SSC-163

Investigation of Bending Moments Within the Midship Half Length of a Mariner Model in Extreme Waves

by

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June 1964

Dear Sir:

"Bending Moment Determination" is a research project at Stevens Institute of Technology sponsored by the Ship Structure Committee. Herewith is a copy of the First Progress Report, SSC-163, Investigation of Bending Moments Within the Midship Half Length of a Mariner Model in Extreme Waves, by N. M. Maniar.

The project was conducted under the advisory guidance of the Ship Hull Research Committee of the National Academy of Sciences-National Research Council.

Comments on this report would be welcomed and should be addressed to the Secretary, Ship Structure Committee.

Yours sincerely,

T. J. Fabik
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

SSC-163

First Progress Report
of
Project SR-165
"Bending Moment Determination"

to the

Ship Structure Committee

INVESTIGATION OF BENDING MOMENTS WITHIN THE MIDSHIP HALF LENGTH OF A MARINER MODEL IN EXTREME WAVES

by

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Stevens Institute of Technology

under

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ABSTRACT

One objective of this project was to obtain experimental model data to describe the lengthwise vertical wave bending moment distribution within the midship half length of a normally loaded Mariner type cargo ship in regular head and following waves having wave height/wave length ratios between 0.05 and 0.11; a second loading conditions was also examined. A second objective was to determine whether the moments tend to reach an upper limit as wave height increases.

A 1/96 scale model was cut to form six segments which were jointed by an aluminum beam. The beam was strain gaged to measure bending moments at the hull cuts at stations 5, 7-1/2, 10, 12-1/2 and 15.

Within practical operational limits for the Mariner type ship, maximum wave bending moments in high regular waves occur in the region from amidships to .125L aft of amidships. Hogging and sagging moment at any section were generally proportional to wave height up to a wave height/wave length ratio of 0.11, the steepest wave that could be generated.

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INTRODUCTION

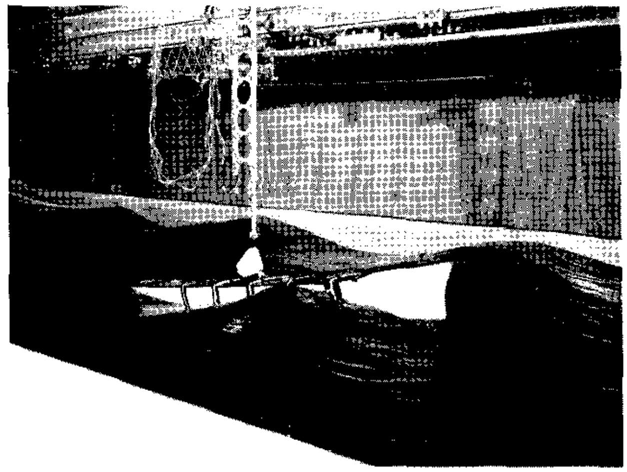
It has been recognized that major progress would be made in the practice of ship design if the maximum longitudinal bending moments experienced by ships could be established. Efforts to achieve this end are being made on theoretical lines, and by way of full scale investigations and model tests.

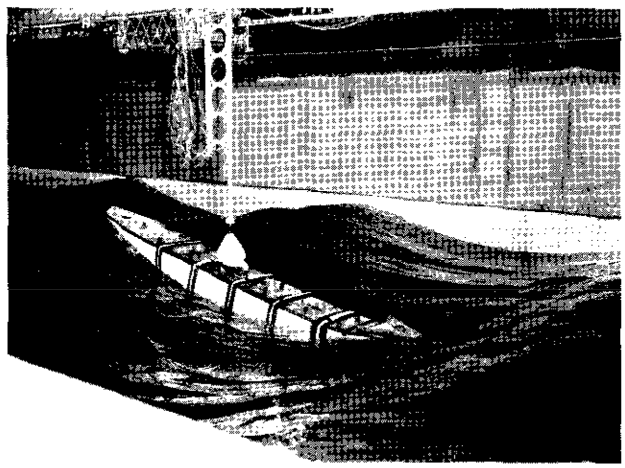
The need of knowing *maximum* bending moments directly implies investigations in extreme waves irrespective of the method of investigation. Before the test reported here, the Davidson Laboratory completed tests on a tanker, destroyer and a Mariner class ship and its variants in steep waves[1-3]. The tests concluded that within practical operational and design limits for commercial ships no dramatic upper limit of wave bending moments at midship is to be expected as wave steepness *increases up to a* value of about 1/9. Since this conclusion was limited to midship bending moment only and it was *known* that the maximum moments under certain circumstances could occur elsewhere it was recommended that the investigations should be extended to examine the longitudinal distribution of moments in extreme waves. The outcome of this thinking was the experiment reported here.

The model selected was that of the original Mariner with one loading variant (Cargo amidship case) tested previously and it was also to be tested in essentially the same wave program as the previous experiment. The purpose of investigating the cargo amidship case was to study the effect of appreciably reducing the longitudinal gyradius on bending moments. The model was multi-segmented and held together by a flexure beam, *(Figs. 1-3). The beam was strain* gaged at stations 5, 7-1/2, 10, 12-1/2 and 15 to measure bending moments.

The tests were performed in regular waves where the wave length to ship length ratios ranged from 0.75 to 1.75 and the wave height to wave length ratios ranged from 0.05 to 0.11. The model with normal weight distribution was tested with forward speed, zero speed and drift speed in head seas, and with forward speed in following seas. In the cargo amidship case the model was tested with zero speed in head seas.

A comprehensive background on the use of scaled model tests to investigate bending moment can be found in International Shipbuilding Progress[3].





FIGS. 1 and 2. PHOTOGRAPHS OF MODEL 2681-1 (NORMAL WEIGHT DISTRIBUTION) AT ZERO SPEED IN WAVES OF $\lambda \cdot 1.25$,

$\frac{h}{\lambda}$ 0.10

DESCRIPTION OF THE EXPERIMENT

Model. The tests were conducted on a 65-in. (1/96 scale) six-segment fiberglass model of the original Mariner, first with normal weight distribution, and then with cargo amidship. The Mariner model and its variant are designated models 2681-1 and 2681-2 respectively. Figure 3 shows the body plan and model layout. Tables 1 and 2 contain the model characteristics and segment properties respectively. The hull was cut at stations 5, 7-1/2, 10, 12-1/2 and 15. The segments were joined together by an aluminum flexure beam, that was

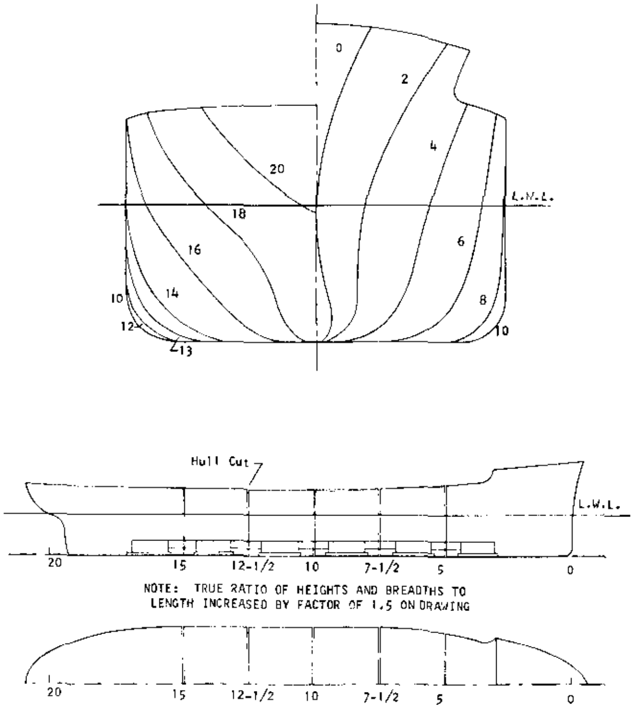


FIG. 3. *MODEL DRAWING*

bolted to aluminum plates imbedded in the segment bottoms. The hull cuts were 1/8 in. wide and sealed with 0.008 in. thick rubber fixed to the hull with electric insulation tape. An accordian fold was put into the sealing rubber to insure that it did not contribute to the hull stiffness.

The model was completely decked over except for a small hatch in the segment between stations 10 and 12-1/2 necessary to accommodate the towing gear and strain gage wiring.

Figure 4 is the structural beam drawing. The beam had six flexure sections located centrally about the hull cuts where the moments were measured. The flexures were 4 in. long, 1-1/2 in. wide and 1.04 in. deep at stations 7-1/2, 10 and 12-1/2, and 0.95 in. deep at stations 5 and 15. The beam moment of inertia was made larger than the inertia obtained by scaling the prototype inertia as the fifth power of the scale ratio. This was done so that the fundamental vibration frequency of the model would be appreciably larger than the encounter frequency and hence less likely to be a source of noise in the bending moment record.

The model weight distributions are given in Fig. 5. In order to obtain the weight distribution for model 2681-1 the normal weight distribution of the ship was divided into six parts corresponding to the six segments of the model. The weight, longitudinal center of gravity and the moments of inertia for each part were calculated and reduced to model scale. It was possible to ballast each segment to its required weight and LCG but the moment of inertia was somewhat larger than required. In Table 2 the ratio $\frac{I\ actual}{I\ required}$ is given for each segment. The influence of the excess segment inertias on the overall inertia of the model was negligible. The weight of the towing gear located in the segment immediately aft of amidships was considered as part of the ballast weight. In the weight variation case the model (2681-2) was ballasted with as small a longitudinal gyradius as possible.

APPARATUS

The experiment was conducted in the Davidson Laboratory Tank No. 3 (300 ft x 12 ft x 5.5 ft).

The model was attached to a towing apparatus which gave the model freedom to pitch, heave and surve ($\pm$6 ft) but restrained the model in roll, yaw and sway. The apparatus consisted of a main carriage attached to the towing cable. The model was connected by a heave mast to a subcarriage on the rail. The towing mast was permitted only vertical transitory motion guided by ball bearing rollers, and the subcarriage had only fore and aft translation motion. The model was attached to the bottom of the heave mast by pivots with an athwartship axis which allowed the model to pitch while restraining it in roll.

The model was run at forward speed by applying a known towing force to the subcarriage by falling weights at the end of a string lead over a pulley system fixed to the main carriage. The main carriage speed, controlled by a hand servo was matched with the model speed. The towing weights were disconnected electrically at the end of the run and the model slowed down of its own accord.

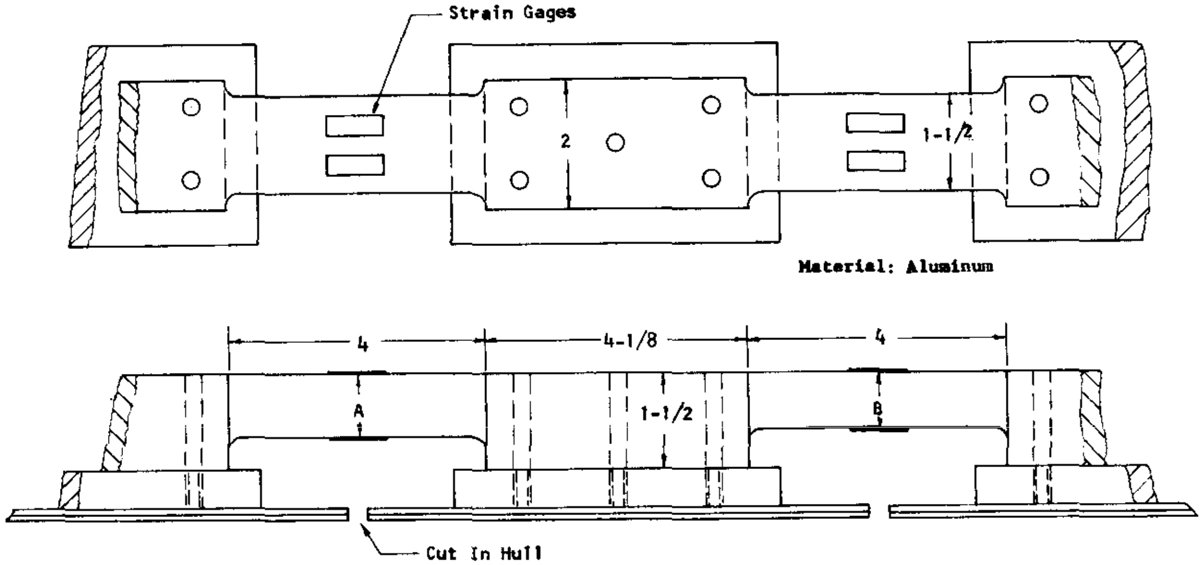
The recording run length was about four model lengths over which the model moved with constant speed. A continuous speed record was obtained by a tachometer and roller, fixed between the model subcarriage and the main tank rail. The average speed was obtained by measuring the time elapsed between two points

TABLE 1. MODEL CHARACTERISTICS

Model Number	2681-1	2681-2
Prototype	Mariner	Mariner
Weight Distribution	Design	Cargo ℄
Ship LBP, Ft.	520.0	520.0
Model Characteristics		
Scale	1:96	1:96
Length on 20 Stations, Inches	65	65
Beam, Inches	9.5	9.5
Draft, Inches	3.47	3.47
B/H	2.72	2.72
C_b	0.61	0.61
C_{ϕ}	0.98	0.98
$\Delta/(L/100)^3$	140	140
LCB, % Station Length from ℄	1.44 Aft	1.42 Aft
Gyradius, % Station Length	24.3	19.5

TABLE 2. SEGMENT PROPERTIES

	Model 2681-1				Model 2681-2		
Segment	Wt. lbs.	LCG From ℄ ins.	I about Seg. LCG lb. in^2	I actual / I req'd	Wt. lbs.	LCG From ℄ ins.	I about seg. LCG lb. in^2
1	8.04	23.29F	165	1.17	5.33	22.75F	157
2	6.50	11.95F	38	1.23	4.32	12.06F	35
3	8.17	3.99F	45	1.10	10.63	2.81F	83
4	8.34	3.91A	53	1.32	18.22	3.87A	111
5	7.49	12.31A	39	1.08	4.45	12.00A	37
6	9.84	22.18A	168	1.04	5.45	22.78A	163



A = 1.04" at STN 7-1/2, 10 and 12-1/2
B = 0.95" at STN 5 and 15

FIG. 4. STRUCTURAL BEAM

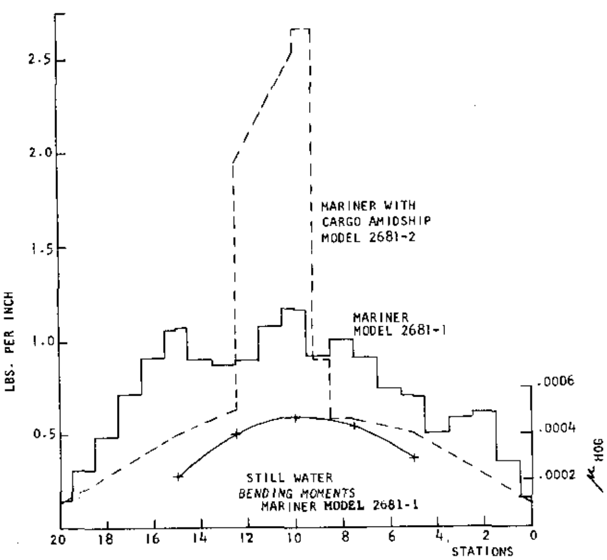
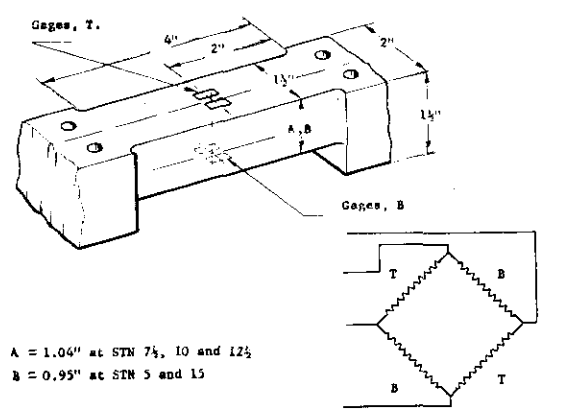


FIG. 5. WEIGHT DISTRIBUTION AND STILL WATER BENDING MOMENTS

20 ft apart.

The wave probe was of the resistance type, 2 ft long, and designed for use in a ± 6 in. wave amplitude range. The probe was linear over the wave amplitude range covered in the test. The static calibration data points deviated less than one percent of the range of calibration from a straight line plot. The probe was located 13 ft 6 in. forward of the null surge position of the model.

Bending moments were determined from bending strains measured by SR-4 A-19-type strain gages. The moments in the beam were measured at stations 5, 7-1/2, 10, 12-1/2 and 15, the locations of the hull cuts. Typical layout of the gages on the flexure at each measuring station is given in the sketch that follows:



The four gages together formed a full Wheatstone Bridge circuit registering bending strains only.

Before installing the beam in the model, it was calibrated statically by applying known moments by loading the beam with concentrated weights. Each set of gages proved to have linear outputs and there was no indication of metal hysteresis.

In order to minimize high frequency noise in the bending moment record, electronic passive filters were introduced in the electrical circuit between the carrier amplifiers and visicorders. The filters performance curve is given in Fig. 6. A filter was introduced in the wave circuit also to avoid phase errors in the phase difference between the wave and the moments.

The outputs of the strain gages and wave wire were amplified by Sanborn Preamplifiers, model 3500-1100 with a carrier frequency of 2400 and 4.5 volts rms. The outputs of amplifiers after passing through the filters were recorded by two visicorders, model 1108.

Samples of oscillograph records of bending moments are given in Figs. 7 and 8.

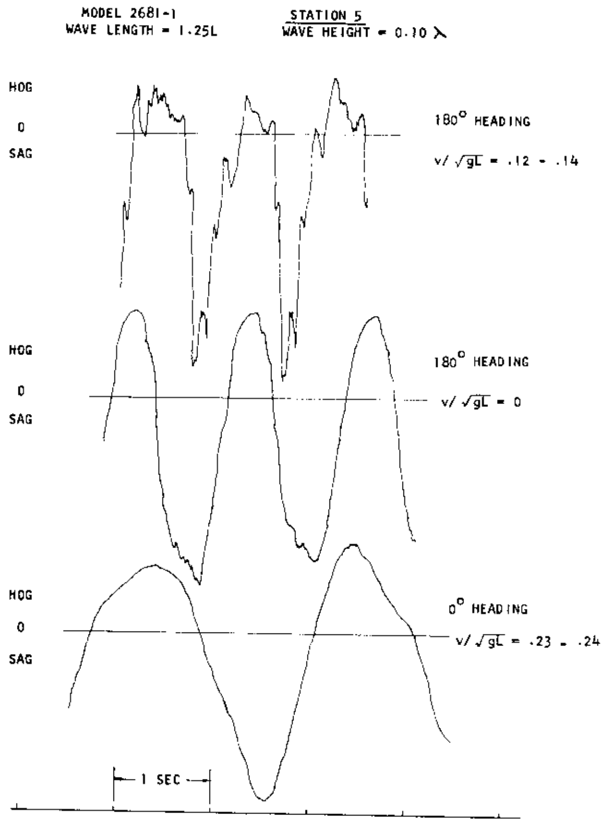


FIG. 7. SAMPLE OSCILLOGRAPH RECORD.

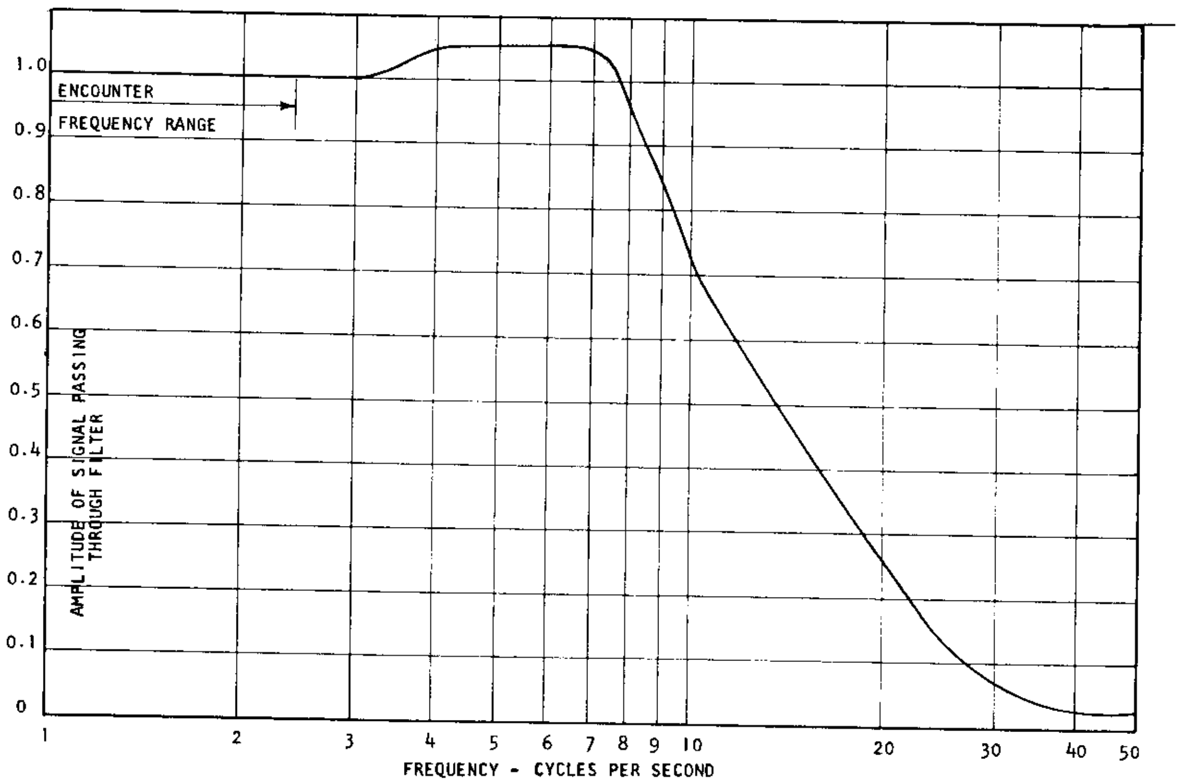


FIG. 6. FILTER RESPONSE

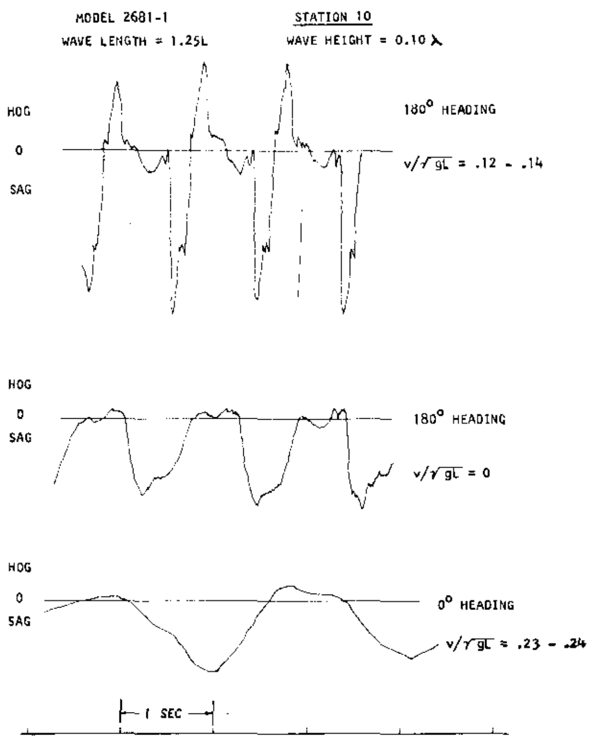


FIG. 8. SAMPLE OSCILLOGRAPH RECORD

TEST PROGRAM

Since this project was an extension of the investigations of midship bending moments by Dalzell[1] its test program was followed for this project. The outline of the test program appears in Table 3. The outline contains the list of model conditions of heading and speed combinations and the regular waves in which the models were tested. Zero speed in following seas was not considered because in the previous project it was learned that the midship bending moments during zero speed in both head and following seas are quite similar.

Ratios of nominal wave length to model length covered by the program were 0.75, 1.00, 1.25, 1.50 and 1.75. The ratios of nominal wave height to wave length covered were 0.05, 0.07, 0.09, 0.10 and 0.11. In waves of $\lambda/L \approx 1.75$, the capacity of the wave maker limited the wave height to $h/\lambda \approx 0.9$.

The test program table refers to speed as forward, zero or drift speed but the actual speed in terms of Froude number appears at the head of the data curves.

The drift speed need qualification. For

TABLE 3. TEST PROGRAM

Model 2681-1

		Number of Wave Heights					
Wave Length / Model Length →		.75	1.00	1.25	1.50	1.75	2.00
Heading	**Speed**						
180°	Forward	5	5	5	5	3	
180°	0	5	5	5	5	3	
180°	Drift	5	5	5	5		3
0°	Forward		5	5	5	3	

Model 2681-2

		Number of Wave Heights				
Wave Length / Model Length →		.75	1.00	1.25	1.50	1.75
Heading	**Speed**					
180°	Forward			5		
180°	0		5	5	5	5

each wave length the speed aimed at was the speed at which the model was run in the previous investigation[1] by Dalzell. Dalzell established the drift speed for all waves of same length as the speed at which the model drifts astern in the highest wave associated with the particular wave length. In lower waves that speed was maintained by applying reverse thrust on the model.

The model with cargo amidships (2681-2) was tested with zero speed in head seas (four wave lengths) and forward speed in head seas (one wave length) only. The program for model 2681-2 had to be curtailed due to an anticipated shortage in the funds.

DATA REDUCTION

The magnitude of wave heights and bending moments for each model run were obtained by averaging the data recorded for 20 ft of model travel. In the case of zero speed the averaging was performed for 20 cycles of the time history. In other cases the number of cycles depended on the model speed, as follows:

	Cycles
Head Seas, forward speed	10-20
Head Seas, drift speed	10-15
Following Seas, forward speed	5-10

For waves measurements were made of the double amplitudes. For bending moments measurements were made of the maxima of both hog and sag moments from still water zero. These moments were exclusive of high frequency noise and whipping moments. Electronic filters rejected all the high frequency noise except the 24 cps noise introduced by the fundamental mode vibration of the beam. Even in this case the filters allowed only about 16 percent of the noise to go through and this much was smoothed out by eye when analyzing the record. It should be noted that the 24 cps noise was recorded only at forward speed in very high head seas. Samples of the oscillograph records of bending moments are given in Figs. 7 and 8.

All the data were non-dimensionalized in the process of data reduction. The wave heights were non-dimensionalized by dividing them by wave lengths and presented as wave steepness. Bending moment was converted to the non-dimensional coefficient μ by dividing them by the quantity $\rho g L^3 B$ where ρg is the weight density of water, L is the model length and B is the maximum model beam.

DATA PRESENTATION

The basic data is presented in the form of two graphs for each combination of model heading, speed and wave length, λ. One of the graphs gives the curves of bending moment coefficients, μ_{sag} and μ_{hog} (μ = moment/ $\rho g L^3 B$) variation along the hull length for constant wave steepness h/λ. The other graphs give the μ_s and μ_h variation with wave steepness at each of the five stations where measurements were made. These graphs appear in Figs. 9-54.

It is necessary to bear in mind that μ_s and μ_h refer to dynamic bending moments and that the origin of the graphs is the still water, zero-speed bending moments.

Figure 55 shows the location of bending moment maxima along the hull length during each different condition of heading, speed and wave length. The values of maxima for constant h/λ of 0.05, 0.07 and 0.09 appear in Figs. 56, 57, and 58 respectively.

For an overall view of bending moments trend with wave height, all the data points of each test station are plotted on a single graph of μ vs. h/λ (Figs. 59-63). Four different symbols are used to distinguish between data for the four basic heading and speed conditions. Two envelopes are drawn to the scatter of the data, one includes all the data and one excludes data of the head-seas forward-speed case.

ANALYSIS AND DISCUSSION

The data analysis and discussion is presented in two steps. In the first step, each case of heading and speed is considered separately and in the second step, an attempt is made to compare these cases.

In view of the limited data for the model with cargo amidships, the discussion of it and its comparison with the normal weight distribution model is presented briefly.

The measured moments are dynamic moments. The still water bending moment coefficients for the normal weight distribution conditions are:

Station	15	12-1/2	10-(℄)	7-1/2	5
Hog	.00022	.00040	.00047	.00043	.00029

The calculated static wave moments at midship in the standard L/20 wave are 0.00078 sag and .00059 hog.

NORMAL WEIGHT DISTRIBUTION MODEL 2681-1

<u>Head Seas, Forward Speed, Figs. 9-18.</u>
In the head-seas forward speed case the Froude number was maintained between 0.13 and 0.14 in all waves. In terms of full-scale, this range is 9.2 to 10.7 knots.

The maximum sagging moments are located between Stations 8 and 9 in the higher waves ($h/\lambda > .07$) while in lower waves ($h/\lambda < .07$) they are located around station 10. The maximum hogging moments are located in the station 11-1/2 - 12-1/2 region, except in λ = 1.00L and 1.25L waves.

In waves of 1.00L and 1.25L for $h/\lambda > .07$ hogging moments larger than at station 12-1/2 are developed at station 5 (Fig. 11, 13). Concurrently sagging moments at station 5 are large also, amounting to 60-70 percent of the peak moments near amidships. During these test rungs a large keel emergence of up to 30 percent of the model length was observed and examination of the bending moment oscillograms showed evidence of flexure beam vibration (Fig. 7). Although accelerations were not recorded, the evidence of beam vibration on the moment

(Manuscript continued on pg.19)

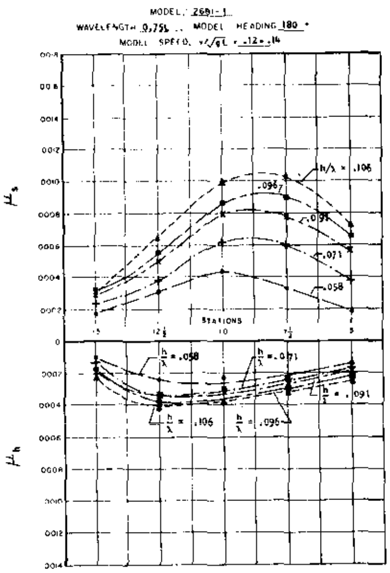


FIG. 9

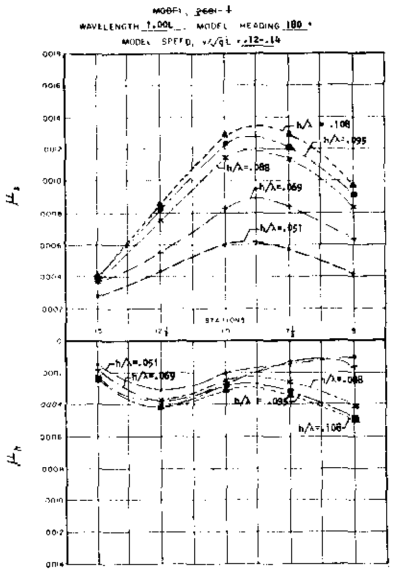


FIG. 11

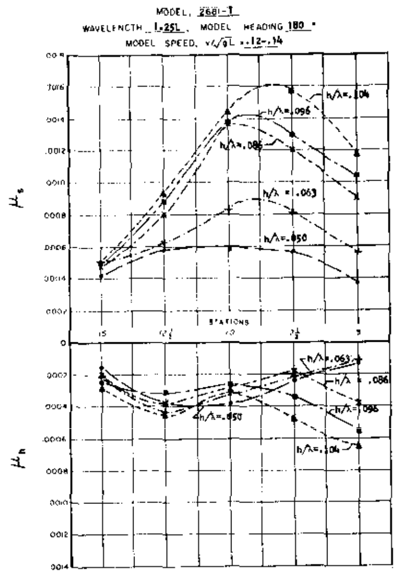


FIG. 13

FIGS. 9, 11, 13. BENDING MOMENTS VARIATION ALONG THE MODEL LENGTH

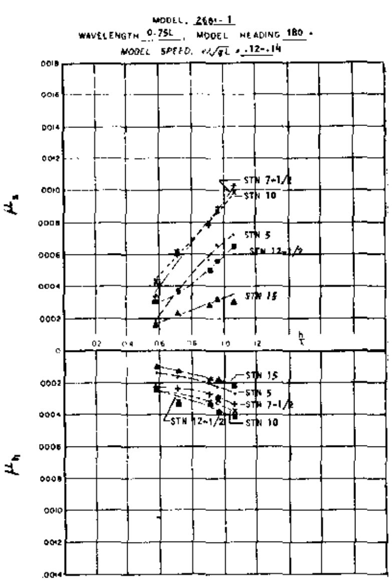


FIG. 10

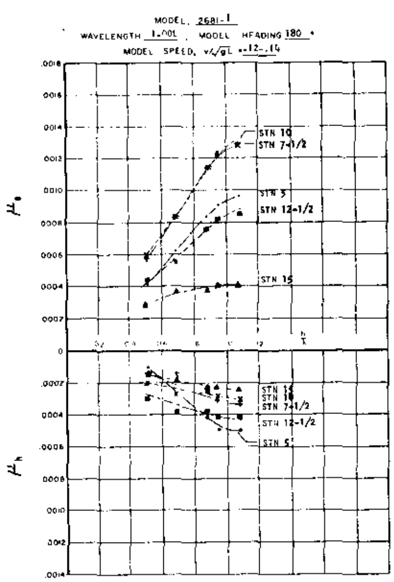


FIG. 12

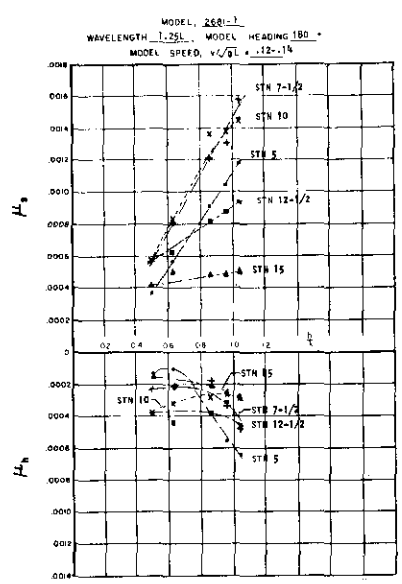


FIG. 14

FIGS. 10, 12, 14. BENDING MOMENTS VARIATION WITH WAVE HEIGHT

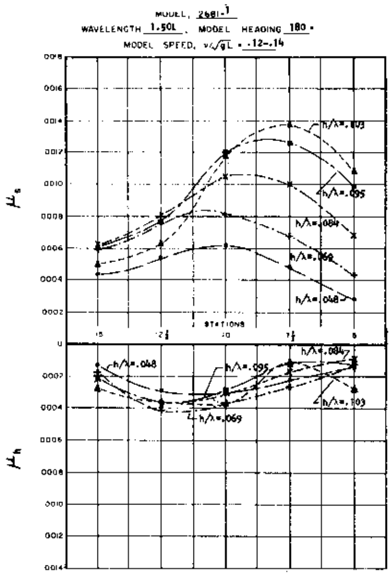


FIG. 15

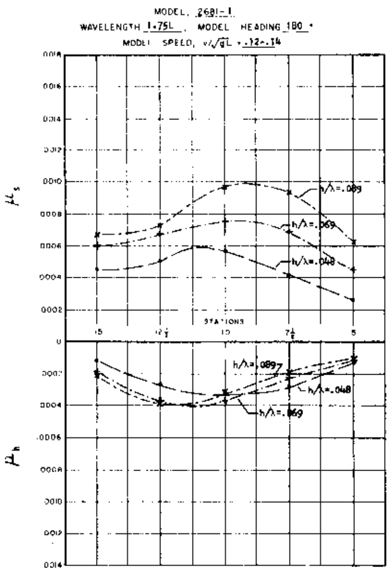


FIG. 17

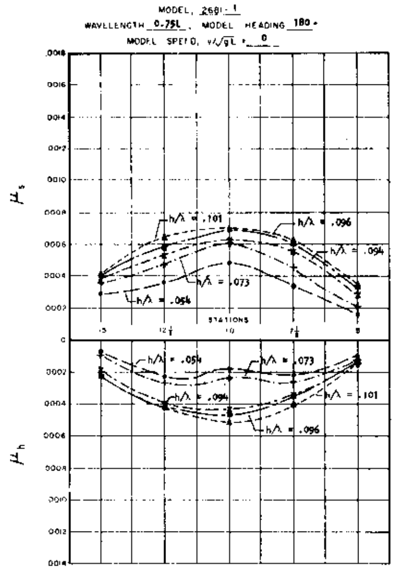


FIG. 19

FIGS. 15, 17, 19. BENDING MOMENTS VARIATION ALONG THE MODEL LENGTH

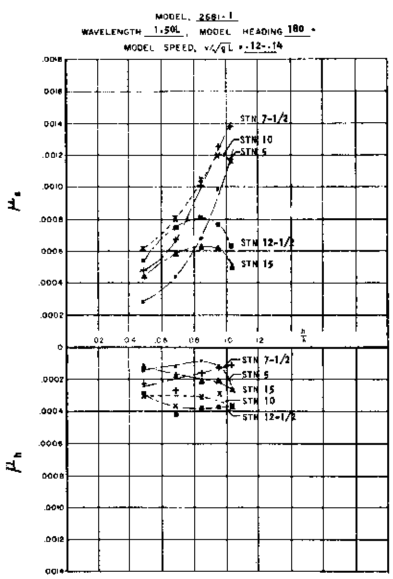


FIG. 16.

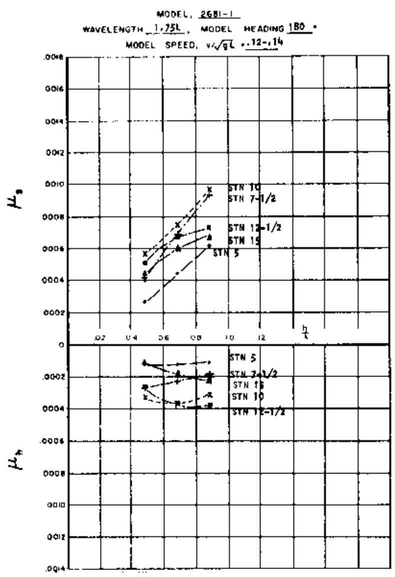


FIG. 18.

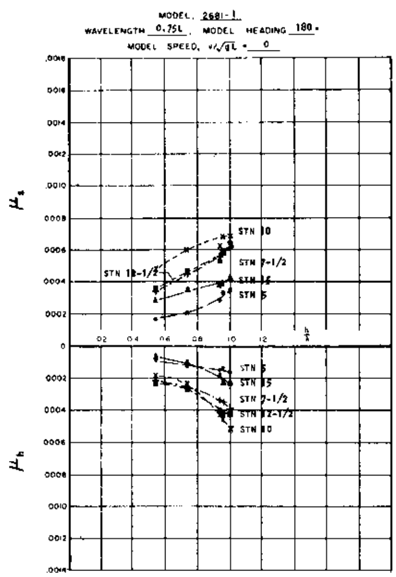


FIG. 20

FIGS. 16, 18, 20. BENDING MOMENTS VARIATION WITH WAVE HEIGHT

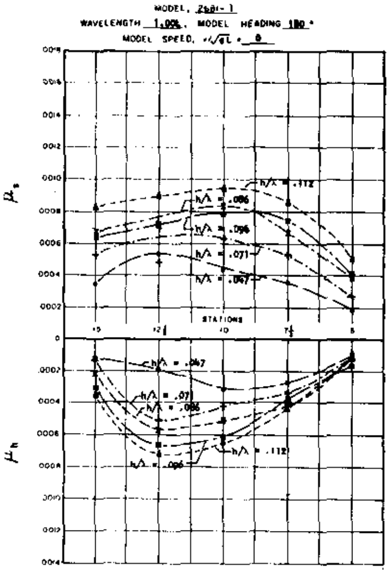


FIG. 21

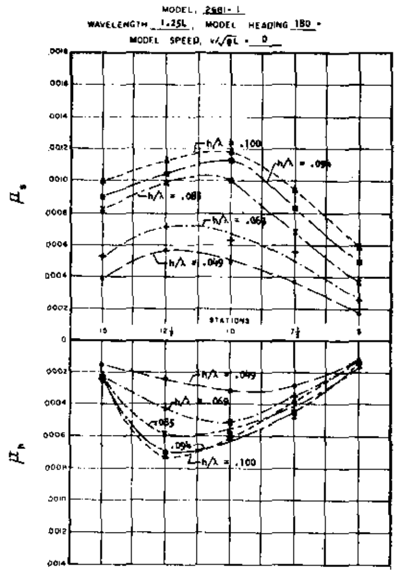


FIG. 23

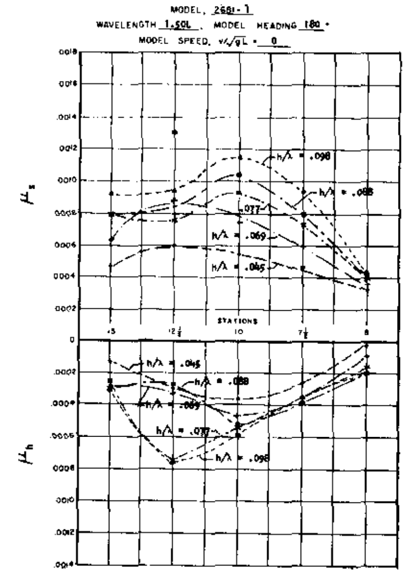


FIG. 25

FIGS. 21, 23, 25. BENDING MOMENTS VARIATION ALONG THE MODEL LENGTH

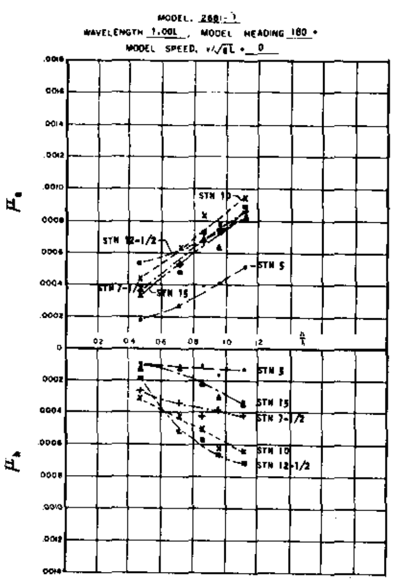


FIG. 22

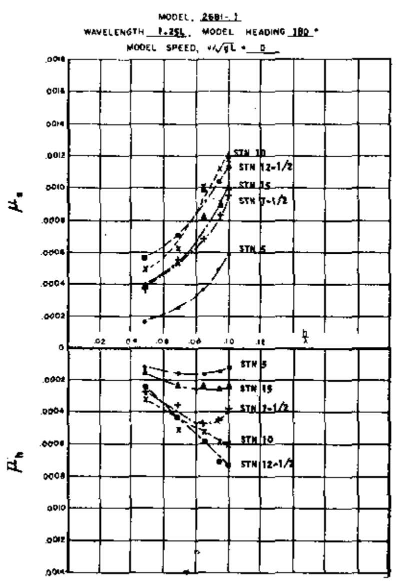


FIG. 24

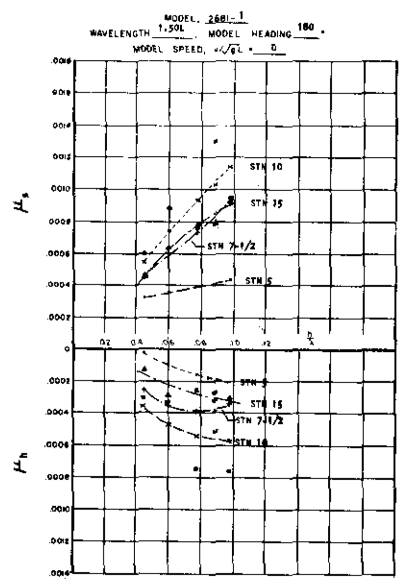


FIG. 26

FIGS. 22, 24, 26. BENDING MOMENTS VARIATION WITH WAVE HEIGHT

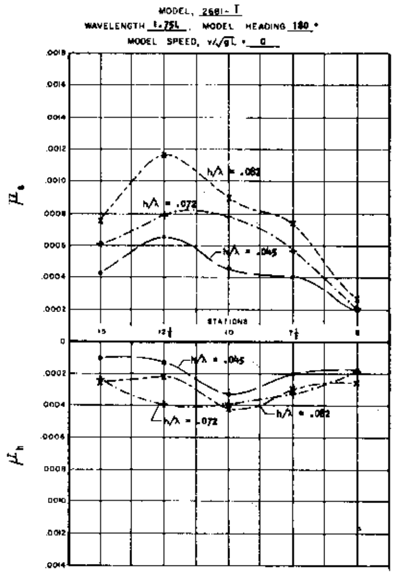


FIG. 27

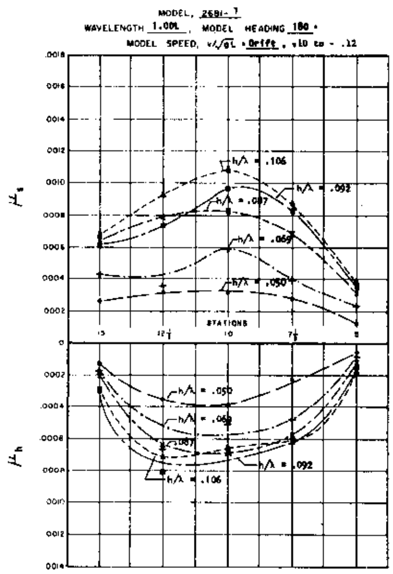


FIG. 29

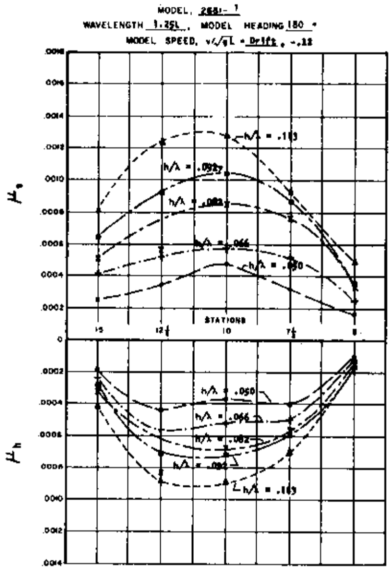


FIG. 31

FIGS. 27, 29, 31. BENDING MOMENTS VARIATION ALONG THE MODEL LENGTH

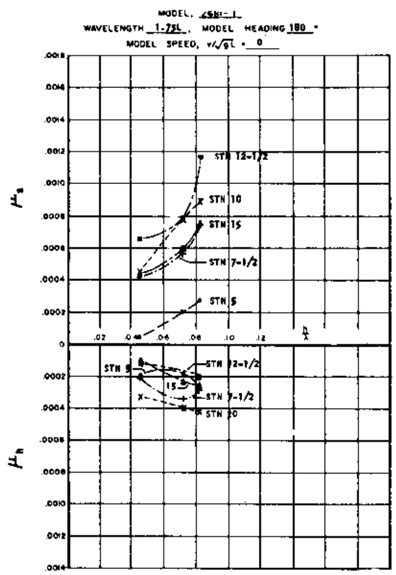


FIG. 28

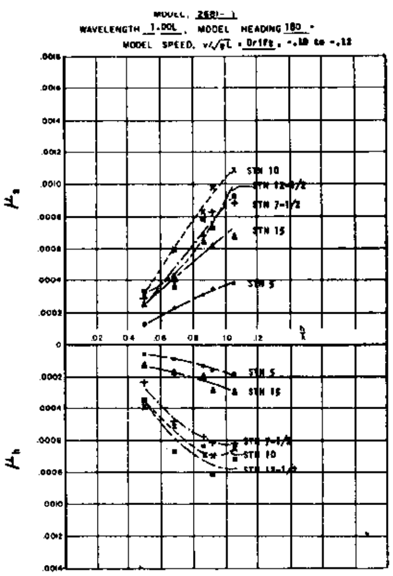


FIG. 30

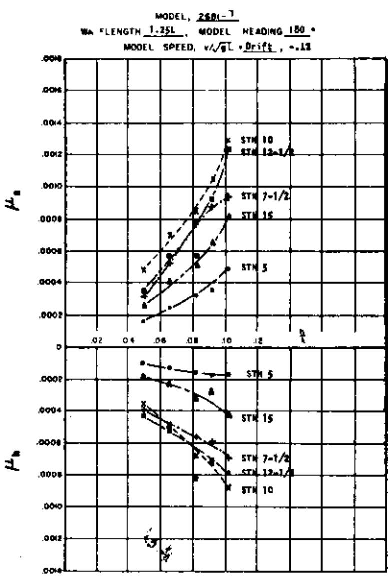


FIG. 32

FIGS. 28, 30, 32. BENDING MOMENTS VARIATION WITH WAVE HEIGHT

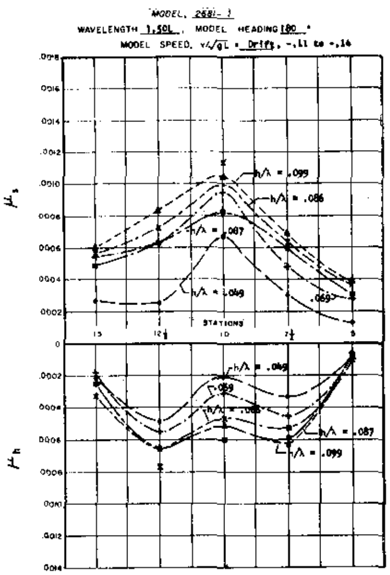


FIG. 33

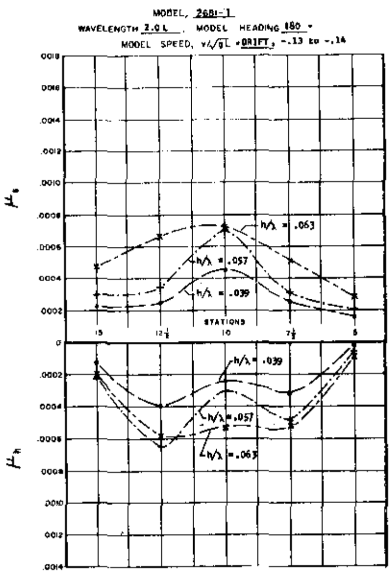


FIG. 35

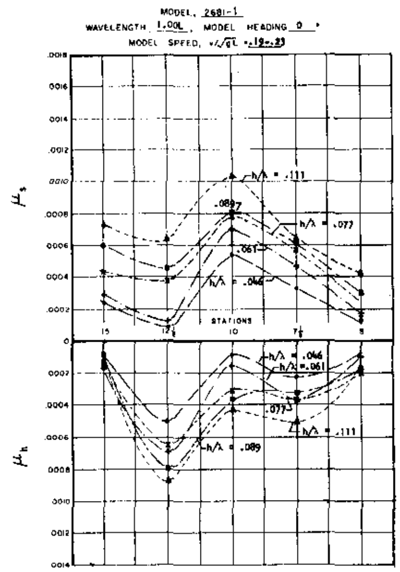


FIG. 37

FIGS. 33, 35, 37. BENDING MOMENTS VARIATION ALONG THE MODEL LENGTH

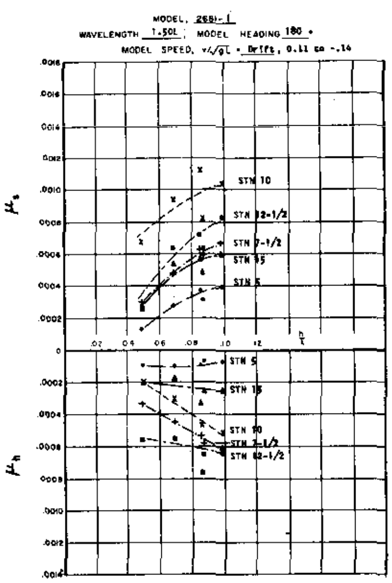


FIG. 34

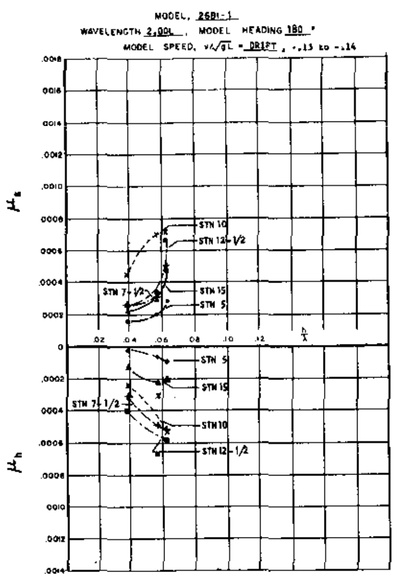


FIG. 36

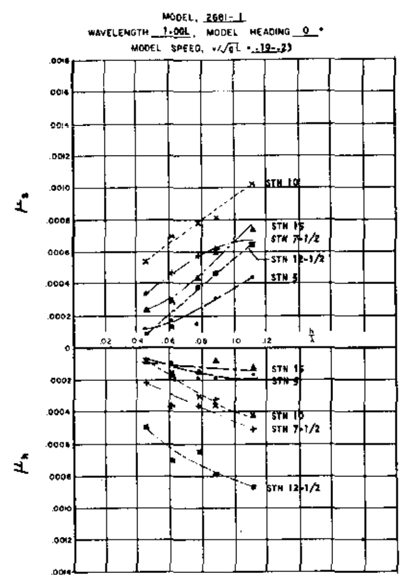


FIG. 38

FIGS. 34, 36, 38. BENDING MOMENTS VARIATION WITH WAVE HEIGHT

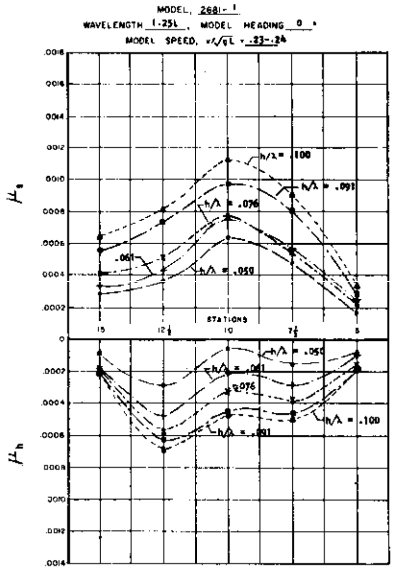


FIG. 39

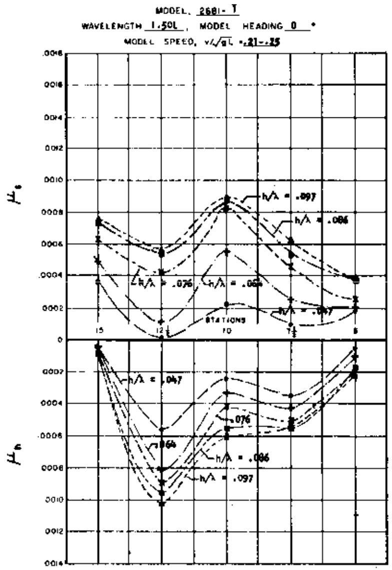


FIG. 41

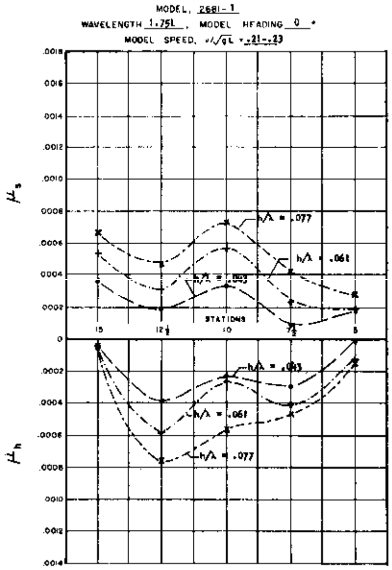


FIG. 43

FIGS. 39, 41, 43. BENDING MOMENTS VARIATION ALONG THE MODEL LENGTH

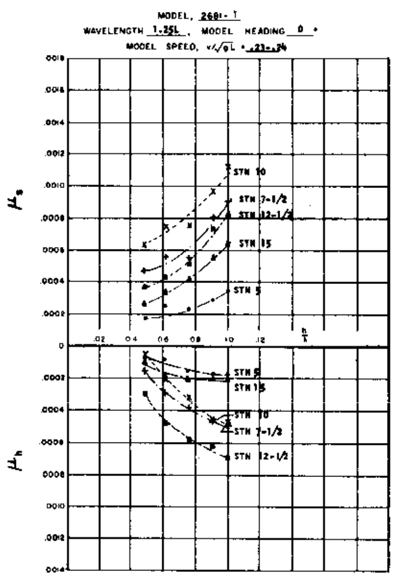


FIG. 40

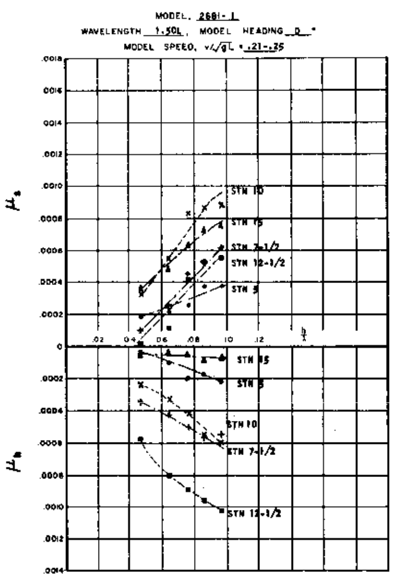


FIG. 42

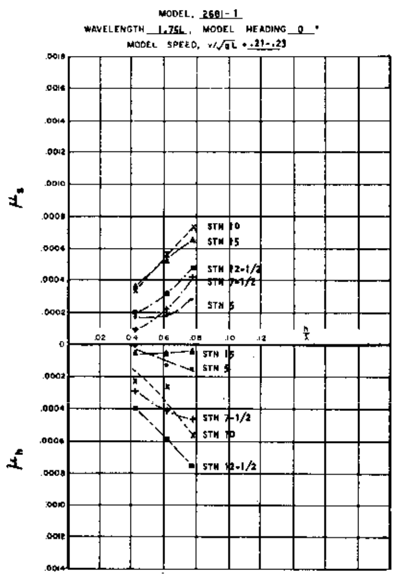


FIG. 44

FIGS. 40, 42, 44. BENDING MOMENTS VARIATION WITH WAVE HEIGHT

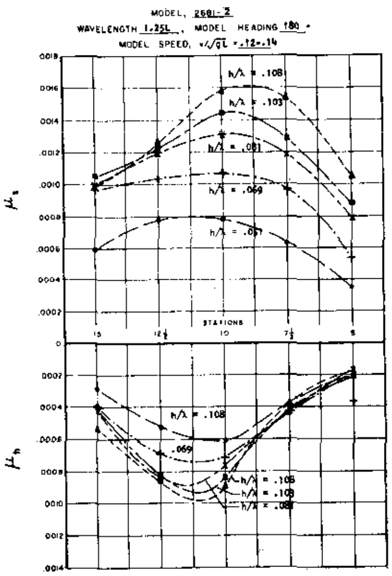


FIG. 45

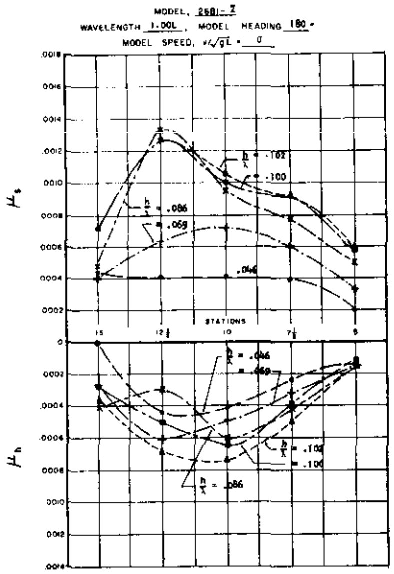


FIG. 47

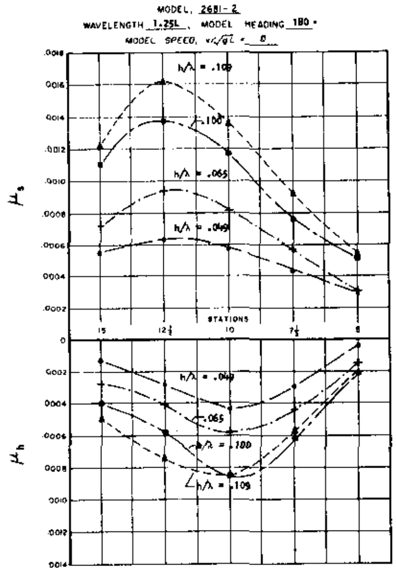


FIG. 49

FIGS. 45, 47, 49. BENDING MOMENTS VARIATION ALONG THE MODEL LENGTH

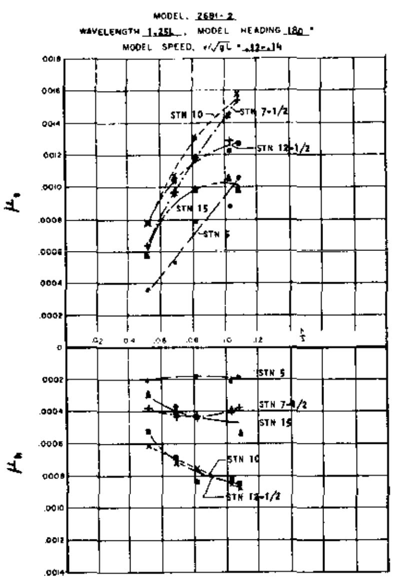


FIG. 46

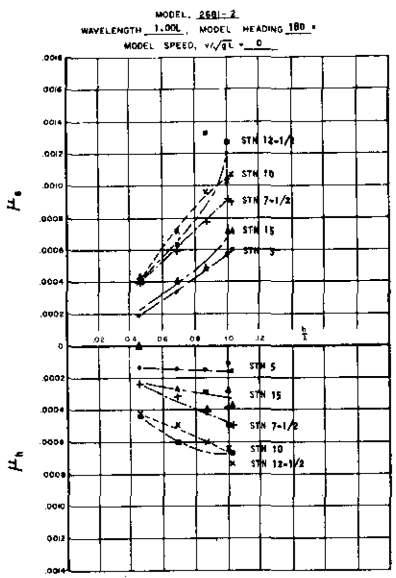


FIG. 48

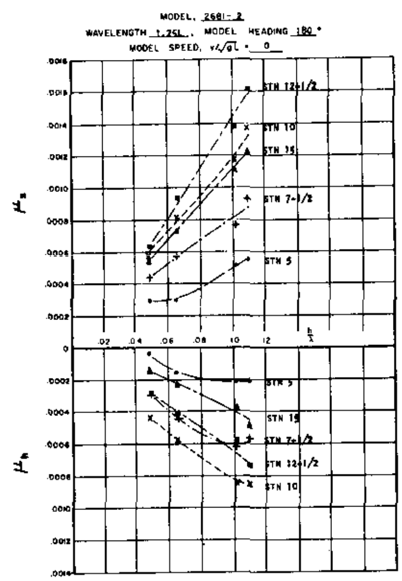


FIG. 50

FIGS. 46, 48, 50. BENDING MOMENTS VARIATION WITH WAVE HEIGHT

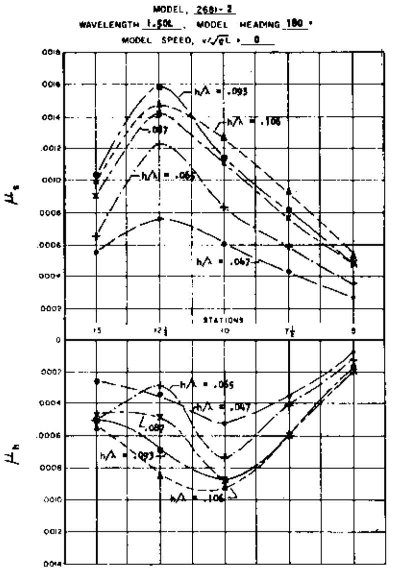


FIG. 51

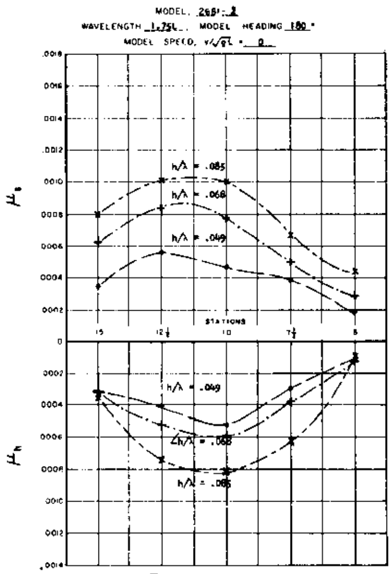


FIG. 53

FIGS. 51, 53. BENDING MOMENTS VARIATION ALONG THE MODEL LENGTH

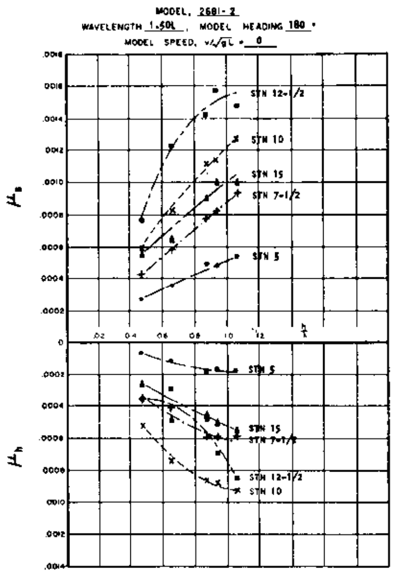


FIG. 52

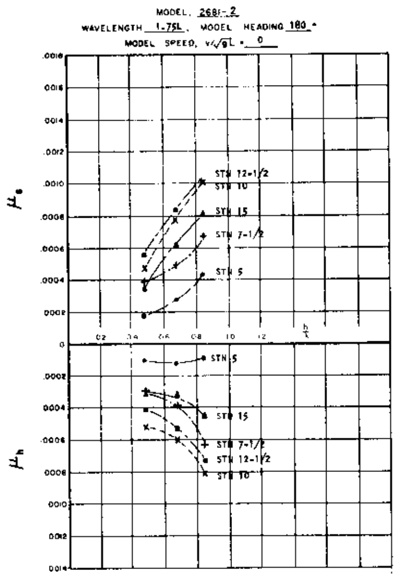


FIG. 54

FIGS. 52, 54. BENDING MOMENTS VARIATION WITH WAVE HEIGHT

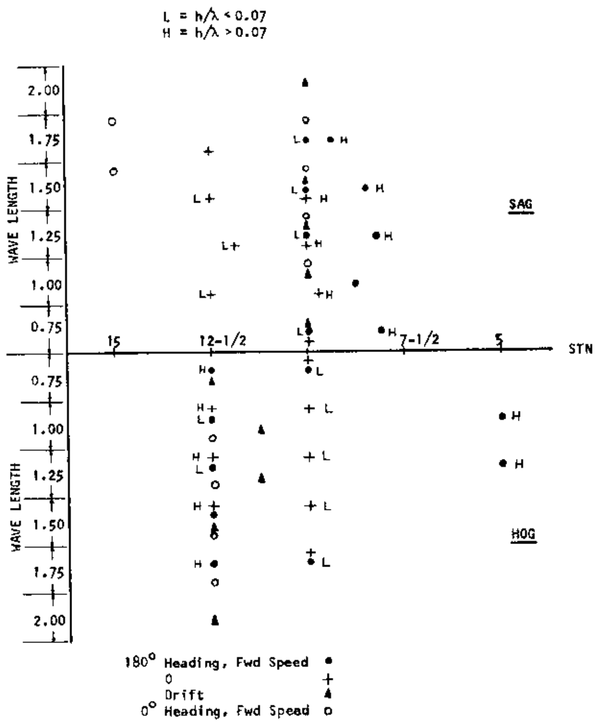


FIG. 55. LOCATION OF BENDING MOMENT MAXIMA, MODEL 2681-1.

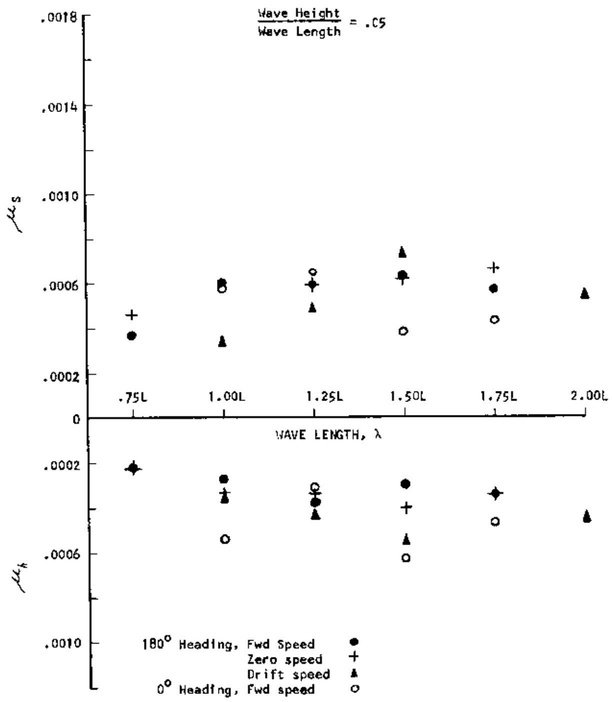


FIG. 56.

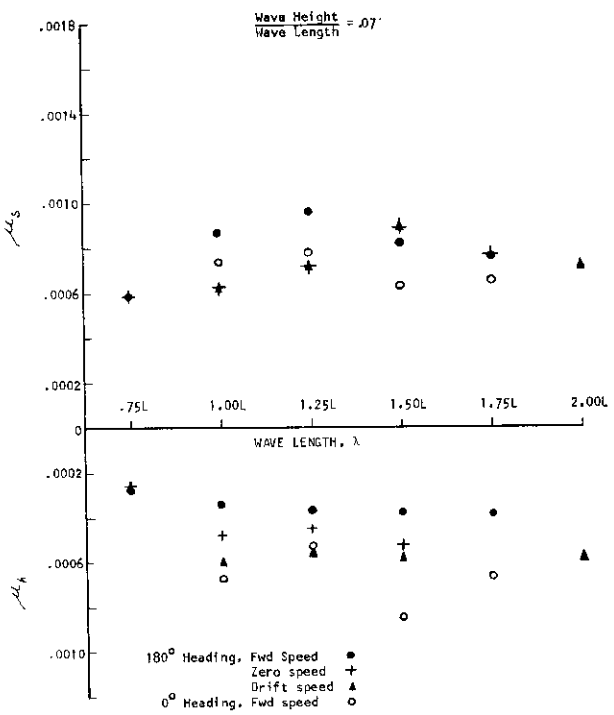


FIG. 57

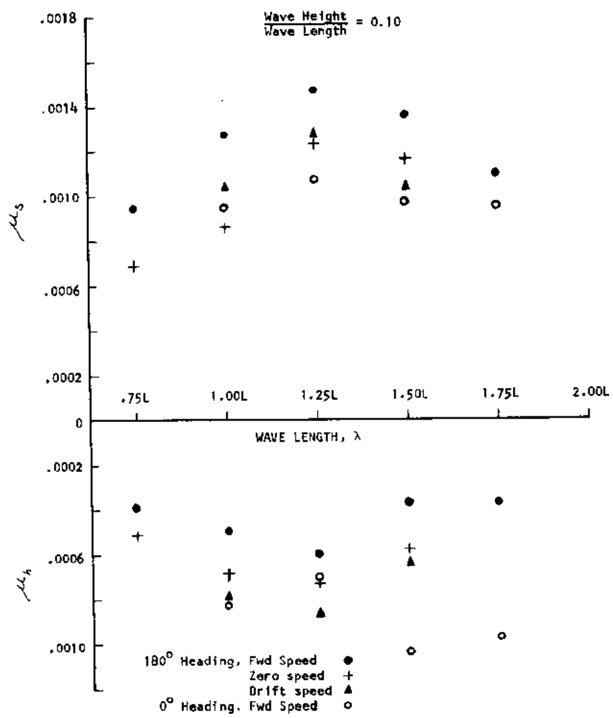


FIG. 58

FIGS. 56, 57, 58. MAXIMUM BENDING MOMENTS VARIATION WITH WAVE LENGTH. MODEL 2681-1. BOTH HEADING AND ALL SPEEDS.

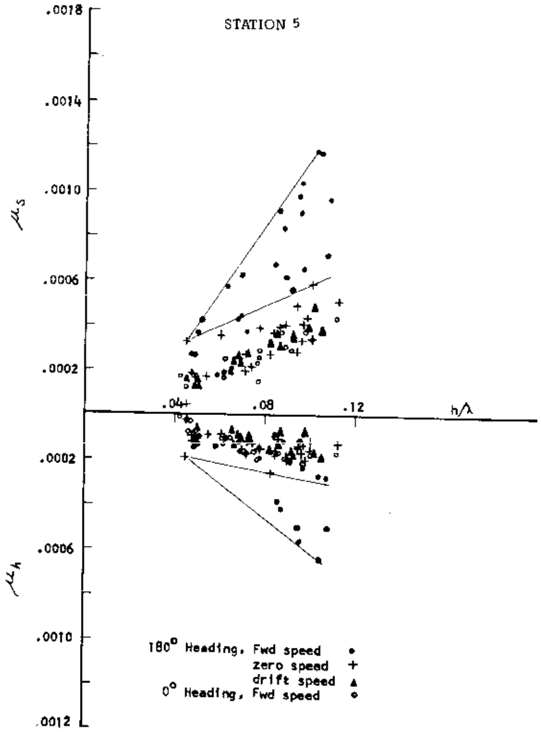


FIG. 59

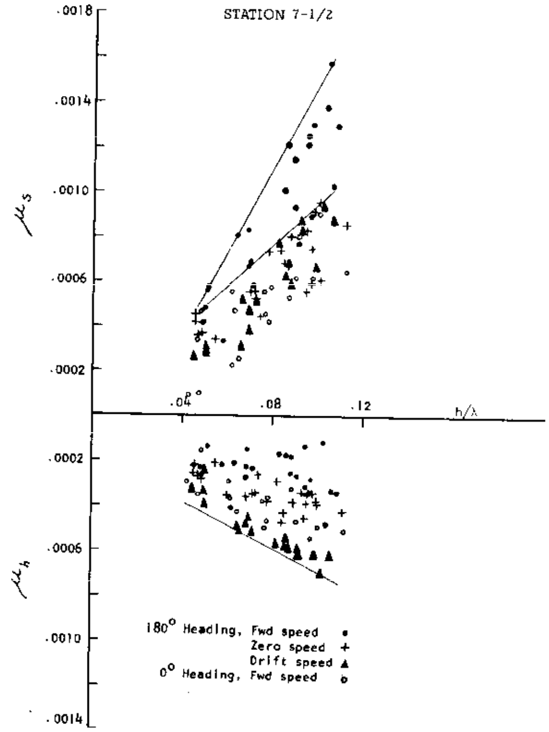


FIG. 60

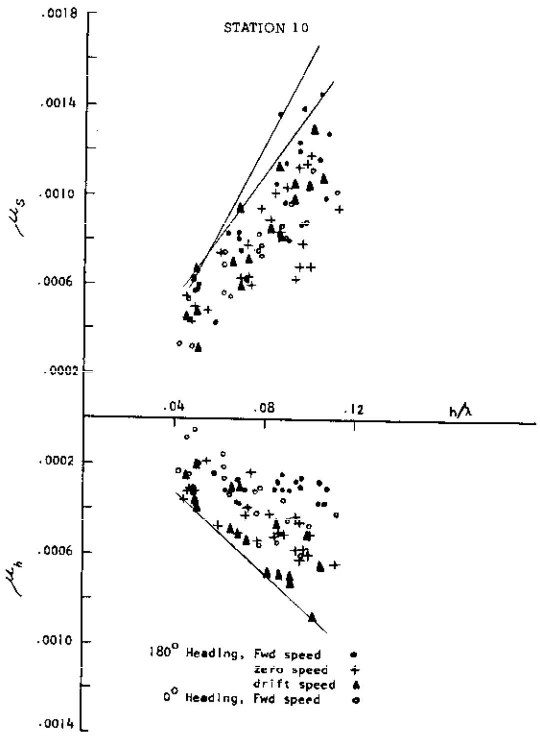


FIG. 61

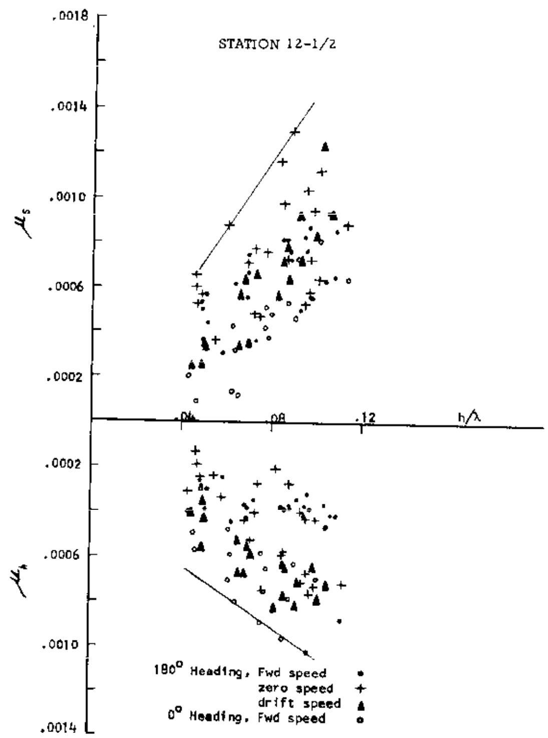


FIG. 62

FIG. 59, 60, 61, 62. BENDING MOMENTS VARIATION WITH WAVE HEIGHT. MODEL 2681-1. BOTH HEADINGS AND ALL WAVE LENGTHS AND SPEEDS.

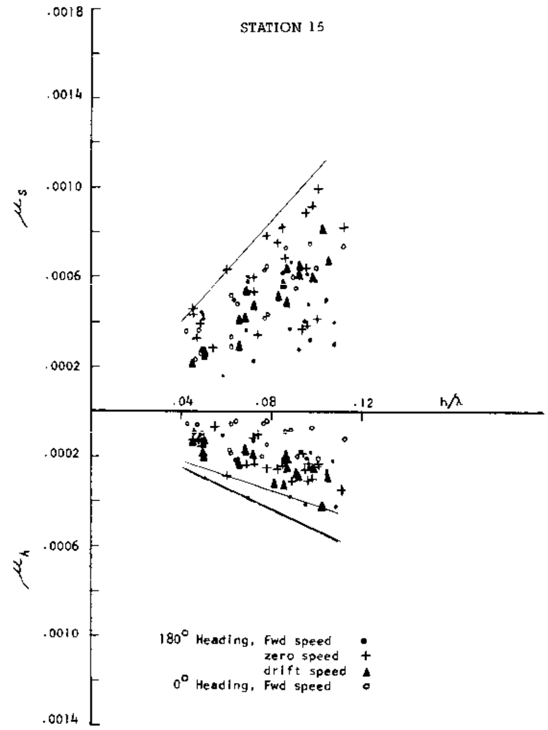


FIG. 63. BENDING MOMENTS VARIATION WITH WAVE HEIGHT. MODEL 2681-1. BOTH HEADINGS AND ALL WAVE LENGTHS AND SPEEDS.

record suggests that slamming occurred and it is believed that this may account for the high values of bending moment.

The highest moments occur in waves of λ = 1.25 (Fig. 56-58). Bending moments well in excess of the calculated static wave moments at amidships in a standard L/20 wave were measured.

The graphs of bending moment vs. h/λ show that sagging moments are close to being linear with wave height for $h/\lambda < .09$. In 1.00L length waves there is a suggestion from the curves that bending moment peaks may be reached at $h/\lambda \approx .12$, but this is not borne out in other waves. The slopes of the dynamic hogging moment curves are small except in 1.00L and 1.25L waves where slamming is suspected and the moment at station 5 increases rapidly with increasing wave height.

Head Seas, Zero Speed, Figs. 19-28.
In the head sea, zero speed case, the maximum sagging moments are located at amidships except in very long waves or in waves with $h/\lambda < .07$ when the maxima are around station 12-1/2. For maxima of hogging moments the situation is reversed where the low, the long and the short waves have maxima at station 12-1/2 while high waves of medium length have maxima at midship. It is significant to note that sagging moments as far aft as station 15 remain as high as 80%-90% of the maximum.

The maximum moments clearly occur in waves of λ = 1.25L when $h/\lambda > .07$, but when $h/\lambda < .07$, the maximum moments, particularly hogging moments, vary little with wave length between λ = 1.00L to λ = 1.75L.

Sagging moments in excess of the calculated midship static wave moment in L/20 waves were measured in waves with $\lambda > .75$L and $h/\lambda > .07$. In the case of hogging moments, the meassured moments remained below the L/20 static wave moment in waves of λ = 1.00L - 1.25L and $h/\lambda > .09$.

Examination of the graphs of bending moments vs. h/λ show that there is no tendency for sagging moments to attain peaks. Also, the slope of curves for various stations for constant wave length is approximately the same.

The preceding description of sagging moment curves fits the hogging moment curves for station 10 and 12-1/2 (where the maxima occur). Curves for station 5, 7-1/2, and 15 have lower slopes and in waves of λ = 1.25L - 1.50L they tend to flatten out at h/λ = .08.

Head Seas, Drift Speed, Figs. 29-36.
The lengthwise distribution of moments have sagging moment maxima in the region of station 10-11 and hogging moment maxima in the region of station 11-12-1/2. In λ = 1.50L -2.00L waves, the hogging moment develops two peaks at stations 7-1/2 and 12-1/2, the latter being the higher peak. Some indications of this appear in $\lambda < 1.50$L waves where the hogging curves are relatively flat at the maxima.

The highest moment occurs in λ = 1.25L waves when $h/\lambda > .07$ and in λ = 1.50L waves when $h/\lambda < .07$.

Statically calculated wave moments at amidships in L/20 waves are exceeded by moments at station 7-1/2, 10, and 12-1/2 in waves of λ = 1.00L - 1.25L and $h/\lambda > .07$.

The first order dependence of moments on wave height is clearly shown by the curves of μ vs. h/λ. The change of slopes with h/λ is gradual and there is no clear and consistent tendency to attain peaks.

Following Seas, Forward Speed, Figs. 37-44.
The Froude number range of 0.19 -0.25 for these tests corresponds to a full-scale speed range of 14.6 - 19.2 knots.

The sagging moment maxima are located at station 10. The moments at station 15 are high also and in longer waves, their values are of the same order of magnitude as the moments at station 10. The only exception to this is in the data in λ = 1.25L wave which do not indicate any secondary peaks aft. No plausible explanation is offered for the different nature of the curves for λ = 1.25L.

Hogging moments in this case develop two peaks at stations 7-1/2 and 12-1/2, respectively, as in the case of head sea, drift-speed case. In this case, the peaks at station 7-1/2 are relatively low.

The maximum sagging moments occur in λ = 1.25L waves and the maximum hogging moments occur in λ = 1.50L waves.

The measured sagging moments at station 10 in waves with $h/\lambda > .08$ and the measured hogging moments at station 12-1/2 in waves with $h/\lambda > .06$ exceed the calculated midship static wave moments in an L/20 standard wave.

The curves of bending moments vs. h/λ are nearly straight lines and by virtue of their shape, do not indicate any peaks.

CARGO AMIDSHIP — MODEL 2681-2

Head Seas, Forward Speed - $\lambda = 1.25L$ Waves only, Figs. 45-46.

The sagging moment maximum drifts from station 11 in the $h/\lambda = .05$ waves to station 9 in the $h/\lambda = .11$ wave. The hogging moment maxima are located about station 11.

Except in $h/\lambda < .05$ waves, the measured bending moments were considerably larger than the statically calculated midship wave moments in L/20 waves.

Head Seas, Zero Speed, Figs. 47-54.

The sagging moment maxima are located about station 12-1/2 while the hogging moment maxima are located about station 10.

The highest moments occur in $\lambda = 1.25L$ - 1.50 L waves.

In the region where the maximum moments occur, the measured moments in the higher waves exceed the statically calculated wave moment at amidships in the L/20 wave.

Generally, both hog and sag moments are nearly linear with h/λ and, consequently, do not show signs of an upper bound. Slopes of moments at various stations for constant wave length are approximately the same except at station 5 where the slope is quite small.

COMPARISONS

Comparison of Data for Various Heading and Speed Combinations.

Figure 55 shows that the maximum sagging moments are located in the station 8-10 region. At zero speed, the sagging moment maximum drifts aft to station 12-1/2 in waves with $h/\lambda <$ .07. The maximum hogging moments are located about station 12-1/2. At zero speeds the maximum drifts forward to midship in waves with $h/\lambda < .07$.

The lengthwise moment distribution curves, show that there are two other areas where large moments occur under certain conditions. In waves of 1.00L and 1.24L, head seas at forward speed, large moments were measured at station 5 and, in following seas, large moments were measured at station 15. Although measurements were not made beyond stations 5 and 15, the slopes of the curves at these stations indicate that the moments developed forward and aft of stations 5 and 15 may possibly be larger than the maximum moments in the middle body. However, note that these two speed conditions would be impossible to realize for the ship in the more severe sea conditions simulated during the tests. The installed horsepower of the Mariner is such that only the conditions of zero-speed and drift speed could be maintained in the steepest waves.

In both head seas, drift speed and following seas, forward speed cases where the model is moving in the same direction as the waves, the hogging moments develop two peaks located at station 7-1/2 and 12-1/2. This is much more pronounced in following seas.

The largest moments occur in 1.25L - 1.50L waves. But, it can be seen in Figs. 56-58 that, as the wave height is reduced from $h = .10\lambda$ to $.05\lambda$ the order of magnitude of maximum moments in 1.00L - 1.75L waves is the same.

In the highest waves, bending moments are greater than the statically calculated wave moments at amidships in a standard L/20 wave.

Generally, dynamic sagging moments are larger than the hogging moments, but the absolute hogging moments are much larger than the absolute sagging moments due to a still water hogging moment.

The curves of moment coefficient versus h/λ for all cases, Figs. 10-44, show that at the locations where the largest moments occur in waves of h/λ up to 0.11, there is no clear tendency for the moments to reach an upper limit. Only at those points along the hull length where moments are small do they tend to level off.

The rate of change of slope with h/λ of these curves is generally small up to $h/\lambda = .09$. Stating this in another way for first order estimating purposes, it would be satisfactory to draw straight lines through the data points in this region. This seems even more reasonable when taking into consideration an experimental data scatter range.

Figures 59-63 present all the data collected at each test station. They help to obtain the maximum moments developed at a station in any wave height in the range of $h/\lambda \approx .05 - .11$. They show that the highest sagging moments were developed at station 7-1/2 - 10 in the head sea forward speed condition. If the forward speed is neglected as impractical, then the highest sagging moments occur at stations 10 and 12-1/2 in drift speed and zero speed cases, respectively. By far, the largest hogging moments occurred at station 12-1/2 in following seas.

Comparison of Models. The model with cargo amidships (2681-2) has larger bending moments than the model with the normal weight distribution (2681-1). Relative to the maxima location for Model 2681-1, sagging moment maxima for 2681-2 are further aft and hogging moment maxima are further forward.

Comparison with other investigations. The investigation reported here is an extension of the investigation of midship bending moments by Dalzell[1]. Model 2251A-V-1 of Dalzell and model 2681-1 of this project are both original Mariners with normal weight distribution and they were both tested in the same wave conditions. One significant difference beween the models was that Dalzell's model had a midship house of appreciable extent whereas this project's model had only a small streamlined coaming (See Fig. 1 and 2). It should be noted that these are the only experiments known to the reporter in which extreme waves were made. Wachnik and Schwartz[3] have performed a very similar test of a Mariner but in relatively low waves, $\lambda/h = 20, 30$, and 40.

Comparison of wave bending moments at station 10 with Dalzell's midship moment results show the following:

a. Sagging moments results of Dalzell were consistently lower than the results here. Out of 17 comparable sets of results, 6 showed differences of 6 percent or less and 4 showed differences between 6 and 15 percent. Average deviations in head seas were 18 percent at forward speed. 13 percent at zero speed, and 10 percent at drift speed. In following seas the average deviation was 10 percent.

b. Dalzell's hogging moment results were generally higher than the results reported here. Of 17 sets of results, 7 showed differences of 5 percent or less and 4 showed differences between 6 and 15 percent. Average deviations in head seas were 30 percent at forward speed, 4 percent at zero speed and 8 percent at drift speed. In following seas the average deviation was 12 percent.

It is seen that there is reasonable agreement between the two sets of values with the exception of the data for the head seas, forward speed case. In all cases a visual comparison of slope variations of corresponding curves shows good agreement between the two sets of results.

The bending moment results in head seas from this project compare very well with the DTMB data presented by Wachnik and Schwartz[3] in the case of the one nominal h/λ ratio of 0.050 common to both sets of data. The following comparison is based on results shown in Fig. 14 of Ref. 3 where $\lambda/L = 1.00$, $h/\lambda = .047$ and the speed is zero.

	$\mu_s + \mu_h$	
Station	DTMB	DL
5	.0026	.0027
7-1/2	.0057	.0063
10	.0075	.0076
12-1/2	.0069	.0073
15	.0036	.0046

CONCLUSIONS

1. Within practical operational limits of speed in head and following waves for the Mariner-type ship, maximum wave bending moments in extreme regular waves occur in the region from amidships to .125L aft of amidships.

2. Hogging and sagging wave bending moments are generally proportional to wave height up to a wave height/wave length ratio of 0.11, the steepest wave that could be generated.

RECOMMENDATIONS

1. Since only a limited number of tests were run with the cargo amidship weight distribution, additional testing should be carried out so that the effect of weight distribution on lengthwise variation of bending moment may be examined more completely.

2. The results presented to date have been based on tests in regular waves of extreme steepness. It is desirable to repeat the tests in realistic irregular waves and compare the results with those predicted from regular wave test data.

3. An attempt should be made to explain why a double reversal appeared in the variation of hogging wave moment along the length of the model in certain conditions.

4. It is desirable to check model tests results against full-scale observations. It is suggested, therefore, that model tests be planned for a ship for which full-scale bending moment and motions data are available.

ACKNOWLEDGEMENT

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