CHAPTER TWO HUNDRED SIXTEEN

DEVELOPMENT OF SHIP WAVE DESIGN INFORMATION

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ABSTRACT

During the last three decades several field and laboratory investigations have been conducted in which the waves generated by a wide variety of vessels have been measured. There is a need to synthesize the data published from these studies and to develop general ship wave prediction methods for designers. To complete this task some additional ship wave data must be collected. This paper initiates the effort to develop these prediction methods. A summary and critique of available data are given. Then, the appropriate portion of these data is employed to develop a ship wave height predictor model that gives the maximum ship wave height as a function of ship speed and displacement, water depth, and distance from the sailing line. This is an interim model that is quite applicable but can be improved pending additional data. Finally, planned future efforts to further develop design wave prediction methods are discussed.

INTRODUCTION

The design of various waterway features such as bank erosion control structures and marina protective works, as well as the establishment of allowable ship speeds in navigable waterways, require a knowledge of the characteristics of the waves generated by the ship traffic using the waterway. The characteristics of the ship waves (wave heights, periods, crest orientations) depend on the ship speed and direction, the water depth, the ship hull form and draft, and the distance from the sailing line.

During the later 19th Century, Kelvin developed the first ship wave theory and Froude conducted towing tank experiments to measure ship wave resistance. However, only during the last twenty-five years has there been a serious effort to conduct field and laboratory measurements of the characteristics of ship-generated waves. Data has been collected in towing tanks and in restricted and open waterways, for deep and shallow water wave conditions generated by a variety of vessels. Typically, for a given test run, reported data consists of the height of the highest wave in a wave record generated by the passing ship and its associated half period, for the particular speed and distance from the sailing line.

Available experimental data covers a wide range of ship types and speeds and waterway conditions; however, certain data deficiencies do

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exit. Specifically, there is insufficient data for large ship draft to water depth ratios. Also, hull forms for the vessels studied are inadequately defined.

The data that are available (plus additional data to be collected) need to be synthesized and analysed to develop a coherent procedure for predicting ship wave heights and periods for given ships, ship speeds, water depths and distances from the sailing line.

Also, design analyses often require more information on ship wave characteristics than the maximum wave height and associated half-period. Of more value, for example, would be a representative wave height similar to the significant wave height from a wind wave record and the typical distribution of wave heights in a ship wave record for given conditions.

With these deficiencies in view, the authors have initiated a study to improve ship wave design information and procedures. This paper presents initial results of the study.

SHIP-GENERATED WAVE CHARACTERISTICS

A brief summary of ship wave characteristics is presented here; see Sorensen (1973) for more details.

As water flows past the bow of a ship, a pressure gradient develops and waves are generated. The pressure gradient and resulting height of generated waves depend on the relative water velocity (i.e. ship speed), the bow shape, the ship draft, and the clearance below the keel (i.e. ship draft to water depth ratio). The resulting pattern of wave crests generated by the bow of a ship moving in deep water (Figure 1) consists of a symmetrical set of diverging waves that move obliquely out from the sailing line and a single group of transverse waves that move in the direction of the sailing line. The transverse and diverging waves meet to form cusps located along lines $19^{o}28'$ out from the sailing line. If the ship speed is increased, this pattern retains the same geometric shape but grows in size as the wave lengths increase. A similar pattern of waves typically with lower wave heights is generated at the ship's stern.

At increasing distances from the bow, diffraction increases the wave crest length and decreases the wave amplitude. Havelock (1908, 1914) demonstrated analytically that the wave heights at the cusp points decrease at a rate inversely proportional to the cube root of the distance from the bow while the transverse wave heights along the sailing line decrease at a rate inversely proportional to the square root of the distance from the bow. Thus, at greater distances from the ship, the diverging waves become more prominent than the transverse waves.

Figure 2 show a typical water surface-time history measured at a point during the passage of a ship. Most published data on ship waves present the maximum wave height, Hm, and the associated half-period, T/2, from such a record.

The transverse waves have a celerity equal to the speed of the ship. Thus, using linear wave theory, their length and period can be calculated for a given ship speed and water depth. The diverging waves have a celerity that is less than the ship speed and equal to V cos θ, where V is the ship speed and θ, defined in Figure 1, is approximately 55^{o}. Thus, the diverging wave length and period can also be calculated (see Sorensen, 1967).

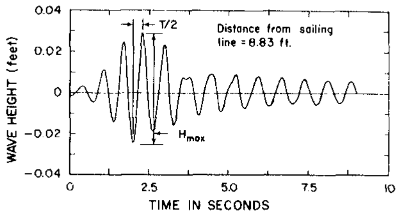

Figure 2 Water Surface Time History at Point For Waves From Mariner Model Ship (Das 1969).

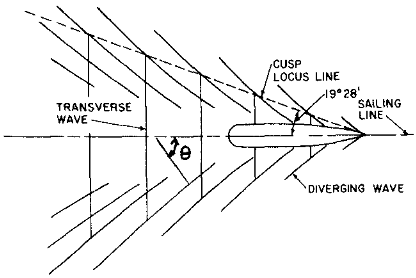

Figure 1 Deep Water Wave Crest Pattern Generated by Ship's Bow

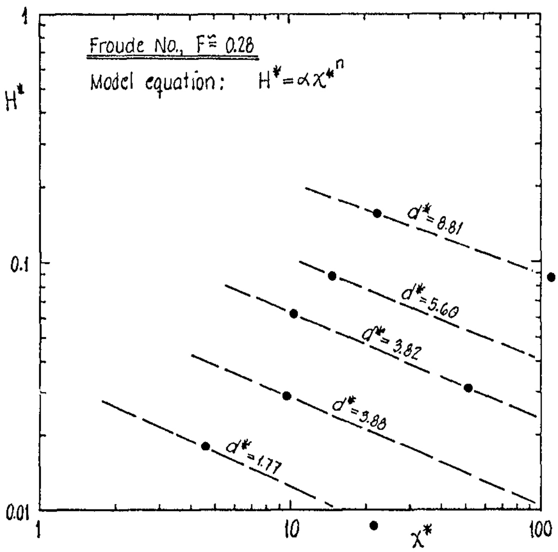

Figure 3 Variation of H* with x* for Various Values of d*. Froude Number = 0.28.

When the water depth is less than about one half the length of the ship waves, the waves "feel" bottom and their characteristics and crest pattern are significantly modified. This "shallow water" condition occurs for depth Froude numbers, F, in excess of approximately 0.6 (Sorensen, 1966), where $F = V/\sqrt{gd}$, and d equals the water depth.

In shallow water, as F increases from 0.6 to 1.0 the cusp locus angle increases from 19°28' to 90°. The leading transverse and diverging wave heights are accentuated at the expense of the following waves. At $F = 1.0$, $V = \sqrt{gd}$ and the transverse and diverging waves combine to form a single wave having a crest line perpendicular to the sailing line. Thus, as would be expected, Hm and T/2 increase at an increasing rate through this range of Froude numbers. Ships rarely operate at speeds exceeding a Froude number of unity (see Schofield, 1974) so the wave pattern and characteristics in this region will not be considered here.

For a given vessel shape and speed, water depth, and distance from the sailing line, there is a significant increase in Hm as the ship draft increases (see Johnson, 1958). On the other hand, light vessels that increase their speed may plane before reaching a Froude number of unity and once planning commences there is essentially no increase in wave height with increasing ship speed.

EXPERIMENTAL DATA

Several laboratory and field investigations of ship-generated waves have been conducted during the last twenty-five years. Table 1 summarizes the test conditions and data collected from published investigations.

Typically, in each investigation the water surface time history was measured at one or a few points (distances from the sailing line) as the ship passes. Few of the actual time history records have been published; most authors just present data on Hm and T/2 as a function of ship speed and distance from the sailing line. Some authors have published an average period, $\bar{T}$, equal to the number of waves divided into the duration of the "wave packet". Wave records with a strong contribution from both diverging and transverse waves would have a bimodal distribution of wave periods so an "average" period could be misleading.

Zabawa and Ostrom (1980) also present ship wave energy density data (for each test run) based on the root mean square wave height for the waves in a given record. Similarly, Ofuya (1970) presents data on the total energy in a ship wave record based on the root mean square wave height and the period of Hm. Das (1969) presents energy spectra for eight of his test runs.

Usually, experiments were conducted with whatever model or prototype vessels were available and most experiments, particularly in the field, were conducted with a small ship-draft to water-depth ratio (D/d). Consequently, the data do not cover waves generated by a uniform range of hull forms and in almost all cases D/d is less than 0.5. Also, for most data sets, the ship hull geometry was very inadequately defined or reported, making it difficult or impossible to quantify the hull form geometry with respect to its wave generating capability. For some data sources, block coefficients (displaced volume/length x beam x draft) could be defined. For others, the

Table 1 - Ship Wave Data Summary

Reference	Model or Prototype	F range	Vessels	D/d	¥/LBD	Data Presented
Johnson, 1958	M	0.6-2.0	Power boat	0.25 0.44,0.23,0.13	0.37 0.58	Only selected Hm, T/2 versus Vs, x data presented.
			Barge	0.37	0.82	
			Canoe	0.52	0.56	
			Rectangle with V-bow(3)	0.19	0.93	
Brebner, et al.,1966	M	0.29-0.89	Ocean liner	0.16,0.60	0.51	Hm versus Vs, x for all conditions;curves only,no data points shown.
			Bulk carrier	0.16,0.60	0.40	
Sorensen, 1966	M	0.4-0.9	Rectangle with V-bow(3)	0.33	0.87	Hm versus Vs, x for 81 test runs.
		0.69-1.58	Idealized hull form	0.50	0.53	Contour plot of wave surface for 7 test runs.
Sorensen, 1967	P	0.25-0.92	Tug	0.16	0.25	Hm,T/2 versus Vs, x. Planing for some cabin cruiser test runs.
			Tug(fire boat)	0.28	0.36	
			USCG Cutter	0.09	0.22	
			Fishing boat	0.08	0.44	
			Cabin cruiser	0.04	0.31	
			Misc. other vessels	-	-	
Hay, 1968	M	0.36-0.76	Cargo ship	0.73, 0.5, 0.4, 0.29	0.52	Hm versus Vs, x for 270 test runs.
			David Taylor Series 60		0.56	
			Tanker		0.69	
			Aux. supply vessel	0.73,0.33	0.63	
			Barge		0.86	
			Tug		0.48	

Table 1 (continued) - Ship Wave Data Summary

Reference	Model or Prototype	F range	Vessels	D/d	$\forall$/LBD	Data Presented
Bidde, 1968	M	0.43-0.85	Cargo ship Barge	0.5, 0.43, 0.40, 0.38 0.40, 0.33 0.25, 0.22	0.52 0.87	Hm versus Vs, x for constant and decreasing water depths out from sailing line, 245 test runs.
Das, 1969	M	0.27-0.96	Cargo ship Cruiser	0.73, 0.12 0.48, 0.08	0.52 -	Hm, T/2 versus Vs, x for 71 test runs; water surface time histories for 8 runs.
Ofuya, 1970	P	0.1-1.0	Cruiser 92 other vessels of opportunity	0.05 -	0.23 -	Hm, Hrms, $\overline{T}$ versus Vs, x; planing for some cruiser runs.
Zabawa and Ostrom, 1980	P	0.46-4.86	Cruiser Boston Whaler	<0.3 <0.3	- -	Hm, Hrms, $\overline{T}$ versus Vs, x for 60 test runs; planing for many runs.
Bhowmik et al. 1982	P	0.10-0.65	59 barge tows of opportunity	0.06-0.3 (approx.)	varied	Hm versus Vs, x; river currents with/against tow; blockage ratio: 14.7-226.9.
Maynord and Oswalt, 1984	M	0.3-0.62	Barge tows	0.90-0.64	varied	Hm versus Vs, x at channel bank; blockage ratio: 4.6-16.4.

block coefficient could at best be estimated, or only a verbal description of the hull form could be obtained.

INTERIM MODEL TO PREDICT SHIP-GENERATED WAVE HEIGHTS

An interim model has been developed to predict ship-generated wave heights at a given location when a ship's speed and displacement, water depth, and distance from the sailing line are known. Obviously, the heights of ship-generated waves depend on hull characteristics other than just the ship's displacement; for example, factors such as the beam to length ratio, beam to draft ratio, and the ratio of the displaced volume to the product of the beam, draft and length (block coefficient) affect wave heights. The model presently considers only the ship's displacement but work is underway to improve the model by considering other relevant hull-shape parameters. Some progress in this direction is presented here.

The data used for developing the interim model was the field data presented by Sorensen (1967) and includes wave height data from seven different ships having displacements ranging from 3 to 18,800 tons, lengths ranging from 23 to 504 feet and drafts ranging from 1.7 feet to 28 feet.

The important variables considered in the interim model to describe the ship-wave generation problem and their dimensions are:

- H = ship-generated wave height, (L)
- d = water depth, (L)
- x = distance from the sailing line to the point where the wave height is measured, (L)
- V = ship speed, (L/T), and
- $\forall$ = volume of water displaced by the ship, (L^3)

In addition, the length, beam, and draft of the ship are important although they are not initially considered in the interim model. Their influence will be discussed later.

Dimensional analysis of the above variables yields four dimensionless variables. The form for each of the dimensionless variables selected for the present analysis was largely dictated by the available data; that is, the dimensionless parameters were selected so that the functional relationship between two variables could be investigated while the remaining variables were held constant or nearly constant. One set of dimensionless variables meeting this criterion is:

$$\frac{V}{\sqrt{gd}} = \text{Froude number}$$

$$\frac{H}{(\forall)^{1/3}} = \text{dimensionless wave height (dependent variable)},$$

$$\frac{x}{(\forall)^{1/3}} = \text{dimensionless distance from sailing line},$$

$$\frac{d}{(\forall)^{1/3}} = \text{dimensionless depth.}$$

where the term, $\forall^{1/3}$, is a characteristic length dimension of the ship.

In the interim model, all of the ship's characteristics are embodied in this parameter which may be physically interpreted as the length of the side of a cube having the same displacement as the ship. If the length, beam, and draft of a ship are also considered, at least three additional dimensionless variables must be added to the above. For example, they could be defined,

$$\frac{L}{(\forall)^{1/3}} = \text{dimensionless length}$$

$$\frac{B}{(\forall)^{1/3}} = \text{dimensionless beam}$$

$$\frac{D}{(\forall)^{1/3}} = \text{dimensionless draft}$$

Other parameters have been used to describe hull forms including the block coefficient, or a parameter suggested by Brebner et al. (1966) defined as the square root of the maximum cross-sectional area of the hull divided by the distance from the bow to the cross-section of maximum area.

EMPIRICAL RELATIONSHIPS

Letting F, H*, x*, and d* be the Froude number, dimensionless wave height, dimensionless distance from the sailing line, and dimensionless water depth, respectively, empirical relationships were established among these variables. Havelock (1908) found that the wave height decreases as the one-third power of the distance from the sailing line; hence, the dimensionless wave height, H*, was assumed to decrease exponentially with distance from the sailing line. Figures 3, 4 and 5 show the decrease of H* with x* for three different values of the Froude number. Each figure also shows how H* varies with the dimensionless depth, d*. In general form, the assumed variation is given by,

$$H^* = \alpha \, x^{*n} \tag{1}$$

where the exponent n and coefficient α are functions of the remaining dimensionless variables. Actually, both n and α were found to be functions of the Froude number and the dimensionless water depth d*. As shown in Figure 6 n could be expressed as,

$$n = \beta \, d^{*\delta} \tag{2}$$

where $\beta = -0.225\ F^{-0.699}$ $\quad 0.2 \leq F \leq 0.55$ (3)

$\beta = -0.342$ $\quad 0.55 \leq F \leq 0.8$

and, $\delta = -0.118\ F^{-0.356}$ $\quad 0.2 \leq F \leq 0.55$ (4)

$\delta = -0.146$ $\quad 0.55 \leq F \leq 0.8$

as shown in Figure 7. Note that the lower and upper bounds for the definitions of β and δ are assumed to be 0.2 and 0.8 respectively since the interim model should not be used much beyond the range of the data from which it was derived.

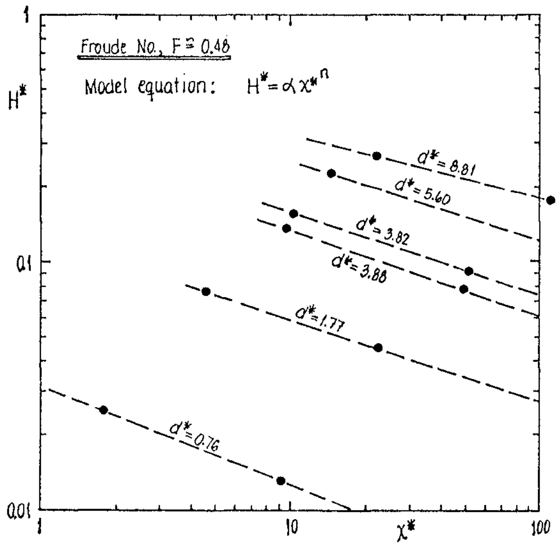

Figure 4 Variation of H* with x* for Various Values of d*. Froude Number = 0.48.

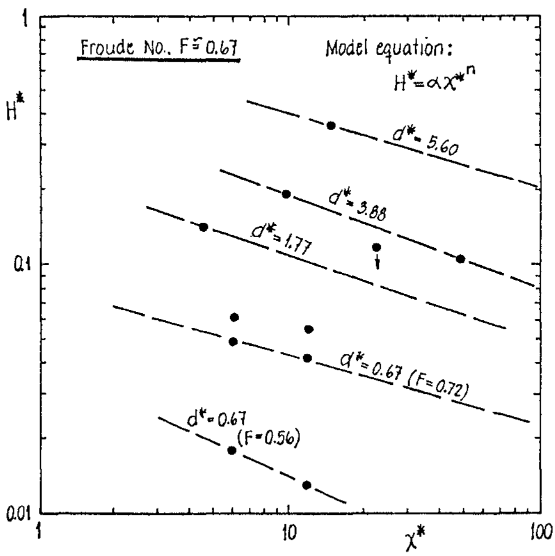

Figure 5 Variation of H* with x* for Various Values of d*. Froude Number = 0.67.

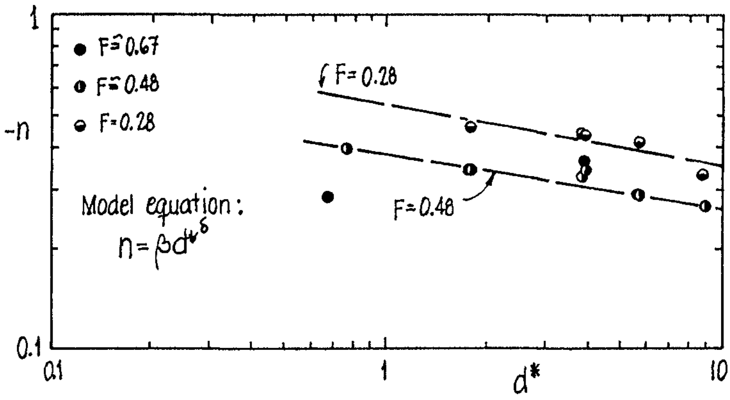

Figure 6 Exponent n as a Function of d* and F.

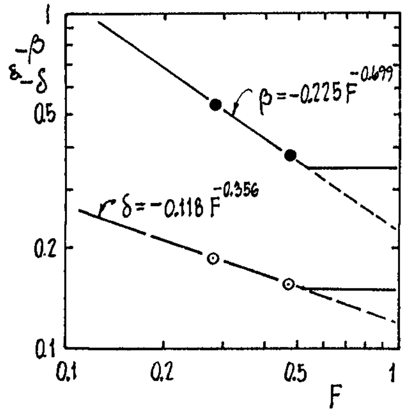

Figure 7 Coefficients β and δ as Functions of Froude Number.

Figure 8 shows the variation of α with d* for three values of F. An empirical expression for α is given by,

$$\log \alpha = a + b \log (d^*) + c (\log^2 (d^*)) \tag{5}$$

As shown in Figures 9 and 10, empirical expressions for the coefficients are given by,

$$a = -0.6/F \tag{6}$$

$$b = 0.75\ F^{-1.125} \tag{7}$$

and

$$c = 2.6531\ F \quad -1.95 \tag{8}$$

Equations 1 through 8 permit calculation of ship-generated wave heights at a location given the ship's displacement and speed, the distance between the location and the ship's sailing line, and the water depth. A comparison between the wave heights predicted by equations 1 through 8 and the original data used to develop the empirical relationships is given in Figure 11. The predicted wave heights are plotted against the measured wave heights used to develop the model. While there is some scatter, the equations do a fair job of predicting the data considering that the ship's characteristics have been embodied into a single parameter, the cube root of the displaced volume, $\forall$.

The interim model was subsequently checked against three other data sets for several ships with known hull forms. Figure 12 compares values of H* calculated using the interim model with the data obtained by Sorensen (1967) for five geometrically similar box-like models. (For clarity, only data from three of Sorensen's models are shown in the figure. All of Sorensen's data follow the same trend.) The models were basically rectangular boxes with pointed bows, each having the same shape but at a different scale. Their lengths varied from 1.5 feet to 4.0 feet. Figure 12 shows that the waves generated by the box hulls exceed those predicted by the interim model; however, measured and calculated values of H* vary linearly suggesting a correction equation given by,

$$H^*_{meas} = 2.427\ H^*_{calc} - 0.0728 \tag{9}$$

The interim model was also evaluated against the laboratory data obtained by Das (1969) for two ships with distinctly different hull forms, a "Cruiser" hull with a relatively broad beam and a "Mariner" tanker hull with a more streamlined form. A comparison of measured values of H* with values of H* predicted by the interim model for the "Cruiser" model is shown in Figure 13. Generally, the "Cruiser" data also suggest a linear correction to bring measured and calculated values together. For the "Cruiser" data the correction equation is given by,

$$H^*_{meas} = 3.158\ H^*_{calc} - 0.1105 \tag{10}$$

The "Cruiser" data also suggest that the hull is more efficient for generating waves than the interim model predicts.

Several data points in Figure 13 are given by Das as being "Cruiser" data in the tables appended to his report. The points, however, are not consistent with the majority of the "Cruiser" data and are suspected of having been obtained from the "Mariner" tanker model.

The "Mariner" data is shown in Figure 14. Again the deviation of

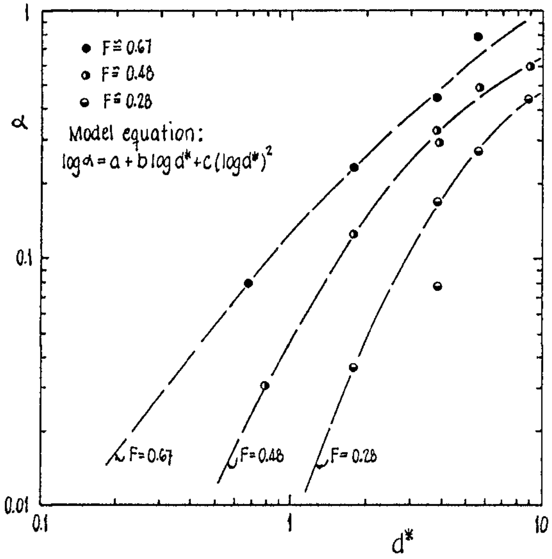

Figure 8 Coefficient α as a Function of d* and Froude Number.

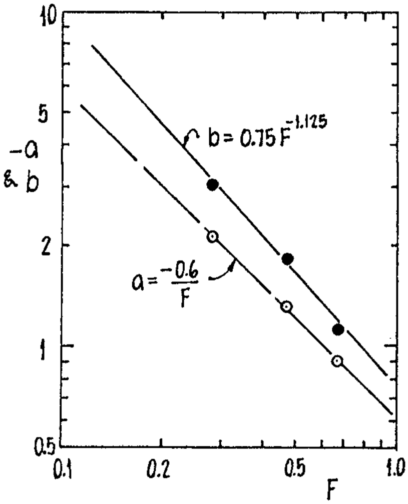

Figure 9 Coefficients a and b as Functions of Froude Number.

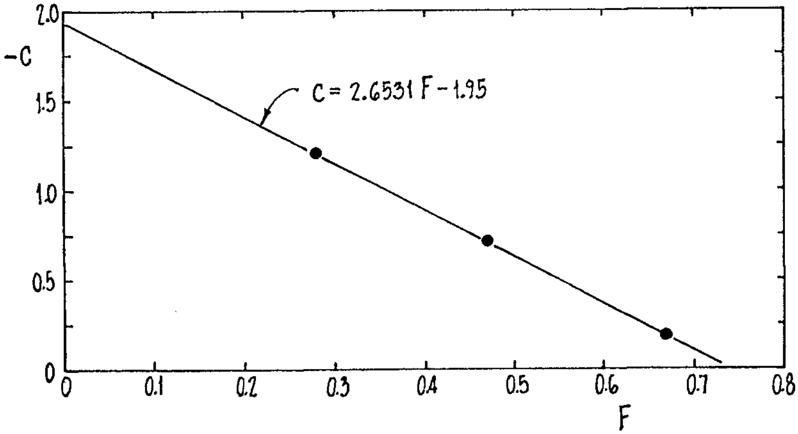

Figure 10 Coefficient c as a Function of Froude Number.

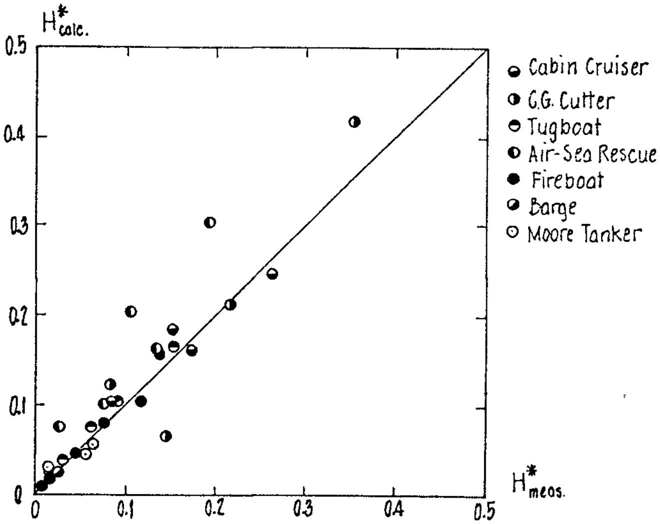

Figure 11 Comparison Between Measured and Calculated Values of H* for Data Used to Develop Model.

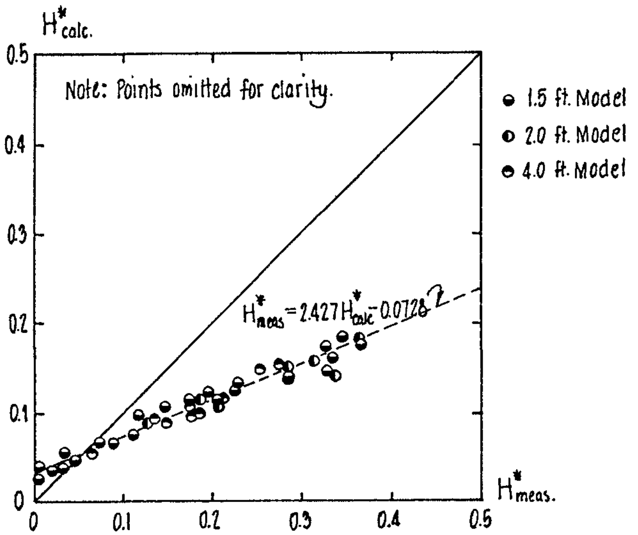

Figure 12 Comparison Between Measured and Calculated Values of H* for Sorensen's (1967) Model Data.

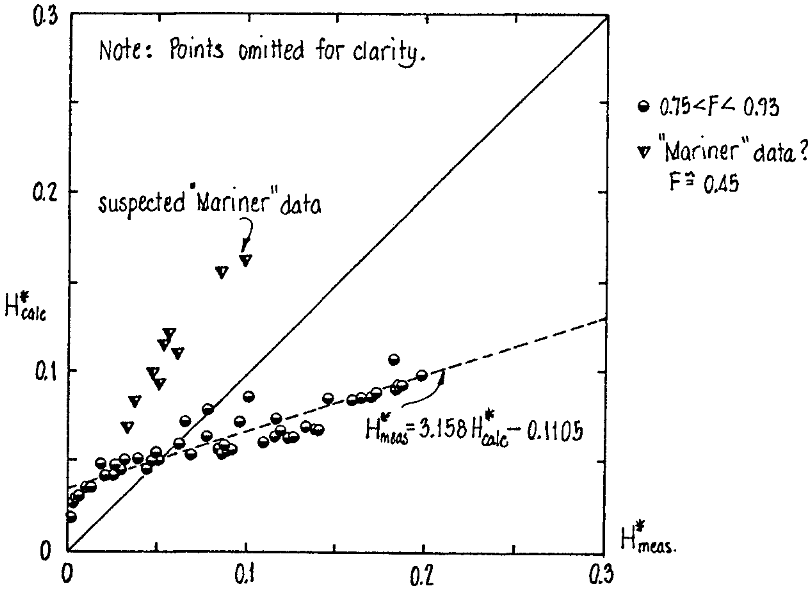

Figure 13 Comparison Between Measured and Calculated Values of H* for Das' (1969) "Cruiser" Data.

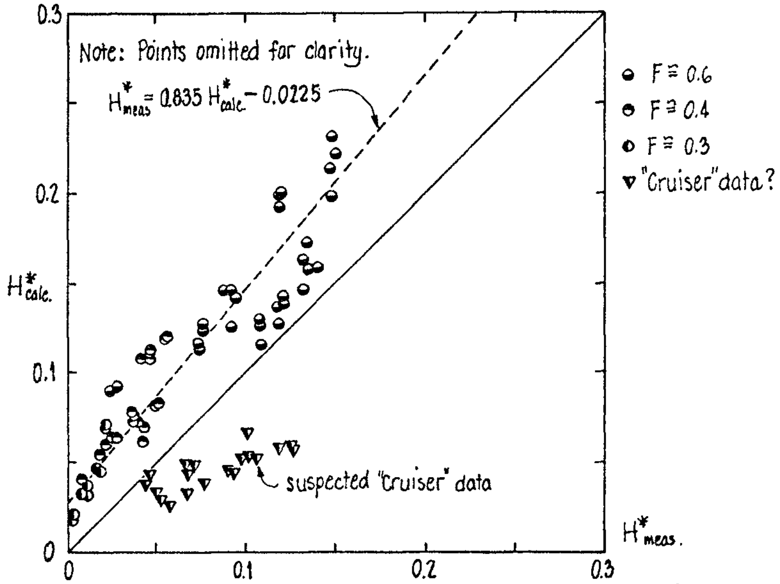

Figure 14 Comparison Between Measured and Calculated Values of H* for Das's (1969) "Mariner" Data.

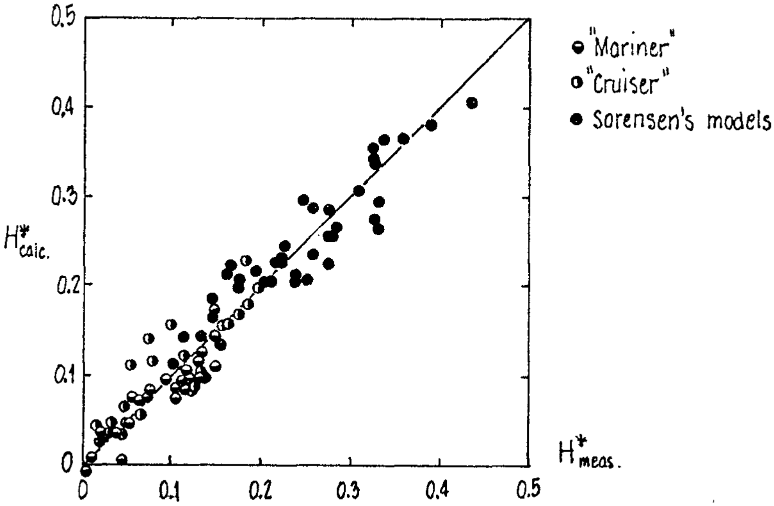

Figure 15 Comparison Between Measured and Calculated Values of H*. Linear Corrections to Sorensen's and Das's Data.

the data from the interim model can be adjusted through a linear correction, in this case given by,

$$H^*_{meas} = 0.835\ H^*_{calc} - 0.0225 \tag{11}$$

A number of data points in Figure 14 are not consistent with the remainder of the "Mariner" data. These points are suspected of being "Cruiser" data instead of "Mariner" data. The "Mariner" data shows that this more streamlined tanker hull is not as efficient in generating waves than is the "Cruiser" hull or Sorensen's box hulls. Generally, the coefficient of H* in equations 9 through 11 is a measure of how efficiently the hull generates waves. The larger the coefficient, the greater the hull's efficiency in generating waves. In fact, the two coefficients in the correction equations should be related to hull characteristics such as the block coefficient or Brebner's parameter. For example, Brebner's parameter (the ratio of the square root of the ship's maximum cross-sectional area to the distance from the bow to the cross-section of maximum area) is believed to be larger for the "Cruiser" hull and for Sorensen's box model hulls than for the more streamlined "Mariner" hull. Unfortunately, the information to calculate Brebner's parameter for the "Cruiser" and "Mariner" hulls is not available. Investigators usually report basic hull dimensions such as length, beam, and draft but rarely report relevant cross-section dimensions that would allow this parameter to be determined.

The interim model was also evaluated against the barge-tow data obtained on the Illinois River by Bhowmik et al. (1982), but without success.

FUTURE WORK

Future work will initially be directed toward obtaining available wave data from various ships for which hull shape is reported in sufficient detail to calculate the relevant hull parameters. These data will be used to refine the interim model to account for hull shape in determining ship-generated wave heights. Specifically, the coefficients of the linear correction equations (equations 9 through 11) will be empirically related to the various dimensionless parameters describing the hull. Since data appears to be available for only a limited number of hulls, additional wave data from hulls with known configuration will need to be collected. Also, data are needed for a wider range of ship-draft to water-depth ratios.

The preceding analysis provides only a method for estimating Hmax which may or may not be the relevant parameter to predict the effects of ship-generated waves on structures or shorelines. Information on the energy contained within the wave packet and its distribution with frequency might, in fact, be more relevant; hence, spectral descriptions of ship generated waves need to be investigated.

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