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J.A. Keuning, P.F. van Terwisga and
L.J.M. Adegeest

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Delft University of Technology
Ship Hydromechanics Laboratory
Mekelweg 2
2628 CD Delft
The Netherlands
Phone 015 - 78 68 82

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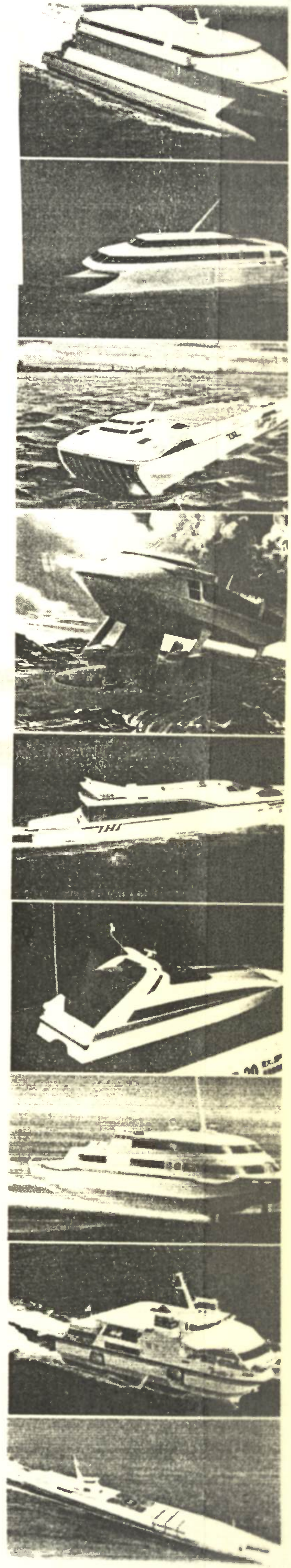

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Experimental and Numerical Investigation into Wave Exciting Surge Forces in Large Following Seas.

by J A Keuning P F van Terwisga L J M Adegeest

Laboratory of Shiphydromechanics
Delft University of Technology
Mekelweg 2
2628 CD Delft The Netherlands

1 *Introduction*

The ability of a ship to be "captured" by a wave and to accelerate to a speed equal to the phase velocity of the wave (the so-called surf-riding phenomenon) is largely determined by the relative magnitude of the horizontal wave exciting forces in these conditions in relation to the resistance and the slope of the resistance curve in the speed region under consideration as well as the thrust characteristics.
This surfing phenomenon has attracted increasing interest from researchers in the last decade because it is considered to be of considerable importance in the prediction of the broaching behaviour of a vessel in large and steep following waves.

Recently reported studies on this subject are among others those of Renilson and Thomas (Ref 1) and Kan (Ref 2).

Renilson and Thomas (Ref 1) carried out model experiments with two models of a typical fishing vessel in following waves and measured the surge force. They found this surge force to be strongly dependend on the position of the craft with respect to the wave crest and the wave steepness. However they formulated an expression for the apparent amplitude of the surge force only, which they found to be largely dependend on the maximum wetted cross sectional area of the hull.

Kan (Ref 2) used an expression for the surge force based on a calculation of the horizontal Froude Kriloff component using linear theory. Using this approximation of the surge force he was able to predict critical and non critical ship speeds and wave steepness regions with respect to the possible occurence of surfing. The outcome from this he compared with model experiments using remotely controlled models.

To find the relation between the surge force in large following waves and a wider range of hull parameters, in particular the length-displacement ratio and the length-beam ratio, it was decided to carry out a series of similar experiments as those of Renilson and Thomas in the Laboratory of Shiphydromechanics of the Delft University of Technology. The models used for these experiments were three unappended models of the Delft Systematic Yacht Hull Series, i.e. without keel and rudder.

The results of these measurements are presented in this paper together with the results of an calculation procedure based on the calculation of the Froude Kriloff force in the time domain over the actual submerged area of the hull of the ship due to wave elevation and resulting motions.

2 *Measurement Set Up*

The tests have been carried out in the #1 towing tank of the Laboratory of Shiphydromechanics of the Delft University of Technology. The main dimensions of this tank are: length 145 meters, width 4.5 meters and maximum waterdepth 2.5 meters. The maximum attainable speed of the towing carriage is 8.0 meters per second. A hydraulically activated flap is being used as a wave generator.

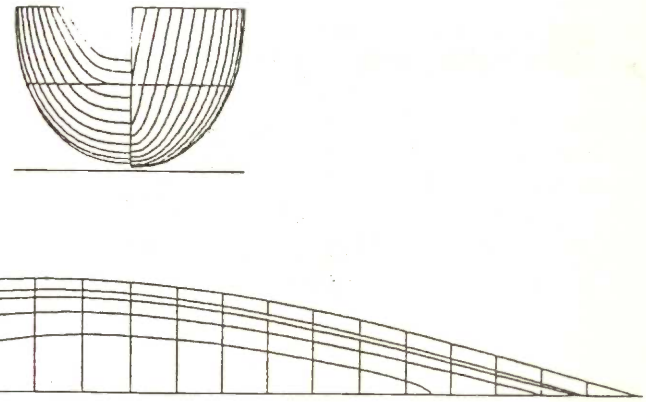
The three models used for the experiment are the models 27, 38 and 39 of the Delft Systematic Yacht Hull Sereis respectively. The body plans of these models are depicted in Figure 1.

The main particulars of these models are presented in Table 1.

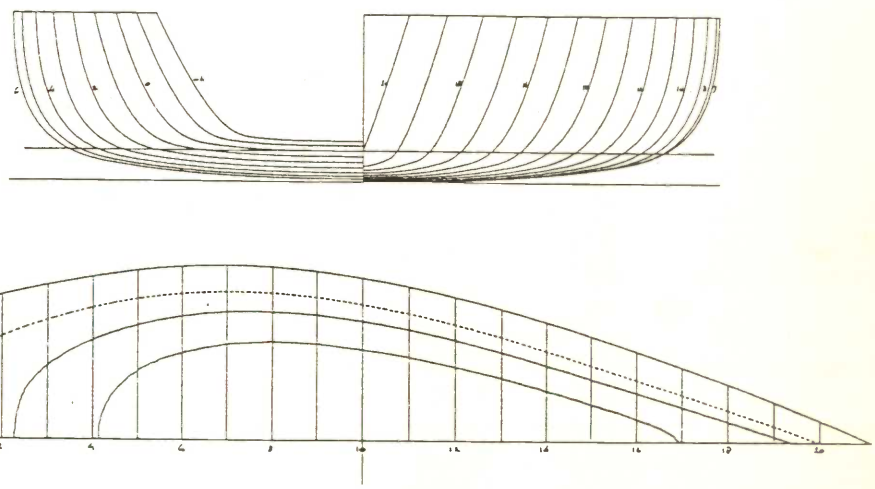
TABLE 1.

Model	# 27	# 38	# 39
Length over all (m)	2.31	2.35	2.31
Waterline Length (m)	2.00	2.00	2.00
Maximum Beam (m)	0.50	0.78	0.47
Waterline Beam (m)	0.44	0.67	0.40
Depth (m)	0.18	0.034	0.058
Displacement (kg)	63.36	19.07	18.96
Lenth-Beam ratio	4.5	3.0	5.0
Beam-Draft ratio	2.46	19.32	6.96
Length-Displacement	5.02	7.49	7.50
Radius of gyration (m)	0.59	0.55	0.58

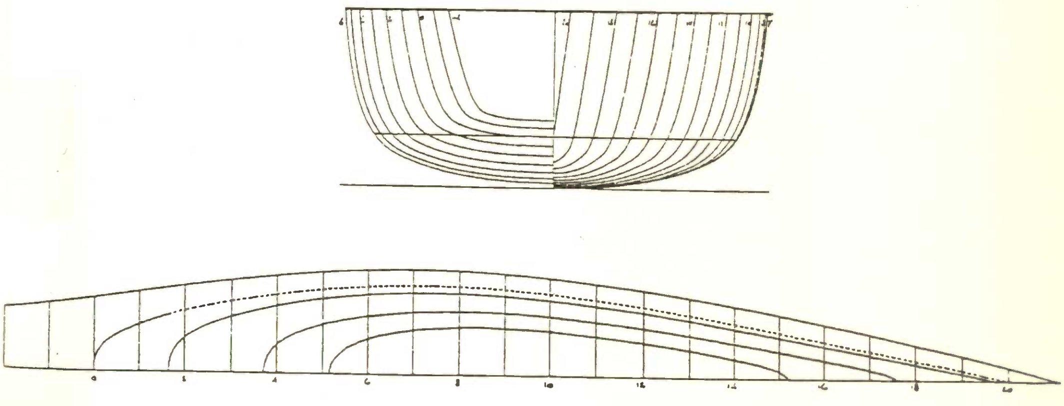
Tabel 1: Main particulars of the models.



SYS 27



SYS 38



SYS 39

Figure 1: Bodyplans of the models used.

The models were constructed of glass fibre reinforced polyester using 3 mm core-mat, yielding relatively light and rigid models.
The models were connected to the towing carriage in such a way that they were free to heave and pitch but restrained in all other modes of motion.
During the tests the horizontal (in an earth fixed coordinate system) surge force on the models was measured using a strain gauge type dynamometer as well as the heave and pitch motion of the model. The motions of the model was measured using wire over potentiometer type displacement meters.
Two wave probes were used during the experiments:
- one in the transverse plane through the centre of gravity of the model on some distance from the model and connected to the towing carriage for the determination of the phase of the wave and
- one on 10 meters distance from the wave generator for the determination of the wave amplitude.

Before starting a measurement run in the down wave direction the model was lifted clear of the waves in order to allow the waves to propagate undisturbed down the basin. The model was then lowered and the run carried out.

To measure the surge force as a functon of the position of the model with respect to the wave a quasi steady approximation was adopted similar to the one used by Renilson. This procedure was as follows:
The model was towed at a forward speed slightly higher or lower than the specific phase velocity of the wave being generated. The speed difference between phase velocity and model speed was chosen such as to assure that the model was exactly overtaking one wave during the complete run down the towing tank, or vice versa was exactly being overtaken by one wave. A typical run duration was about 30 to 40 seconds, which was considered to be long enough to justify the static position assumption. The two forward speed conditions have been tested in order to investigate a possible speed influences on the quantities measured.

In Figure 2 a definition sketch of the coordinate system used and the variable ξ determining the relative position of the model with respect to the wave top is presented.

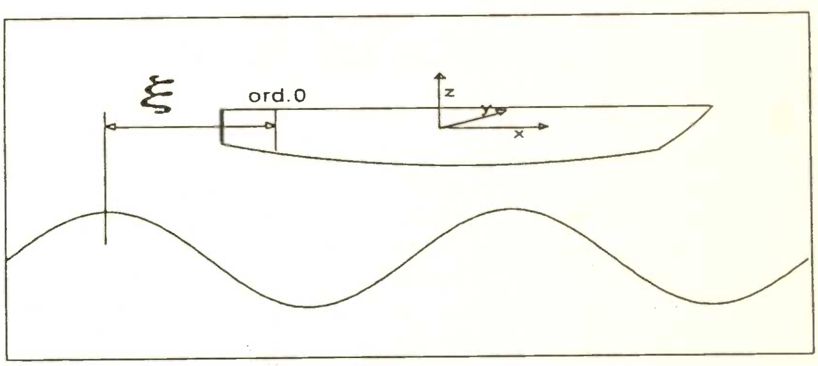


Figure 2: Definition sketch.

3 *Measurement Scheme*

For all three models the following experiments were carried out:

1) the calm water resistance, the sinkage and the trim as function of the forward speed.
2) the added resistance, the heave and the pitch motion of the model in following regular waves with wavelength varying from 3.3 to 0.8 times the waterline length of the model with the model at one fixed forward speed corresponding to a Froude number of 0.35.
3) an extensive series of quasi static measurements, following the procedure previously described, using 10 different wavelengths in the same range, i.e. from 0.8 to 3.3 times the waterline length of the model, with two different waveheights corresponding to a steepness ratio λ/H of 17 and 25 respectively.
4) a repetition of a number of measurements as mentioned under 3) but with another speed of advance of the model.

In addition a series of experiments were carried out with different starting conditions regarding forward speed of the model and position on the wave to establish regions of initial conditions under which the model "would" or "would not" start to surf. During these tests the models were free to surge with a very large amplitude and a constant towing force corresponding to the calm water resistance was applied to the model. If necessarry the speed of the towing carriage was adapted to "follow" the model. The results of these tests are not further dealt with in this paper.

4 *Results*

The results of the measurements are presented in the following figures.

Figure 3 shows the results of the upright calm water total resistance of the three models as function of the forward speed.

In Figure 4 the results of the added resistance measurements with the constant forward speed are presented. The added resistance is presented in the usual non dimensional format. The lines in this figure present the results of calculations of the added resistance carried out by using the SEAWAY code as described in Ref 3 by Journee using the well known Gerritsma-Beukelman formulation. The SEAWAY code is based on linear two dimensional strip theory.

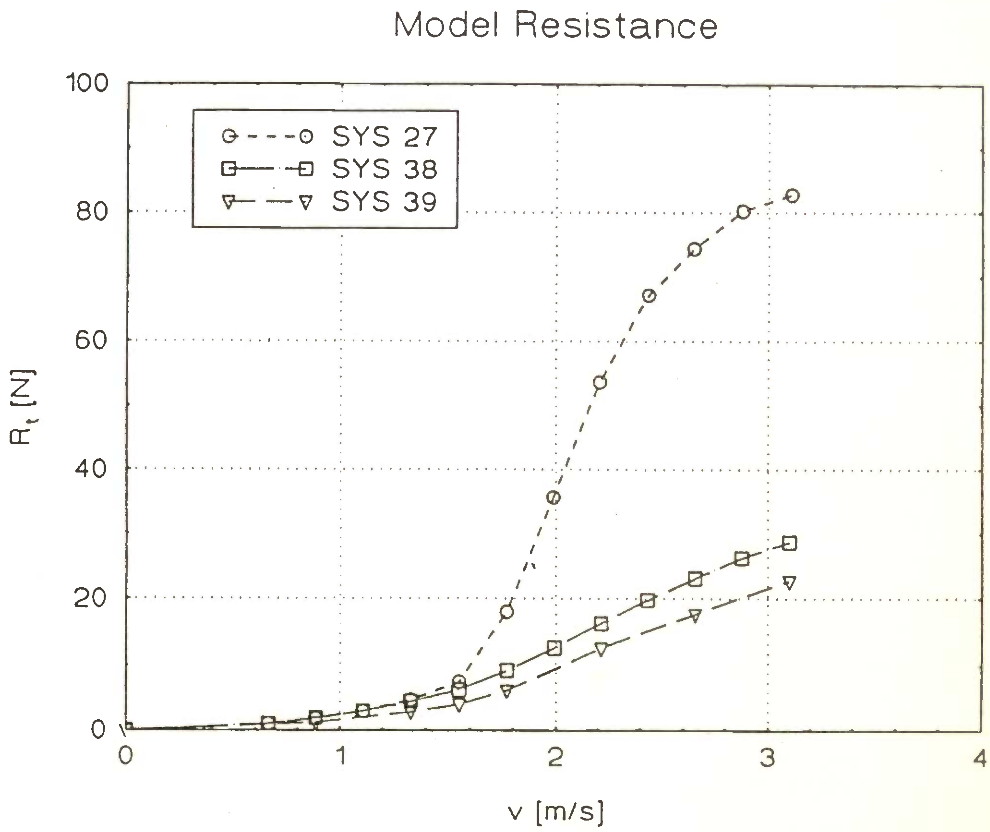


Figure 3: Total calm water resistance of the models.

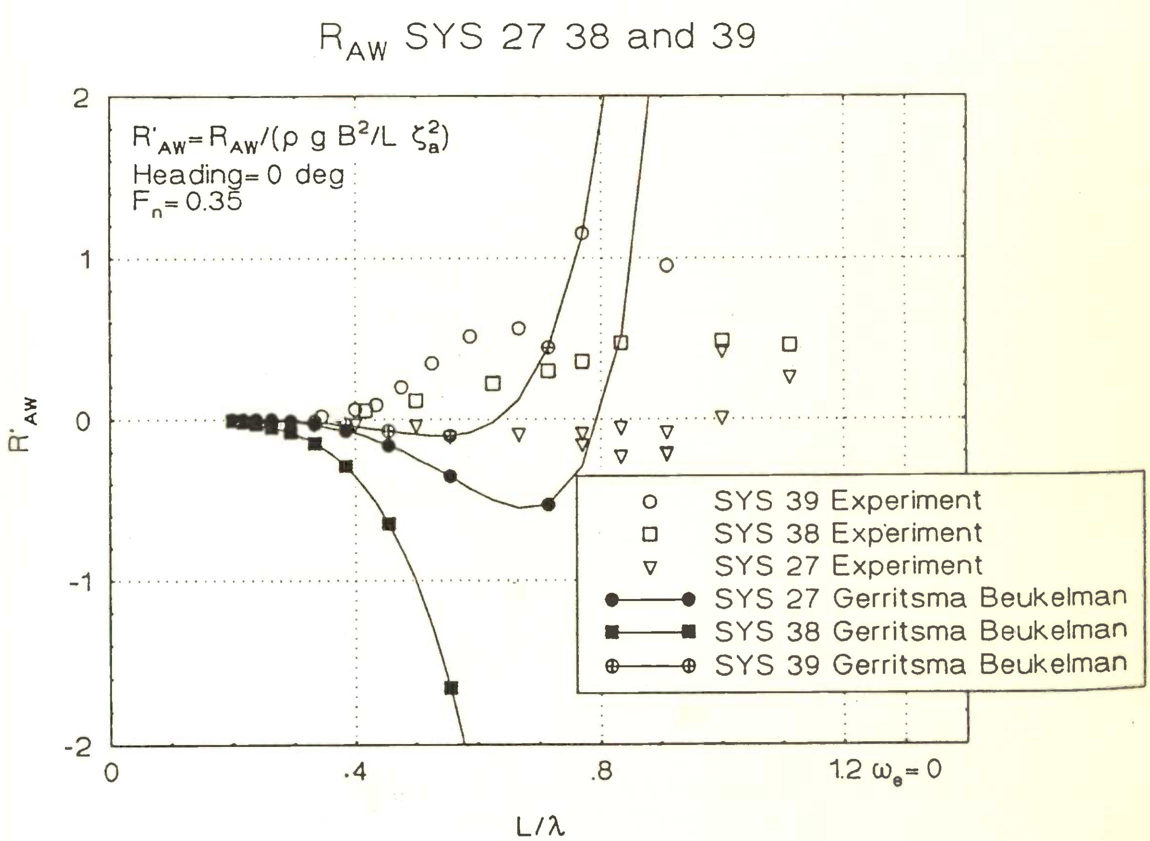


Figure 4: Added resistance in waves at Fn = 0.35

In figure 5 and 6 the results of the surge force measurements are presented as function of the position of the model with respect to the wave-crest for the three different models for three different wavelengths and for a steepness ratio of 25 and 17 respectively.

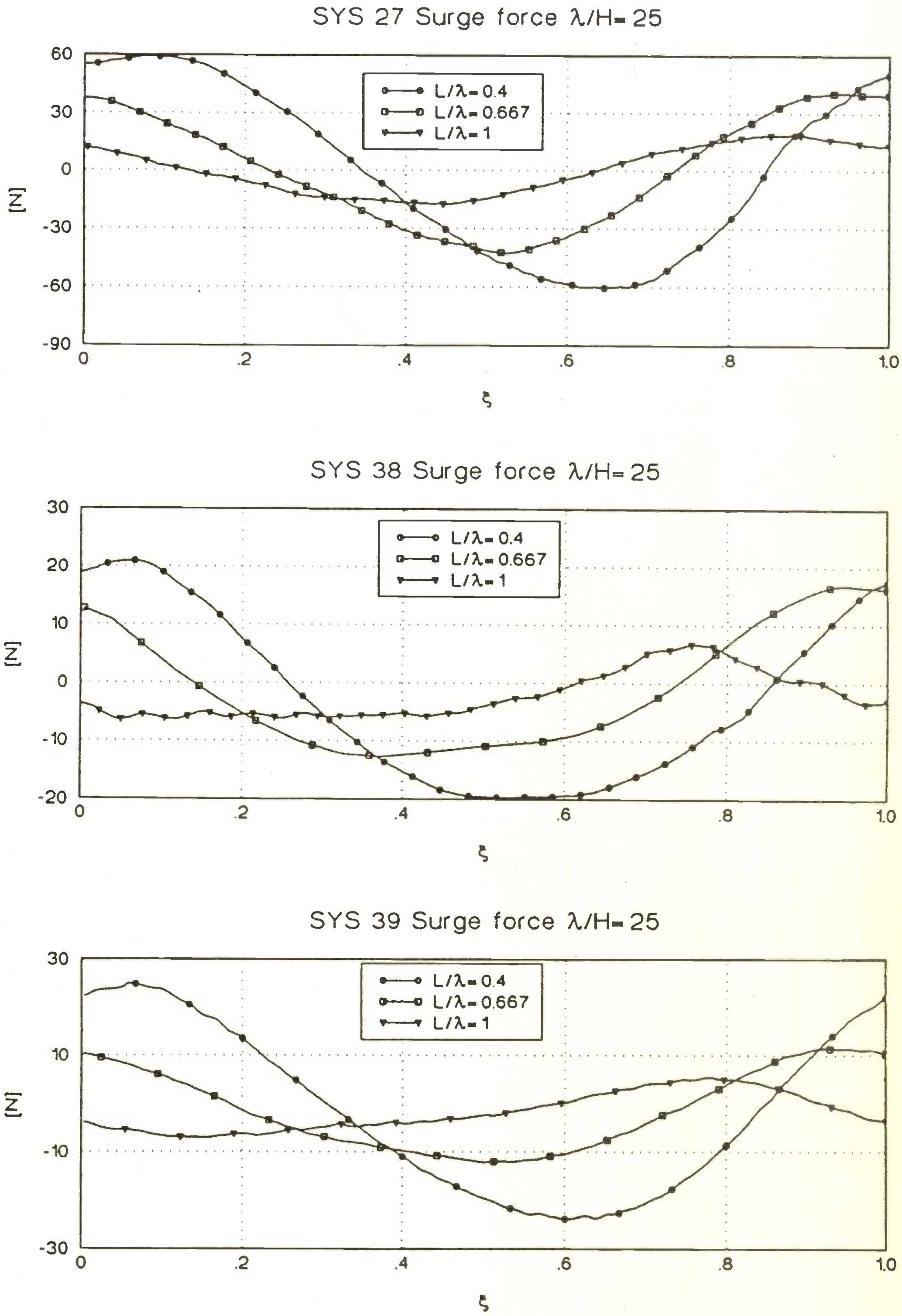


Figure 5: Measured surge force for model #27, #38 and #39 for wave steepness of 25

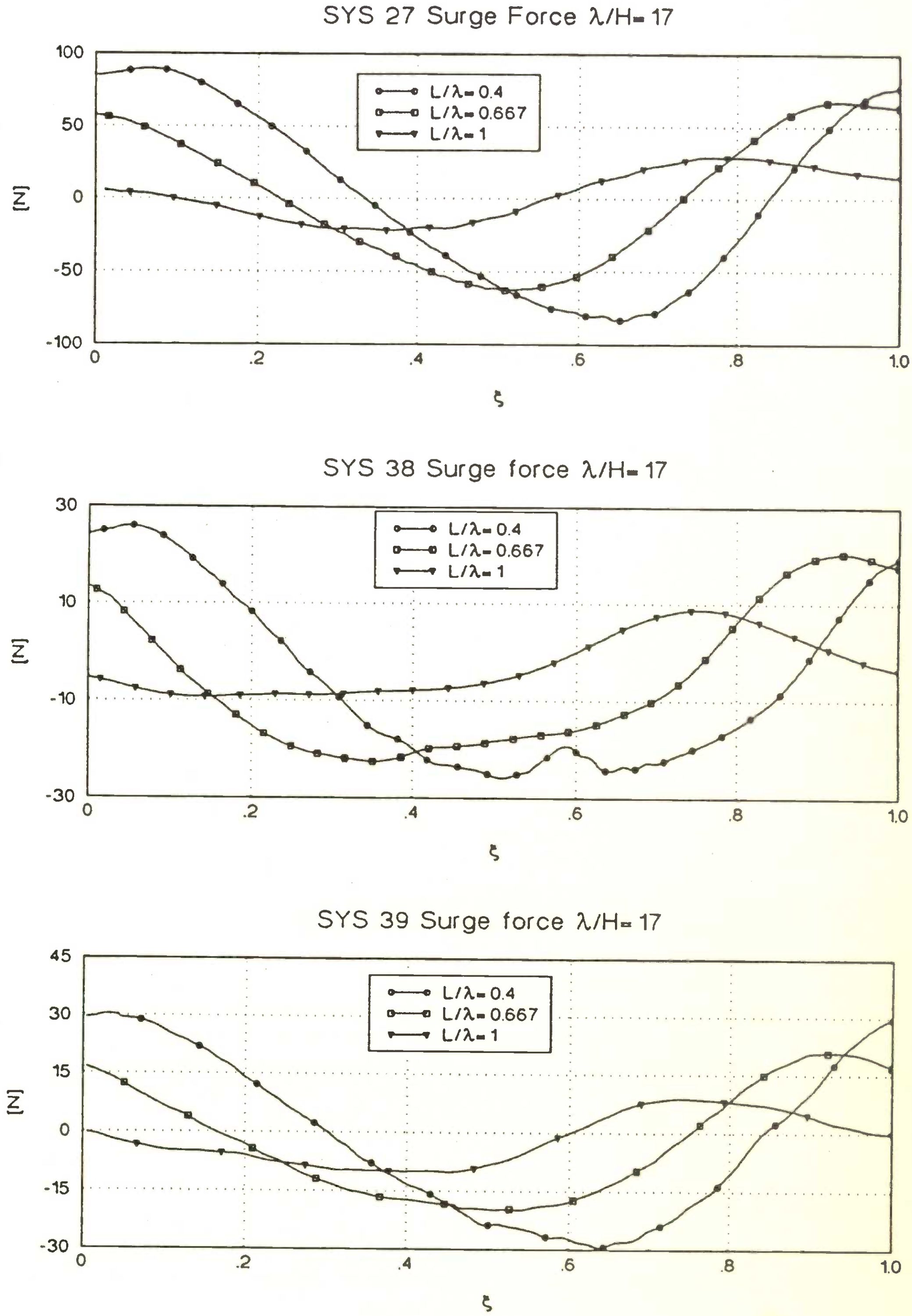


Figure 6: Measured surge force for model #27, #38 and #39 for wave steepness of 17

In Figure 7 only the apparent amplitude of the surge force measured during the experiment as function of the wavelength-shiplength ratio and wave steepness is presented for the three models.

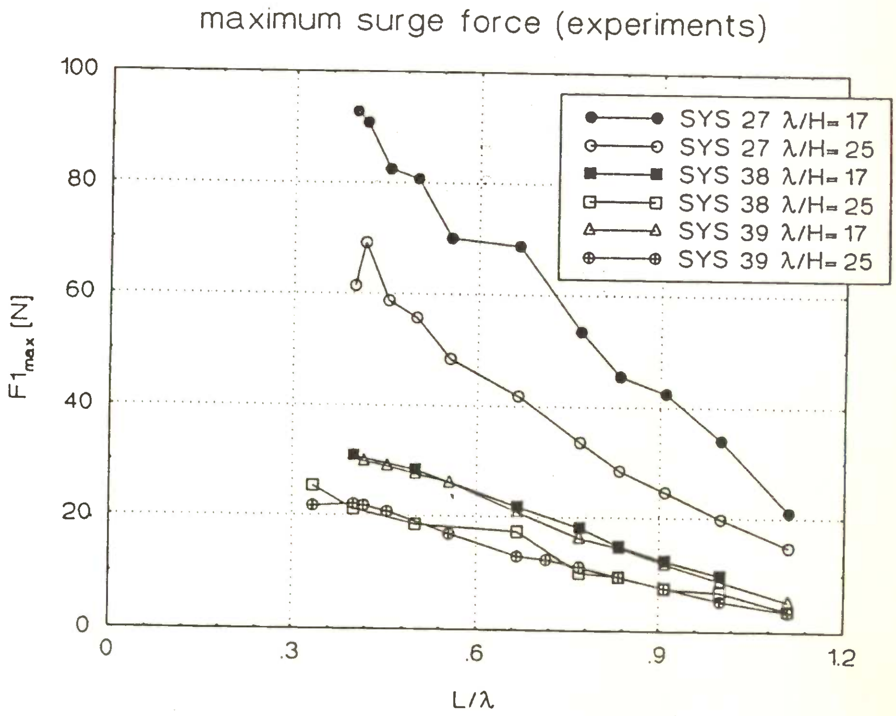


Figure 7: Maximum amplitude of the surge force measured as function of wave length and wave steepness.

5 *Discussion of the results.*

As may be seen from Figure 4 the magnitude of the added resistance of the models at constant forward speed in following waves is relatively small. The correlation with the computations using the Gerritsma-Beukelman approximation for the added resistance in conjunction with a linear strip theory code is poor. This was already known from previous towing tank experiments with models of commercial ships in following waves. It should be noted however that the Gerritsma-Beukelman approximation was never intended for use in these conditions, i.e. following waves.

From Figure 7 (it should be noted that full dimensional surge forces are presented here) it may be concluded that the maximum amplitude of the surge force is roughly proportional to the weight of displacement of the model for all three models, i.e the heavier model experiences larger surge forces. This dependency appears to be a rather linear relation.

From the results it is also obvious that there is a strong relation between wave height and apparent amplitude of the surge force, which however proved to be nonlinear with respect to the waveheight.

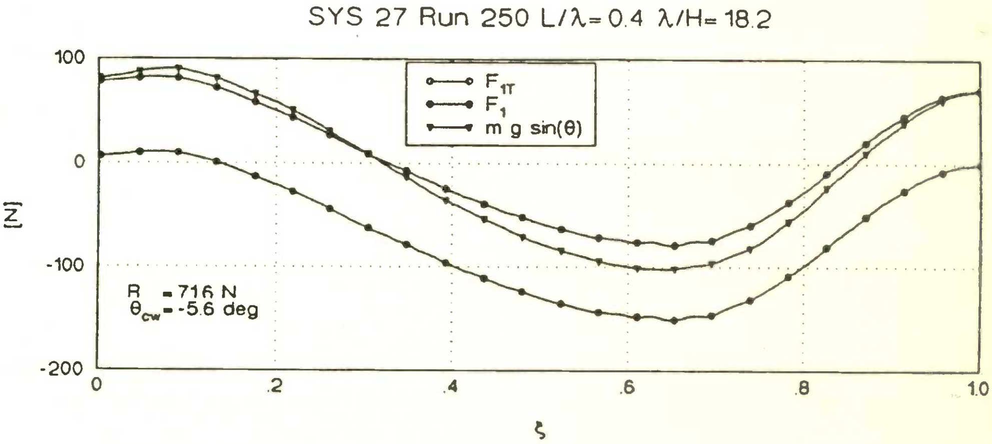
From Figure 5 and 6, showing the surge force as function of the position of the wave top with respect to ordinate 0 of the model, the strongly non-linear character of the force with respect to the phase of the wave may be seen. This is particu-

lary true for the lighter and/or beamier models and appears to increase with increasing wave steepness. These results correspond with the results found by Renilson on his fishing boat models. All models experience the largest surge force whilst being on the wave crest of the following wave, although there is a shift in phase ξ with increasing wavelength.
This of course explains the importance of a nonlinear time domain simulation when assessing the surge and/or surf-behaviour of craft in following waves. Due to the low frequency of encounter and the large non-linearity an assesment using the period-averaged value as customary in the usual (headseas) added resistance calculations is not justifiable.

A first attempt to approximate the measured surge force was made by using the measured pitch motion of the craft and use this in the simple formulation:

$$F_{surge} = m\ g\ \sin(\theta)$$

in which (m * g) should be considered to represent the displaced volume of the craft rather than the weight which ofcourse would not yield a horizontal component.
The result of such a approximation is presented in Figure 8 for two different cases.



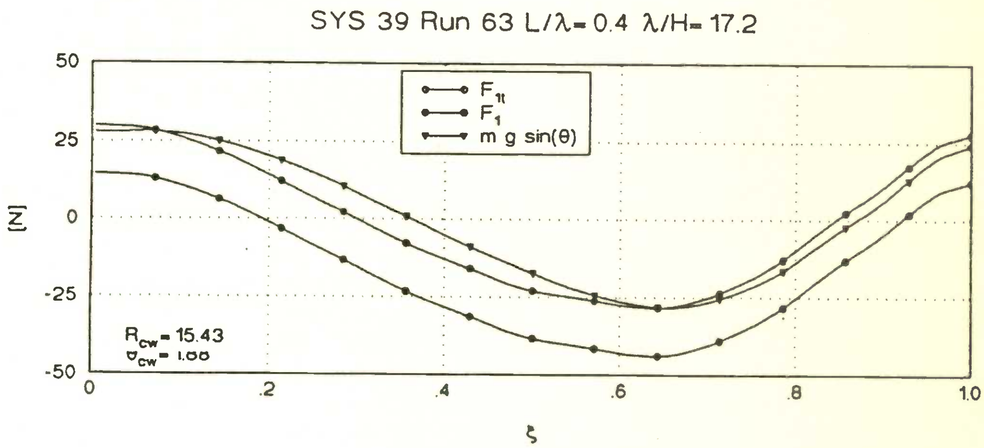


Figure 8: Approximation of the surge force using
$F_{surge} = m * g \sin(\theta)$

As may be seen from this figure the correlation the measured and the approximated surge signal is astonishing good, for both conditions.
This approximation actually represents a Froude Kriloff approach of the surge force, as it has also been used by Kan and Renilson.
Renilson used an approximation based on the maximum submerged cross sectional area of the hull only. The results of his calculations for the three models investigated in this study are presented in Figure 9. His approximation yields the maximum exciting surge wave force amplitude only and does not provide any information on the dependency of the force on the position of the craft on the wave.

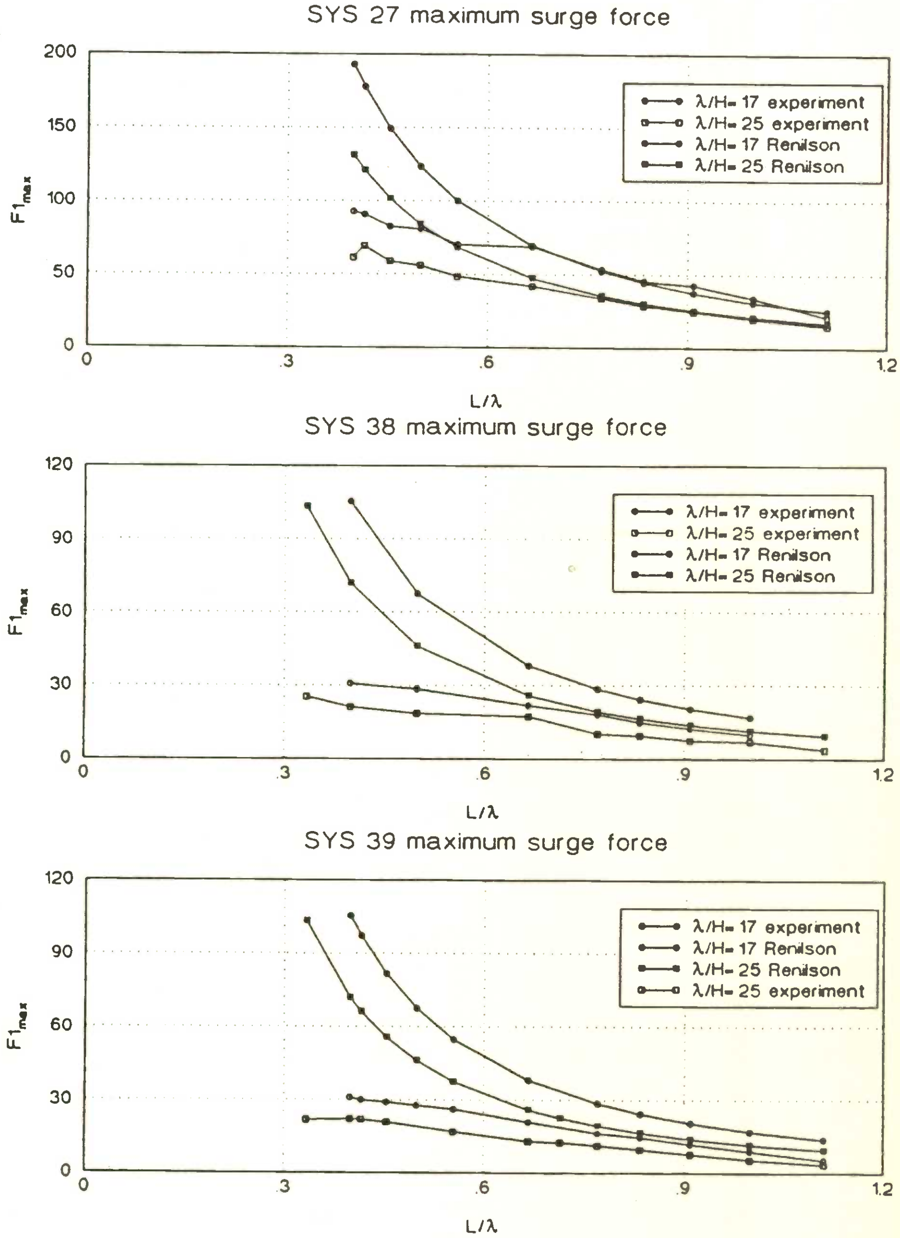


Figure 9: Maximum surge force as calculated using Renilson compared with the measurements.

Kan however presents an approximation which yields the force as a function of phase also.
He used a linear calculation method of the wave excited surge force based on a Froude Kriloff approximation, which does not yield the considerably non-linear character of the wave excited surge force with respect to the phase ξ.

The Froude Kriloff approach to the wave excited surge force in these large waves at near surfing conditions however is quite justifiable because diffraction and radiation effects may be considered to be small due to the very low frequency of encounter of the incoming wave and the relatively large wavelengths.
The linear approach however does not appear to be justifiable, which may be due to the large relative motions performed by the craft with respect to the incoming wave and the resulting rather significant change in actually submerged hull geometry associated herewith.

Therefore it was decided to calculate the wave excited surge forces using a modified version of the code SIMMOLO as developped by Adegeest and described in Ref 4.
Using this code the integral of the Froude Kriloff pressures over the instanteneous wetted area of the heaving and pitching model in waves is being calculated.
The sinkage and the trim of the model due to its high forward speed had to be brought into the calculations since the code SIMMOLO did not yield those results. These have been taken from the results of the towing tank measurements. In the simulation model the force and moment causing the sinkage and trim have been included as an additional time independent buoyancy force equivalent to the force and moment resulting from the sinkage and trim. This proved to be a significant modification to the calculated results. During the simulations the model was fixed in longitudinal direction. The force in the earth-fixed X direction has been used.

The results of these calculations are shown in Figure 10 and Figure 11 for model #27 and #39 respectively. The calculations are presented in this report for two wavelengths, i.e. 2.5 and 1.0 times the waterline length of the model and for the steepest wave only.
As may be concluded from these figures the correlation between the measured and the calculated wave excited surge force is quite good, in particular for the longer wave. Both the wave excited surge force amplitude as the character of the force with respect to the parameter ξ are quite properly predicted. In the shorter wave some discrepancies still occur. Within the scope of the present study it was not possible to investigate whether this was due to hull representation and/or numerical problems within the code or due to the ommittance of the mentioned diffraction and radiation effects. It seems however that the proper prediction of the force by incorporating the nonlinear effects may be of greater importance..

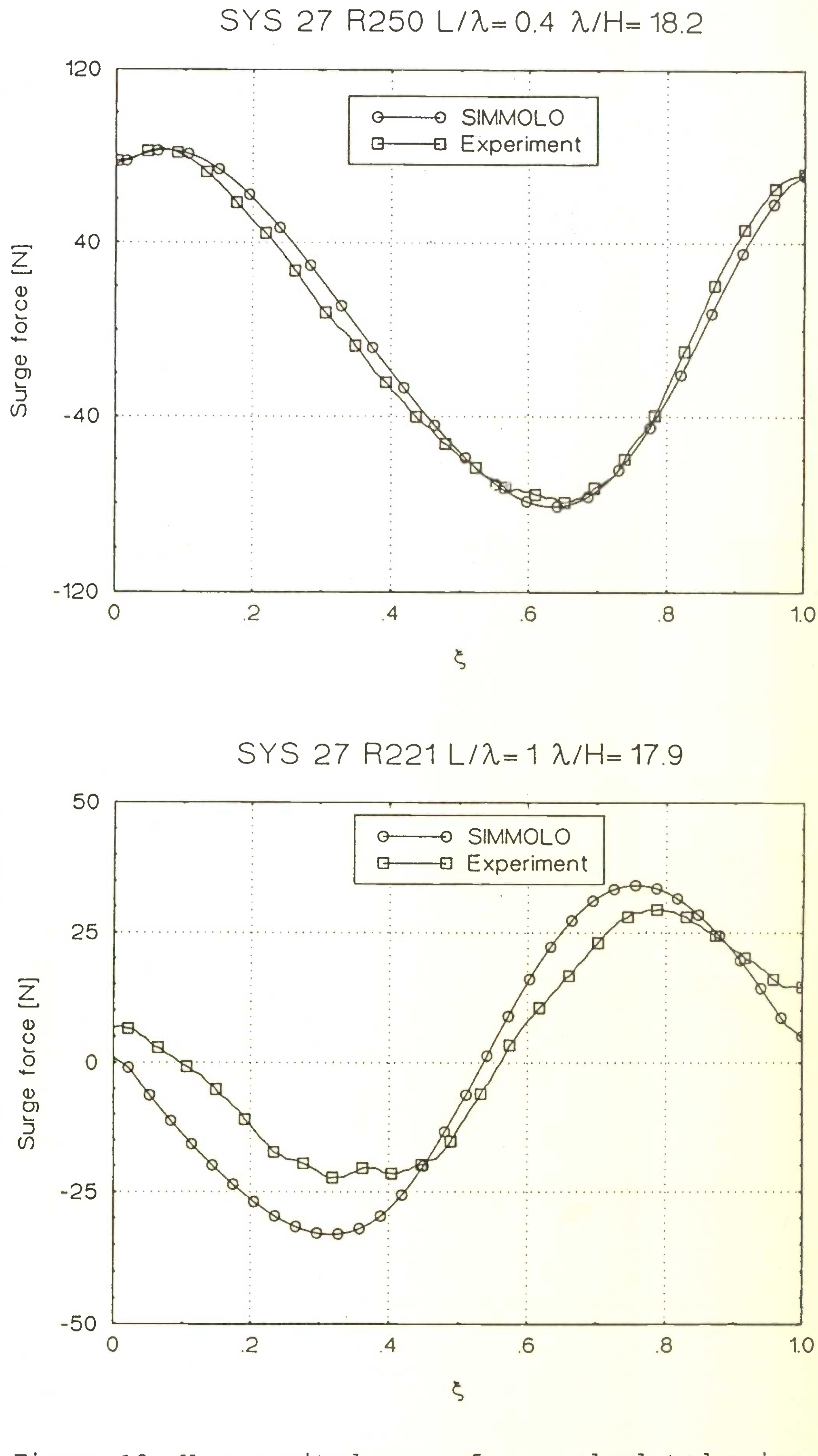


Figure 10: Wave excited surge force calculated using SIMMOLO for model #27

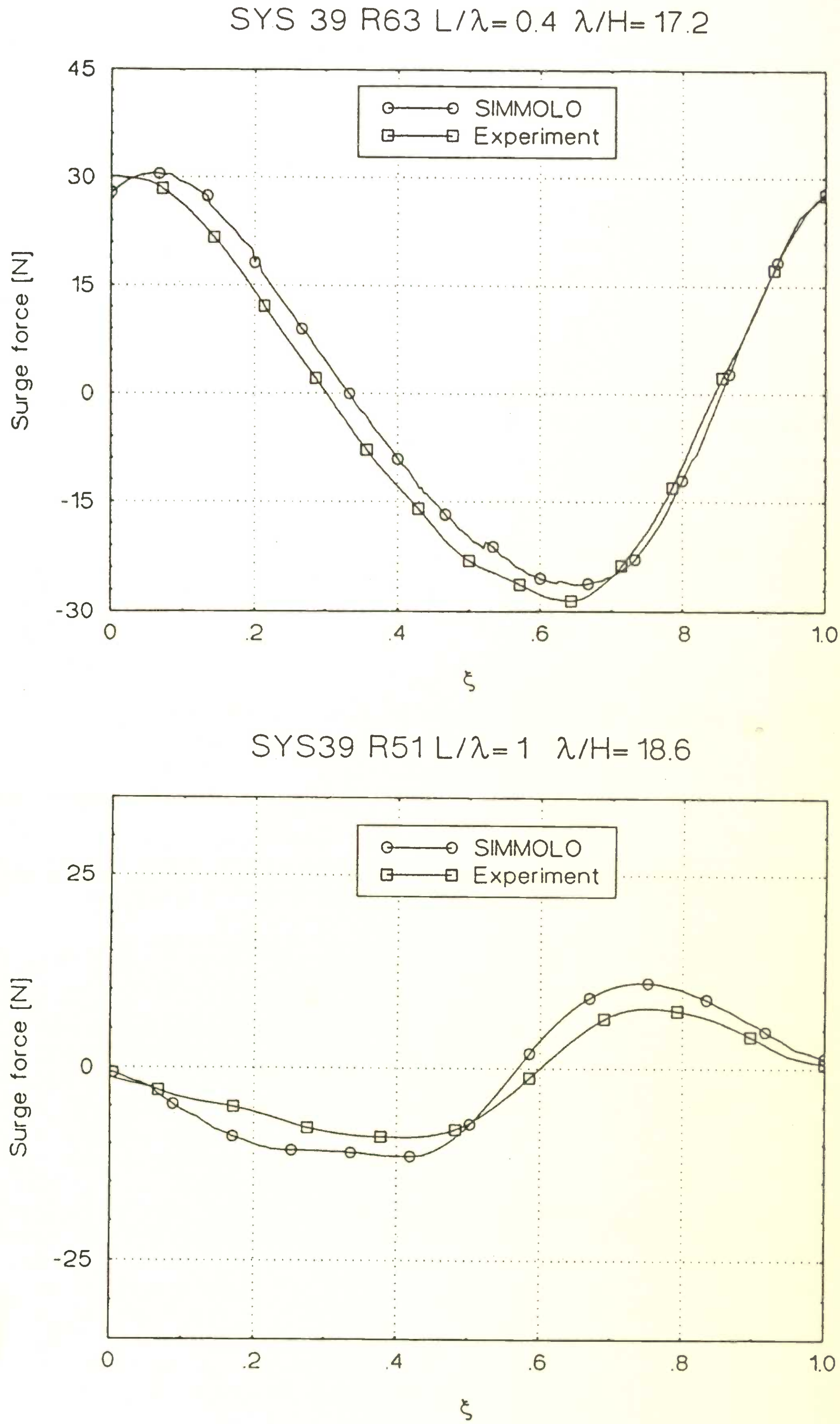


Figure 11: Wave excited surge force calculated using SIMMOLO for model #39.

6 *Conclusions.*

The wave excited surge force on a craft in large following waves can be calculated using a non-linear Froude Kriloff approximation using the actual wetted surface of the craft with respect to the incoming waves and due to its relative motions. Both the amplitude as well as the non-linear character of the force with relation to the position of the craft on the wave can be properly predicted. The inclusion of the non-linear effect appears to be more significant than the possible effect of diffraction and radiation in those circumstances.

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List of Symbols

B	Beam [m]
L	Length (waterline) [m]
F_n	Froude number [-]
F_{IT}	Measured total x-force (earth_fixed) [N]
F_I	Wave excited surge force (earth-fixed) $F_{IT}+R_t$ [N]
H	Wave height [m]
R_t	Calm water model resistance [N]
R_{AW}	Added resistance in waves [N]
R'_{AW}	Dimensionless added resistance in waves [-]
v	model speed [m/s]
ζ_a	Wave amplitude [m]
θ	Pitch angle [deg]
λ	Wave length [m]
ξ	Position of model relative to wavecrest [-]
ρ	Mass density of water [kg/m$_3$]
ω_e	frequency of encounter [rad/s]