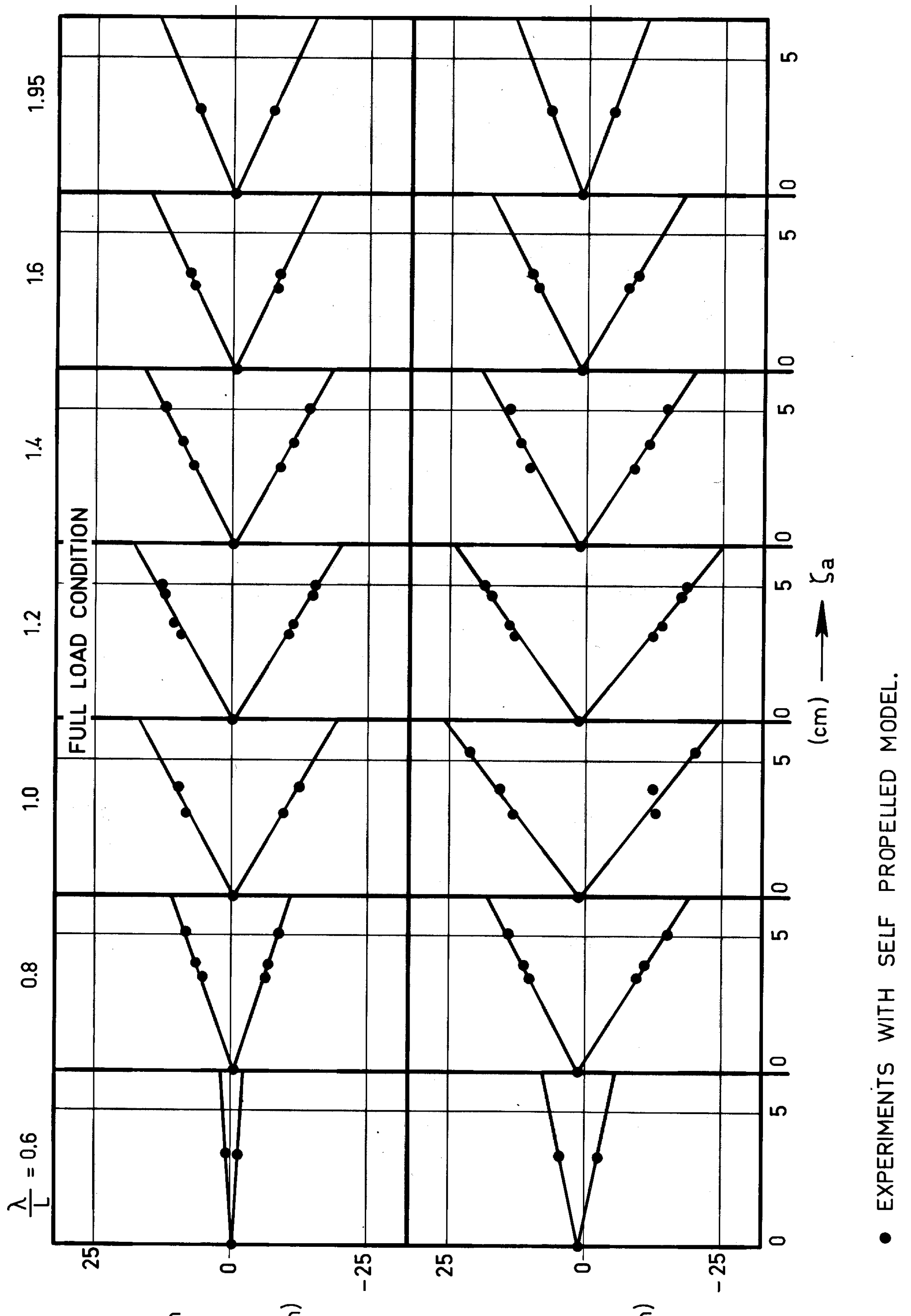


Figure 16-a Relation between Extreme Values of Absolute and Relative Motions and Wave Amplitude (Full Load Condition, Station 20, Fn = 0.15)

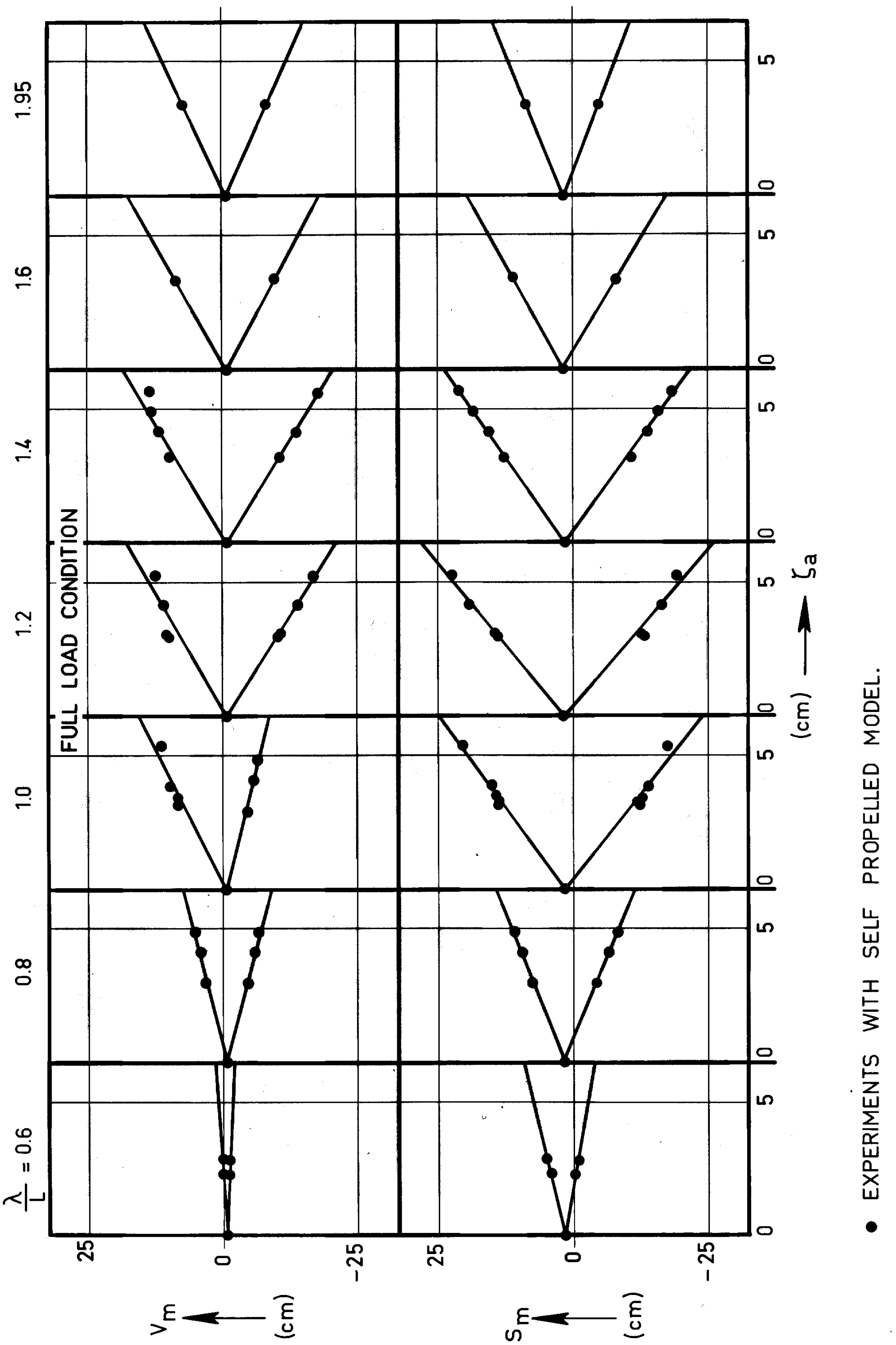


Figure 16-b Relation between Extreme Values of Absolute and Relative Motions and Wave Amplitude (Full Load Condition, Station 20, Fn = 0.20)

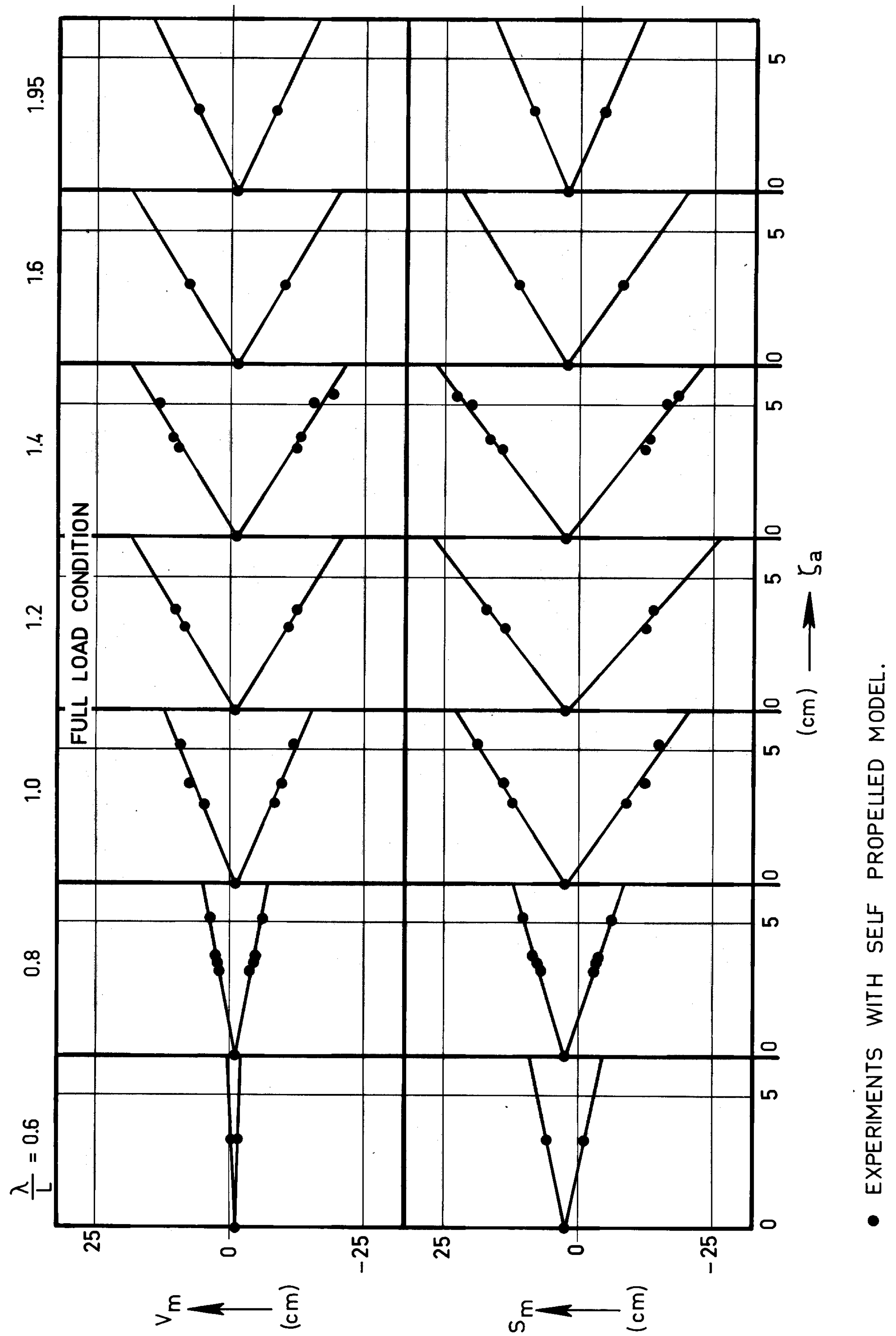


Figure 16-c Relation between Extreme Values of Absolute and Relative Motions and Wave Amplitude (Full Load Condition, Station 20, Fn = 0.25)

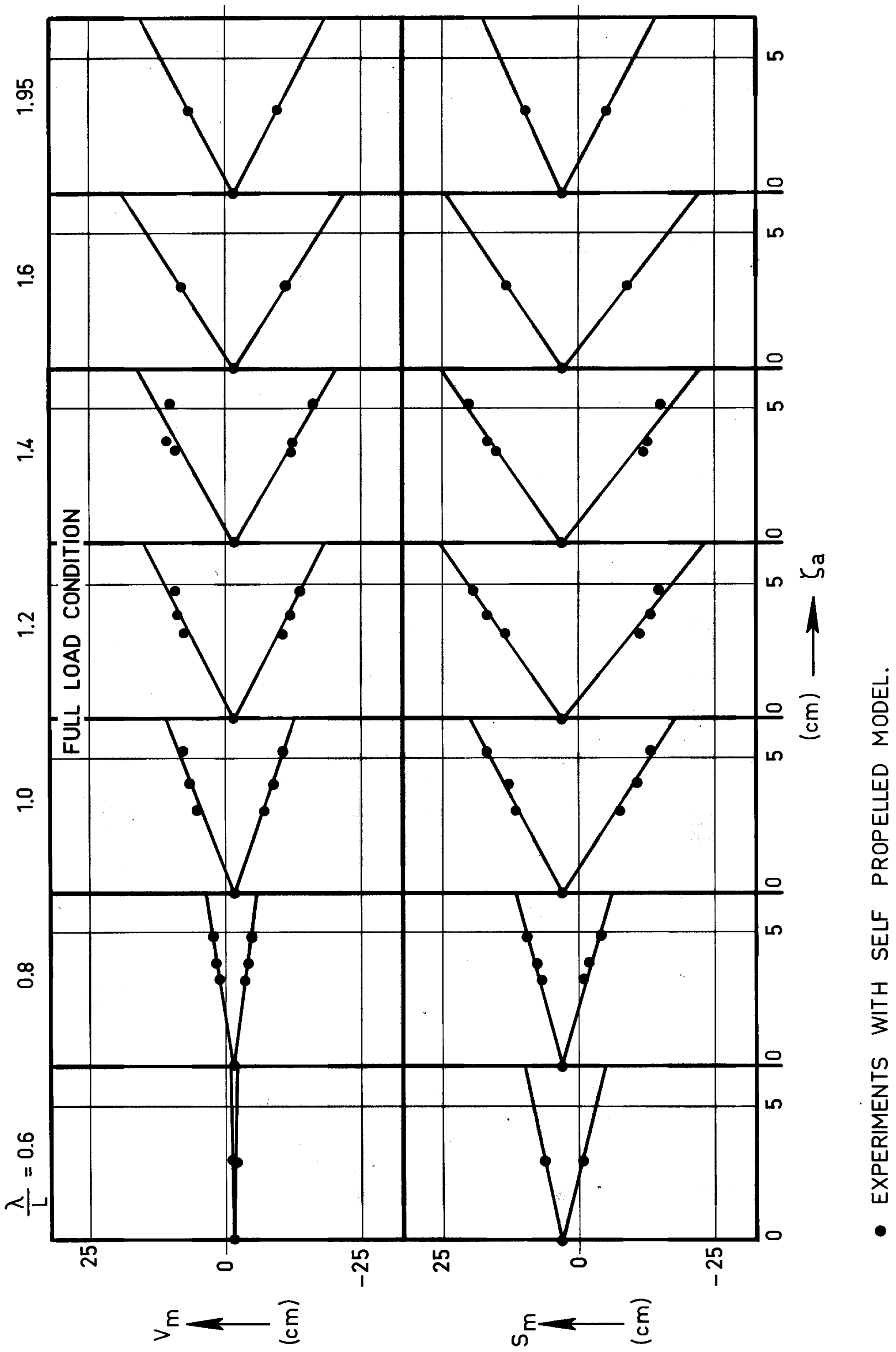


Figure 16-a Relation between Extreme Values of Absolute and Relative Motions and Wave Amplitude (Full Load Condition, Station 20, Fn = 0.30)

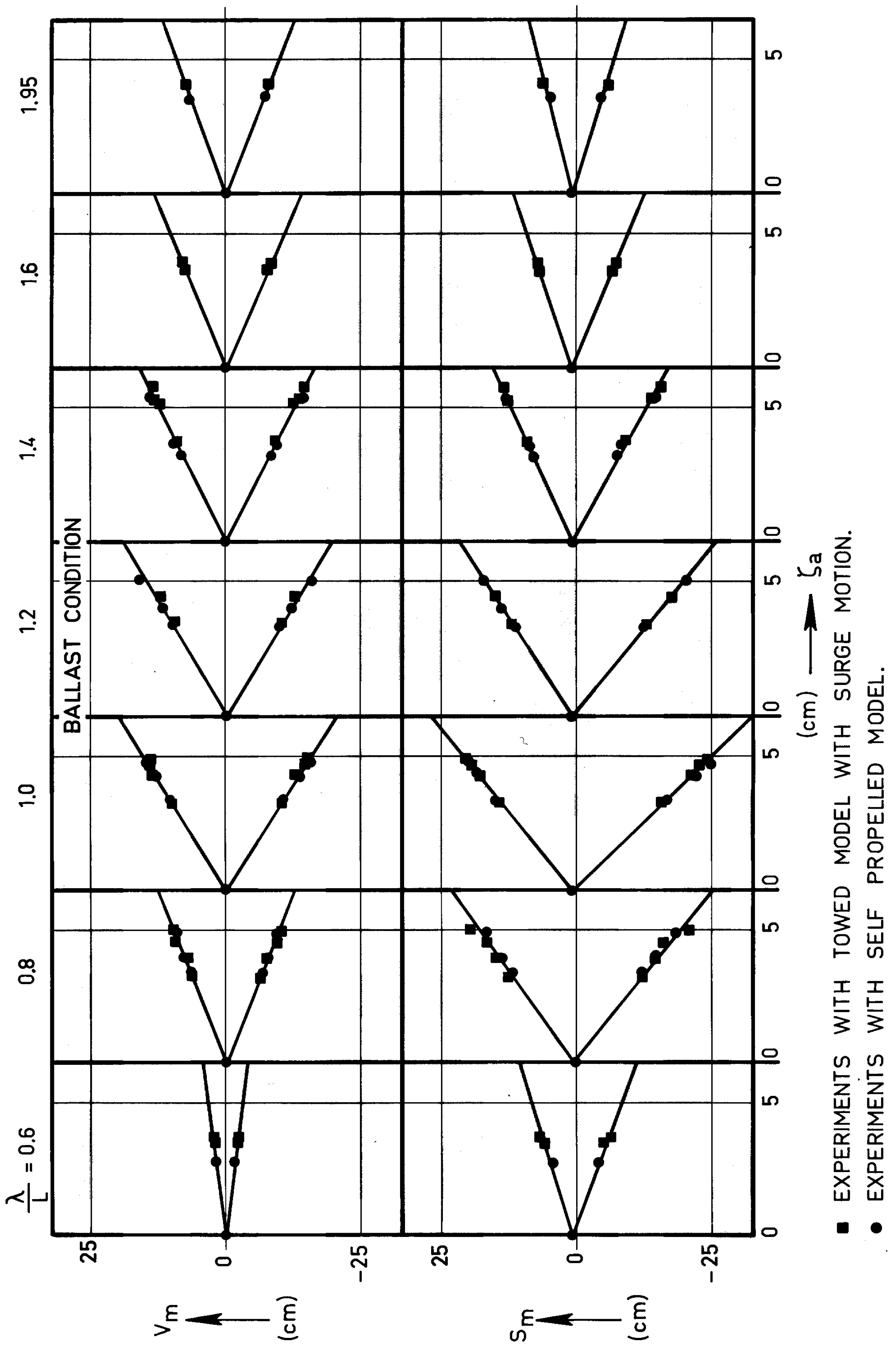


Figure 17-a Relation between Extreme Values of Absolute and Relative Motions and Wave Amplitude (Ballast Condition, Station 18, Fn = 0.15)

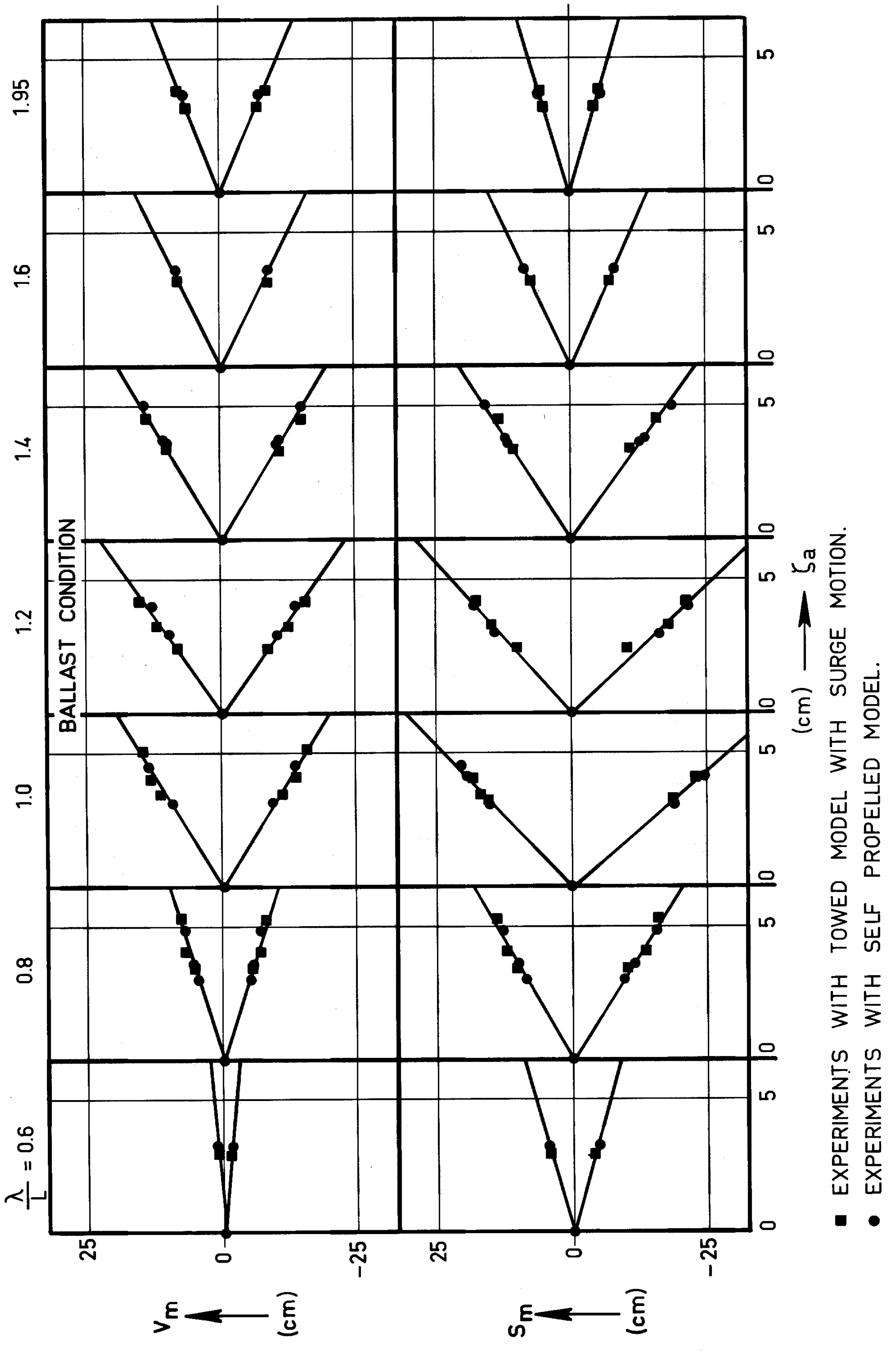


Figure 17-b Relation between Extreme Values of Absolute and Relative Motions and Wave Amplitude (Ballast Condition, Station 18, Fn = 0.20)

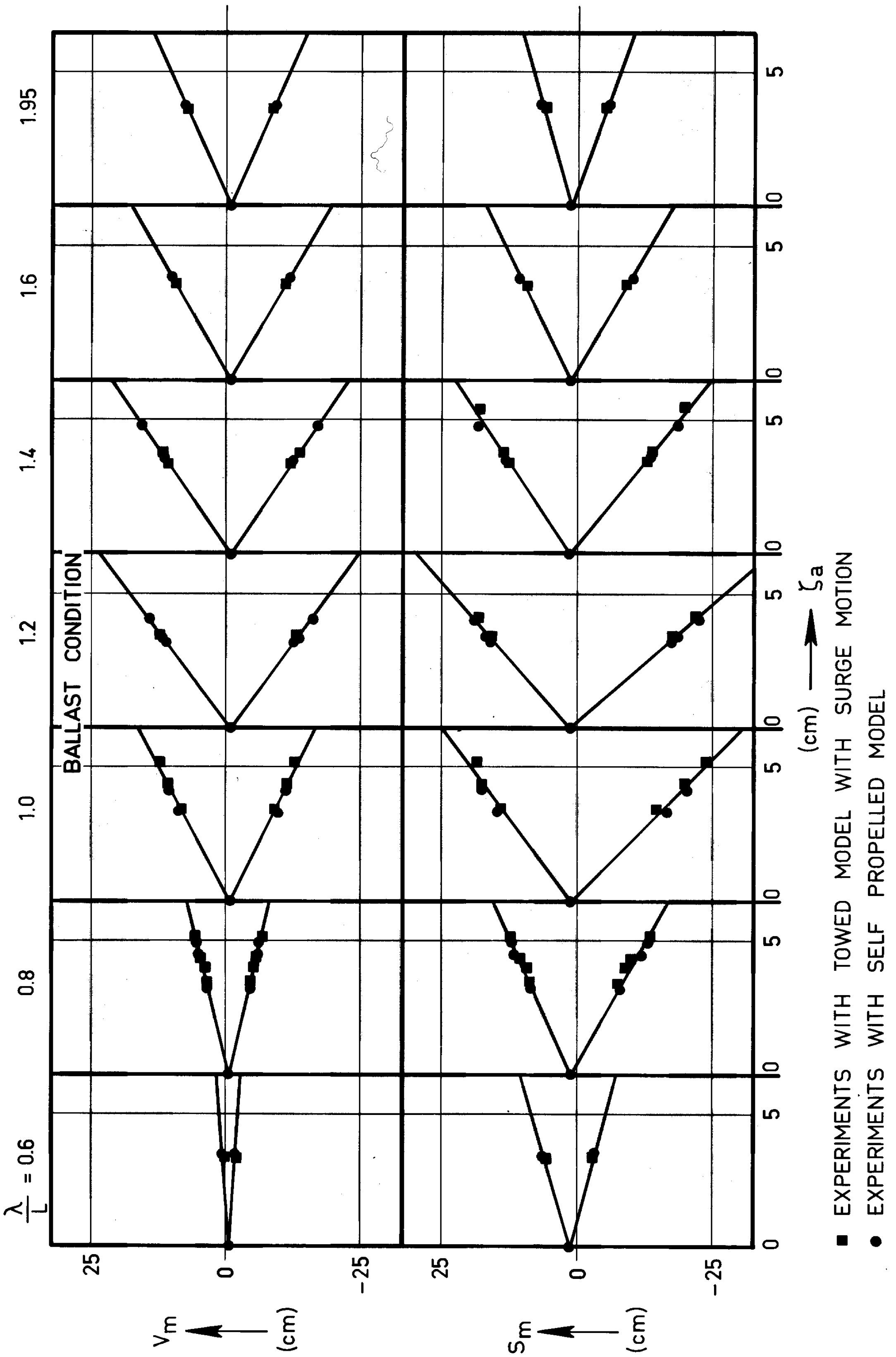


Figure 17-c Relation between Extreme Values of Absolute and Relative Motions and Wave Amplitude (Ballast Condition, Station 18, Fn = 0.25)

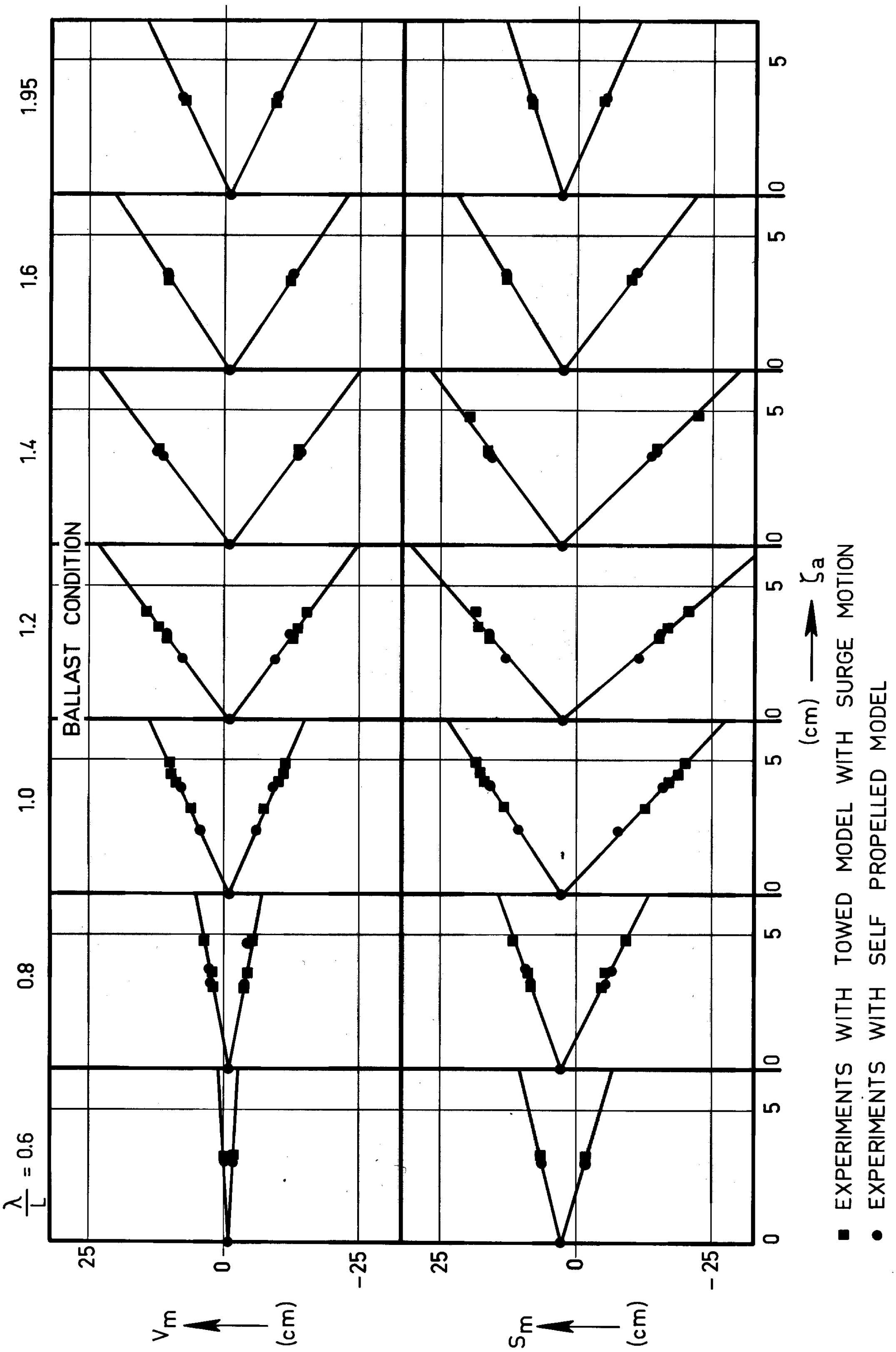


Figure 17-d Relation between Extreme Values of Absolute and Relative Motions and Wave Amplitude (Ballast Condition, Station 18, Fn = 0.30)

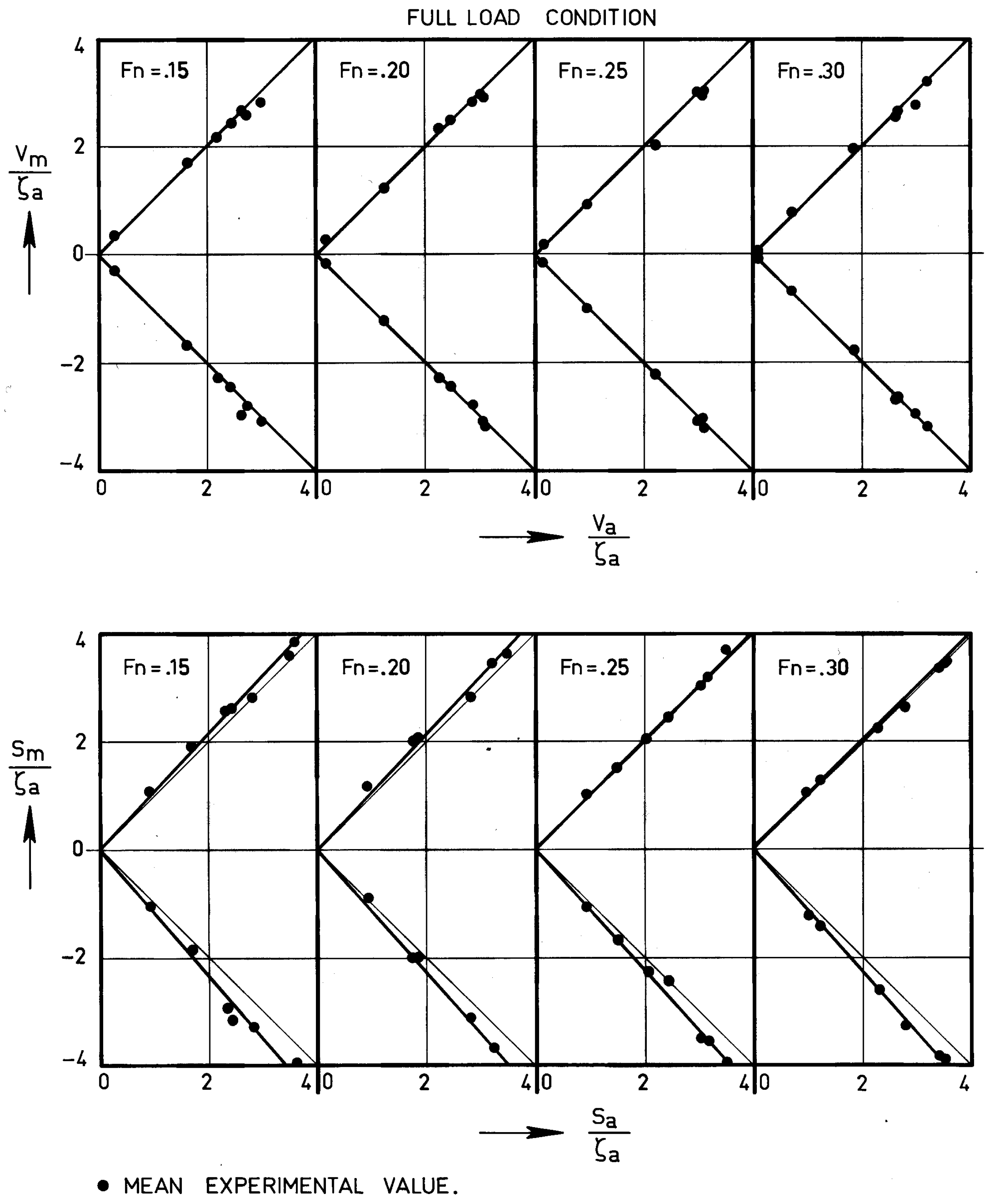


Figure 18 Relation between Measured Extreme Values of Absolute and Relative Motion and Motion Amplitude Calculated from Heave, Pitch and Wave (Full Load Condition, Station 20)

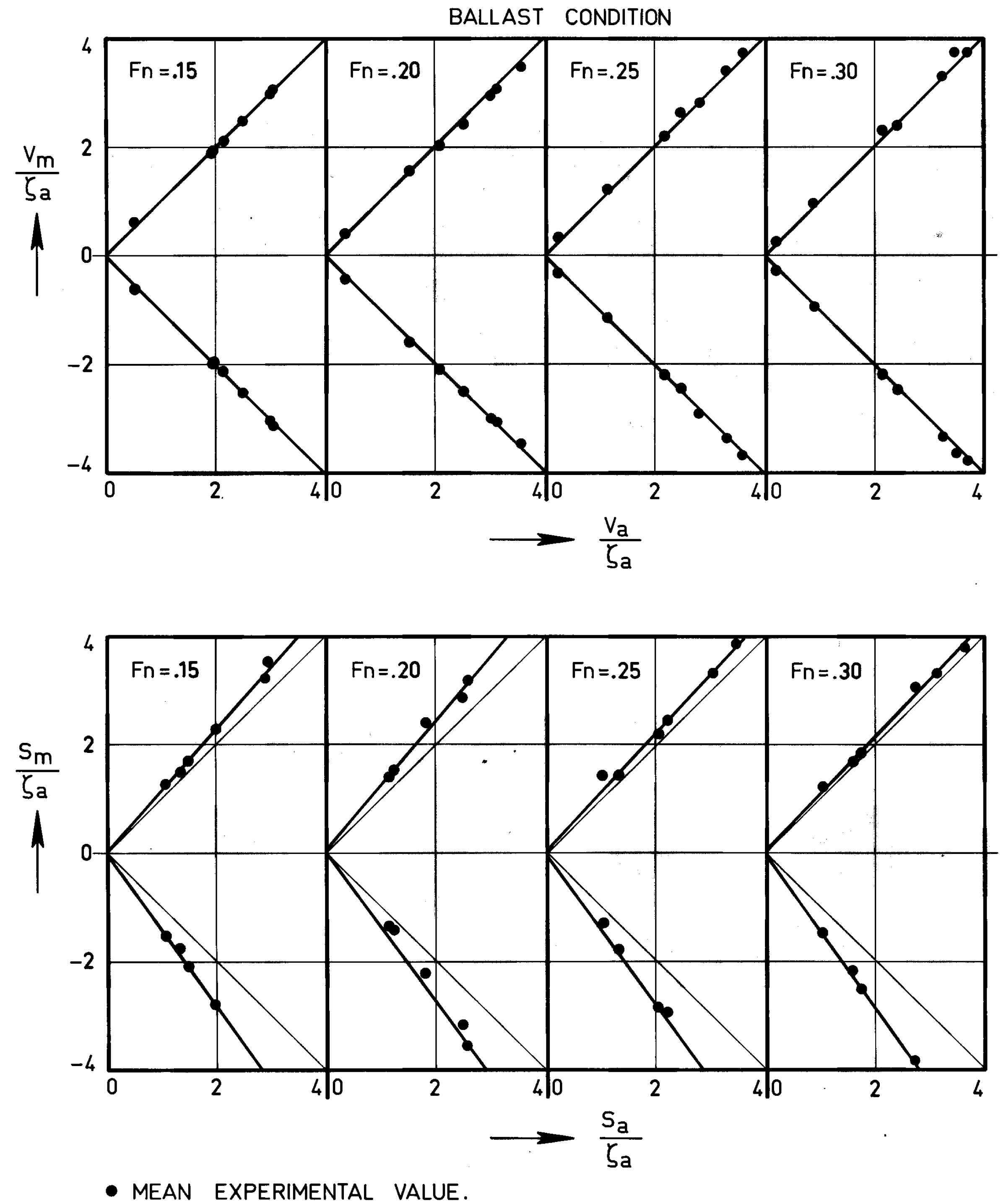


Figure 19 Relation between Measured Extreme Values of Absolute and Relative Motion and Motion Amplitude Calculated from Heave, Pitch and Wave (Ballast Condition, Station 18)

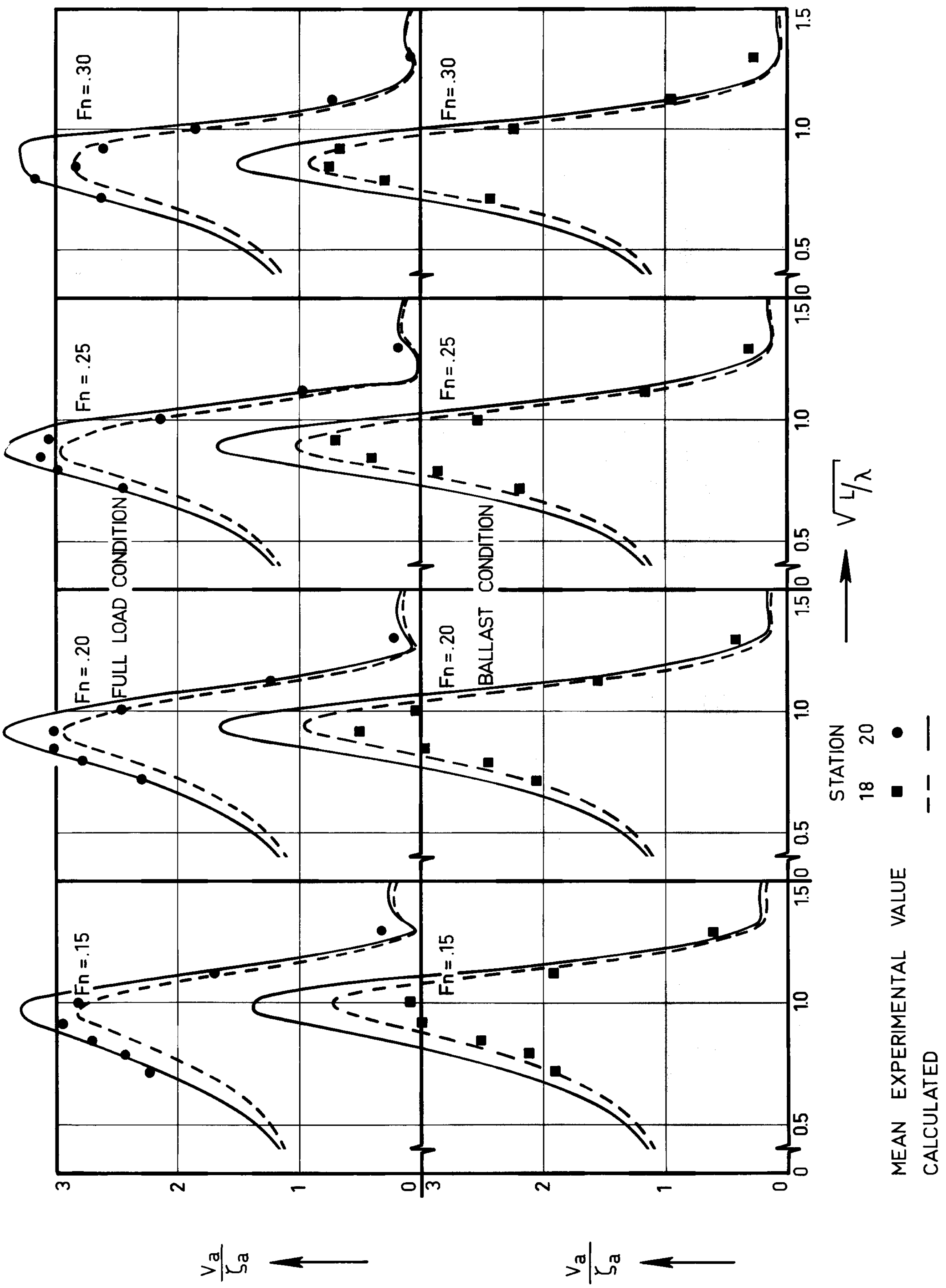


Figure 20 Measured and Calculated Absolute Motion Amplitude Characteristics in Regular Waves

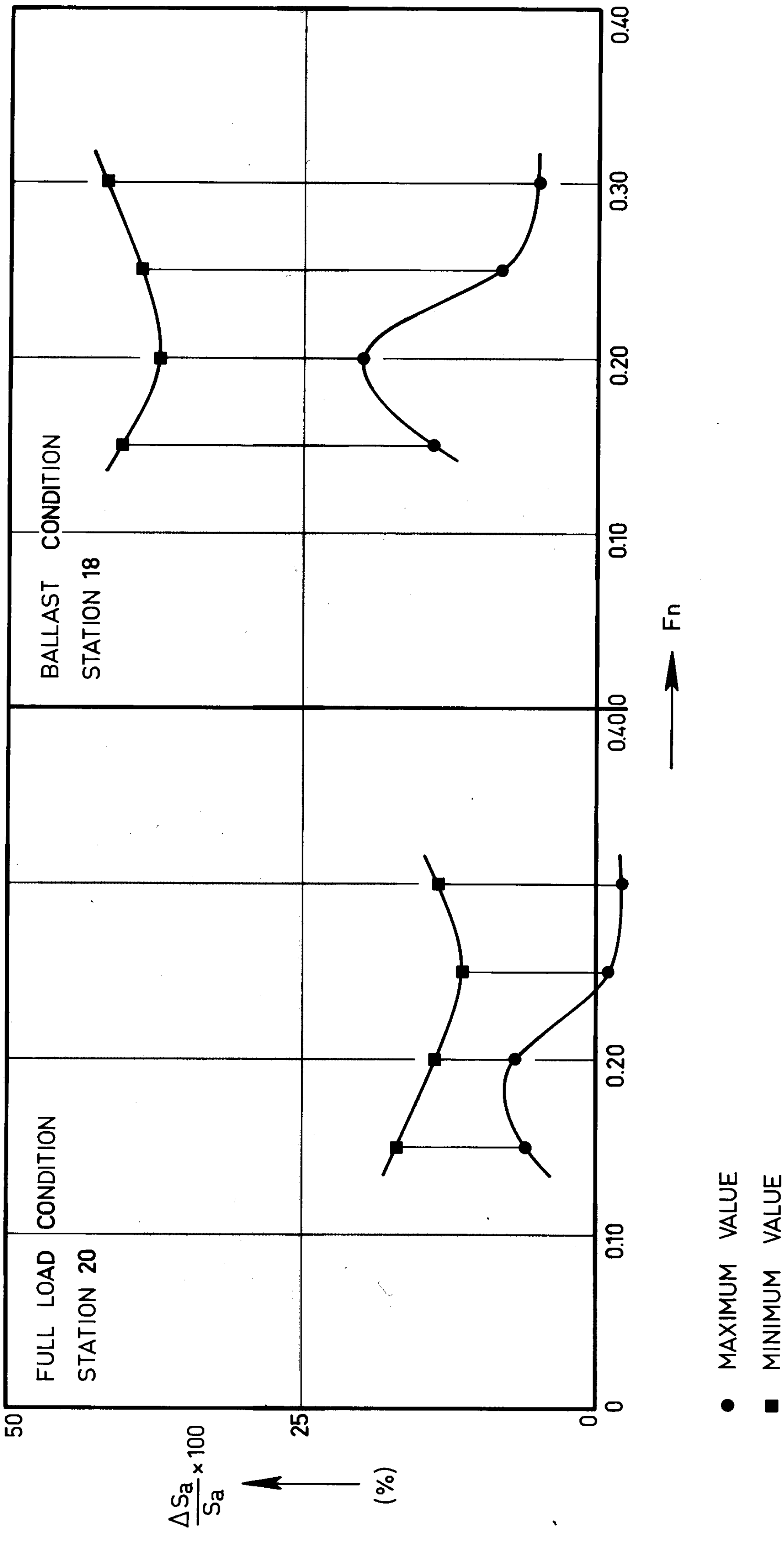


Figure 21 Maximum and Minimum Values of Dynamic Swell-Up

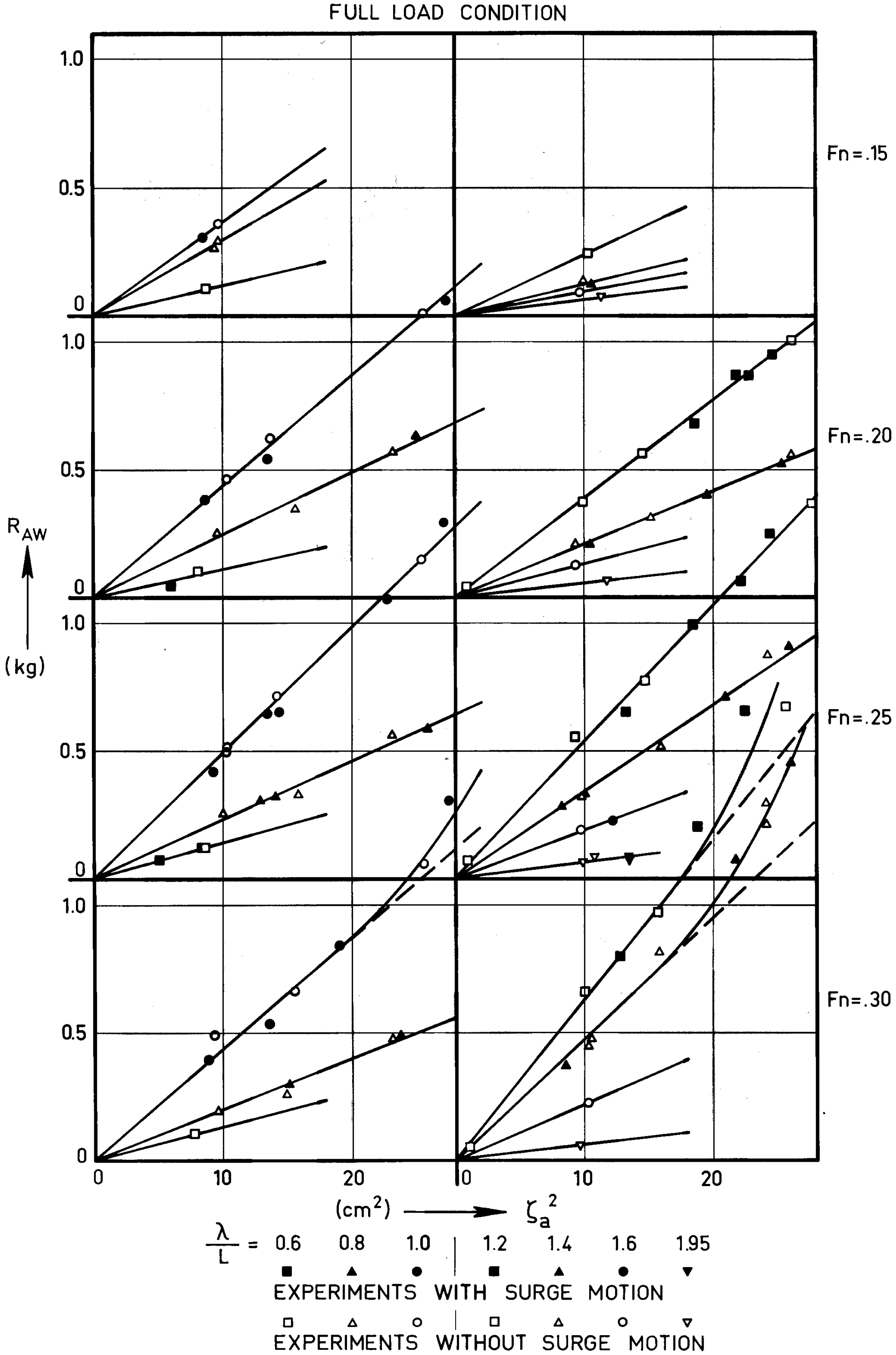


Figure 22 Relation between Added Resistance and Wave Amplitude Squared (Full Load Condition)

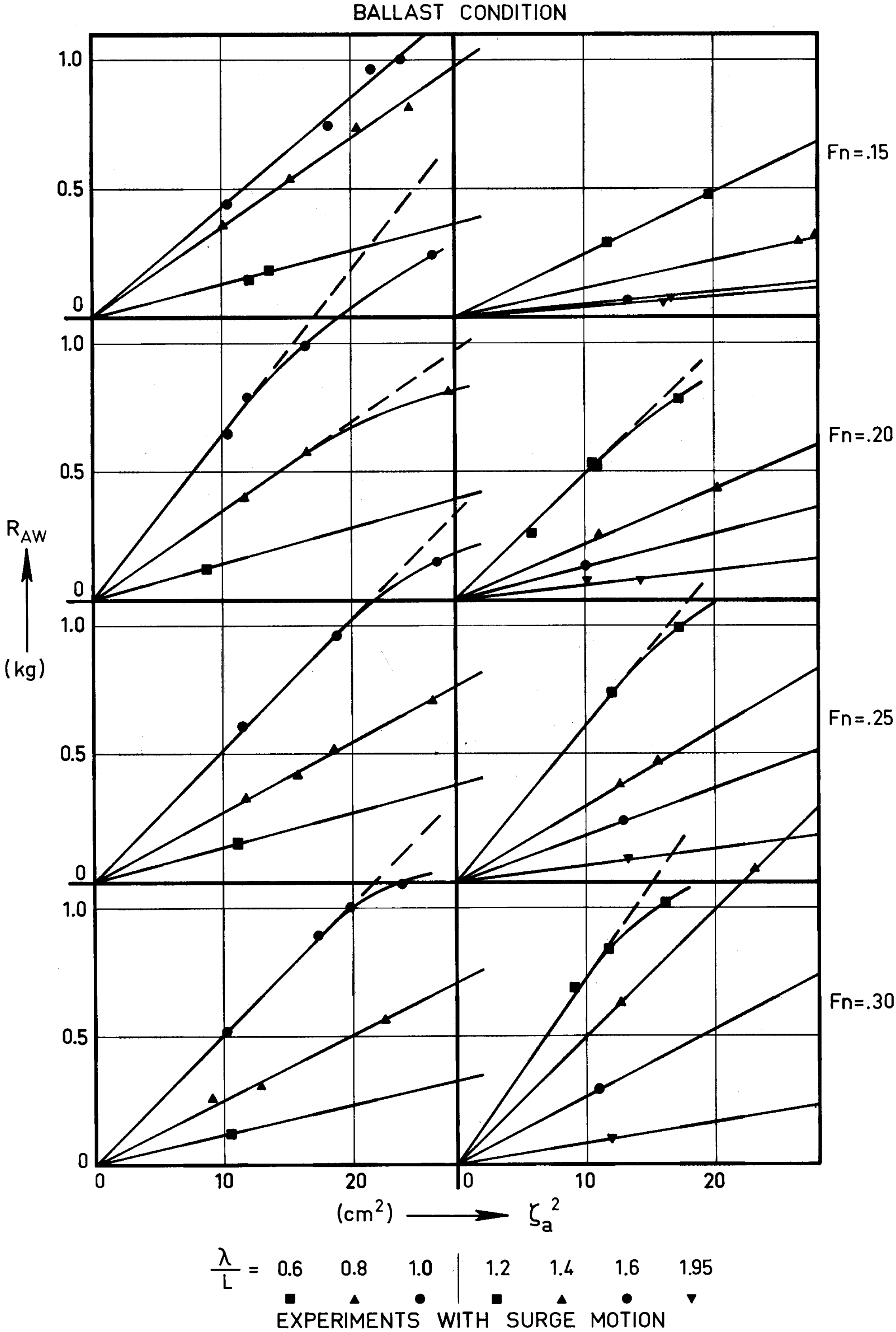


Figure 23 Relation between Added Resistance and Wave Amplitude Squared (Ballast Condition)

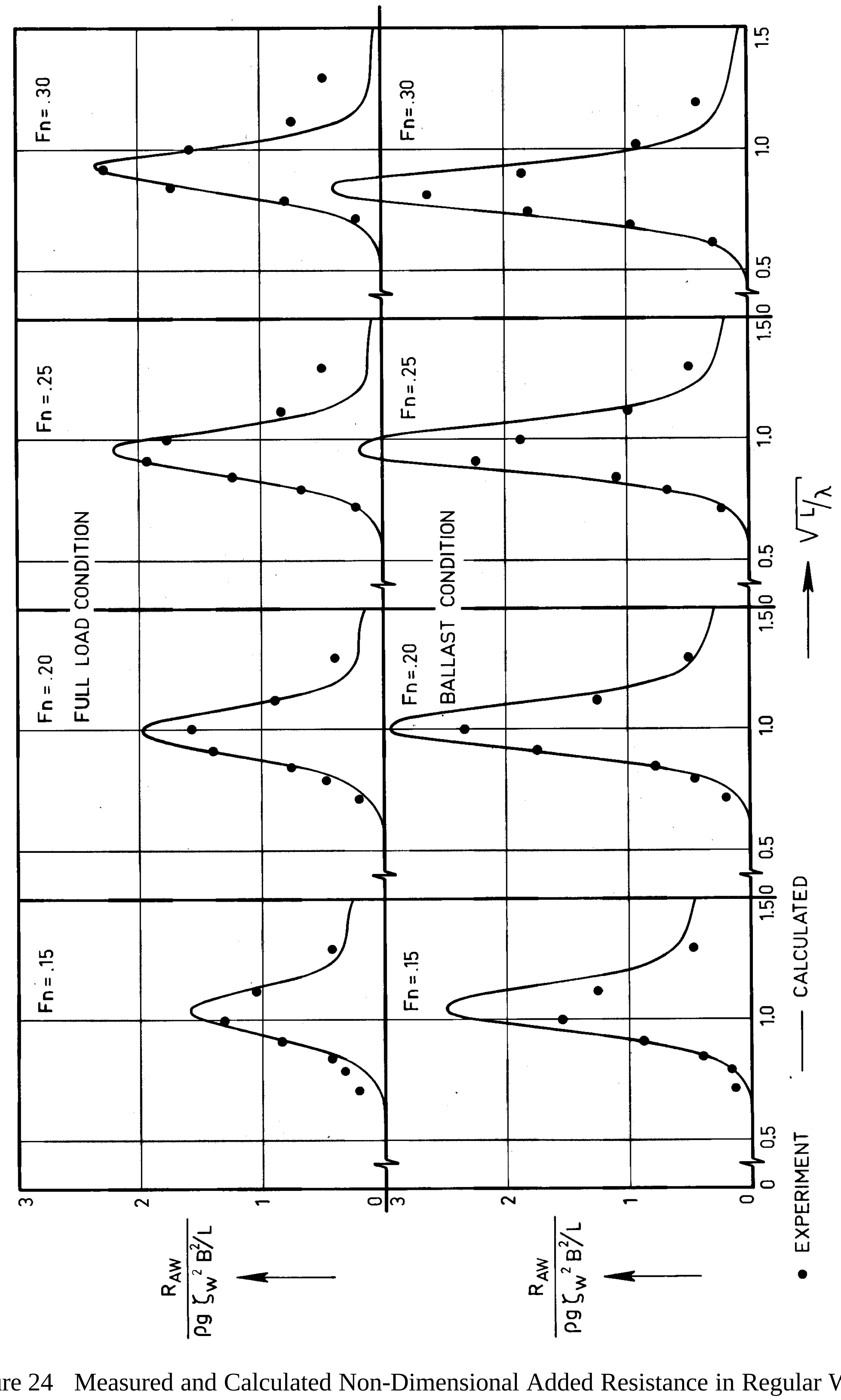


Figure 24 Measured and Calculated Non-Dimensional Added Resistance in Regular Waves

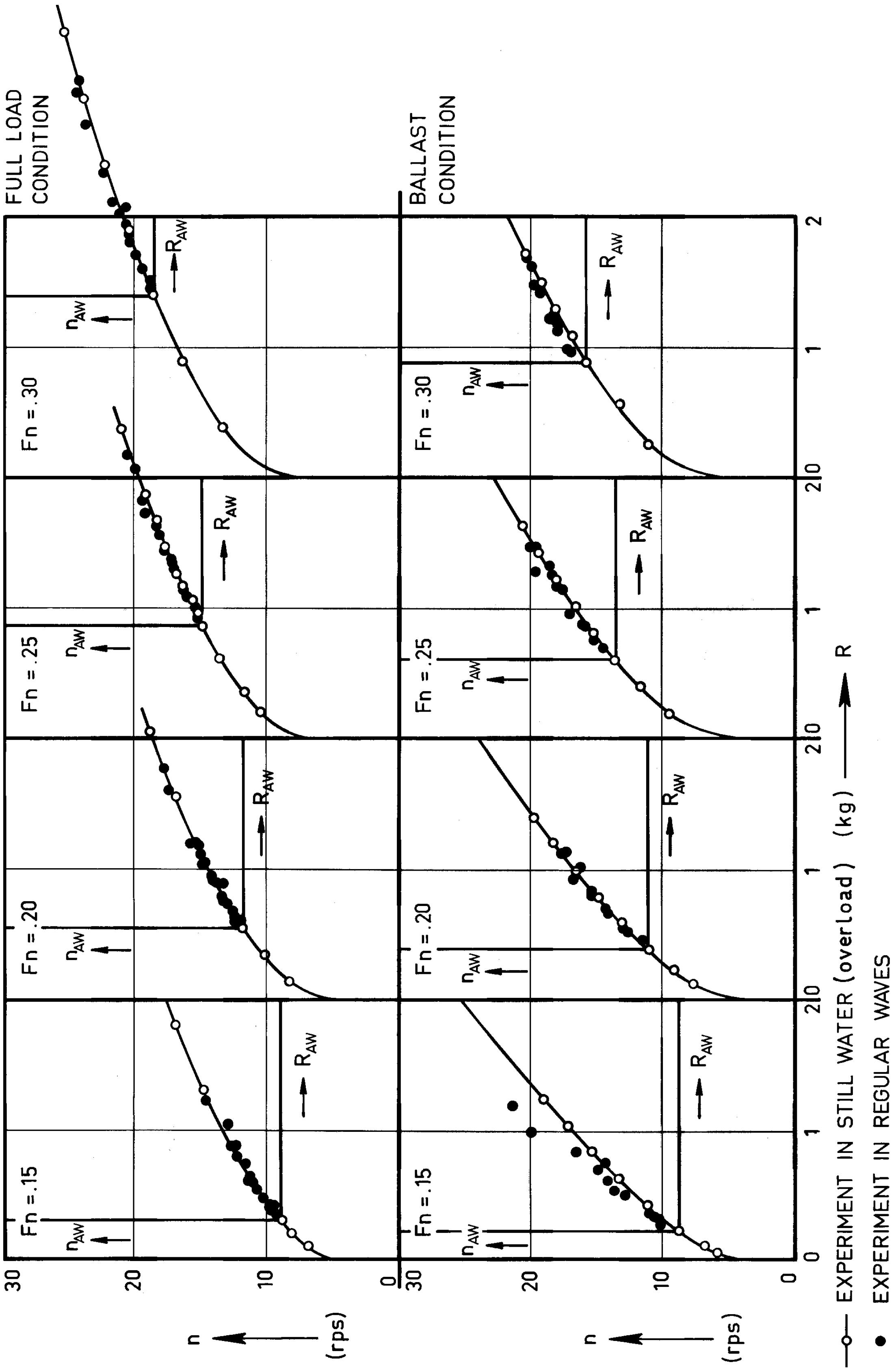


Figure 25 Measurements of Resistance and Propeller Rate in Still Water and in Regular Waves

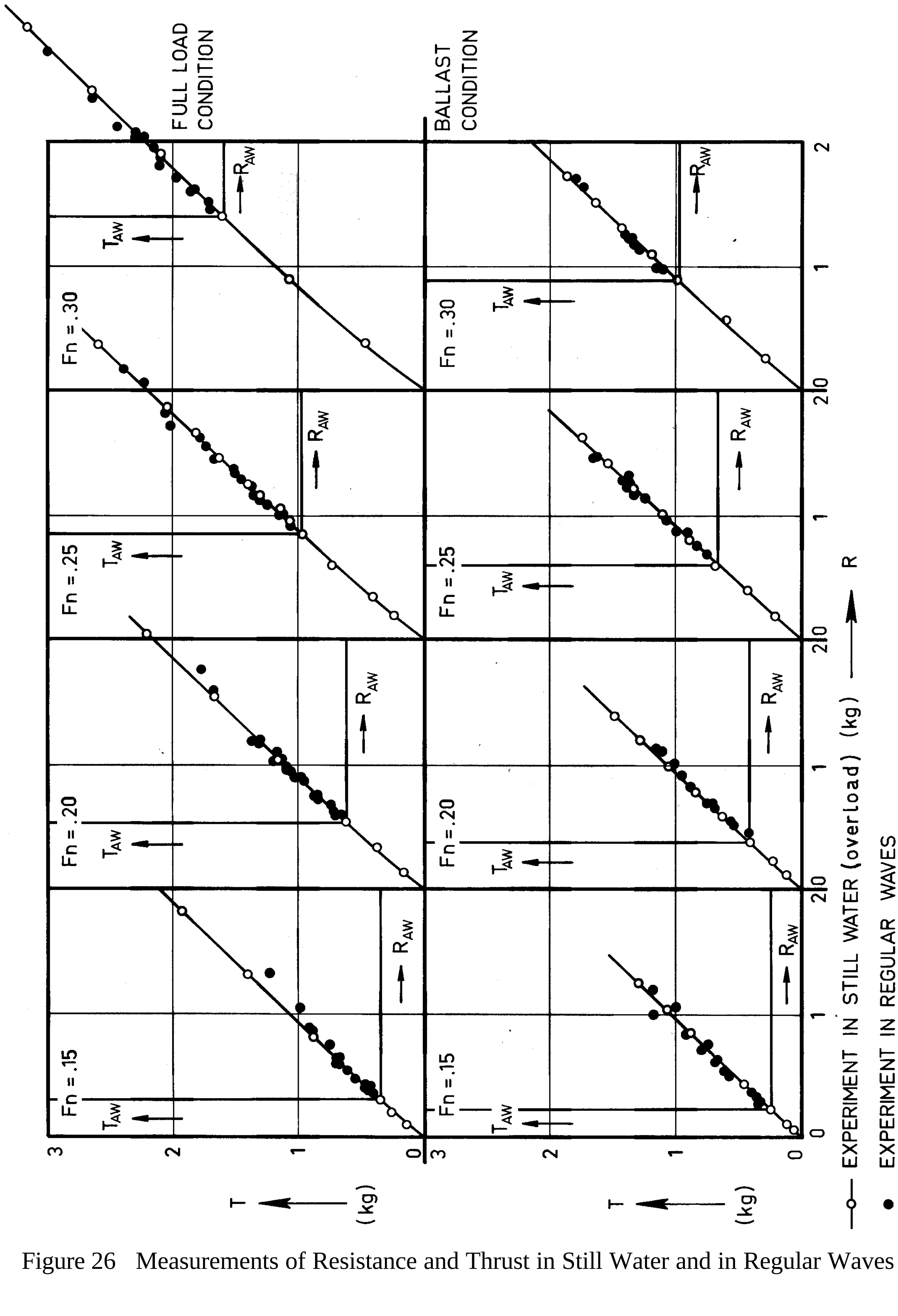


Figure 26 Measurements of Resistance and Thrust in Still Water and in Regular Waves

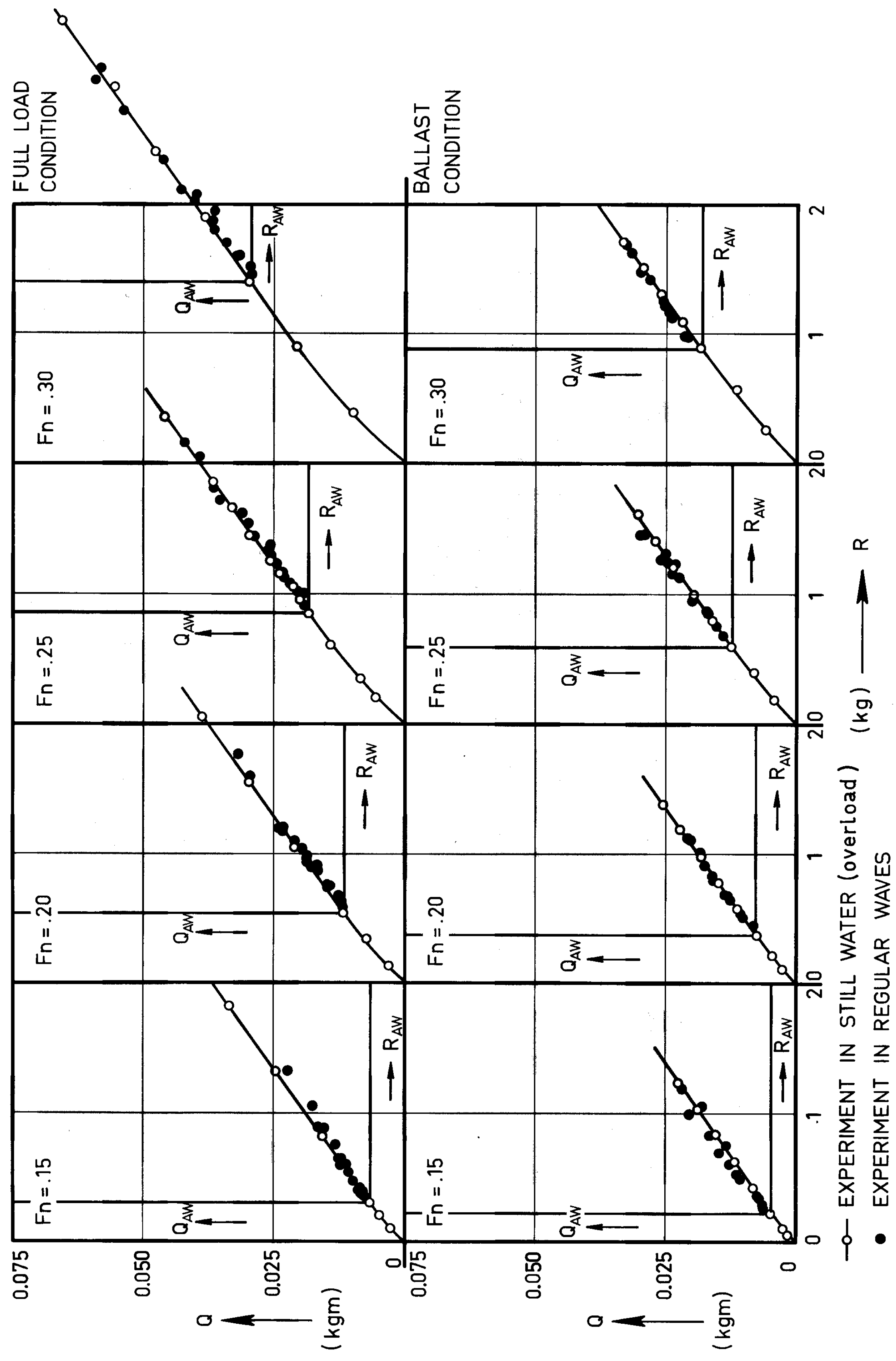


Figure 27 Measurements of Resistance and Torque in Still Water and in Regular Waves