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August 1981

EXPERIMENTAL STUDY OF SWATH MODEL ROLLING IN BEAM WAVES

by

Edward Numata

Prepared for

Code 111
David W. Taylor Naval Ship Research
and Development Center

under

Office of Naval Research
Contract N00014-79-C-0950
Project NR 062-582

(DL Project 4783/075)

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STEVENS INSTITUTE
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Experiments were conducted with a model of a single-strut-per-hull SWATH ship and three variants (Higher GM, Wide Spacing, Deep Draft) at zero speed in beam regular and irregular waves. Each model configuration tended to roll at its natural frequency ω when excited by regular waves with a frequency 2ω, or by irregular waves with a modal frequency of 2ω.

omega

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Approved
Daniel Savitsky
Deputy Director

INTRODUCTION

In 1978 Davidson Laboratory was contracted by the Naval Sea Systems Command to carry out model tests of two Small-Waterplane-Area-Twin-Hull (SWATH) configurations. Both configurations had a full-scale length of 200 feet and a displacement of about 1800 L. Tons. One configuration had one strut per demihull (single strut), a total waterplane area of 1839 sq. ft. and a hull spacing of 55 feet. The other had two struts per demihull (tandem strut), a total waterplane area of 1093 sq. ft. and a hull spacing of 76.7 feet. Zero speed tests in regular and irregular beam waves revealed the following roll motion tendencies.

In regular waves with a uniform height of 0.05 x hull length, the single strut model had two modes of rolling motion.

a. Rolling due to differential heave motion at wave excitation frequency ω_w for ω_w = 1.45 to 0.70 rad/sec (natural heave frequency = 0.80 rad/sec).

b. Rolling at natural roll frequency ω_φ = .32 rad/sec in wave frequencies between 0.50 rad/sec and 0.70 rad/sec.

The tandem strut model always rolled at wave excitation frequency but facility limitations prevented full examination of wave frequencies below the natural heave frequency of 0.56 rad/sec.

In irregular waves with a significant height of 0.075 x hull length and a peak energy (modal) frequency of 0.575 rad/sec, each model tended to experience large rolling oscillations at its natural rolling frequency (single strut = 0.32 rad/sec, tandem strut = 0.25 rad/sec). Since there was very little wave spectrum energy at these natural frequencies to genarate linear excitation to roll, the origin of the observed large rolling amplitudes cannot be explained by linear theory.

Since the single strut configuration exhibited anomalous rolling behavior in both regular and irregular waves, it was suggested that additional experimental studies be conducted on this type of SWATH configuration. Specifically, the effect of changes in the following configuration and wave parameters would be investigated.

GM_T (by changing the vertical CG)
Draft
Hull Spacing
Regular Wave Height

The work was performed under Office of Naval Research Contract N00014-79-C-0950. Code 111, David W. Taylor Naval Ship Research and Development Center (DTNSRDC) monitored the technical aspects of the project.

MODEL

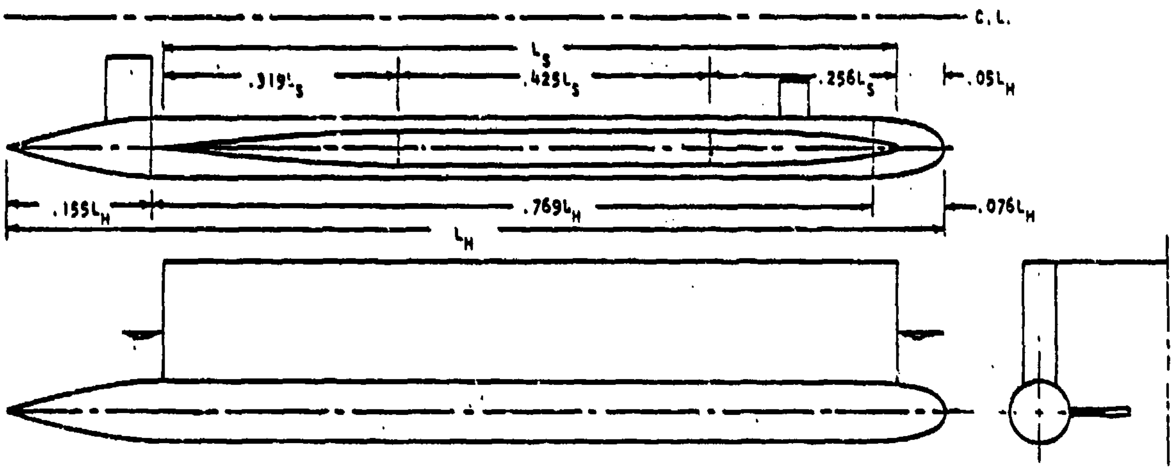
An existing single strut SWATH model, Davidson Laboratory (DL) No. 4571A, was used as the baseline configuration in this investigation. Figure 1 shows the baseline geometry and gives model and full-scale particulars for a linear scale ratio of 35.17. This scale ratio was chosen so that the displacement of the unappended model would scale up to 2900 long tons (the full-scale displacement of the SWATH 6 series models that have been tested extensively at DTNSRDC). Sizes and locations of the stabilizing fins on the inboard side of each hull are also shown in Figure 1. The fins were fixed at zero angle of incidence during the tests. No other appendages were fitted.

Table 1 gives ship-scale particulars for the baseline and three variants identified as Higher GM, Wide Spacing, and Deep Draft. The desired particulars of the variants were obtained on the model as follows.

<u>Higher GM</u>. Solid ballast was shifted from the upper flanges of deck beams to (1) the underside of the beams and (2) to the bottom of a cavity in each demihull. This shift increased transverse GM by approximately 50 percent; roll inertia decreased slightly (5 percent).

<u>Wide Spacing</u>. Four transverse channel beams, which bridged the two demihulls, were cut in the model centerplane and rejoined by adjustable plate straps. Either the Baseline demihull spacing or a 12 percent increase in spacing could be obtained by shifting the attachment screws in the straps. Location of solid ballast on each demihull was identical with the Baseline arrangement, thereby increasing roll inertia while maintaining the same VCG; transverse GM was approximately doubled as a result of the increase in transverse waterplane inertia.

<u>Deep Draft</u>. Hull centerline draft was increased 23 percent by shifting solid ballast so as to maintain approximately the same transverse GM as for the Baseline. Roll inertia increased only slightly (3 percent) owing to the compensating effects of a 10 percent increase in displacement and a 7 percent decrease in the square of roll gyradius.



PARTICULARS

Hull Length	234.5 Ft	71.48 m
Diameter	14.6 Ft	4.45 m
Prismatic Coeff.	.902	.902
Strut Length	183.5 Ft	55.93 m
Thickness	8.2 Ft	2.50 m
Waterplane Coeff.	.839	.839
Fwd Fins Chord	7.4 Ft	2.25 m
Span	9.0 Ft	2.74 m
LE from Hull Nose	33.6 Ft	10.24 m
Aft Fins Chord	12.9 Ft	3.93 m
Span	15.6 Ft	4.75 m
LE from Hull Nose	196.7 Ft	59.95 m

FIGURE 1. MODEL 4571A GEOMETRY SCALED TO 2900 L. TONS

TABLE 1A

PARTICULARS OF BASELINE AND THREE VARIANTS

		Baseline	Higher GM (Low CG)	Wide Spacing	Deep Draft
Hull Centerline Spacing	ft	64.5	64.5	72.0	64.5
Draft to Hull Centerline	ft	19.2	19.2	19.2	23.6
Draft to Keel	ft	26.5	26.5	26.5	30.9
Displacement, Unappended	LT	2900	2900	2900	3218
Displacement, with Fins	LT	2921	2921	2921	3239
LCB = LCG, from Hull NOSE	ft	108.4	108.4	108.4	107.4
LCF " " "	ft	98.6	98.6	98.6	98.6
VCG above keel	ft	30.45	27.55	30.45	29.50
Transverse GM	ft	6.65	9.60	13.00	6.80
Longitudinal GM	ft	33.10	36.00	33.10	30.65
Roll Gyradius, K_φ	ft	32.1	31.5	35.2	31.0
Period, T_φ	sec	18.3	14.9	14.8	17.7
Frequency, ω_φ	rad/sec	.343	.422	.425	.355
Pitch Period, T_θ	sec	14.3	13.7	14.3	*
Frequency, ω_θ	rad/sec	.439	.459	.439	*
Heave Period T_z	sec	8.2	8.2	8.2	8.6
Frequency ω_z	rad/sec	.766	.766	.766	.731

*Pitch oscillations in calm water were non-uniform; period could not be determined.

TABLE 1B

PARTICULARS OF BASELINE AND THREE VARIANTS

		Baseline	Higher GM (Low CG)	Wide Spacing	Deep Draft
Hull Centerline Spacing	m	19.660	19.660	21.946	19.660
Draft to Hull Centerline	m	5.852	5.852	5.852	7.193
Draft to Keel	m	8.077	8.077	8.077	9.418
Displacement, Unappended	MT	2946	2946	2946	3269
Displacement, with Fins	MT	2967	2967	2967	3290
LCB = LCG from Hull Nose	m	33.040	33.040	33.040	32.736
LCF from Hull Nose	m	30.053	30.053	30.053	30.053
VCG Above Keel	m	9.281	8.397	9.281	8.992
Transverse GM	m	2.027	2.926	3.962	2.073
Longitudinal GM	m	10.089	10.973	10.089	9.342
Roll Gyradius	m	9.784	9.601	10.729	9.449
Period	sec	18.3	14.9	14.8	17.7
Frequency	rad/sec	.343	.422	.425	.355
Pitch Period	sec	14.3	13.7	14.3	*
Frequency	rad/sec	.439	.459	.439	*
Heave Period	sec	8.2	8.2	8.2	8.6
Frequency	rad/sec	.766	.766	.766	.731

*Pitch oscillations in calm water were non-uniform; period could not be determined.

INSTRUMENTATION AND TEST PROCEDURE

Testing was conducted in DL Tank 3 which is 313 ft long by 12 ft wide by 5.5 ft deep (95.4 m x 3.66 m x 1.68 m). Instrumentation for sensing roll, pitch, heave, sway and wave elevation was utilized. Although all tests were to be in beam waves where no direct wave excitation of pitch was expected, it was observed in earlier tests that significant amplitudes of pitching due to heave coupling occurred. Accordingly, both roll and pitch were sensed by a free gyroscope on the model. A lightly tensioned heave string extended vertically upward from the model CG and was wound around a pulley mounted on a carriage above the model; the rotational motion of the pulley was sensed by a transducer. Sway was sensed in a similar manner by a string attached just above the waterline amidships on the outboard side of the leeward demihull, extending downwave to a pulley and sway motion transducer suspended from the carriage. Carriage speed was manually controlled to match the free drifting speed of the model. A wave probe was suspended from the carriage to sense elevation of incident waves. The probe was upwave about 11 ft from the model CG on the model centerline.

Output signals from the motion transducers were conditioned and recorded as analog time histories on magnetic tape and on strip charts. The signals were simultaneously digitized using a tankside PDP-8e digital computer, and the digitized data were processed using a standard program which performed a harmonic analysis of responses in regular waves. Amplitude and phase of the fundamental oscillation, as well as amplitudes and phases of the half harmonic and second harmonic for each response were recorded on a typewritten listing.

Regular wave periods ranging from 8 sec to 19 sec (.78 to .33 rad/sec) prototype scale were chosen to bracket and define peak responses in heave, pitch and roll. Wave heights ranged up to 10 ft (3.05 m).

Prior to testing, inclining experiments were performed to measure the transverse metacentric heights, GM, for the Baseline, Higher GM and Deep Draft configurations. The VCG (KG) was then determined by KM - GM = KG, where the height of the metacenter, KM, was calculated from the geometry of each configuration. Since only the hull spacing was changed for the Wide Spacing configuration, the VCG was the same as for the Baseline; the increase in GM was equal to the calculated increase in KM due to the increased waterplane inertia. See Table 1 for values of GM and VCG.

Free oscillation experiments were conducted in calm water to measure natural periods of roll, pitch and heave for each model configuration. Two configurations, Higher GM and Wide Spacing, were found to have the same roll natural period. A chart record of the roll extinction time history for each model was analyzed to determine the logarithmic decrement δ, and the damping factor $\delta/2\pi$ was then calculated. The roll radius of gyration of each model was measured, and is listed in Table 1.

The measured values of GM, roll gyradius k_φ and roll natural period were checked for consistency between the various configurations as follows. If it is assumed that roll damping and added inertia are each small, the following formula for undamped roll period can be used:

$$T_\varphi = \frac{Ck_\varphi}{\sqrt{GM}}$$

or

$$C = T_\varphi \sqrt{GM}/k_\varphi \qquad (1)$$

Also, assuming small damping and a single degree of freedom oscillation resulting from an initial disturbance, where the equation of motion is

$$mk_\varphi^2 \ddot{\varphi} + A\dot{\varphi} + \Delta GM\varphi = 0$$

then it can be shown that the damping factor is

$$\delta/2\pi = 0.5A/\omega_\varphi \, mk_\varphi^2 \qquad (2)$$

where A is a damping coefficient and m will be approximated by the displacement mass Δ/g. The following table shows values of C computed from Eq. (1), and a comparison of $\delta/2\pi$ obtained by experiment versus $\delta/2\pi$ computed by Eq. (2).

	C	$\delta/2\pi$ Experiment	$\delta/2\pi$ Computed*
Baseline	1.47	.017	.017
Higher GM	1.47	.014	.014
Wide Spacing	1.52	.015	.011
Deep Draft	1.49	.018	.016

*Computed on the assumption that in Eq. (2), A is same for all configurations, and is equal to 1091.

Each model configuration was tested in an irregular wave spectrum having a modal frequency ω_o (at peak energy) approximately twice the natural roll frequency ω_φ of the model. Since the Baseline and Deep Draft configurations had ω_φ = 0.343 and 0.355 rad/sec, respectively, a wave spectrum with an ω_o of 0.71/rad/sec was chosen; its significant height $H_{1/3}$ was 10 ft (3.05m). Similarly, a spectrum with ω_o = 0.80 rad/sec and $H_{1/3}$ = 8 ft (2.44 m) was used for the Higher GM and Wide Spacing configurations whose ω_φ values were 0.422 and 0.425, respectively. Figure 2 shows the two wave spectra.

In the irregular wave tests, output signals from the motion transducers were conditioned and recorded as analog time histories on magnetic tape and on strip charts. The signals were simultaneously digitized using a tankside PDP-8e digital computer, and the digitized data were processed using a standard program which identified the peaks and troughs of each response, typed the averages and extremes of all such peaks and troughs in a given run, and furnished the mean value of each response.

All test runs were recorded on videotape using a Sony Videorecorder, Model AV3650 (black and white).

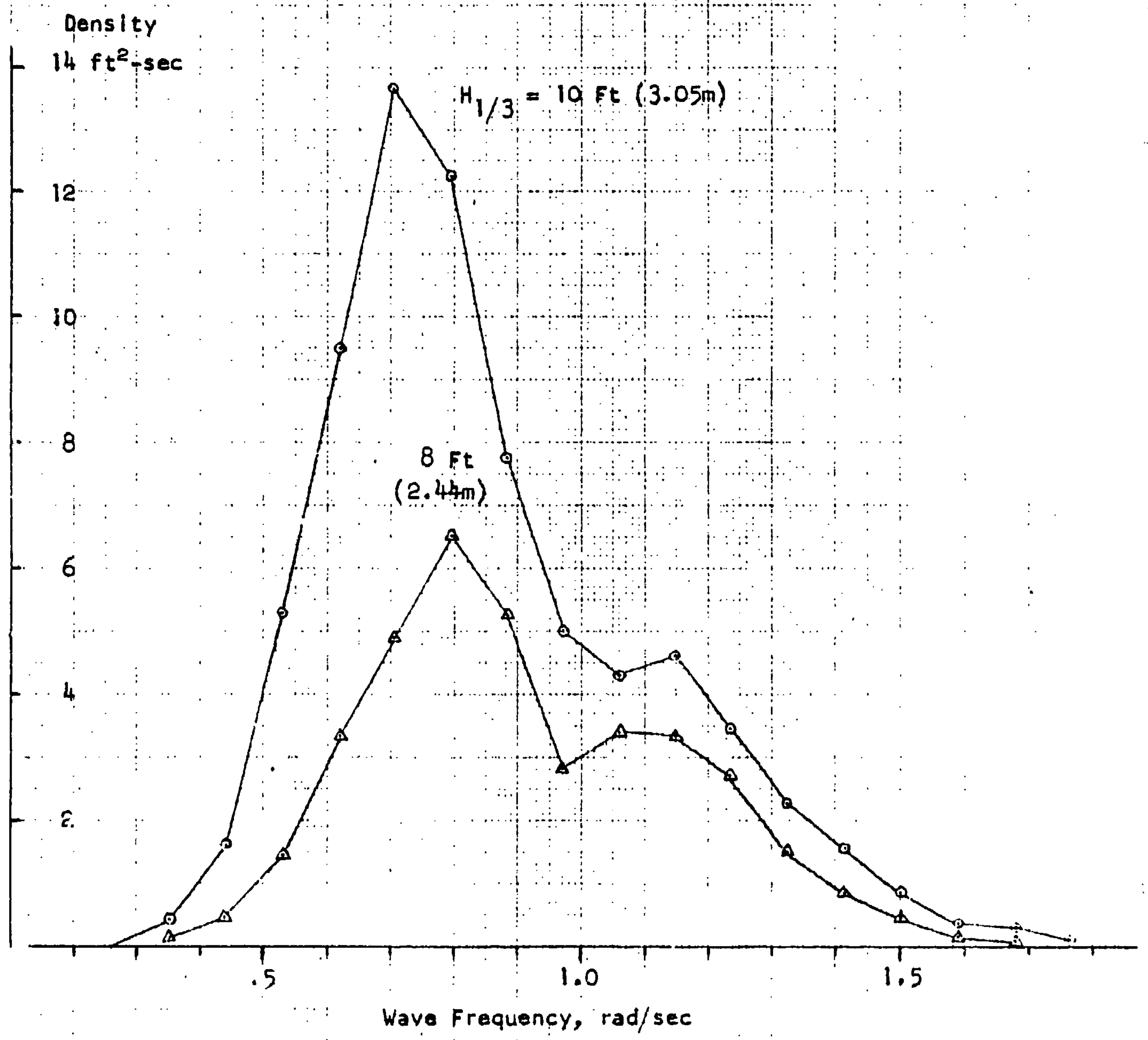


FIGURE 2. WAVE SPECTRA

TEST RESULTS: REGULAR WAVES

Pages 12 through 14 list normalized motion responses for the Baseline configuration and for each of the three variants. Heave and sway amplitudes have bean divided by wave amplitude, a. Roll and pitch amplitudes have been divided by maximum wave slope, ka, where $k = \omega_w^2/g$, ω_w is wave frequency and g is acceleration of gravity.

At low wave frequencies, mean drift force was near zero and the model tended to oscillate about a fixed location in the basin. Thus, the model encountered the waves at a frequency $\omega_e = \omega_w$. At wave frequencies $\omega_w \geq 0.7$, the model tended to drift downwave, thus making the encounter frequency $\omega_e < \omega_w$. Both ω_w and ω_e are listed in the tables of responses.

As noted in the INTRODUCTION, a primary objective was to document cases where the model rolled at its own natural frequency ω_φ when encountering waves with a much higher frequency $\omega_e >> \omega_\varphi$. Since such cases were observed in the region of $\omega_e = 2\omega_\varphi$, it was convenient to use a harmonic analysis program to compute the amplitude of the half harmonic, $\varphi_{\frac{1}{2}}$, at $\omega_e/2$. The tables list the first harmonic and half harmonic normalized roll responses φ/ka and $\varphi_{\frac{1}{2}}$/ka, respectively. Only the first harmonic normalized amplitudes are given for pitch, heave and sway because no half-harmonics were observed for these motions.

Figure 3 presents first harmonic roll responses versus wave frequency. First harmonic peak amplitudes change slightly as GM is increased from the Baseline value, either by lowering the CG or by increasing hull spacing. However, a draft increase causes a substantial increase in peak roll amplitude compared to the Baseline. This increase in roll cannot be explained by a change in damping because experimental damping factors, page 9, are almost identical for the Baseline and Deep Draft configurations. Also, increasing hull spacing causes a reduction in peak rolling amplitude, a trend which runs counter to an observed small decrease in damping factor compared to the Baseline configuration.

MOTIONS IN REGULAR BEAM WAVES
BASELINE CONFIGURATION

Run	Wave Freq. ω_w rad/sec	Wave Ampl. a ft	Wave Slope* deg	First Harmonic Roll φ/ka deg/deg	First Harmonic Pitch θ/ka deg/deg	First Harmonic Heave z/a ft/ft	First Harmonic Sway y/a ft/ft	½ Harm. Roll $\varphi_{\frac{1}{2}}$/ka deg/deg	Enc.*** Freq. ω_e rad/sec
20	.333	3.55	.98	3.70	.14	1.00	1.06	-	.333
21	.341	3.70	1.05	6.25	.22	.98	.84	-	.341
19	.350	3.85	1.12	7.35	.19	.95	1.54	-	.350
18	.362	3.40	1.04	3.20	.27	1.08	1.33	-	.362
22	.367	4.15	1.30	.85	.27	.97	1.19	-	.367
16	.376	3.60	1.15	5.15	.24	1.04	1.72	-	.376
17	.400	4.00	1.39	1.75	.41	1.12	1.24	-	.400
15	.419	4.35	1.61	1.15	.68	1.01	1.25	-	.419
14	.441	4.80	1.92	.60	.84	.86	1.26	-	.441
13	.490	5.10	2.39	.34	.65	1.04	.91	**	.490
12	.527	5.20	2.73	.24	.47	1.04	.82	**	.527
11	.573	5.00	3.02	.34	.48	1.16	.77	**	.573
9	.595	5.00	3.24	.34	.44	1.18	.83	**	.595
8	.598	5.00	3.27	.43	.45	1.23	.72	**	.598
10	.595	2.50	1.62	.23	.46	1.32	.84	**	.595
7	.620	4.90	3.42	.38	.48	1.29	.52	**	.620
27	.631	2.50	1.80	.34	.45	1.29	.76	**	.631
29	.666	2.50	1.99	.39	.64	1.66	.79	**	.666
6	.697	5.00	4.36	.08	.65	1.58	.70	**	.697
26	.702	2.50	2.20	.19	.60	1.64	.72	3.40	.702
24	.746	5.00	4.95	.20	.55	1.43	.78	**	.723
25	.746	2.50	2.47	.23	.76	1.99	.96	3.50	.740
30	.785	5.00	5.48	.30	.50	1.44	.63	**	.745
28	.785	2.50	2.74	.25	.72	1.82	.65	**	.767

*Wave slope corrected for bottom effect on frequencies less than 0.66

**Half harmonic occurs during early part of run, but disappears during analysis portion of run

***Frequency of encounter due to vessel drift to leeward

MOTIONS IN REGULAR BEAM WAVES
HIGHER GM VARIANT

Run	Wave Freq. ω_w rad/sec	Wave Ampl. a ft	Wave Slope* deg	First Harmonic Roll φ/ka deg/deg	First Harmonic Pitch θ/ka deg/deg	First Harmonic Heave z/a ft/ft	First Harmonic Sway y/a ft/ft	½ Harm. Roll $\varphi_{\frac{1}{2}}$/ka deg/deg	Enc.*** Freq. ω_e rad/sec
42	.380	3.67	1.19	3.05	.23	.96	1.19	-	.380
41	.412	4.20	1.52	7.00	.34	.91	1.18	-	.412
40	.432	4.60	1.78	6.15	.28	.94	1.46	-	.432
43	.459	5.10	2.15	3.25	.57	.98	1.14	-	.459
39	.490	5.05	2.35	.76	.70	.95	1.01	-	.490
38	.512	5.00	2.51	.51	.58	1.14	.81	-	.512
37	.566	4.95	3.14	.19	.44	1.18	.80	**	.566
36	.602	5.00	3.31	.18	.45	1.12	.86	**	.602
35	.623	4.95	3.49	.18	.47	1.19	.79	**	.623
34	.658	4.95	3.90	.17	.54	1.43	.72	**	.658
33	.697	5.00	4.36	.14	.66	1.53	.69	**	.683
44	.697	2.50	2.18	.30	.64	1.62	.63	**	.697
32	.741	5.00	4.88	.20	.53	1.53	.68	**	.718
45	.736	2.50	2.41	.21	.76	1.88	.55	**	.722
31	.785	5.00	5.48	.36	.56	1.39	.66	-	.749
46	.785	2.50	2.74	.18	.80	1.91	.47	**	.760
53	.841	5.00	6.28	.49	.48	.95	.57	-	.784
47	.841	2.50	3.14	.29	.43	1.09	.48	.65	.808
52	.841	1.25	1.57	.30	.36	.87	.46	3.55	.830
51	.841	.62	.78	.30	.24	.61	.16	-	.841
48	.890	2.50	3.53	.46	.19	.70	.49	3.00	.845
49	.890	1.25	1.76	.30	.05	.79	.55	7.30	.873
50	.890	.62	.88	.30	-	.40	.50	-	.880

*Wave slope corrected for bottom effect on frequencies less than 0.66 rad/sec.

**Half harmonic occurs during early part of run, but disappears during analysis portion of run.

***Frequency of encounter due to vessel drift to leeward.

MOTIONS IN REGULAR BEAM WAVES
WIDE SPACING VARIANT

Run	Wave			First Harmonic				½ Harm.	Enc.***
	Freq. ω_w rad/sec	Ampl. a ft	Slope* deg	Roll φ/ka deg/deg	Pitch θ/ka deg/deg	Heave z/a ft/ft	Sway y/a ft/ft	Roll $\varphi_{\frac{1}{2}}$/ka deg/deg	Freq. ω_e rad/sec
75	.411	4.20	1.52	3.55	.46	.95	1.13	-	.411
74	.432	4.60	1.78	4.35	.50	1.17	.70	-	.432
73	.445	4.90	1.98	6.35	.45	1.12	.93	-	.445
72	.473	4.75	2.10	3.00	.38	1.14	1.12	-	.473
71	.522	5.00	2.59	.11	.47	1.06	.90	-	.522
70	.563	4.90	2.88	.10	.42	1.09	.91	-	.563
69	.612	4.75	3.24	-	.47	1.34	.67	-	.612
68	.670	5.10	4.11	.04	.55	1.43	.85	-	.670
66	.731	5.00	4.75	.24	.54	1.43	.69	-	.706
67	.731	2.50	2.37	.16	.80	1.90	.59	-	.720
65	.785	5.00	5.48	.39	.54	1.30	.60	-	.752
60	.841	2.50	3.14	.29	.41	1.10	.64	-	.811
61	.834	1.25	1.55	.29	.34	.99	.42	-	.814
59	.898	2.50	3.59	.58	.16	.84	.34	-	.841
63	.898	1.25	1.80	.28	.02	.23	.21	2.15	.858
64	.963	1.25	2.06	.30	.03	.25	.40	-	.931

DEEP DRAFT VARIANT

Run	Wave			First Harmonic				½ Harm.	Enc.***
	Freq. ω_w rad/sec	Ampl. a ft	Slope* deg	Roll φ/ka deg/deg	Pitch θ/ka deg/deg	Heave z/a ft/ft	Sway y/a ft/ft	Roll $\varphi_{\frac{1}{2}}$/ka deg/deg	Freq. ω_e rad/sec
87	.336	3.65	1.01	5.95	.29	1.05	.80	-	.336
88	.351	3.20	.935	10.25	.42	1.05	2.09	-	.351
86	.390	3.85	1.29	5.19	.45	.95	1.90	-	.390
85	.420	4.40	1.61	2.03	.94	.99	1.06	-	.420
84	.475	4.80	2.14	.16	.68	.95	.90	**	.475
83	.573	5.00	3.02	.18	.54	1.18	.86	**	.573
82	.623	4.95	3.49	.30	.68	1.52	.75	**	.623
81	.688	5.00	4.24	.12	.92	1.38	.63	**	.676
80	.692	2.50	2.14	.23	1.13	2.06	.65	1.50	.688
79	.741	2.50	2.44	.12	.68	1.54	.86	5.30	.723
78	.785	2.50	2.74	.11	.32	.11	.70	6.25	.769

*Wave slope corrected for bottom effect on frequencies less than 0.66 rad/sec.

**Half harmonic occurs during early part of run, but disappears during analysis portion of run.

***Frequency of encounter due to vessel drift to leeward.

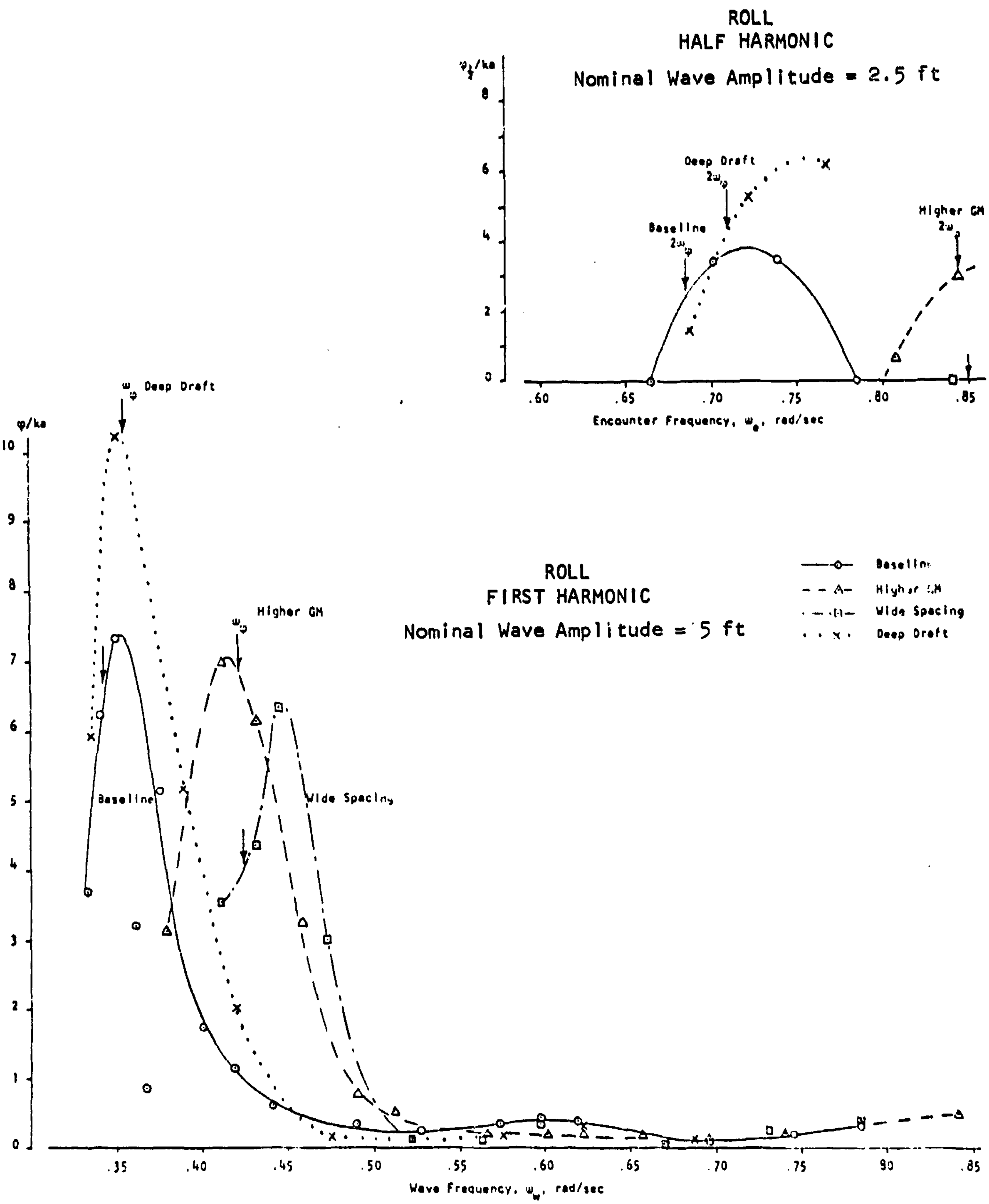
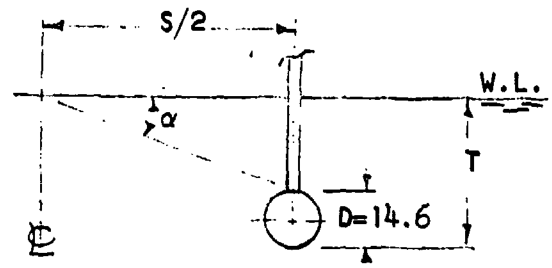


FIGURE 3. ROLL RESPONSES IN BEAM REGULAR WAVES, FREE-TO-DRIFT

Roll damping factors are relatively small and roughly equal among the baseline and its three variants, page 9. This suggests that first harmonic rolling amplitudes should be large for all configurations unless influenced by other hydrodynamic or geometric differences between them. In viewing videotape records of the tests, it appeared that when peak rolling occurred, the strut had emerged until the top of its lower hull was just below the water surface. Since all four configurations behaved in this manner, it seemed appropriate to compare peak rolling amplitudes to the geometric angle $\alpha = \tan^{-1} (T-D)/(S/2)$ illustrated in the end elevation sketch below



	T ft	S/2 ft	α deg	Peak φ/ka	(φ/ka)/α
Baseline	26.5	32.25	20.3	7.4	.36
Higher GM	26.5	32.25	20.3	7.0	.34
Wide Spacing	26.5	36.0	18.3	6.4	.35
Deep Draft	30.9	32.25	26.8	10.2	.38

This comparison shows that peak rolling amplitudes correlate well with the geometric angle α. Thus, for these moderate size waves, where maximum wave slope is between 1 and 2 degrees, peak rolling amplitudes appear to be limited by the attitude where the hull is just about to broach.

Figure 3 also shows a plot of the limited data obtained on half harmonic roll amplitudes. These data were obtained at wave frequencies ranging from 0.69 to 0.89 rad/sec, i.e., approximately twice the natural rolling frequencies which range from 0.343 to 0.425 rad/sec. Figure 4 shows a representative time history of model roll at half the encountered wave frequency; roll amplitude starts at a low level and slowly increases to a stable level. Occurrence of stable half-harmonic rolling was as follows:

	Wave Amplitude, ft			
	5.0	2.5	1.25	0.62
Baseline	No	Yes	*	*
Higher GM	No	Yes	Yes	No
Wide Spacing	No	No	Yes	*
Deep Draft	No	Yes	*	*

*not tested

It is evident that more test runs should have been made to better define the boundaries of half harmonic rolling behavior; unfortunately, time and funding limitations did not permit this.

Figure 5 presents normalized first harmonic amplitudes of pitch, heave and sway in regular beam waves. Although there was no direct excitation of pitch in beam waves, pitch oscillations occurred over the entire frequency range due to heave motion coupling into pitch. Pitch peaks occur at pitch resonance and also at heave resonance.

The Deep Draft Variant had the largest roll amplitudes at resonance. Figure 5 shows that the Deep Draft also exhibits the largest heave and pitch resonant amplitudes among the four configurations. As in the case of rolling, it is believed that resonant heave and pitch amplitudes are limited in the upward direction to the level where the hulls are just about to broach. Thus, the Baseline, Higher GM and Wide Spacing variants all have the same draft and the same amplitudes at heave resonance; the Deep Draft variant shows a resonant heave amplitude proportionately larger than the other three configurations.

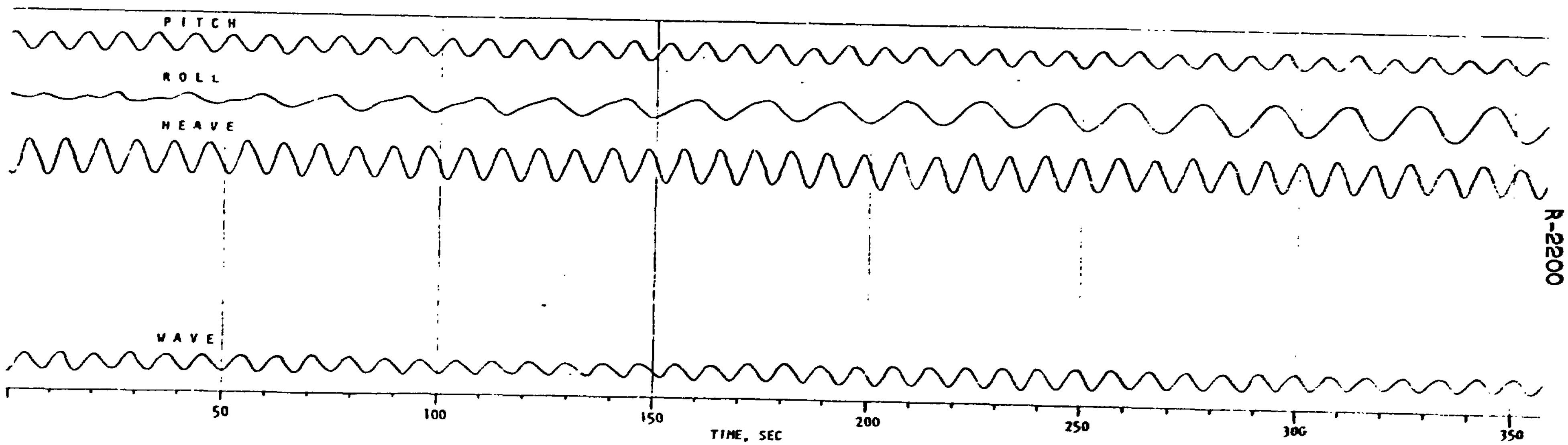


FIGURE 4. TIME HISTORY IN REGULAR WAVES, BASELINE CONFIGURATION

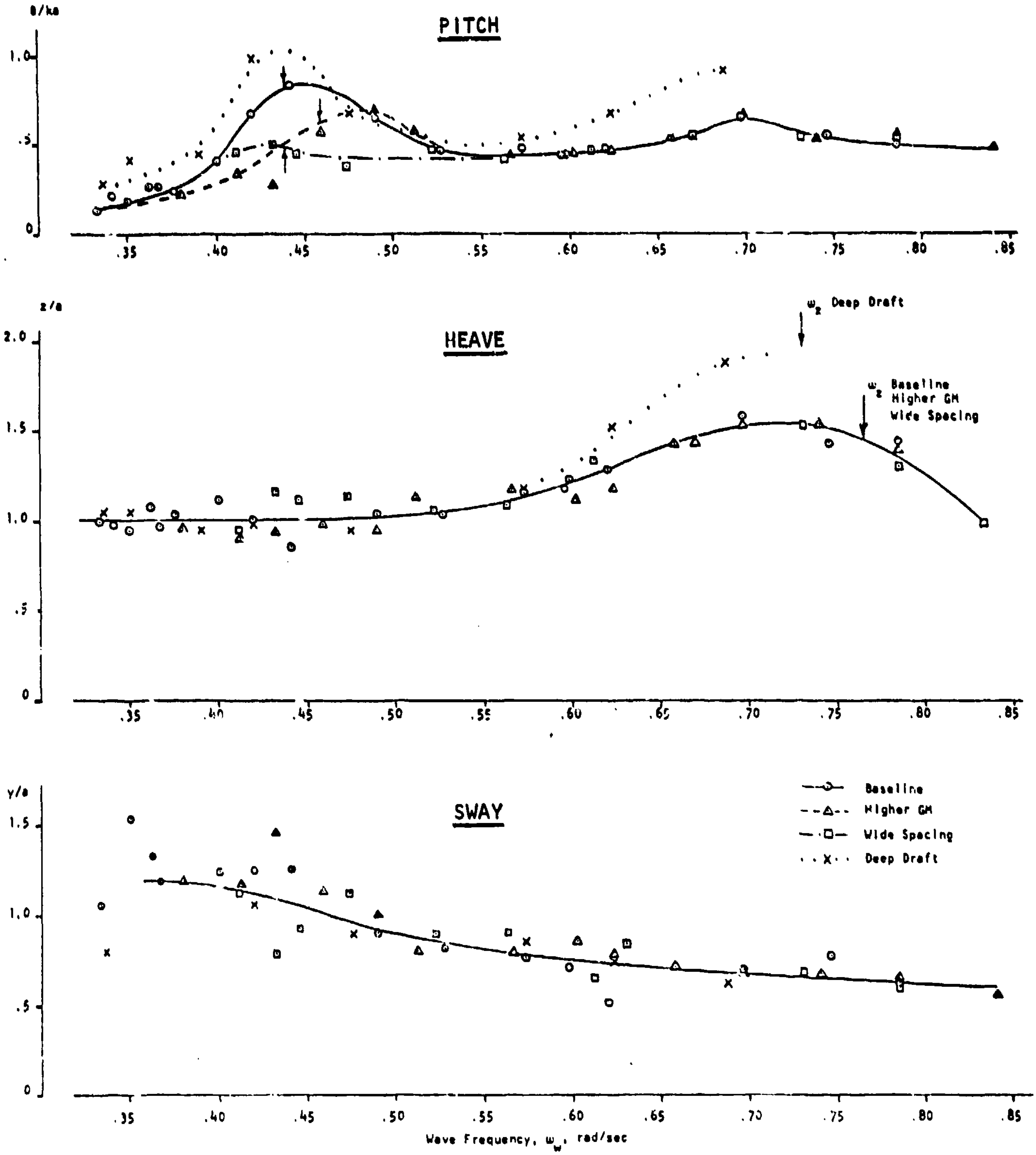


FIGURE 5. MOTION RESPONSE IN BEAM REGULAR WAVES
FREE-TO-DRAFT, NOMINAL WAVE AMPLITUDE = 5 FT

TEST RESULTS: IRREGULAR WAVES

Statistics of pitch, roll and heave responses in beam irregular waves for the Baseline and three variants are presented on pages 22 and 23. Explanatory notes and a comparison of roll statistics for the four configurations are given on page 21.

As noted on page 9, an irregular wave spectrum was chosen for each configuration such that the spectrum modal frequency (of peak energy) was twice the natural rolling frequency of that configuration. The intent was to see if large rolling amplitudes at the natural rolling frequency would occur. Figure 6 shows a representative portion of the time history of Baseline configuration motions. As suspected, the largest amplitudes are at rolling frequencies roughly equal to the natural frequency of rolling. Roll statistics on page 21 show that roll amplitudes increase in the following progression: Wide Spacing (lowest), Baseline, Higher GM, and Deep Draft (largest). A viewing of the videotape records confirmed that rolling amplitude peaks were limited to where the upside hull was just broaching the wave surface. The rolling of all configurations is asymmetrical, with the upward rolling motion of the seaward hull always being larger than its downward motion.

The representative time history of motions, Figure 6, also shows that pitch and heave motions tend to occur at a uniform frequency close to the natural heave frequency ω_z. For the Baseline configuration, ω_z = 0.766 rad/sec which is within the frequency range of peak wave spectrum energy, Figure 2. The three variants show a similar matching of ω_z and frequency range of peak wave energy.

Figure 7 presents a comparison of roll response spectra for the four configurations. A logarithmic ordinate scale of spectrum density has been used to show the very small roll responses in the region of wave modal frequencies (0.7 to 0.8 rad/sec) and the very large responses in the region of roll natural frequencies (0.34 to 0.42 rad/sec) where

RESPONSE STATISTICS IN BEAM IRREGULAR SEAS

	Baseline	Higher GM	Wide Spacing	Deep Draft
Roll Natural Freq, rad/sec	.343	.422	.425	.355
Wave Spectrum Modal Freq, rad/sec	.71	.80	.80	.71
Wave Significant Height, ft	10.	8.	8.	10.
RMS Wave, ft	2.55	1.89	1.89	2.55
RMS Roll, deg	3.26	3.68	2.22	7.22
RMS Roll/RMS Wave	1.28	1.95	1.17	2.83

PITCH angle is about a transverse space axis with bow up as positive

ROLL angle is about a longitudinal body axis with starboard side down as positive. The starboard side is the seaward side

HEAVE, in feet, is along a vertical space axis with up as positive

MEAN	is mean of all oscillations
RMS	is root mean square of oscillations
OSC	is number of oscillations used for averages
AVG	is average of all counted oscillations
1/3, 1/10	are averages of highest third and highest tenth of all counted oscillations
EXTREME	are values, (+) and (-), encountered in the particular reproducible wave sequence used in the test, and should not be construed as the extremes in any other sea having the same significant height

DAVIDSON LABORATORY 17-DEC-79

RUN 56 BASELINE IRREGULAR WAVES SIGNIFICANT HEIGHT 10 FT

SPEED 0.00 FPS WAVE ENCOUNTERS 117

	MEAN/RMS	OSC	AVG	1/3	1/10	EXTREME
PITCH DEG.	0.116	83	1.63	2.09	2.34	2.73
	1.109		-1.36	-1.98	-2.28	-2.70
ROLL DEG.	-1.447	64	0.85	3.76	5.51	7.31
	3.264		-4.90	-8.32	-11.17	-13.38
HEAVE FT.	-1.470	80	2.57	4.44	5.51	7.07
	3.162		-5.46	-7.51	-8.96	-9.83

DAVIDSON LABORATORY 17-DEC-79

RUN 54 HIGHER GM IRREGULAR WAVES SIGNIFICANT HEIGHT 8 FT

SPEED 0.00 FPS WAVE ENCOUNTERS 108

	MEAN/RMS	OSC	AVG	1/3	1/10	EXTREME
PITCH DEG.	0.160	76	1.29	1.84	2.16	2.69
	0.851		-0.94	-1.46	-1.85	-2.38
ROLL DEG.	-1.217	52	2.11	5.34	8.07	10.53
	3.683		-5.46	-9.01	-11.91	-14.73
HEAVE FT.	-0.803	71	1.81	3.31	4.33	5.61
	2.072		-3.34	-4.73	-5.58	-6.65

DAVIDSON LABORATORY 17-DEC-87

RUN 58 WIDE SPACING IRREGULAR WAVES SIGNIFICANT HEIGHT 8 FT

SPEED 0.00 FPS WAVE ENCOUNTERS 110

	MEAN/RMS	OSC	AVG	1/3	1/10	EXTREME
PITCH DEG.	0.165	73	1.25	1.78	2.00	2.25
	0.830		-0.93	-1.40	-1.75	-2.34
ROLL DEG.	-1.072	60	0.82	2.95	4.54	6.39
	2.221		-3.43	-5.51	-7.21	-10.28
HEAVE FT.	-0.571	73	2.05	3.44	4.20	5.10
	2.092		-3.17	-4.82	-5.83	-6.43

DAVIDSON LABORATORY 19-DEC-79

RUN 77 DEEP DRAFT IRREGULAR WAVES SIGNIFICANT HEIGHT 10 FT

SPEED 0.00 FPS WAVE ENCOUNTERS 104

	MEAN/RMS	OSC	AVG	1/3	1/10	EXTREME
PITCH DEG.	-0.001	82	1.31	1.88	2.26	2.51
	1.025		-1.30	-2.04	-2.65	-3.14
ROLL DEG.	-2.359	46	5.11	10.53	13.13	14.43
	7.219		-12.15	-17.77	-21.29	-23.03
HEAVE FT.	-1.462	76	1.65	3.45	4.52	5.32
	2.637		-4.57	-6.72	-7.80	-8.98

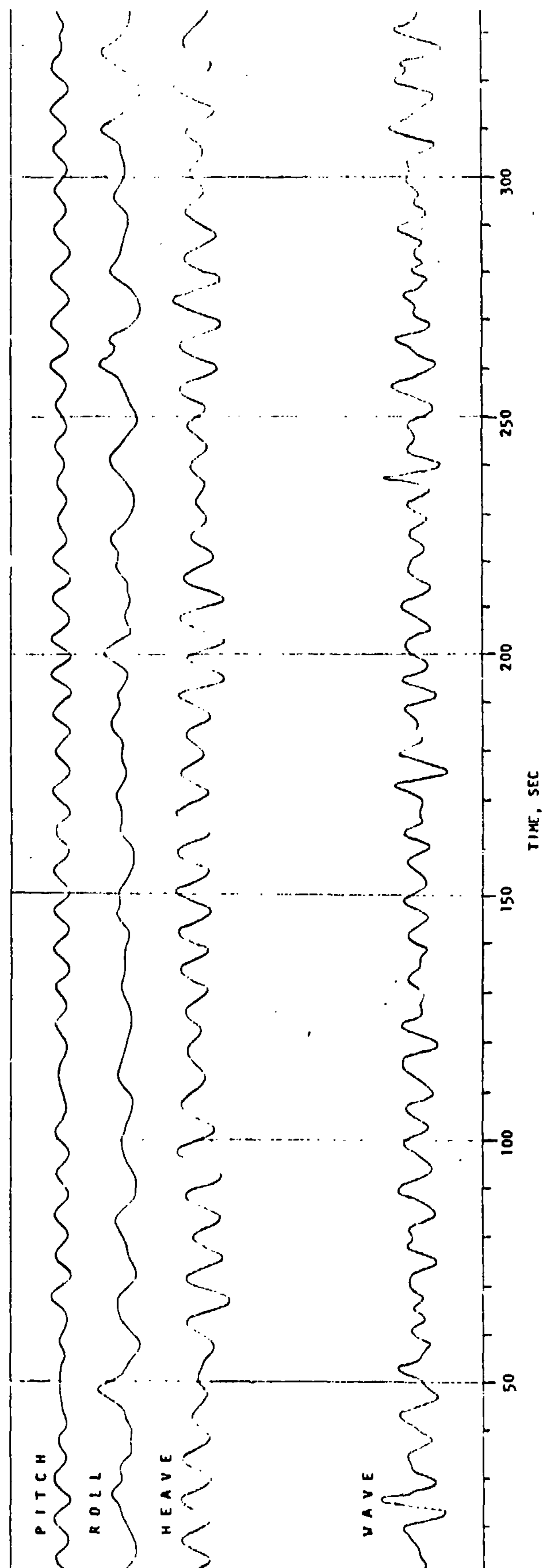


FIGURE 6. TIME HISTORY IN IRREGULAR WAVES, BASELINE CONFIGURATION

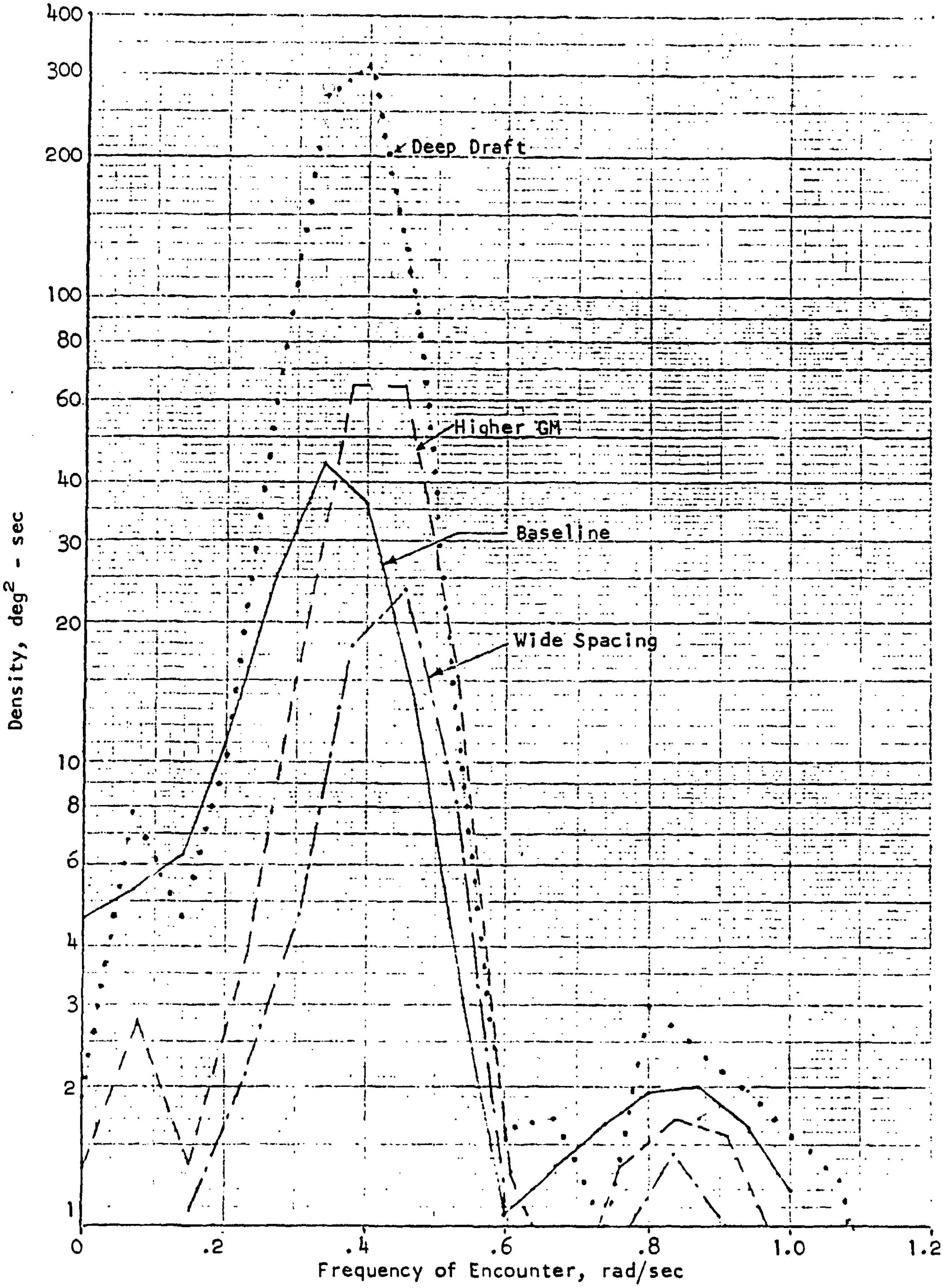


FIGURE 7. ROLL SPECTRA IN IRREGULAR BEAM SEAS AT DRIFT SPEED

there was little wave spectrum energy. This rolling behavior in irregular waves is reminiscent of the large half-harmonic rolling amplitudes which occurred in low amplitude, regular waves with a frequency of two times the natural rolling frequency.

The literature on rolling of ships in irregular waves has few references to the type of rolling behavior observed in the present tests. The combination of rolling at zero forward speed with a very low level of damping is usually a condition not encountered with conventional catamarans and monohulls. However, somewhat analogous behavior has been investigated in the field of space technology.

In Reference 1, Dalzell reports on an experiment in which a vertical axis cylindrical tank, partially filled with water, was subjected to random excitation in the vertical direction. Fluid level oscillations along the axis were measured and the excitation spectra and fluid level spectra were compared. Figure 8, adapted from Reference 1, is a log-log chart showing a very narrow band excitation spectrum centered at twice the natural frequency Ω_{oo} of the first axi-symmetric mode of free surface oscillation. The resulting fluid response spectrum shows a modest peak at excitation frequency $2\Omega_{oo}$, and a peak two orders of magnitude higher at the natural frequency Ω_{oo}. This fluid free surface response spectrum is strikingly similar to the SWATH roll response spectra of Figure 7. The oscillating tank and rolling SWATH also are characterized by small damping and large half harmonic responses under harmonic excitation at a frequency twice the natural frequency. However, the analogy stops there because theoretically a tank free surface has no linear response to axial excitation, in contrast to the theoretically linear rolling response of a SWATH vessel.

Unfortunately, theoretical tools are not available for use in predicting asymmetrical and subharmonic SWATH rolling responses of the type observed in these experiments. Thus, existing mathematical models of SWATH motions in six degrees of freedom should be expected to underestimate statistics of rolling motion in beam irregular waves at zero speed, particularly in seas of moderate height where peak wave energy

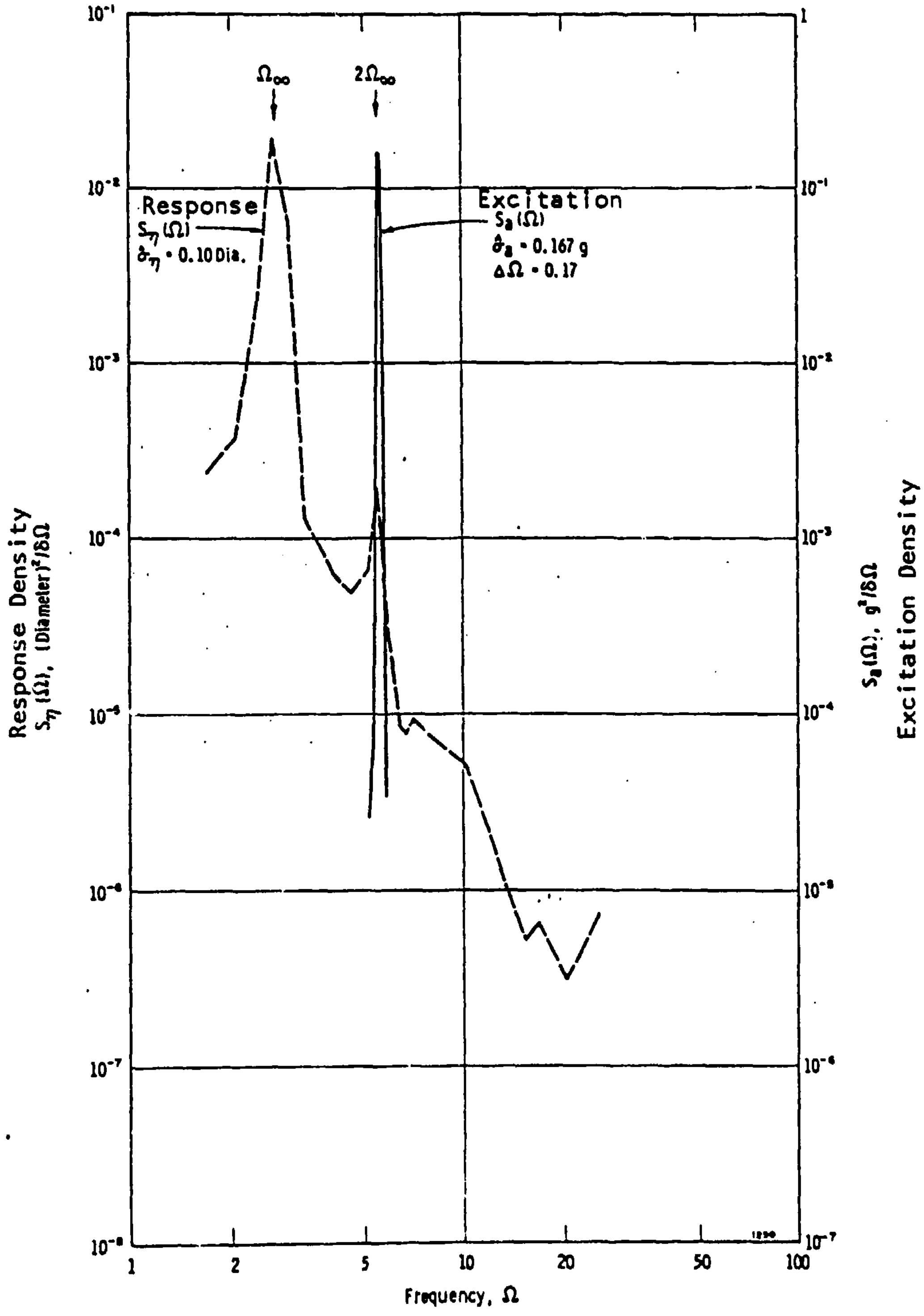


Figure 11. Spectra: Very Narrow Band Random Excitation, $\Delta\Omega = 0.17$, Maximum Excitation Level

FIGURE 8. (FROM REFERENCE 1)

occurs at a frequency approximately twice the roll natural frequency and near the heave natural frequency. For the Baseline SWATH and its three variants, such irregular seas commonly have significant heights of 8 to 10 ft (2.44 to 3.05 m), seas which should have a high probability of occurrence in most ocean areas. Thus, underprediction of roll response under such conditions is of serious consequence in evaluating platform suitability for operations that are conducted at zero speed, and possibly also at low forward speeds where active fin control is ineffective in damping rolling motions. On the other hand, in light of the observed limiting effect of hull broaching, available theoretical tools will overpredict roll in State 7 seas where peak wave energy occurs near the roll natural frequency.

SUMMARY

A limited experimental program was conducted with a model of a 2900-ton single strut-per-hull SWATH ship and three variants, at zero speed in beam regular and irregular waves. The results may be summarized as follows:

1. When each configuration was tested in low amplitude regular waves of approximately twice the roll natural frequency, stable rolling at the roll natural frequency was observed, i.e., in a half harmonic mode.

2. When each configuration was tested in irregular waves having a spectrum energy peak at a frequency twice the roll natural frequency, the apparent frequencies of the largest roll oscillations were approximately equal to the roll natural frequency.

3. Of the four configurations, the Wide Spacing variant showed lowest peak roll amplitudes at resonance in regular waves, and in irregular waves; highest roll was experienced by the Deep Draft variant.

4. Rolling amplitude extremes for all configurations generally were characterized by the upwave hull just broaching the wave surface. This observation appears to explain both the larger rolling amplitudes of the Deep Draft variant and the smaller rolling amplitudes of the Wide Spacing variant.

5. The peak half harmonic rolling amplitude was relatively unaffected by a 50 percent increase in transverse GM, but there was a shift in the wave frequency at which the peak roll occurred.

The observed asymmetric rolling behavior cannot be predicted by presently available theory, thus indicating an area where additional research is needed. Additional model testing should be performed to determine to what extent added roll damping, whether generated by forward speed or by the adoption of lower hulls with elliptical sections, will affect rolling in the half harmonic mode and analogous behavior in random waves.

REFERENCES

1. Dalzell, J. F., "Exploratory Studies of Liquid Behavior in Randomly Excited Tanks: Longitudinal Excitation," Southwest Research Institute Report No. 1, Contract NAS8-20319, May 1967.

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