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MEASUREMENTS AND CALCULATIONS OF SHIP RESISTANCE IN WAVES

by

O. J. Sibul

This research was carried put under the Naval Ship Systems Command General Hydromechanics Research Program, Project S-R 009 01 01, administered by The Naval Ship Research and Development Center

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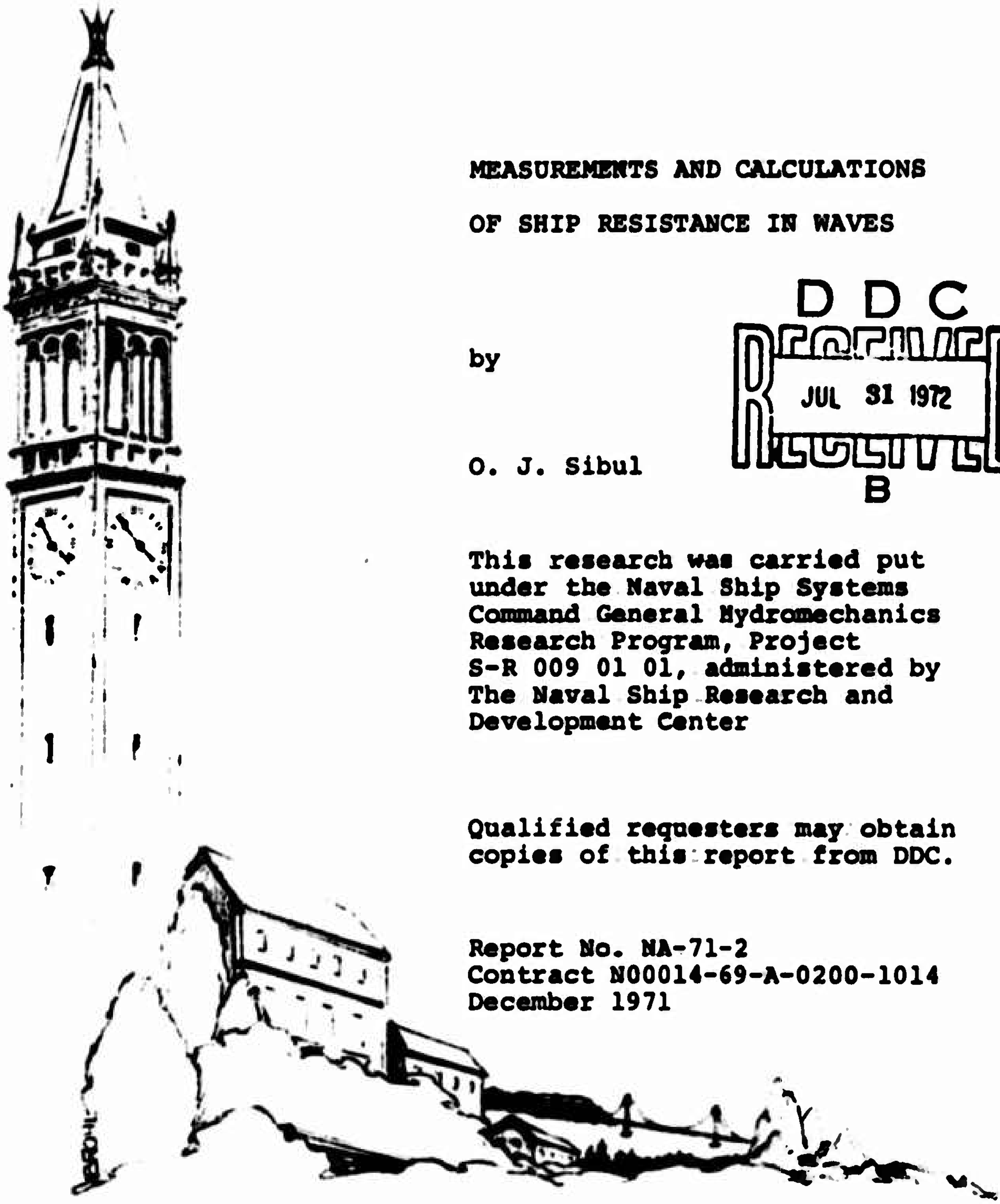

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There are indications that it may be possible to establish standard series of hull forms for added-resistance calculations from available data. The added resistance data is tabulated for Series 60 hull forms.

Drift force in waves was measured on a Series 60, C_B = 0.60 model and compared with Newman's theory.

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NOMENCLATURE

A	Wave amplitude = $\frac{H}{2}$
B	Beam of the ship, in feet
D	Draft of the ship, in feet
$\bar{F}_x$	Average drift force, in pounds
F_N	Froude number: $\frac{v}{\sqrt{gL}}$
g	Acceleration due to gravity
H	Wave height, in feet
$H_{sign}=H_{1/3}$	Significant wave height, i.e. the average of the 1/3 highest waves
K	Wave number $\frac{2\pi}{\lambda}$
K_W	Added resistance coefficient
L	Length of the ship on waterline, in feet
R_a	The added resistance due to a wave component, in pounds. It is the difference between the resistance in waves and in calm water.
R_{ta}	The total added resistance in a spectrum of waves
$S(\omega)$	Spectral density
$S(\omega_e)$	Spectral density of wave encounter
T	Wave period, in seconds
$T^2(\omega_e)$	Transfer function (response operator) = $\frac{1}{A^2} R_a(\omega_e)$
V	Ship speed, in knots
v	Ship speed, in ft/sec
Δ	Displacement, in pounds
λ	wave length, in feet
ρ	Density of water
ω	Circular frequency $\frac{2\pi}{T}$
ω_e	Circular frequency of encounter

I. INTRODUCTION

One of the main objects of the present study was to investigate the difference in results for constant-thrust and constant-velocity methods of towing ship models in waves. A new dynamometer was developed to measure the added resistance of small ship models in waves while the model is towed at a constant velocity. The instrumentation and preliminary results were described in Reference 1. The results indicated a reasonably good agreement between the constant thrust and constant velocity methods of towing. The investigation was continued for several additional hull forms and the results are given in this report.

The study establishes that the constant-thrust and constant-velocity methods yield equivalent results. The constant-velocity method is easier to perform and the results are more accurate.

During several years of investigation, the question has been asked whether the added resistance in waves is proportional to the second power of the wave height. This relationship is necessary if the spectral method in its present form is to be applicable in predicting the added resistance in irregular waves. Hence, the more accurate constant-velocity method was used to study the effect of wave height on the added resistance. The guarded recommendation resulting from this study is that the spectral method may be accepted at the present state of the art. The limitations described in the report should be kept in mind, as the response operators are derived in uniform-wave tests.

The ultimate objective of the study is to provide the designer with a means of estimating the resistance of a new design in various sea states. The necessary response operator can be calculated theoretically, or derived experimentally in uniform waves. At the present time the theoretical calculations yield somewhat questionable results. An empirical response operator, on the other hand, requires that a model be built for each proposed design and tested in uniform waves. It may be possible that this can be avoided when adequate experimental data are available, and arranged in tables, similar to those for the Taylor Standard Series in calm water. Some tests have been made to investigate the feasibility of this idea. Earlier results are presented in dimensionless form and tabulated for easy application for computer calculations.

The instrumentation and methods of towing were described in Reference 1. Hence, they will not be repeated here. The objective of this report is to present and discuss new results.

II. CONSTANT-THRUST AND CONSTANT-VELOCITY METHODS OF TOWING

The first set of experiments to compare the two different methods of towing was made in irregular waves with a fine model of block coefficient $C_B = 0.49$. The results as reported in Reference 1 indicated that the measurements by the two methods agree reasonably well under the given conditions. Later the work was extended to three Series 60 5-foot models. The results are given in Figures 1 and 2 for $C_B = 0.60$, in Figure 3 for $C_B = 0.70$, and in Figure 4 for $C_B = 0.80$. All the models were towed by the constant-velocity method at a speed corresponding to a Froude number equal to 0.20. In addition, the $C_B = 0.60$ model was tested also at a speed corresponding to a Froude number of 0.30. At least 10 different wave lengths were used for each set of experiments to achieve a good definition of the curve. The wave heights were adjusted in each case to give a reciprocal wave steepness $\lambda/H = 40$. Several runs were made in each set of tests to measure the calm water resistance for the given speed. The added resistance R_a was calculated as the difference between the calm water resistance and the total measured resistance in a given wave condition. The data plotted in Figures 1 to 4 have a form which is accepted as the response operator and used to calculate the response spectrum. Δ is the total displacement of the model in pounds, and H is the wave height, measured from the trough to the crest (double amplitude). One has to remember that the parameter is not dimensionless, and adjustments have to be made if the results are applied for different scale ratios.

The results for constant-thrust tests, as given for comparison in Figures 1 to 4, were taken from earlier experiments, reported in Reference 2.

There is some difference in results. However, no trend can be established. It is thought that the difference could have been caused by a possible error in constant-thrust measurements, for such measurements are very hard to perform. Because of the friction between the subcarriage and the main carriage, it takes a certain force to get the subcarriage rolling, with a resultant dead-span. This results in a range of uncertainty for the exact value of the resistance. Another possible source of error in constant-thrust measurements is the fact that the calm-water resistance was measured in separate sets of experiments, and not in consecutive runs with the wave tests, as was the case in the recent set of tests for constant velocity. The results of constant-velocity tests exhibit very good repeatability, and it is not hard to draw a curve through the experimental results.

From these results, as well as from the results reported in Reference 1, it is concluded that either method can be used to measure the added resistance in waves. The constant-velocity method is recommended because it is much simpler to apply, and the results are more accurate and reliable.

III. THE RELATIONSHIP BETWEEN THE ADDED RESISTANCE AND THE WAVE HEIGHT

There has been some question as to whether the linear spectral method can be used to predict the added resistance in irregular waves from the responses as measured in regular waves. The linear spectral method can be used for cases where the response is proportional to the input (such as ship motions), and also where it is proportional to the second power of the input.

It is artificial to look for exponential dependence of the added resistance upon the wave height. The depdence is some function of a more complicated form, in fact, a function of several variables. However, at the present time we need a relatively simple engineering solution to predict the powering requirements for various ship hull forms in waves. Present applications of the spectral methods require that the added resistance be proportional to the second power of the wave height for a given wave length. It is necessary to determine for what range of hull forms, speeds, frequencies, etc. (important for a naval architect), the second-power relationship can be used with sufficient accuracy to yield results which are acceptable from the engineering point of view.

The second-power relationship between the added resistance and the wave height seems to be approximately true for merchant ships, but considerable variation has been found for ships of low block coefficients, especially at low speeds and smaller wave heights. Hence, extensive experiments were made by the constant-velocity method of towing to study the relationship between the wave height and the added resistance. The results are given in Figures 5 through 7. The steepness experiments were made in wave lengths which give a nearly maximum response in added resistance for the given Froude number. The λ/L values, where the steepness effect experiments were made, are indicated in Figures 1, 3, and 4.

Figures 5, 6, and 7 indicate that the results for the entire range of wave heights cannot be represented by a single straight line. This is actually nothing new. The same phenomenon was found in earlier experiments (Reference 2, Figure 36) where the power of wave height (slope of the line on log-log scale) varied depending upon the hull of the ship, the Froude number, and the wave steepness. It is interesting to note, however, that the data for waves steeper than approximately 1:60 can be represented rather well by a line with slope 2. The differences occur for lower waves. This is completely contradictory with what we would expect. No explanation can be offered at the present time. Theories for wave forces on ship hulls, as well as ship motions, are based on waves of small steepness. Naturally one expects to use experimental results obtained in waves of small height. Furthermore, green water was washing over the deck in most of the experiments where waves were steeper than 1:40 (see Figures 5-7). This is a condition an experimenter tried to avoid, because of the expected nonlinearities, and also the fact that the deck of the model does not always represent an actual condition on a full-size ship. At the present time we do not know the complete answer to the problem. It may be that testing should be done in regular waves with water washing over the deck, because most cases, where we are interested in added resistance, occur in heavy seas with green water on deck. Considering all this and the fact that we do not have any other reliable method to predict the resistance of ships in a seaway, it is recommended that the spectral method be accepted as the best that can be achieved in the present state of the art. The response operator should be derived from tests in regular waves with the reciprocal wave steepness $\lambda/H < 60$. An approximate value of $\lambda/H = 40$ can be recommended. This wave size will give forces which can be measured with good accuracy using even relatively small models. Furthermore, it has been customary to derive the response operator for the ship motions in the same wave-steepness range.

IV. RESPONSE OPERATOR FOR SERIES 60 MODELS

The main reason for the present study was to provide the designer with a means of estimating the resistance of a new design in various sea states. Our evidence above indicates that the spectral method can be used to estimate the added resistance in waves with sufficient accuracy for practical purposes. The necessary response operator can be calculated theoretically, or derived experimentally in uniform waves. Theoretical calculations yield somewhat questionable results at the present time. An empirical response operator requires, on the other hand, that a model be built for each proposed design and tested in uniform waves. It may be possible that this can be avoided when adequate experimental data are available, and arranged similarly to the standard resistance series in calm water. To make a start, the data of the Series 60, C_B = 0.60, 0.70, and 0.80 models were plotted in Figure 8 as a dimensionless added resistance coefficient K_W against dimensionless frequency $\omega_e\sqrt{\frac{L}{2\pi g}}$. Curves are in very good agreement with each other in the range $1.0 < \omega_e\sqrt{\frac{L}{2\pi g}} < 1.8$. Block 0.70 and 0.80 models yield almost identical values, except for short wave lengths. The model with block coefficient 0.60 has somewhat reduced resistance in longer waves, while for intermediate wave lengths the results are identical with the other two models. For short waves ($\lambda/L < 0.65$) there is some indication that the curve will go up again after passing a minimum. This range should be further investigated. It can be done better with larger models. For small models the wave lengths are so short in this range that the wave heights are reduced appreciably by viscous effects and the tank-wall resistance as the waves travel down the tank. This range should not be ignored. For a 500 ft. ship $\lambda/L = 0.65$ means a wave length λ = 325 ft., or period T = 8 sec. Sea states up to 7 have appreciable energy levels at this period.

It is recommended that the study of added resistance in waves should be extended to hull forms other than Series 60. A systematic investigation may establish parameters which can be used to relate a given new design to data which are already available and can be used for the feasibility study of the new designs.

The results should be given in curves as well as in tabulated form so that a tedious and inaccurate reading of the curves may be avoided. The curves serve to provide the basis for a preliminary inspection for such parameters as the location and size of the maximum response, as well as the area under the curve. An easy way to relate the location of the maximum response to various sea states and ship velocities is very important. It can be done in several ways. One possibility is given in Figure 9, which helps to translate the dimensionless frequency $\omega_e\sqrt{\frac{L}{2\pi g}}$ as given in Figure 8 into a more meaningful wave-length/ship-length ratio λ/L. Curves in Figure 9 are based on the following relationship which can be easily derived:

$$\omega_e \sqrt{\frac{L}{2\pi g}} = \frac{1}{\sqrt{\lambda/L}} \left(1 + F_N \frac{\sqrt{2\pi}}{\sqrt{\lambda/L}}\right)$$

It is recommended that data should be collected by using the constant-velocity method. This method is very much easier to handle, and the results are more accurate (1).

A considerable amount of data has been collected over the years by the constant-thrust method. The data for Series 60 models, as given in Reference 2, have been rearranged and are given here as Figures 10 to 12, and tabulated in Tables I and II. The data are arranged so that it can be easily used as computer input to calculate the added resistance in irregular waves for any desired scale. Let K_W be the added resistance coefficient, so that

$$R_a = K_W \rho g\ A^2\ \ B^2/L \tag{1}$$

This coefficient was used by Maruo (3) in his theory of the added resistance in waves.

According to the spectral method, the relation between the resistance in a random seaway, the resistance in regular waves, and the sea spectrum is given by the following formula:

$$R_{ta} = 2 \int_0^\infty S(\omega_e) \quad T^2(\omega_e) d\omega_e \tag{2}$$

Here R_{ta} is the total added resistance in a spectrum of waves, $S(\omega_e)$, which has been corrected to the frequency of encounter, ω_e; $T^2(\omega_e) = \dfrac{R_a(\omega_e)}{A^2}$ is the response operator, $R_a(\omega_e)$, the added resistance in uniform waves, and $A = H/2$ is the wave amplitude. The response operator can be easily calculated for a desired scale from tabulated values of K_W:

$$\frac{R_a}{A^2} = K_W \rho g \; B^2/L \tag{3}$$

K_W is given in Table I for Series 60 models. B is the beam of the ship and L the length of the ship. The appropriate period of encounter is

$$\omega_e = \left(\omega_e \sqrt{\frac{L}{2\pi g}}\right) \Big/ \sqrt{\frac{L}{2\pi g}} \tag{4}$$

$\rho g \; B^2/L$ and $\sqrt{\frac{L}{2\pi g}}$ are constants for a given ship size, and can be easily applied by the computer to the tabulated values. The constant 2 in Equation (2) is for the case where the wave spectrum is the so-called half-amplitude spectrum, and the response operator is drawn upon the wave amplitude, and not the wave height (double amplitude). It is important to point out that various forms of spectra are used, such as amplitude, double amplitude, etc. For each case a different constant will apply. This constant can be easily derived, provided that one understands the definition of the given wave spectrum and the response operator.

As already mentioned, Figures 10-12 were derived from earlier tests made by the use of the constant-thrust method. The curves in those figures were used to tabulate the values in Tables I and

II. There seems to be a tendency for the coefficient K_W to increase again for higher frequencies of encounter, after passing a minimum. The tendency exists for constant thrust as well as for constant velocity methods, and is best illustrated in Figure 12. At the present time there are not sufficient data to be more definite, hence it has been assumed for the tabulated values that the curves approach zero as the frequency increases.

For comparison, experimental points from the present constant-velocity tests are plotted also in Figures 10-12.

V. DRIFT FORCE

If the forward velocity of the ship is equal to zero, the added resistance becomes a drift force which causes a freely floating ship to drift (usually in the direction of the wave travel). This force was measured on a 5-foot model of Series 60, C_B = 0.60. The model was fixed in head seas to the dynamometer so that it was restricted against all the motions except heave and pitch. The force on a 5-foot model is very small, hence it was evaluated by the integration method described in Reference 1. The results are given in Figures 13 and 10. In Figure 13 dimensionless parameters are used to match Newman's calculations for the same ship (4). It gives a comparison of the present measurements with calculations in Figure 2 of Reference 4. The results indicate that Newman's theory overestimates the drift force by a considerable amount. The theory predicts that the maximum drift force coefficient should occur in wave lengths λ/L = 0.60 - 0.70. The tests, on the other hand, indicate the maximum at wave lengths equal to the ship length. If the drift force for a 5-foot model of Series 60, C_B = 0.60 is calculated from Newman's data for λ/L = 0.725, and λ/H = 40, the result is a force of approximately 0.42 pounds. This force corresponds to the calm water resistance at a Froude number equal to about 0.35 for the same model.

Figure 10 puts the results in the same perspective as the added resistance of the model in waves, because in fact the drift force corresponds to the mean added wave resistance at zero forward speed.

VI. CONCLUSIONS AND RECOMMENDATIONS

It is concluded:

1. There is no clear difference between the results of constant-thrust and constant-velocity methods of towing. Either method can be used to measure added resistance in waves. The constant-velocity method is recommended because it is much simpler, and the results are more accurate and reliable.

2. It is recommended that the spectral method be accepted for predicting the added resistance in waves. The response operator should be derived from the tests in regular waves with the reciprocal wave steepness $\lambda/H < 60$. An approximate value of $\lambda/L = 40$ can be recommended. The limitation is based on the finding that the added resistance is proportional to the second power of the wave height provided that the waves are steeper than 1:60. There can be a considerable variation in this relationship for low waves.

3. There are indications that it may be possible to establish a standard series of hull forms for the added-resistance calculations. If there are enough data available, new designs can be interpolated in this series, and estimations for the powering requirements in various sea states can be made.

It is recommended that the experimental study of the added resistance in waves be extended to hull forms other than Series 60. A systematic investigation may establish parameters which can be used to relate a proposed design to data which are already available.

TABLE I

Added Resistance Coefficient K_w for Series 60 Models

$\omega_e\sqrt{\frac{L}{2\pi g}}$	K_w for a given Froude Number F_N																	
	C_B = 0.60						C_B = 0.70						C_B = 0.80					
	F_N= 0.00	0.10	0.15	0.20	0.25	0.30	F_N= 0.00	0.10	0.15	0.20	0.25	0.30	F_N= 0.00	0.10	0.15	0.20	0.25	0.30
0.7	0.2																	
0.8	0.3													0.1	0.1	0.1	0.1	
0.9	0.4	0.1	0.1	0.1	0.1	0.1		0.1	0.1	0.1	0.1			0.3	0.3	0.3	0.3	
1.0	0.5	0.8	0.8	0.8	0.8	0.8		0.8	0.8	0.8	0.8			0.9	0.9	0.9	0.9	
1.1	0.7	2.0	2.0	2.0	2.0	2.0		2.6	2.6	2.6	2.6			2.8	2.8	2.8	2.8	
1.2	0.8	4.4	4.4	4.4	4.4	4.4		5.1	5.1	5.1	5.1			5.8	5.8	5.8	5.8	
1.3	1.0	7.1*	7.5	7.5	7.5	7.5		5.2	7.0	8.5	8.5			4.8	8.5	9.9	9.9	
1.4	1.2	5.0	7.6	10.2*	11.4	11.6		3.6	5.4	7.1	10.5			3.9	6.1	7.8	9.7	
1.5	1.2*	3.4	5.9	8.8	10.8	13.2		2.5	4.1	5.3	7.4			3.2	4.3	5.4	6.3	
1.6	1.1	2.3	4.4	6.7	9.0	10.7		1.7	3.0	4.1	5.8			2.6	3.1	4.9	4.4	
1.7	0.8	1.6	3.2	5.0	7.2	8.4		1.1	2.2	3.2	4.7			2.1	2.3	3.1	3.6	
1.8	0.5	1.1	2.3	3.6	5.4	6.5		0.7	1.6	2.4	3.9			1.6	1.8	2.6	3.3	
1.9	0.2	0.7	1.7	2.4	3.9	5.2		0.4	1.1	1.9	3.3			1.2	1.5	2.4	3.1	
2.0	0.1	0.5	1.0	1.6	2.7	4.0		0.2	0.7	1.4	2.8			0.8	1.3	2.2	2.9	
2.1		0.3	0.6	1.0	1.9	3.0			0.3	1.1	2.4			0.5	1.0	2.0	2.7	
2.2		0.1	0.3	0.6	1.1	2.2			0.2	0.8	2.0			0.2	0.9	1.8	2.5	
2.3			0.1	0.3	0.7	1.6				0.6	1.7			0	0.7	1.6	2.3	
2.4				0.1	0.3	1.1				0.5	1.4				0.5	1.5	2.1	
2.5					0.2	0.7				0.3	1.0				0.3	1.3	2.0	
2.6						0.4				0.2	0.7				0.2	1.1	1.8	
2.7						0.2				0.1	0.6					1.0	1.6	
2.8						0.1					0.4					0.8	1.4	
2.9											0.3					0.7	1.2	
3.0											0.1					0.5	1.1	

* maximum value

TABLE II

Location of maximum response for Series 60

Froude No. F_N	$C_B = 0.60$		$C_B = 0.70$		$C_B = 0.80$	
	$\omega_e\sqrt{\frac{L}{2\pi g}}$ for max K_w	MAXIMUM K_w	$\omega_e\sqrt{\frac{L}{2\pi g}}$ for max K_w	MAXIMUM K_w	$\omega_e\sqrt{\frac{L}{2\pi g}}$ for max K_w	MAXIMUM K_w
0	1.50	1.2				
0.10	1.30	7.1	1.24	6.0	1.21	5.8
0.15	1.33	8.3	1.27	7.2	1.28	8.9
0.20	1.40	10.2	1.32	8.7	1.31	10.5
0.25	1.42	11.5	1.36	11.4	1.35	11.8
0.30	1.46	13.9				

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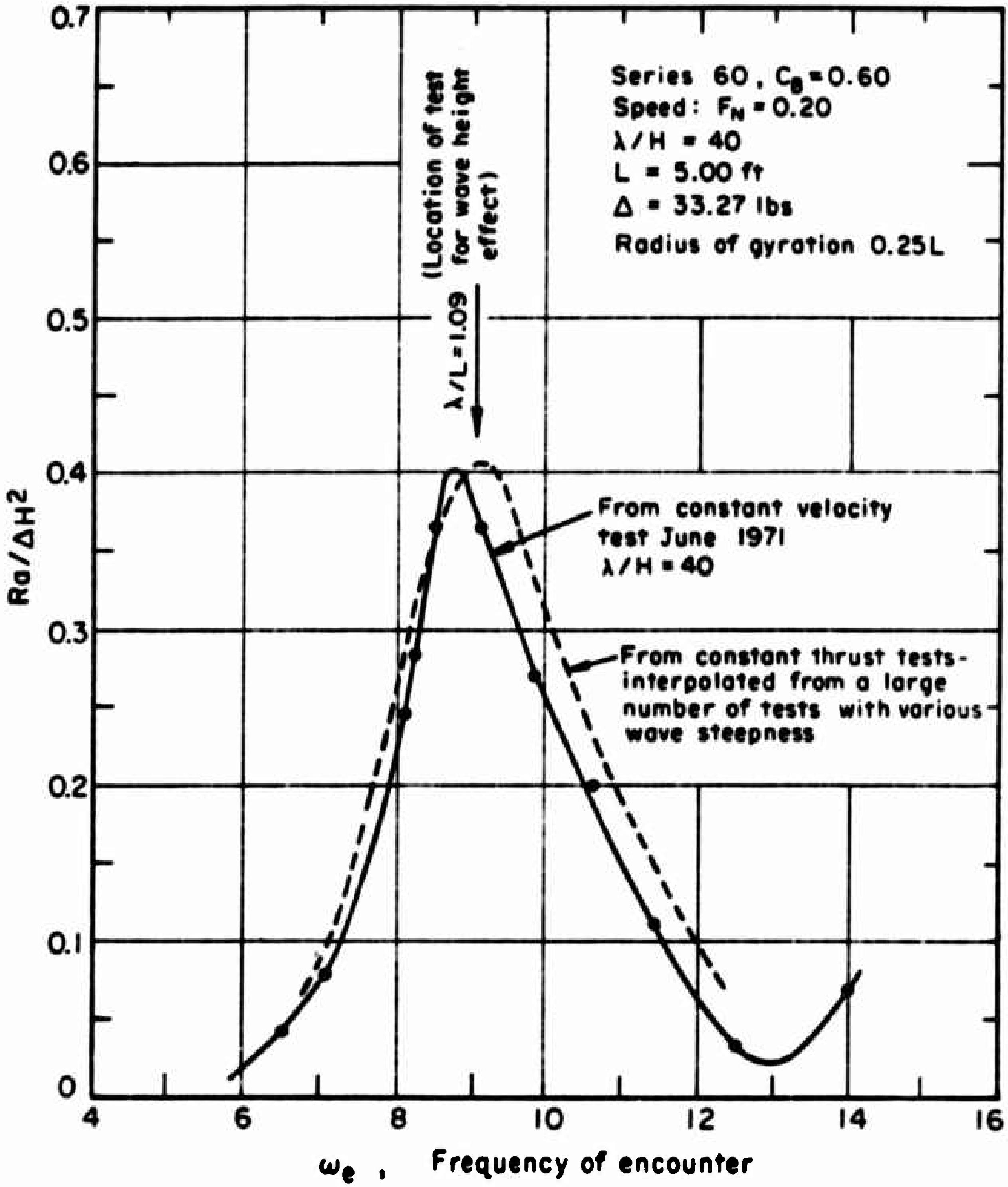

FIG. 1 RESPONSE OPERATOR
(CONSTANT VELOCITY TOWING)

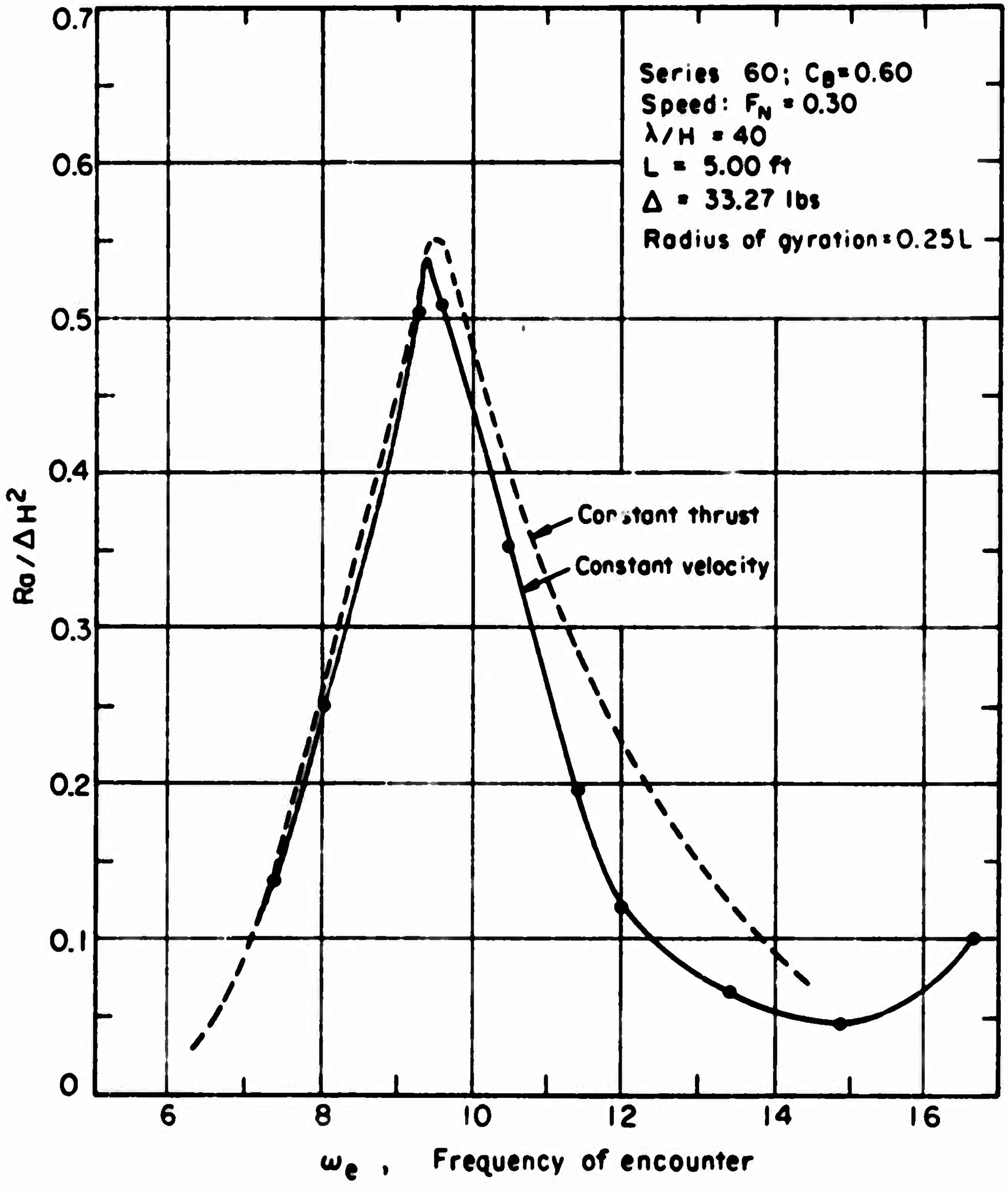

FIG. 2 RESPONSE OPERATOR
(CONSTANT VELOCITY TOWING)

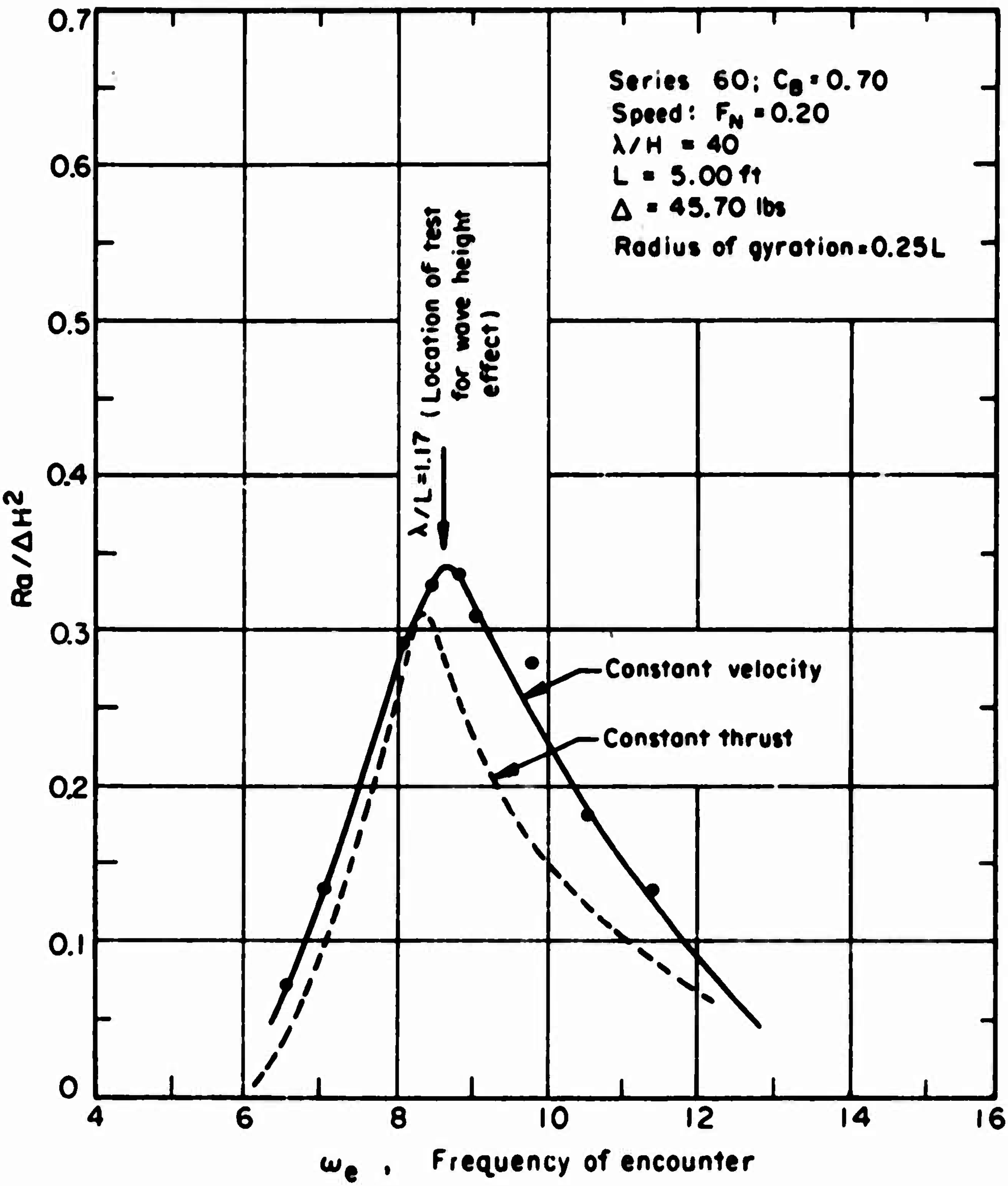

FIG. 3 RESPONSE OPERATOR
(CONSTANT VELOCITY TOWING)

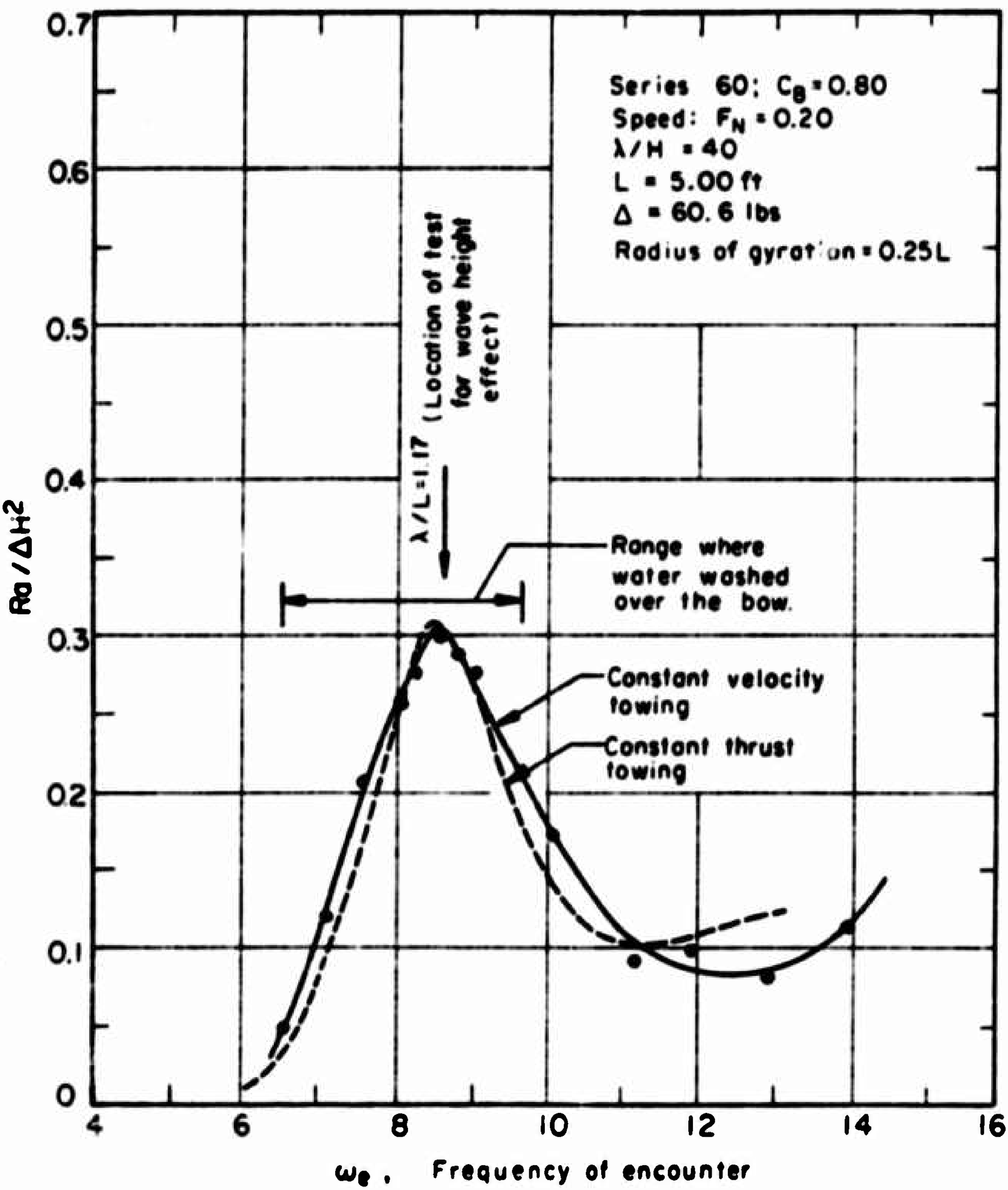

FIG. 4 RESPONSE OPERATOR
(CONSTANT VELOCITY TOWING)

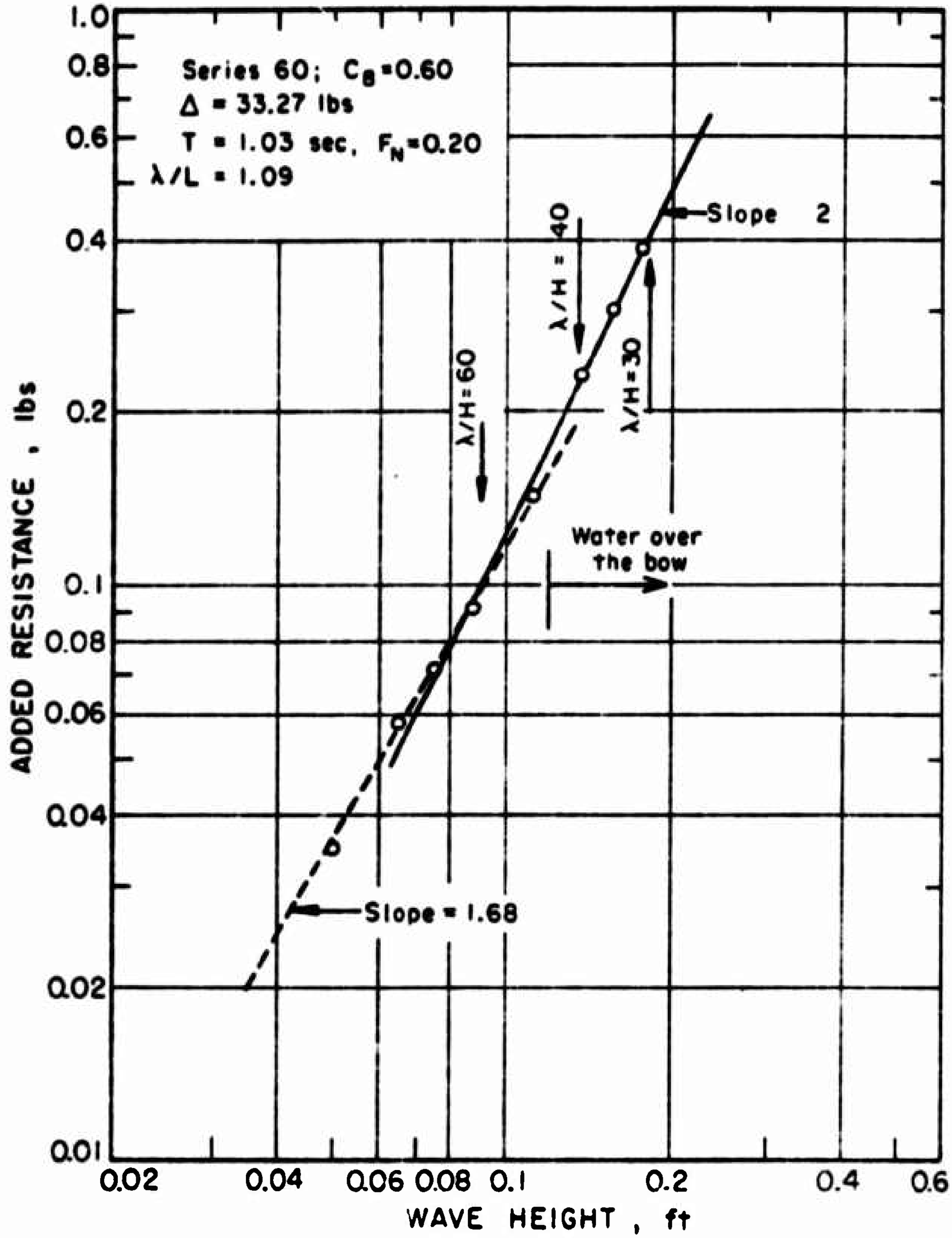

FIG. 5 ADDED RESISTANCE AS A FUNCTION OF WAVE HEIGHT

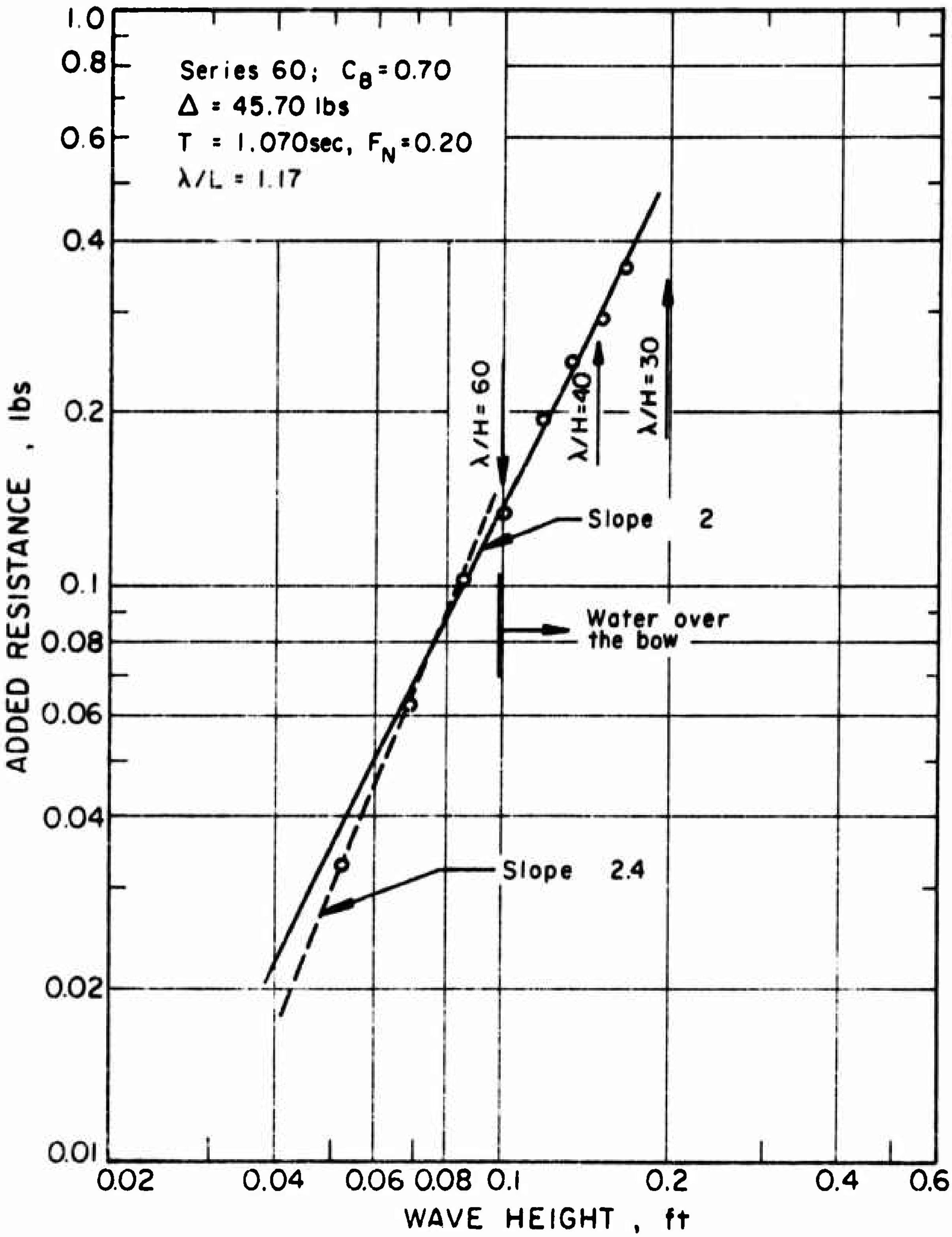

FIG. 6 ADDED RESISTANCE AS A FUNCTION OF WAVE HEIGHT

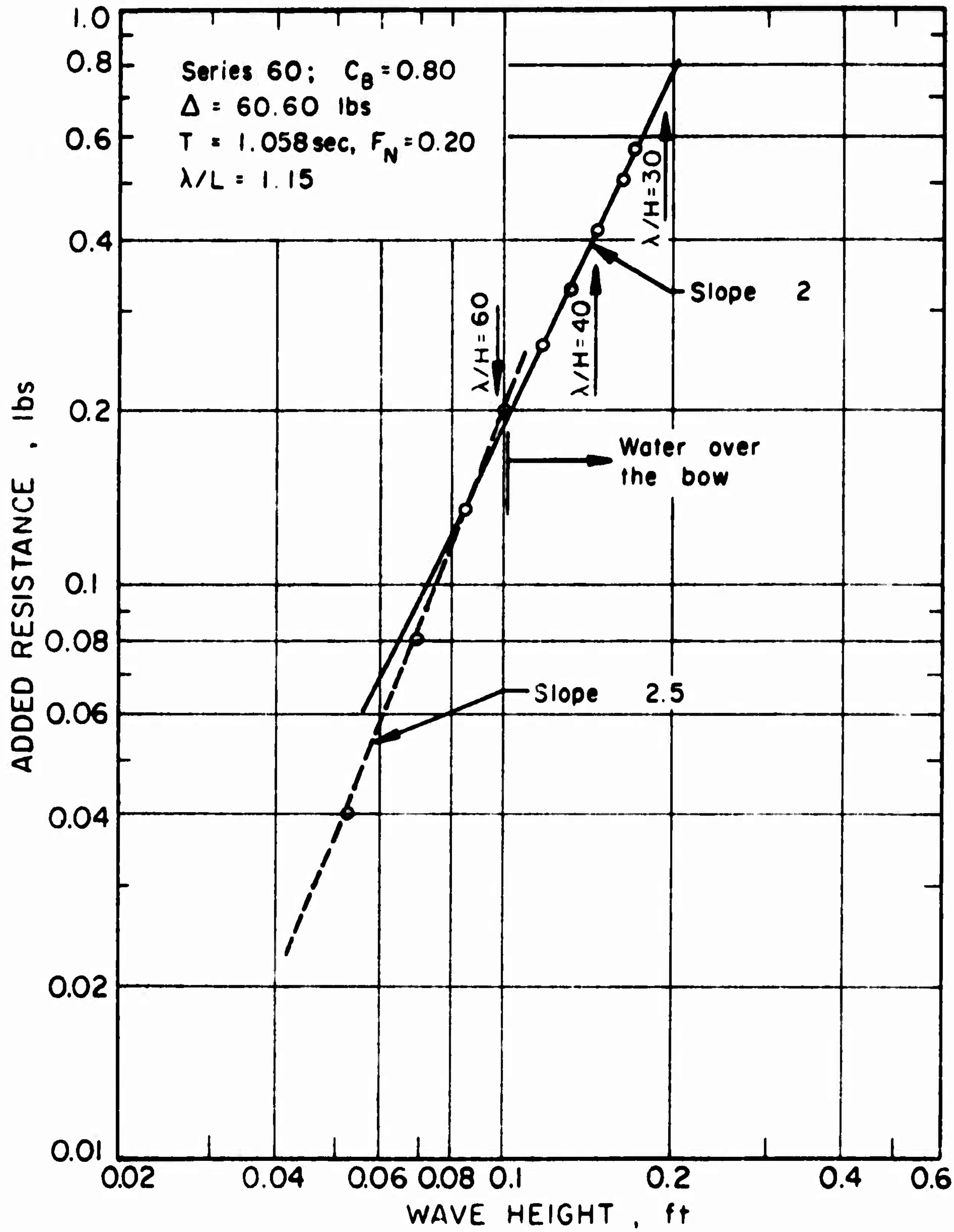

FIG. 7 ADDED RESISTANCE AS A FUNCTION OF WAVE HEIGHT

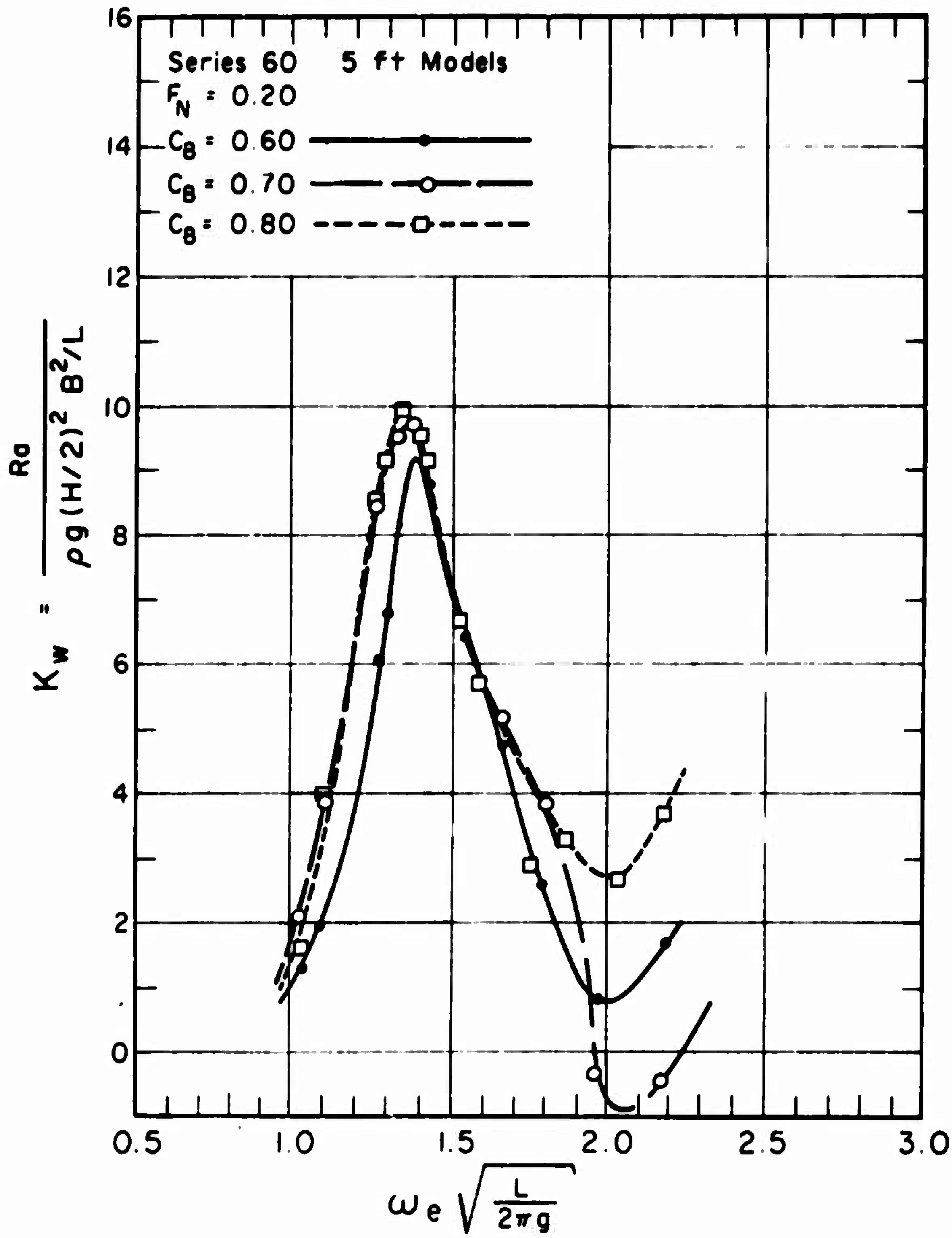

FIG. 8 ADDED RESISTANCE COEFFICIENT IN WAVES (CONSTANT VELOCITY)

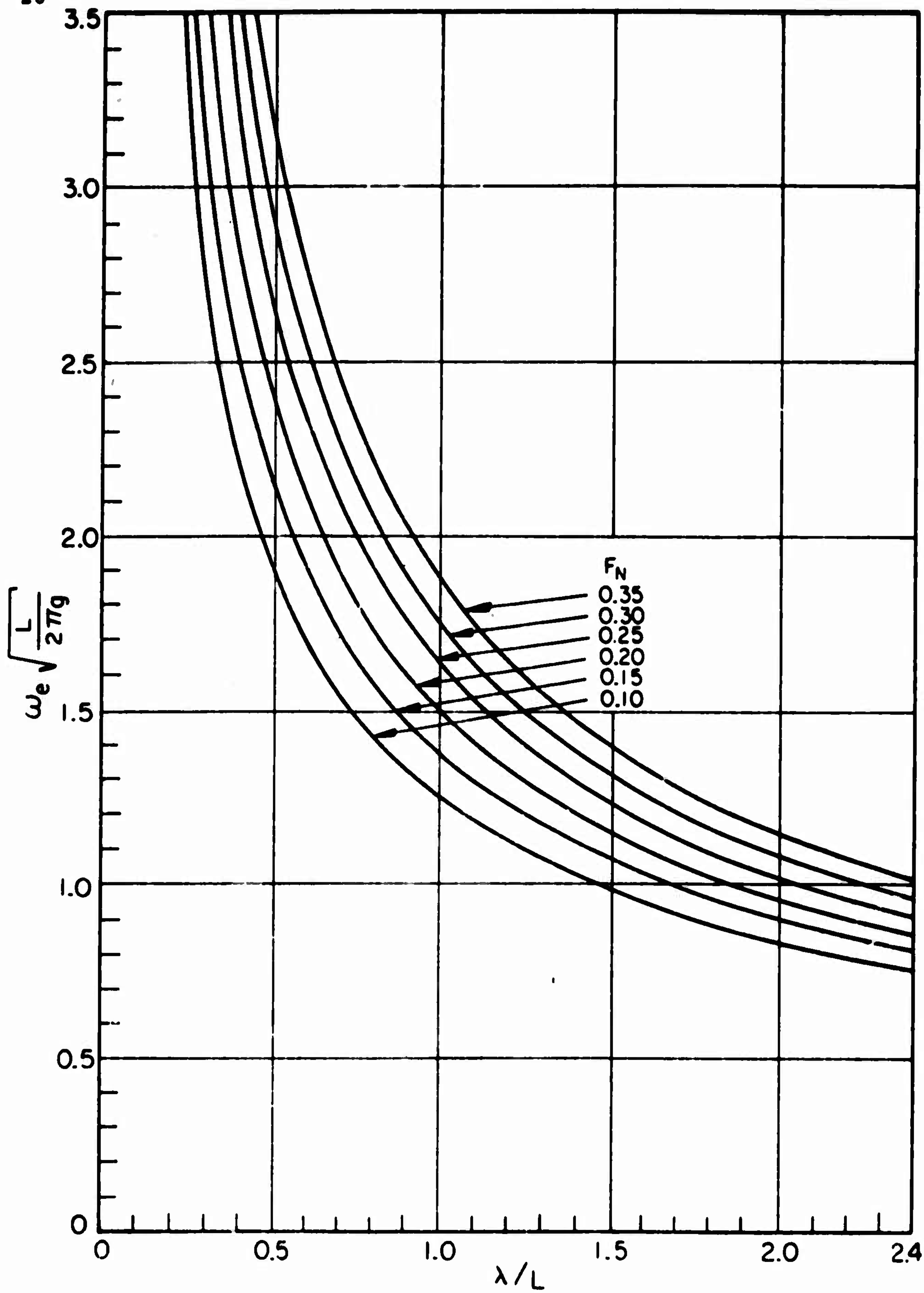

FIG. 9 RELATIONSHIP BETWEEN THE PERIOD OF ENCOUNTER AND THE WAVE LENGTHS FOR VARIOUS SHIP SPEEDS

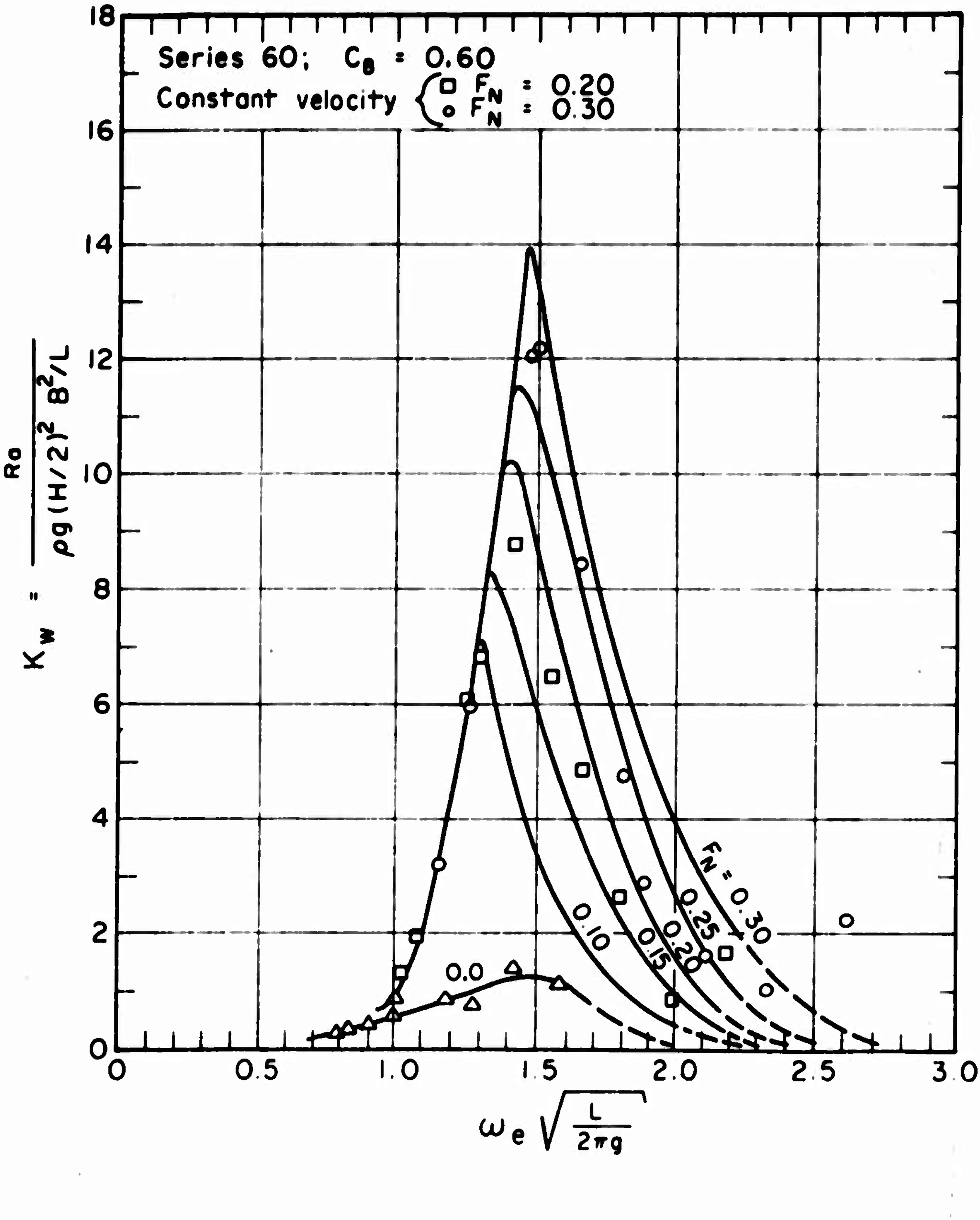

FIG. 10 ADDED RESISTANCE COEFFICIENT IN WAVES
(CONSTANT THRUST)

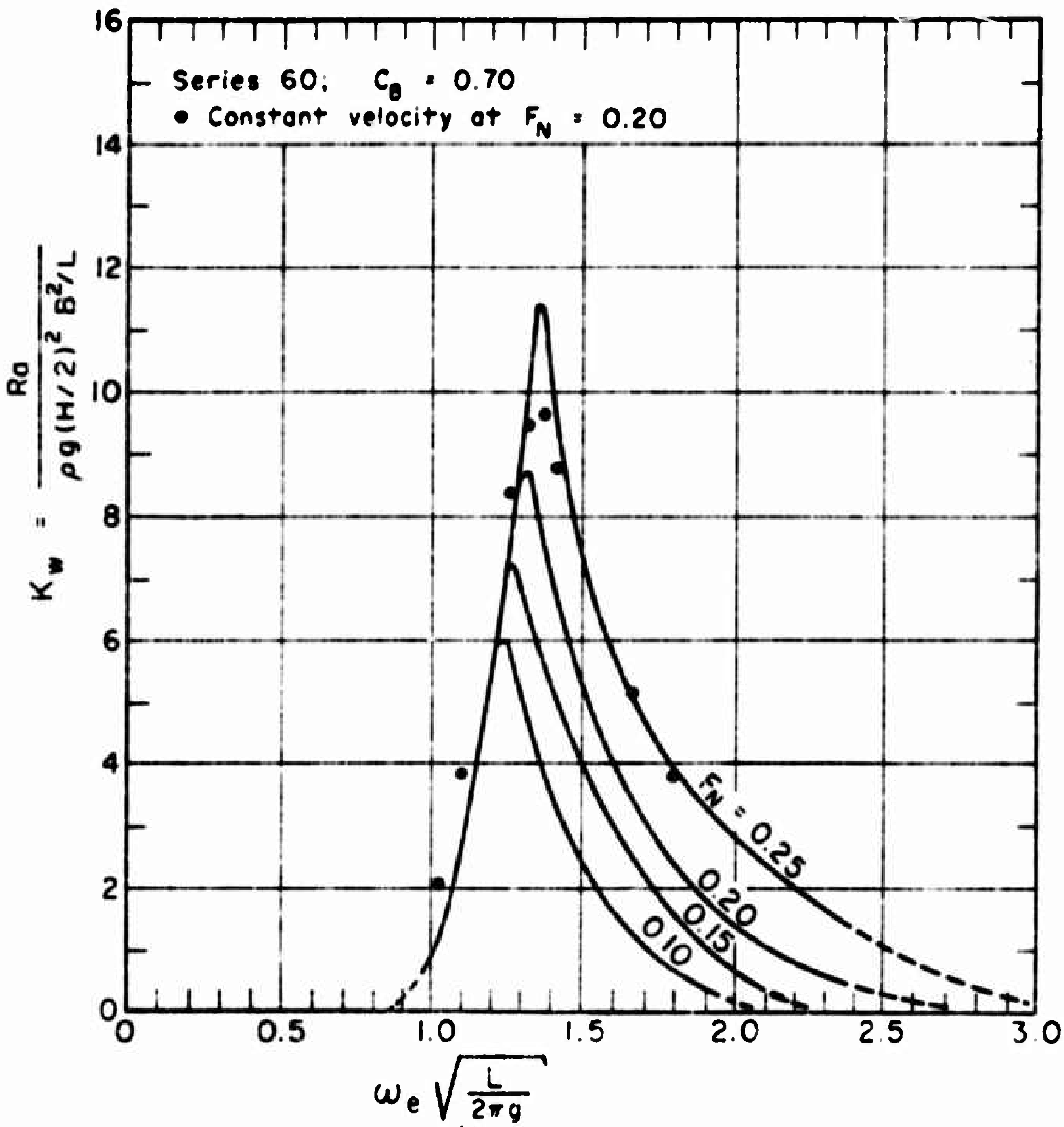

FIG. 11 ADDED RESISTANCE COEFFICIENT IN WAVES
(CONSTANT THRUST)

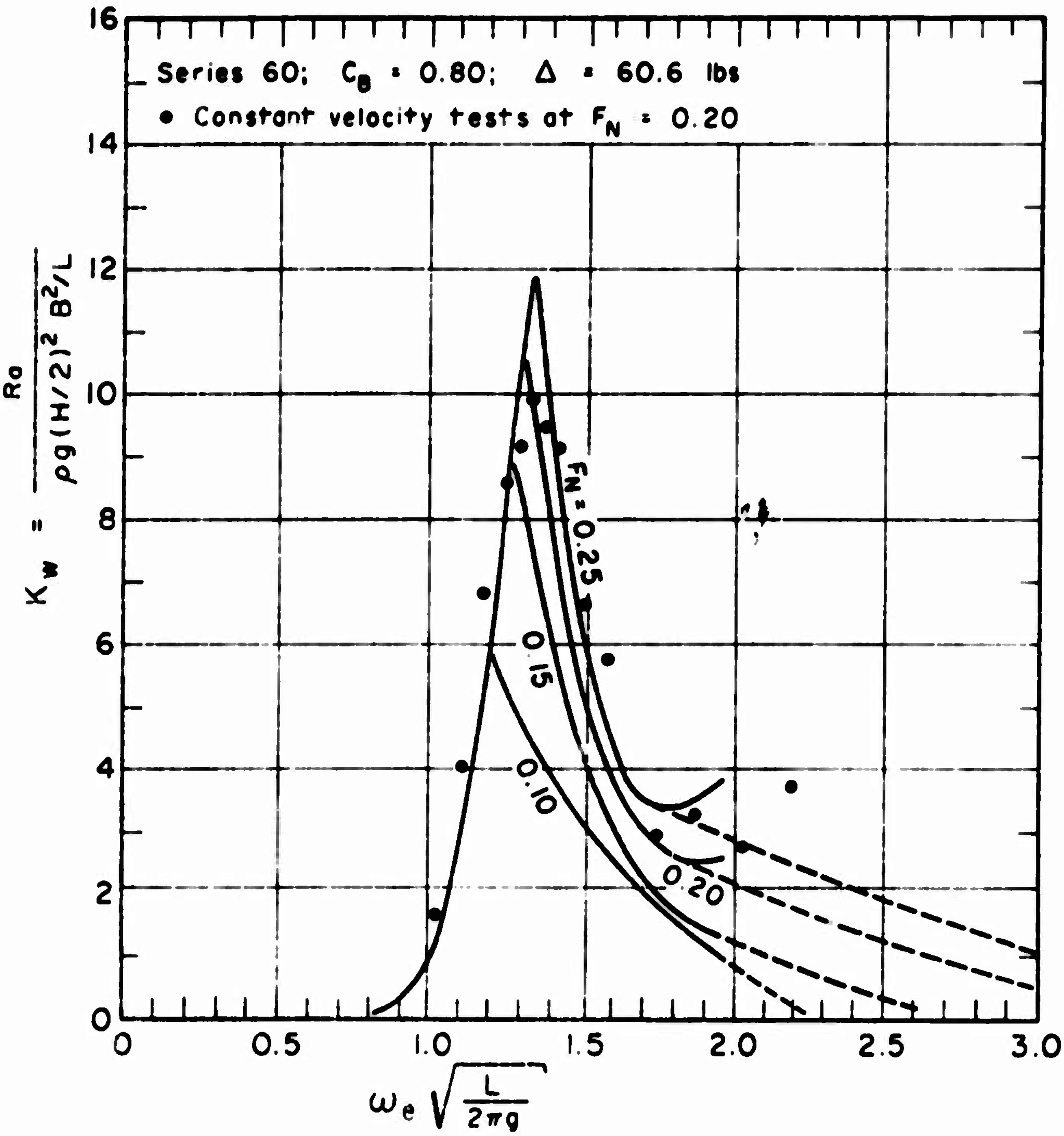

FIG. 12 ADDED RESISTANCE COEFFICIENT IN WAVES
(CONSTANT THRUST)

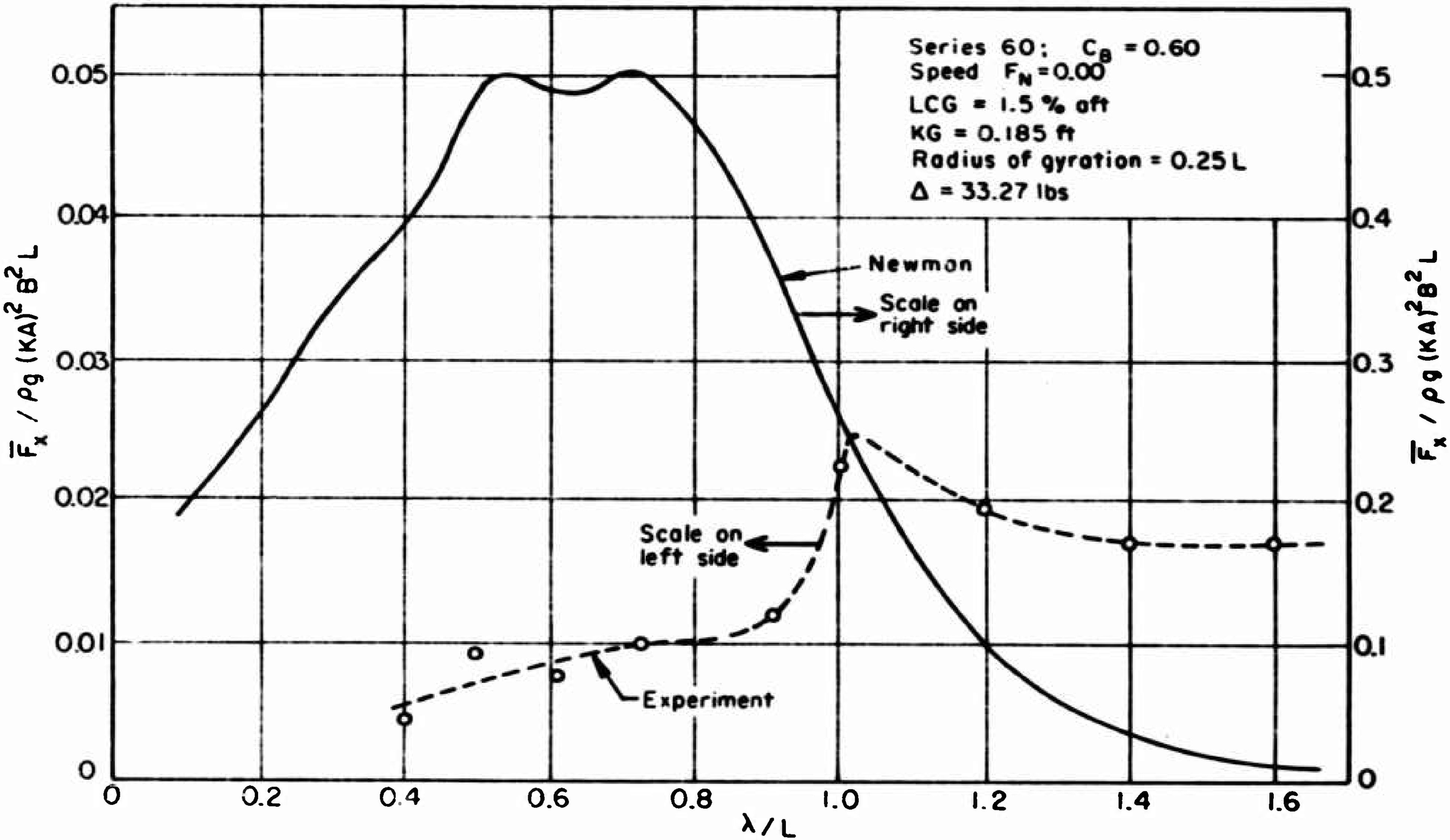

FIG. 13 DRIFT FORCE