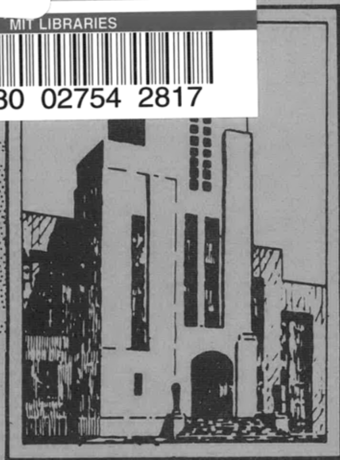
Report 1198



DEPARTMENT OF THE NAVY

DAVID TAYLOR MODEL BASIN

HYDROMECHANICS

AERODYNAMICS

STRUCTURAL MECHANICS

APPLIED MATHEMATICS

STATISTICAL PRESENTATION OF MOTIONS AND HULL BENDING MOMENTS OF DESTROYERS

by

John T. Birmingham, Roman L. Brooks, CDR, USN,
and Norman H. Jasper, Dr. Eng.

[redacted]

STRUCTURAL MECHANICS LABORATORY
RESEARCH AND DEVELOPMENT REPORT

September 1960

Report 1198

DEPARTMENT OF THE NAVY
DAVID TAYLOR MODEL BASIN
WASHINGTON 7, D.C.

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To: Chief, Bureau of Ships (335) (in duplicate)

Subj: Motions and hull bending moments of destroyers; forwarding of report on

Encl: (1) "Statistical Presentation of Motions and Hull Bending Moments of Destroyers," by J. T. Birmingham, R. L. Brooks, CDR, USN, and N. H. Jasper, Dr. Eng., DATMOBAS Report No. 1198, September 1960 3 copies

1. Under Task 1973, Project S-F013 0301, the David Taylor Model Basin is conducting a long-range investigation of strains in ships at sea to evaluate and improve methods for the design of ship girders and structural components. In enclosure (1) are reported stresses and motions measured on several types of destroyers. Criteria are derived from these measurements for use in design and operation problems involving bending moments and ship motions.

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STATISTICAL PRESENTATION OF MOTIONS AND HULL BENDING MOMENTS OF DESTROYERS

by

John T. Birmingham, Roman L. Brooks, CDR, USN,
and Norman H. Jasper, Dr. Eng.

September 1960

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ABSTRACT

The motions and longitudinal hull bending moments that a destroyer of the DD 692 Class is expected to experience over a wide range of operating conditions are presented in statistical form. The data are based on extensive measurements made on USS CHARLES S. SPERRY (DD 697). Data obtained from tests on a DD 931-Class destroyer and a Dutch destroyer are also analyzed.

Criteria are derived for use in design and operational problems involving bending moments and ship motions.

INTRODUCTION

The David Taylor Model Basin is conducting a long-range investigation of strains in ships at sea to evaluate and improve methods for the design of ship girders and structural components.[1] Information on wave loads, stresses, and motions that ships experience in service has been collected on several types of ships.[2,3,4]

This report concerns measurements made on several types of destroyers. Longitudinal hull girder stresses and ship motions were recorded from September 1955 to February 1957 while USS CHARLES S. SPERRY (DD 697) was carrying out its assigned mission* in the Atlantic Ocean and the Mediterranean Sea. Hull girder stresses and motions were measured on USS BARRY (DD 933) during January 1959. Severe whipping stresses were recorded on a Dutch destroyer during tests conducted by the David Taylor Model Basin in cooperation with the Netherlands Navy in April 1956.[5]

The extensive data on SPERRY are analyzed by statistical methods and are presented for the DD 692 Class in the same way as the data for ESSEX-Class aircraft carriers.[4] Maximum motions and bending moments for DD 931 Class are approximated by weighting the limited BARRY data with the SPERRY data. The whipping stresses measured on the Dutch destroyer, which were far more severe than those measured on SPERRY and BARRY, are used to predict whipping stresses in rough seas for DD 692- and DD 931-Class destroyers.

TEST INSTALLATION

The general locations of instrumentation used on SPERRY to measure the motions and midship bending moments are shown in Figure 1. The motion-measuring transducers consisted of: a linear accelerometer located at the calculated center of gravity of the ship oriented to measure vertical acceleration, a stable element used to measure roll and pitch angle, and an

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[1]References are listed on page 36.

*SPERRY was operating with USS VALLEY FORGE (CVS 45) during most of the testing periods.

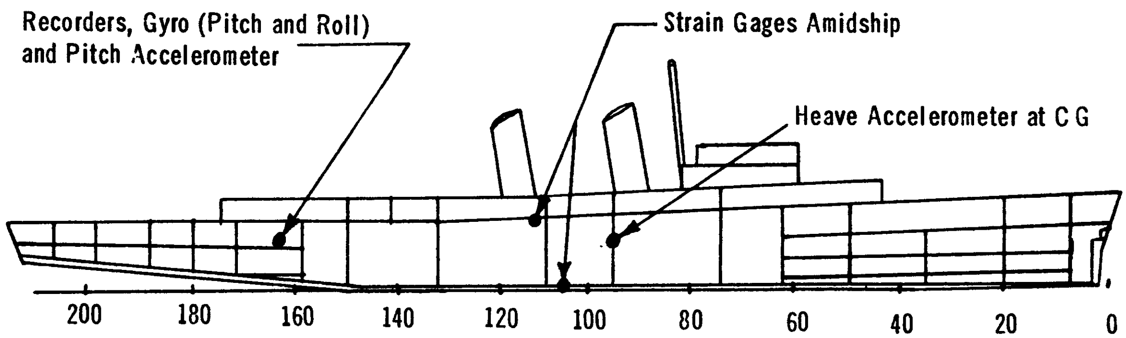


Figure 1a – Inboard Profile Indicating General Location of Instruments

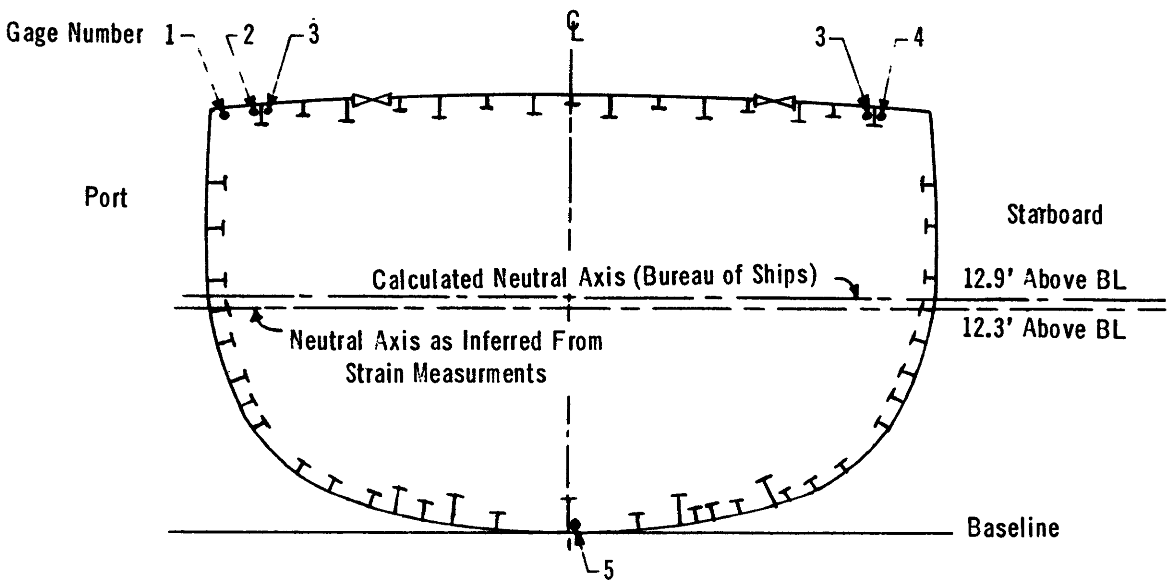


Figure 1b – Midship Section Looking Forward Showing Strain Gage Locations

Figure 1 – Location of Instruments on USS SPERRY (DD 697)

angular accelerometer to measure roll and pitch acceleration. Longitudinal strain was measured at five locations near amidship (see Table 1).

The Taylor Model Basin automatic statistical recorder and its associated sensing devices used on the SPERRY tests were described in Reference 6. The five channels of the recorder were utilized as follows: Channel 1 recorded heave accelerations; Channels 2 and 3 recorded the hull girder strain near the midship section in the main deck longitudinals and the keel, respectively; and Channels 4 and 5 recorded roll and pitch angles, respectively. Output of Strain Gages 1, 2, and 4 and angular acceleration were recorded on a four-channel Sanborn recorder.

Characteristics of the destroyers referred to in this report are shown in Table 2.

TABLE 1

Longitudinal Strains near Amidships

Gage Number	Quantity Measured	Distance from Calculated Neutral Axis
1	Longitudinal dyadic stress in port deck edge plate	10 ft above
2	Longitudinal strain in port outboard longitudinal*	10.1 ft above
3**	Longitudinal strain main deck due to vertical bending*	10.1 ft above
4	Longitudinal strain in starboard outboard longitudinal*	10.1 ft above
5**	Longitudinal strain in keel due to vertical bending*	12.7 ft below

*Strain gages located on longitudinals and keel were placed at the approximate neutral axis of the beam-plate combination.

**Gages 3 and 5 were arranged to measure longitudinal strain due to hull bending in the fore-and-aft plane of symmetry (vertical bending).

TABLE 2

Characteristics of SPERRY, BARRY, and a Dutch Destroyer

	SPERRY	BARRY	Dutch Destroyer*
Length between perpendiculars, ft	369.0	407.0	354.0
Beam, ft	40.57	45.0	37.1
Depth, ft	24.17	26.7	20.8
Draft (design), ft	14.5	14.6	12.76
Displacement (full load), tons	3,350	3,950	2,690
Section modulus applicable to gage locations on main deck, $in.^2ft$	7,750	8,650	4,251
Frequency of first mode of vertical flexural hull vibration, cps	79	78	78
Moment of inertia of midship section, $in.^2ft^2$	78,300	113,000	48,000

*Characteristics for the Dutch Destroyer were obtained from Reference 5, where it is labeled ship "P".

TEST RESULTS

Oscillograms showing the maximum measured motions and stresses recorded on SPERRY are shown in Figures 2, 3, and 4.

Measurements made on SPERRY, and not statistically analyzed, were used to provide data to aid in selecting the quantities for statistical analysis and to provide other background information. The condensed results of these supplemental measurements are summarized in the following paragraph.

The strain measurements of Gages 1, 2, and 4 assured that local stresses were not modifying the hull girder strain measurements of Gages 3 and 5 recorded on the statistical recorder. Evaluation of strain measurements at the main deck and keel indicated the position of the neutral horizontal axis of the midsection to be 12.3 ft above the baseline; this is in fair agreement with the position of 12.9 ft calculated by the Bureau of Ships. The calculated position will be used for further evaluation throughout this report. The most severe strains for vertical bending were always much larger than those for athwartship bending. Therefore, the athwartship bending strains are not analyzed in this report.

The operating and environmental conditions for the sea tests of SPERRY were determined from several sources. The characteristic wave heights and the wave directions were determined by averaging several independent visual observations made by trained personnel from the VALLEY FORGE Aerology Department and from stereophotographs of the sea. Estimates made by SPERRY personnel were used to check these observations. The ship's speed was based on the shaft rpm readings of the SPERRY bell log. The ship's course was obtained from a special log of all course and speed changes kept by the Quartermaster Department on SPERRY.

STATISTICAL ANALYSIS

All the test data obtained on SPERRY were measured in the course of normal operations in the Atlantic Ocean. Oscillographic data were recorded during 360 hr of these operations. Of these data approximately 25 hr, representing 45 different combinations of steady operational and environmental conditions, were analyzed. Conditions represented in the data analyzed are shown in Table 3.

SPERRY data selected for statistical analysis were the wave-induced variations of roll and pitch angle, vertical accelerations of the center of gravity of the ship,* and hull strains, all recorded on the TMB automatic statistical recorder. From these measurements

(Text continued on page 8.)

*These accelerations are referred to as heave accelerations in this report.

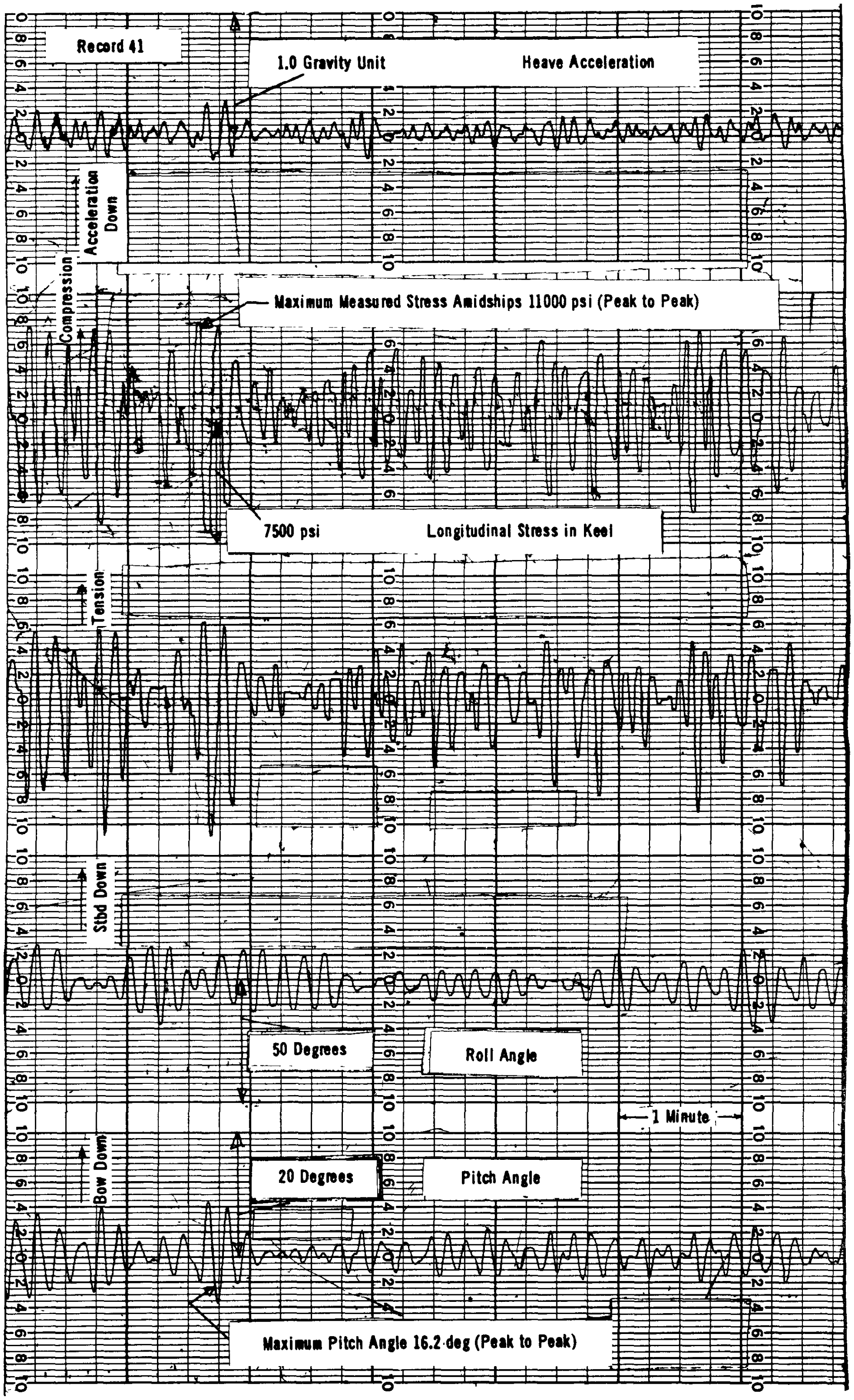


Figure 2 – Oscillogram Showing Maximum Longitudinal Stress Amidships and Maximum Pitch Angle

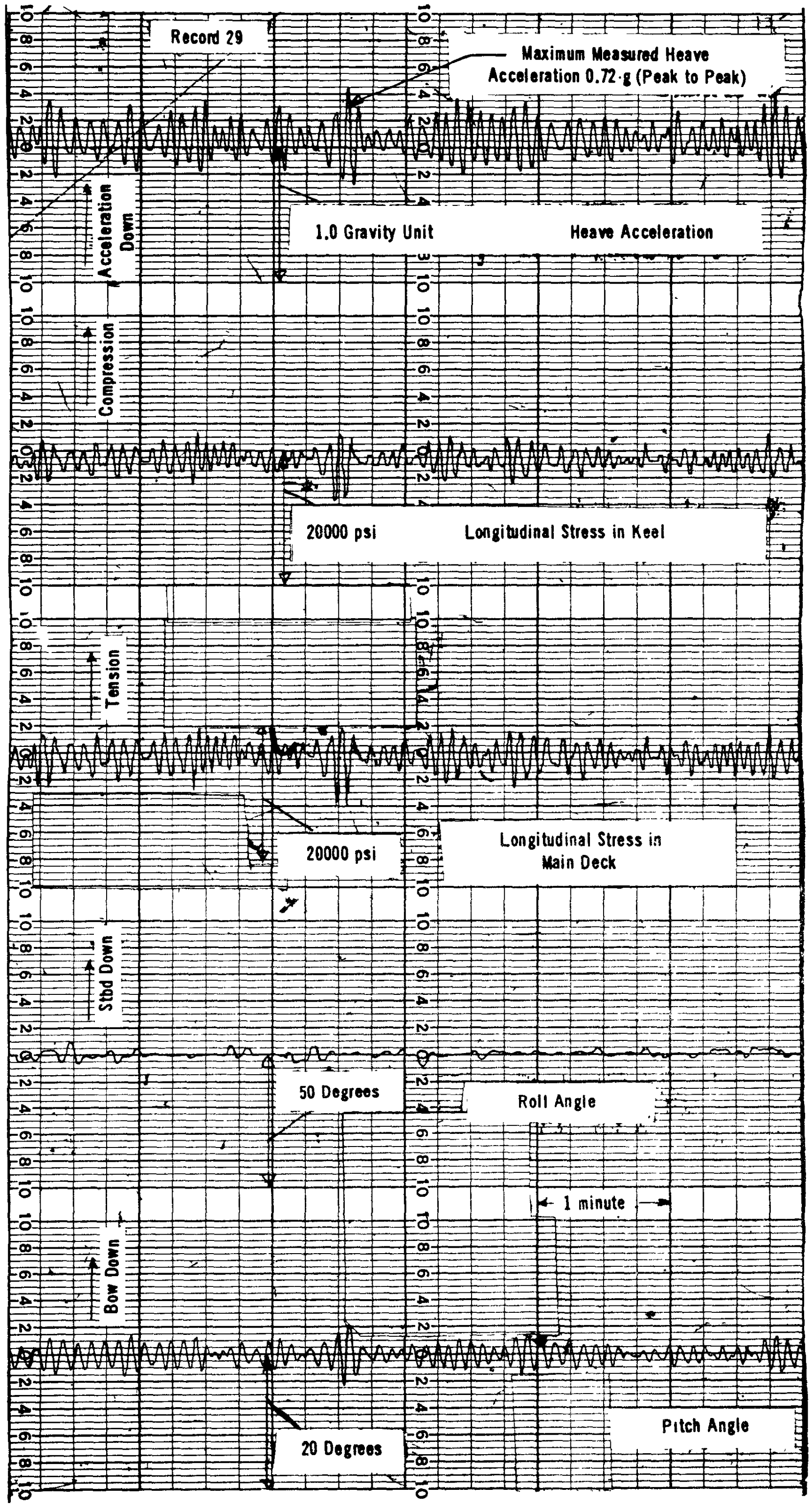


Figure 3 – Oscillogram Showing Maximum Heave Acceleration

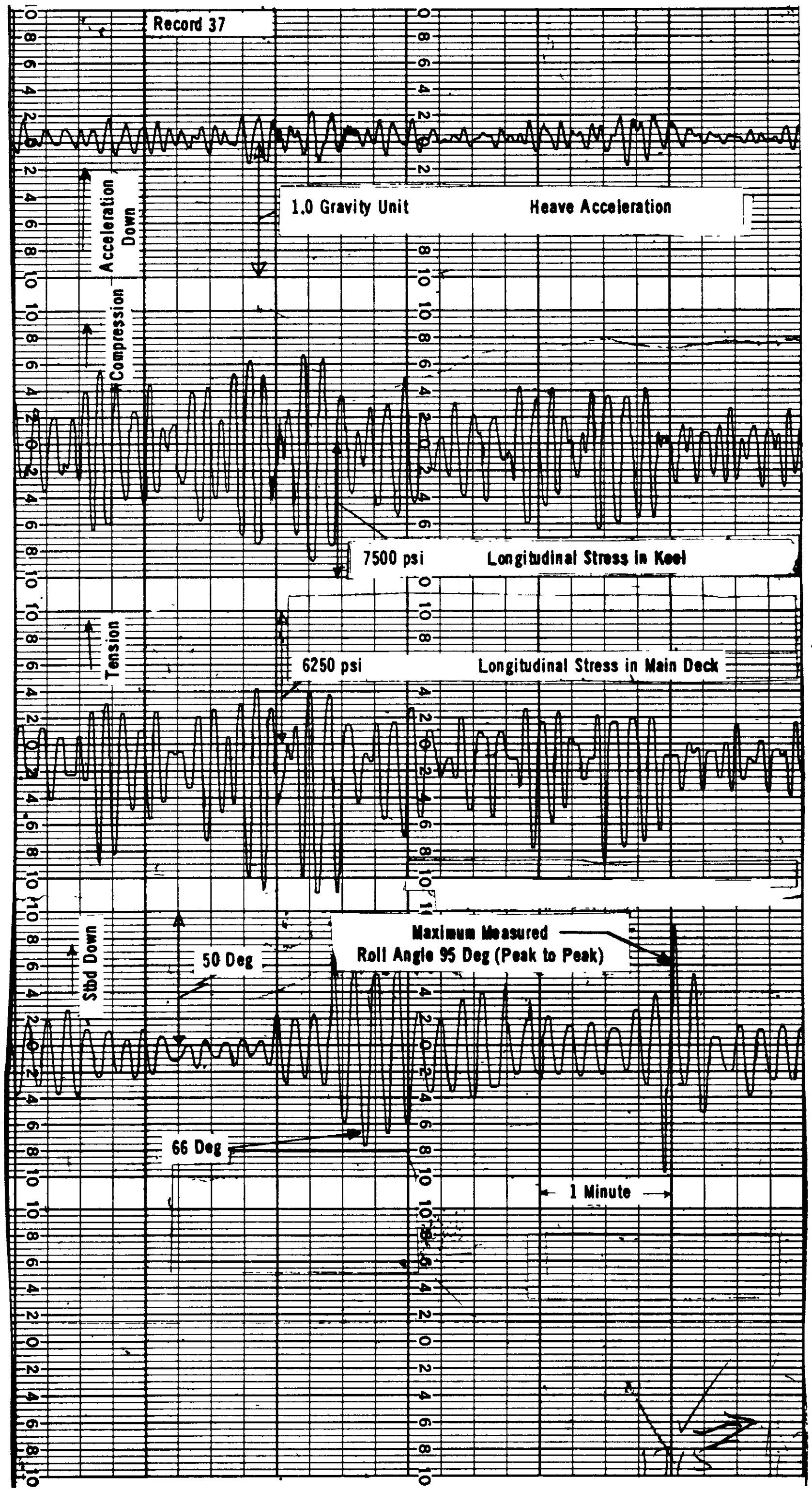


Figure 4 – Oscillogram Showing Maximum Roll Angle

TABLE 3

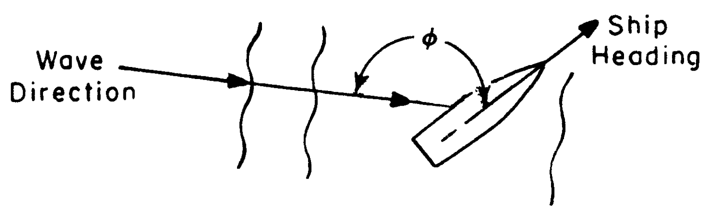
Wave and Ship Conditions Analyzed

Characteristic Wave Height ft*	†Sea Direction for Indicated Ship Speeds				
	5 to 10 Knots	10 to 15 Knots	15 to 20 Knots	20 to 25 Knots	25 Knots
0 to 4	B; QF; F**	H; QH; F	H; QF	B	
4 to 6	H; QH; B; F	H; QH; B	H; QH; QF	H; QF	
6 to 8	QH; QF	QH	QH; B; F	QH; B; QF; F	H
8 to 15	H; QH; B; QF; F	QH; B; F	QH		
> 15					

*The characteristic wave height is the average height of the highest waves observed in each of a number of groups of waves.

**H – head seas; QH – quarter-head seas; B – beam seas; QF – quarter-following seas; and F – following seas.

†In this report ϕ, shown in the accompanying sketch as the heading of the ship relative to the direction from which the waves come, is defined as follows: For head seas, $\phi = 0$ deg; for quarter-head seas, $\phi \approx 45$ or 315 deg; for beam seas, $\phi \approx 90$ or 270 deg; for quarter-following seas, $\phi \approx 135$ or 225 deg; for following seas $\phi \approx 180$ deg.



and related weighting factors, distribution patterns are synthesized, and the following specific information is given for DD 692-Class destroyers:

1. Average, mean square, and expected maximum hull stresses* and motions for various operating conditions (sea state, speed, and heading).

2. The predicted maximum longitudinal hull bending moment, stress, and motion expected during the operating life of the ship. The vibratory stresses are also considered in predicting the maximum level of midship bending moments for design purposes.

3. The frequency distribution of stresses and ship motions.

Maximum values of longitudinal hull bending moment, stress, and motion expected during the operating life of the ship are also predicted for DD 931-Class destroyers.

---

*All stresses given in this report are derived from the measured strains. The hull bending moments are deduced from the strain measurements and the applicable calculated section modulus.

To represent severe continuous operating conditions, the sea conditions assumed in the calculations are those for the North Atlantic Ocean. The probable speeds and headings at which these ships would be expected to operate under wartime conditions and the fraction of time the ships would spend at each of the various conditions were estimated by the commanding officers of a number of ships of the DD 692 Class. This information is given in Table 2 of Reference 7.

Recorded strain and motion data were classified according to appropriate ranges of ship speed, wave height, and ship course relative to the wave direction. Statistical methods were used to determine the ship's response in terms of mean square and maximum measured values for a wide variety of operating conditions. Measured and statistical estimates of extreme values are compared. The results are given in Table 4.

The motions and stresses analyzed statistically are those associated with the rigid-body motions of the ship (heaving, rolling, and pitching) and do not include vibratory motions and stresses induced by slamming or pounding.

STATISTICAL BACKGROUND

The statistical methods utilized here are discussed in References 3 and 8. The basic ideas are repeated here to preserve continuity.

Wave heights, ship motions, and hull bending moments experienced under a given set of conditions can be described in terms of their distribution functions. It has been shown[2,3,4] that the applicable distribution functions are approximated by the Rayleigh distribution for a given set of steady operating conditions (sea state, ship speed, and heading) and by log-normal distributions if the operating conditions are allowed to vary over a wide range, such as would occur over a typical year. Inasmuch as the Rayleigh distribution is applicable to a given combination of sea, speed, and heading, it will be called the "short-term" distribution. The log-normal distribution will be designated the "long-term" distribution. The distribution patterns give the probability of exceeding any given magnitude of motion or bending moment and can be utilized as a load spectrum in designing for endurance strength.

The Rayleigh distribution of a variable x is defined by the single parameter E,* the mean square value of x; i.e., $E = x^2$. The log-normal distribution of x is defined by two parameters, the mean value of log x and the variance of log x.

*If $f(t)$ is a random function with a Gaussian distribution, zero mean value, and a power spectrum $G(\omega)$, then the area under the power spectrum is equal to twice the mean square value σ^2 of $f(t)$; and if, furthermore, the power spectrum is narrow, then the mean square value E of the peak-to-peak variation equals $8\sigma^2$; i.e., four times the area under the power spectrum, and the peak-to-peak variations follow the Rayleigh distribution.

TABLE 4

Basic Statistical Data for DD 692-Class Destroyers

Wave Height Class, ft	Record Number	Date of Record	Local Time of Record	Ship Speed, knots	Wind and Wave Data: Estimates of Characteristic Wave Height, ft — Sea: Average of Visual Estimates	Sea: From TMB Analysis of Stereo-Photo	Number of Visual Estimators	Swell: Average of Visual Estimates	Swell: From TMB Analysis of Stereo-Photo	Associated Information: Heading of Sea Relative to Ship, deg	E, Mean Square Value of Wave Height Estimated from Wind Data, ft²	Stereo Photograph Analyzed†	Local Time of Photograph	Approximate Position of CVS 45 When Stereo Photos Were Taken, Time : Lat, Long	Distance in Miles between CVS 45 and DD 697	Response of Ship to Sea — Heave Acceleration: E, Value of Mean Square, g²	N_h, Variations per Hour	Predicted Maximum Value in One Hour, g	Number of Variations in Sample	Maximum Measured Variation in Sample, g	Maximum Predicted Variation in Sample, g	$R = \frac{\text{Predicted Max}}{\text{Measured Max}}$	Stress, Main Deck Amidships: E, Value of Mean Square, kips²	N_h, Variations per Hour	Predicted Maximum Value in One Hour, kips	Number of Variations in Sample	Maximum Measured Variation in Sample, kips	Maximum Predicted Variation in Sample, kips	$R = \frac{\text{Predicted Max}}{\text{Measured Max}}$	Pitch Angle: E, Value of Mean Square, deg²	N_h, Variations per Hour	Predicted Maximum Value in One Hour, deg	Number of Variations in Sample	Maximum Measured Variation in Sample, deg	Maximum Predicted Variation in Sample, deg	$R = \frac{\text{Predicted Max}}{\text{Measured Max}}$	Roll Angle: E, Value of Mean Square, deg²	N_h, Variations per Hour	Predicted Maximum Value in One Hour, deg	Number of Variations in Sample	Maximum Measured Variation in Sample, deg	Maximum Predicted Variation in Sample, deg	Predicted Max …
0–4	1	Sep 14 1955	0820 0850	12	3	–	1	–	–	340		–	–	–	22.0	0.0041	564	0.17	282	0.21	0.15	0.71	1.85	584	3.50	292	3.5	3.3	0.93	0.896	512	2.4	256	2.5	2.2	0.90	48.6	408	17.2	204	18.5	16.2	0.
	2	Oct 20 1955	1813 1835	16	–	5.0	5	3.7	5.0	340	8.0	G-49	1715	2000 : 35N, 71W	20.0	0.029	484	0.42	274	0.41	0.40	0.98	5.39	720	5.9	264	6.4	5.5	0.85	1.62	720	3.3	264	4.0	3.0	0.75	5.56	360	5.7	132	9.0	5.2	0.
	3	Sep 12 1955	1940 2017	15	4.8	4.4	4	–	6.9	025	9.2	A-200	1701	2000 : 40N, 51W	26.0	0.007	651	0.21	402	0.34	0.20	0.59	5.74	600	6.1	370	7.3	5.9	0.80	2.35	556	3.8	343	4.6	3.7	0.80	10.9	404	8.1	249	8.4	7.8	0.
	4	Nov 15 1955	1035 1107	9	–	2.9	1	2.7	3.7	090	9.2	H-87	1115	1200 : 38N, 73W	70.0	0.003	682	0.14	364	0.14	0.13	0.93	0.097*	300	0.74	160	0.7			0.25*	600	1.27	320	1.2			14.2	319	9.1	138	16.0	8.4	-
	5	Oct 13 1955	1230 1238	12	–	5.6	7	3.7	4.5	105	5.2	E-21	1215	1200 : 35N, 27W	4.4	0.006	622	0.20	80	0.21	0.16	0.76	5.68	412	5.8	55	6.0	4.9	0.83	1.95	493	3.5	66	2.7	2.9	1.07	62.2	378	19.5	49	20.0	17.8	0.
	6	Oct 13 1955	0700 0739	14	–	2.2	5	4.0	3.5	080	5.2	E-17	1046	0800 : 35N, 26W	8.2	0.008	638	0.23	415	0.33	0.22	0.67	3.44	403	4.6	262	5.2	4.4		1.44	529	3.0	344	3.7	2.9	0.79	32.7	335	13.6	218	17.5	13.3	0.
	7	Nov 15 1955	0834 0906	23	–	3.6	2	3.7	3.9	260	5.2	H-47	0750	0800 : 37N, 73W	2.0	0.003	900	0.14	480	0.12	0.14	1.17	0.36*	960	1.57	512	1.5			0.033*	783	0.483	416	0.45			12.9	195	8.3	72	10.0	7.4	
	8	Oct 2 1955	0724 0800	10	–	2.8	3	4.4	4.5	213	9.2	D-17	1300	1200 : 39N, 13W	6.8								0.65	125	1.8	73	1.5	1.7	1.13	0.74	228	2.0	137	1.2	1.9	1.58	49.8	285	16.8	177	21.0	16.0	0.
	9	Nov 15 1955	1400 1440	20	–	3.5	3	2.8	4.5	230	9.2	H-109	1155	1200 : 38N, 73W	60.0	0.0016	657	0.10	438	0.13	0.10	0.77	0.21	186	1.1	124	1.2	1.0	0.84	0.085*	660	0.72	440	0.7	–	–	8.27	241	6.74	161	8.0	6.4	0.
	10	Jan 24 1956	1738 1818	8			3	2.0	–	180		–	–	– – –	–	0.0005*	540	0.06	270	0.06			1.25	398	2.7	199	2.5	2.5	1.00	0.182*	480	1.06	246	1.0	–	–	27.88	312	12.60	156	13.50	12.40	0.
4–6	11	Feb 2 1956	1316 1356	5	5	–	4	–	–	000	–	–	–	– – –	–	0.0042	662	0.17	441	0.15	0.16	1.07	2.12	530	3.6	353	5.0	3.5	0.70	0.88	509	2.4	339	2.6	2.3	0.87	7.98	412	6.9	275	10.0	6.7	0.
	12	Sep 11 1955	1410 1450	11	5.0	5.4	3	–	6.5	345	13.6	A-119	1435	1200 : 40N, 58W	6.0	0.0042	621	0.16	414	0.17	0.16	0.94	7.50	435	6.6	290	6.2	6.6	1.06	3.75	509	4.8	339	4.6	4.7	1.02	9.35	378	7.5	252	9.5	7.2	0.
	13	Oct 18 1955	1205 1245	15	–	5.6	4	6.1	–	000	16.0	F-289	1245	1200 : 35N, 59W	3.5	0.0158	676	0.32	451	0.33	0.31	0.94	4.41	600	5.3	400	6.0	5.2	0.85	1.73	624	3.3	416	4.2	3.2	0.76	8.73	345	7.2	230	8.5	6.9	0.
	14	Oct 19 1955	0749 0823	17	4.8	5.8	4	–	5.1	020	13.6	F-344	1015	1200 : 35N, 67W	4.8	0.029	693	0.44	393	0.46	0.42	0.91	7.99	622	7.2	394	8.0	6.9	0.86	3.95	648	5.1	367	5.0	4.9	0.98	12.0	287	8.3	182	10.5	7.9	0.
	15	Oct 14 1955	1437 1506	21	–	6.9	4	6.0	5.9	000	18.0	E-71	1445	1200 : 34N, 34W	10.0	0.036	702	0.49	351	0.56	0.46	0.82	7.65	764	7.1	382	8.0	6.8	0.85	2.91	642	4.3	321	4.4	4.1	0.93	47.5	352	17.0	176	19.5	16.0	0.
	16	Feb 2 1955	1220 1300	5	6	–	4	–	–	320	–	–	–	– – –	–	0.0075	860	0.23	430	0.22	0.21	0.96	1.81	500	3.4	333	3.8	3.3	0.87	1.55	748	3.2	374	3.4	3.0	0.88	41.0	450	15.8	300	17.0	15.3	0.
	17	Oct 11 1955	0725 0750	15	–	4.2	5	6.2	5.4	035	10.4	D-85	0948	0800 : 37N, 15W	12.8	0.017	610	0.33	254	0.27	0.31	1.14	8.03	545	7.1	227	7.3	6.6	0.90	6.46	497	6.3	207	5.6	5.9	1.05	128.0	366	27.5	116	38.5	25.0	0.
	18	Oct 20 1955	1839 1900	16	–	5.0	5	3.7	5.0	040	8.0	G-49	1715	2000 : 35N, 71W	22.0	0.024	680	0.40	240	0.40	0.36	0.90	3.69	560	4.8	196	5.2	4.4	0.85	1.77	615	3.4	215	4.2	3.1	0.73	34.5	364	14.3	109	16.0	13.0	0.
	19	Feb 2 1956	1415 1447	5	6	–	4	–	–	250	–	–	–	– – –	–	0.006	714	0.20	381	0.21	0.19	0.90	2.49	405	3.9	216	5.0	3.7	0.75	1.51	497	3.1	265	3.2	2.9	0.91	60.0	444	19.0	237	20.0	18.2	0.
	20	Oct 12 1955	0700 0740	15	–	8.5	6	5.5	5.4	085	18.0	D-148	0812	0800 : 36N, 21W	26.0	0.019	650	0.35	433	0.36	0.34	0.94	2.69	501	4.1	334	5.2	3.9	0.75	1.94	584	3.5	389	3.6	3.4	0.94	202.0	369	34.4	246	48.0	33.5	0.
	21	Oct 19 1955	1120 1130	20	4.8	5.8	4	–	5.1	225	13.6	F-344	1015	1200 : 35N, 67W	5.0	0.034	714	0.47	119	0.39	0.40	1.02	7.09	690	6.8	115	6.7	5.9	0.87	3.07	642	4.5	107	4.0	3.8	0.96	3.97	288	4.7	48	3.5	3.9	1.
	22	Oct 14 1955	1337 1406	25	–	6.9	3	6.1	6.9	225	16.0	E-64	1345	1200 : 34N, 34W.	10.0	0.041	648	0.52	313	0.53	0.49	0.93	6.79	556	6.6	269	6.2	6.1	0.99	5.48	565	5.9	273	5.2	5.6	1.08	31.8	337	13.6	163	13.0	11.2	0.
	23	Oct 1 1955	0700 0730	9	–		3	5.9	–	163	–	–	–	– – –	–	0.0122	538	0.27	269	0.37	0.26	0.71	6.34	514	6.3	257	7.0	5.9	0.85	3.90	458	4.9	229	5.6	4.6	0.82	24.00	388	11.20	144	16.0	10.9	0.

*The E values for conditions marked with an asterisk were computed by using the approximation $E \cong \frac{X^2_{max}}{\log N}$, where X_{max} is the largest observed peak to peak variation, and N is the number of variations in the sample.

**For this one condition, the stress data is derived by converting data taken from the keel strain gages and from the measured position of the neutral axis–determined to be 12.32 feet above the keel as shown in Figure 1.

***These sea states were of a severity which caused the Task Force Commander to change course many times in the effort to come to a course that would permit the men on the destroyers to rest. The seas were actually confused in direction and are included here because they have induced motions that would normally be expected from heavy beam and head seas.

†Stereo photographs are identified by the roll letter and the sequence number stamped on the film.

TABLE 4 (Continued)

Wind and Wave Data

Wave Height Class, ft	Record Number	Date of Record	Local Time of Record	Ship Speed, knots	Sea: Average of Visual Estimates	Sea: From TMB Analysis of Stereo-Photo	Number of Visual Estimates	Swell: Average of Visual Estimates	Swell: From TMB Analysis of Stereo-Photo	Heading of Sea Relative to Ship, deg	E, Mean Square Value of Wave Height Estimated from Wind Data, ft²	Stereo Photograph Analyzed †	Local Time of Photograph	Approximate Position of CVS 45 When Stereo Photos Were Taken. Time: Lat, Long	Distance in Miles between CVS 45 and DD 697
6–8	24	Oct 14 1955,	1312 1337	26	–	7.2	3	6.1	7.1	355	16.0	E-62	1315	1200 : 34N, 34W	10.0
6–8	25	Oct 19 1955	1420 1500	10	–	9.2	4	6.6	6.3	330	20.0	F-362	1445	1200 : 35N, 67W	9.0
6–8	26	Oct 19 1955	1540 1615	12	7.7	8.2	1	–	11.0	060	20.0	F-365	1551	2000 : 35N, 68W	12.0
6–8	27	Oct 11 1955	1655 1735	15	–	6.2	7	8.0	6.5	050	12.0	D-122	1616	2000 : 37N, 18W	11.0
6–8	28	Oct 11 1955	1547 1556	17	–	6.2	7	8.0	6.5	045	12.0			– – –	12.0
6–8	29	Oct 14 1955	1406 1436	25	–	6.2	7	8.0	6.5	320	12.0	D-122	1616	2000 : 37N, 18W	10.0
6–8	30	Oct 17 1955	1035 1115	18	–	4.1	4	7.3	5.7	285	20.0	F-222	0945	0800 : 35N, 57W	9.0
6–8	31	Nov 16 1955	2143 2219	23	–	–	3	7.5	–	090	30.0			– – –	149.0
6–8	32	Feb 2 1955	1940 2020	9	7	–	4	–	–	230	–	–	–	– – –	–
6–8	33	Oct 12 1955	1530 1600	21	–	6.5	3	6.9	6.3	230	16.0	D-199	1600	2000 : 35N, 22W	5.0
6–8	34	Sep 15 1955	0913 0945	16	7.2	6.3	2	–	5.9	160	24.0	B-218	0925	0800 : 43N, 37W	14.0
6–8	35	Nov 16 1955	2104 2137	23	–	–	1	7.5	–	170	30.0	–	–	– – –	149.0
8–15	*** 36	Dec 10 1955	1040 1120	7	12.0	16.8	3	12.1	–	*** 350	48.0	J-40	1045	1200 : 36N, 72W	7.0
8–15	*** 37	Dec 9 1955	1700 1730	8	10.5	7.3	4	9.9	9.3	*** 350	24.0	J-3	1530	1200 : 36N, 70W	8.0
8–15	38	Oct 1 1955	1220 1300	9	–	5.8	6	9.0	7.0	345	28.0	C-495	1245	1200 : 43N, 14W	8.1
8–15	39	Oct 16 1955	0850 0930	12	–	8.0	1	10.3	10.4	025	24.0	E-145	0645	0800 : 34N, 45W	28.6
8–15	40	Sep 22 1955	1430 1445	20	–	5.9	3	10.0	11.2	040	28.0	C-233	1434	1200 : 48N, 08W	16.00
8–15	*** 41	Dec 9 1955	2122 2155	7	10.5	7.3	4	9.9	9.3	*** 005 to 045	24.0	J-3	1530	1200 : 36N, 70W	7.0
8–15	42	Sep 28 1955	1715 1745	10	–	5.5	4	9.0	9.0	255	24.0	C-418	1715	2000 : 42N, 13W	13.0
8–15	43	Sep 20 1955	1133 1206	9	–	9.6	3	8.0	10.0	125	32.0	B-165	1202	1200 : 45N, 17W	31.0
8–15	44	Jan 30 1956	1815 1900	8	–	6.1	4	9.3	11.6	170	20.0	–	–	– – –	–
8–15	45	Sep 28 1955	1035 1115	12	–	6.1	4	9.3	11.6	175	20.0	B-163	1113	1200 : 45N, 17W	20.0
8–15	*** 46	Dec 9 1955	2010 2050	7	10.5	7.3	4	9.9	9.3	*** 005	24.0	J-3	1530	1200 : 36N, 70W	7.0
8–15	*** 47	Dec 10 1955	0130 0205	7	12.5	15.3	3	12.7	12.2	*** 315	40.0	J-35	0945	0800 : 36N, 72W	6.0

Response of Ship to Sea — Heave Acceleration and Stress, Main Deck Amidships

Record Number	Heave: E, Value of Mean Square, g²	Heave: N_h, Variations per Hour	Heave: Predicted Maximum Value in One Hour, g	Heave: Number of Variations in Sample	Heave: Maximum Measured Variation in Sample, g	Heave: Maximum Predicted Variation in Sample, g	Heave: $R = \frac{\text{Predicted Max}}{\text{Measured Max}}$	Stress: E, Value of Mean Square, kips²	Stress: N_h, Variations per Hour	Stress: Predicted Maximum Value in One Hour, kips	Stress: Number of Variations in Sample	Stress: Maximum Measured Variation in Sample, kips	Stress: Maximum Predicted Variation in Sample, kips	Stress: $R = \frac{\text{Predicted Max}}{\text{Measured Max}}$
24	0.079	737	0.72	307	0.71	0.67	0.99	16.4	763	10.9	318	10.0	9.7	0.97
25	0.025	636	0.40	424	0.38	0.39	1.03	7.60	592	6.9	395	8.1	6.7	0.84
26	0.040	648	0.51	378	0.52	0.49	0.95	10.20	622	8.1	363	8.0	7.8	0.97
27	0.016	597	0.32	398	0.31	0.31	1.00	3.69	556	4.9	371	6.0	4.7	0.78
28	0.018	693	0.35	104	0.31	0.30	0.97	4.81	633	5.6	95	5.7	4.8	0.84
29	0.096	724	0.79	362	0.72	0.75	1.04	17.58	784	10.8	392	10.0	10.0	1.00
30	0.012	680	0.28	454	0.27	0.27	1.00	5.76	206	5.5	137	5.0	5.3	1.06
31	0.015	643	0.31	386	0.28	0.30	1.07	4.13	235	4.8	141	4.6	4.5	0.98
32	0.021	642	0.37	428	0.39	0.36	0.92	1.43	444	3.0	293	4.0	2.9	0.73
33	0.0033	850	0.15	425	0.18	0.14	0.78	3.98	178	4.5	89	5.0	4.2	0.84
34	0.0059	520	0.19	277	0.27	0.18	0.67	13.4	238	8.5	126	7.5	8.0	1.07
35	<<0.00002	180	0.013	100	<<0.01	–	–	2.13	60		36	3.4		
*** 36	0.023	498	0.38	332	0.35	0.37	1.06	17.36	543	12.3	362	10.6	10.5	1.01
*** 37	0.0224	580	0.38	290	0.36	0.35	0.97	20.5	502	11.3	251	11.6	10.7	1.09
38	0.0051	627	0.18	418	0.22	0.18	0.82	4.83	566	5.6	377	6.4	5.4	0.84
39	0.013	607	0.29	405	0.25	0.28	1.12	5.67	557	6.0	371	7.0	5.8	0.83
40	0.041	660	0.52	165	0.45	0.46	1.02	12.89	692	9.2	173	8.8	8.2	0.95
*** 41	0.037	475	0.48	261	0.45	0.46	1.02	** 36.7	445	15.0	245	11.0	14.2	1.3
42	0.004	450	0.16	225	0.21	0.15	0.71	6.24	304	6.0	152	6.0	5.5	0.92
43	0.0017	560	0.10	308	0.11	0.10	0.91	13.63	313	8.9	172	8.3	8.2	0.99
44	* 0.0012	334	0.083	250	0.08			4.18	302	4.9	151	7.0	4.6	0.65
45	0.0013	465	0.09	310	0.11	0.09	0.82	11.97	261	8.2	174	8.1	7.7	0.95
*** 46	0.031	500	0.44	334	0.37	0.42	1.13	23.95	443	12.1	295	11.25	11.6	1.03
*** 47	0.022	404	0.36	233	0.32	0.35	1.09	16.68	344	9.9	201	9.8	9.4	0.96

Response of Ship to Sea — Pitch Angle and Roll Angle

Record Number	Pitch: E, Value of Mean Square, deg²	Pitch: N_h, Variations per Hour	Pitch: Predicted Maximum Value in One Hour, deg	Pitch: Number of Variations in Sample	Pitch: Maximum Measured Variation in Sample, deg	Pitch: Maximum Predicted Variation in Sample, deg	Pitch: $R = \frac{\text{Predicted Max}}{\text{Measured Max}}$	Roll: E, Value of Mean Square, deg²	Roll: N_h, Variations per Hour	Roll: Predicted Maximum Value in One Hour, deg	Roll: Number of Variations in Sample	Roll: Maximum Measured Variation in Sample, deg	Roll: Maximum Predicted Variation in Sample, deg	Roll: $R = \frac{\text{Predicted Max}}{\text{Measured Max}}$
24	4.99	706	5.8	294	6.0	5.2	0.87	12.8	314	8.6	131	7.5	7.6	1.01
25	3.81	600	4.9	400	5.0	4.8	0.96	24.5	403	12.2	269	15.0	11.8	0.79
26	6.66	612	6.6	357	7.5	6.3	0.83	35.2	423	14.6	247	17.0	14.0	0.82
27	3.50	537	4.7	358	5.6	4.5	0.80	84.0	362	22.4	241	27.5	21.5	0.78
28	3.75	580	4.9	87	4.2	4.2	1.0	54.3	387	17.9	58	17.5	14.9	0.85
29	9.23	654	7.8	327	8.8	7.3	0.82	16.5	368	9.8	184	12.0	9.3	0.77
30	1.02	483	2.5	322	2.6	2.4	0.93	82.9	327	22.0	218	23.5	21.5	0.92
31	1.48	392	3.0	235	3.4	2.8	0.93	88.8	318	23.5	191	23.5	21.6	0.92
32	2.79	520	4.2	347	4.2	4.1	0.97	261.2	408	38.7	272	42.0	37.2	0.89
33	1.05	186	2.4	93	2.2	2.3		27.6	282	12.5	141	20.0	11.7	0.59
34	1.65	377	3.1	201	3.2	3.0	0.94	152.0	315	29.6	168	31.0	28.0	0.90
35	* 0.217	180		100	1.0			8.82	118	6.5	65	7.5	6.1	0.81
*** 36	16.8	471	10.0	314	11.8	9.9	0.83							
*** 37								459.2	396	53.0	198	93.0	49.4	0.53
38	1.65	525	3.1	349	3.5	3.1	0.89	66.4	297	19.4	197	29.0	19.0	0.67
39	5.73	477	6.0	318	5.5	5.8	1.05	124.9	403	27.4	269	29.2	26.4	0.91
40	9.43	612	7.8	153	8.2	6.6	0.81	65.6	404	19.8	101	20.5	17.4	0.84
*** 41	41.0	372	15.6	206	16.2	14.8	0.91	290.0	372	41.4	205	50.0	39.4	0.79
42	2.36	384	3.7	192	3.8	3.5	0.95	220.3	354	36.0	177	34.0	32.8	0.97
43	5.32	349	7.3	192	6.2	6.0	0.97	141.4	387	29.0	213	30.0	26.0	0.87
44	2.59	300	3.8	150	3.5	3.6	1.03	69.3	340	20.0	170	17.5	18.8	1.07
45	4.03	287	4.8	191	4.6	4.7	1.02	121.9	338	26.6	225	26.5	25.6	0.97
*** 46								433.8	342	50.0	228	51.5	48.5	1.06
*** 47	22.0	338	11.3	197	11.6	10.8	0.93							

*The E values for conditions marked with an asterisk were computed by using the approximation $E \cong \frac{X^2_{max}}{\log N}$ where X_{max} is the largest observed peak to peak variation, and N is the number of variations in the sample.

**For this one condition, the stress data is derived by converting data taken from the keel strain gages and from the measured position of the neutral axis–determined to be 12.32 feet above the keel as shown in Figure 1.

***These sea states were of a severity which caused the Task Force Commander to change course many times in the effort to come to a course that would permit the men on the destroyers to rest. The seas were actually confused in direction and are included here because they have induced motions that would normally be expected from heavy beam and head seas.

†Stereo photographs are identified by the roll letter and the sequence number stamped on the film.

SHORT-TERM DISTRIBUTION

The short-term or Rayleigh distribution of variations in the measured quantities corresponding to a particular set of operating conditions (sea state, speed, and course) is defined by the corresponding mean square value E of the variations; see Table 4.

For illustrative purposes, consider the sample short-term distribution of peak-to-peak variation* in pitch angle shown in Figure 5. The distribution indicates the relative probability $p(x)$ of a pitch angle of magnitude x. The area under the curve, Figure 5a, up to any value x_i is the fraction P of all members of the population (all pitch angles) which have values less than x_i. Therefore, the probability of exceeding the value x_i is $100(1-P)$ percent. For the Rayleigh distribution $P(x) = 1 - e^{-x^2/E}$.

All Rayleigh distributions become identical if the probability P is plotted against $v^2 = x^2/E$ instead of against x directly. With this artifice, it is necessary to know only the value of E corresponding to a particular sea condition, ship speed, and heading to obtain the probability of exceeding any value of x from a single straight-line graph (Figure 5b) which is equally applicable to wave heights, ship motions, and hull stresses.

For any set of operating conditions, characteristic and extreme values can be predicted from a knowledge of the corresponding value of E. Useful statistical estimates are made as follows:[9]

1. The most frequent magnitude of the variations is $0.707\sqrt{E}$.
2. The average magnitude of the variations is $0.866\sqrt{E}$.
3. The most probable extreme value x_m experience in a sample of N variations is $x_m = k\sqrt{E}$. For large values of N (> 100), k is approximately equal to $\sqrt{\log_e N}$.

For design purposes the extreme values of the various variables may be estimated statistically as follows:

Let the value of E corresponding to the most severe service condition be E_m. If the ship is expected to experience N variations during the time it is exposed to this operating condition, then

$$x_{m_1}^2 = E_m(y + \log_e N)$$

where N is assumed to be large.

*The motion, stress, and bending moment will be given in terms of their variation, which is defined as the magnitude of the change for a maximum value to the succeeding minimum value.

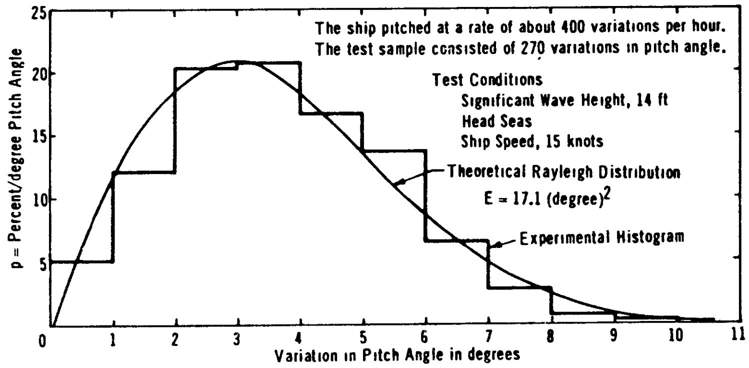


Figure 5a – Distribution of Variation in Pitch Angle for DD 692-Class Destroyer

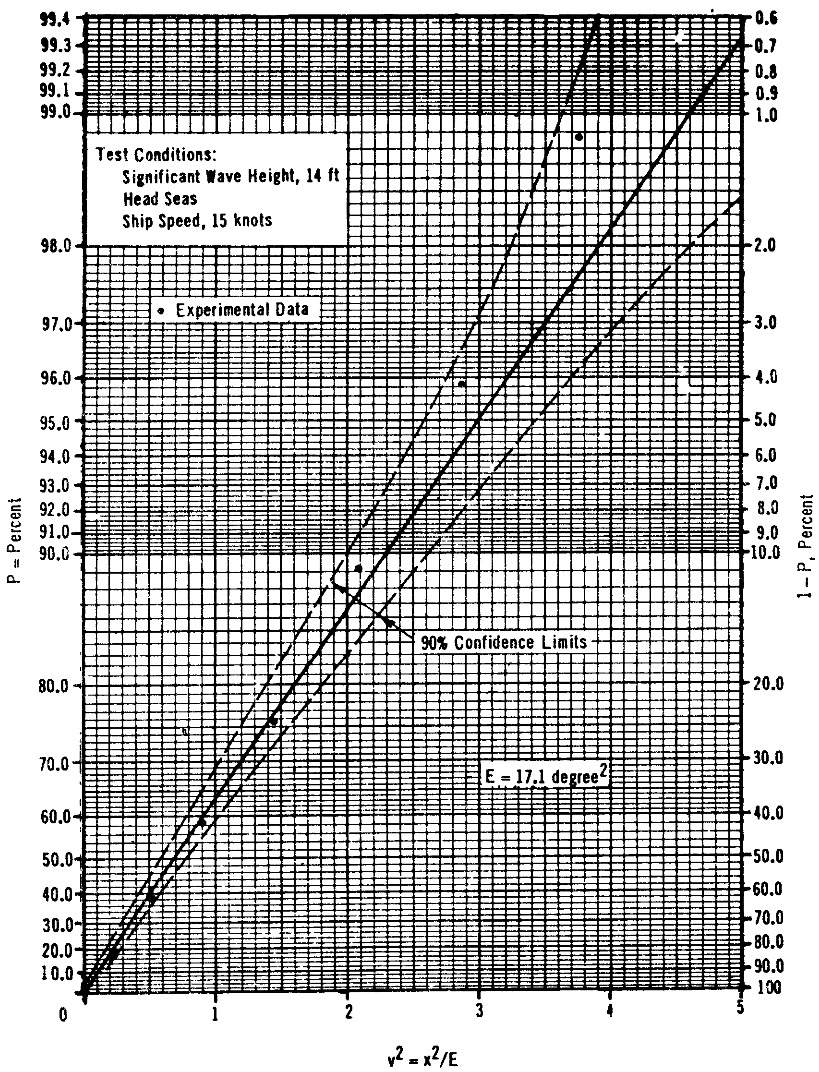


Figure 5b – Cumulative Distribution of Variation in Pitch Angle for DD 692-Class Destroyer

Figure 5 – Sample of Rayleigh (Short-Term) Distributions

The value of y is a function of the risk f* (selected by the designer). Table 1 of Reference 10 gives y as a function of f. For example, if we take one chance in a thousand, $f = 0.001$ and $y = 6.9$. For $f < 0.1$, $y \approx \log_e (1/f)$.

The value x_{m_1} is then that magnitude of the variable which, on the average, is exceeded only by the fraction f of many similar ships operating under the most severe service conditions.

LONG-TERM DISTRIBUTION

The short-term distributions, each of which is characterized by a value E, are now used as building blocks to construct the long-term frequency distribution patterns of the ship responses to the sea, applicable to wartime service in the North Atlantic Ocean. Distribution patterns for other "missions" or operating areas can be readily computed from data given in this report. Each of the short-term distributions is weighted in accordance with the relative fraction of time (f_1, f_2, f_3) in which DD 692-Class destroyers will operate at a given ship speed f_1, in a given sea state f_2, and at a given heading to the waves f_3.

The weighting factors f_1 and f_3 are based on estimates made by officers with experience on DD 692-Class destroyers, as reported in Reference 7. The factors f_2 were taken from the frequency distribution of wave heights shown as Figure 13 in Reference 2 and are applicable to Weather Station C, 52° N 37° W, North Atlantic Ocean.

The fractions f_1 of time that the ship will make the given speeds for the specified range of characteristic wave heights, including all headings relative the predominant wave direction, are:

Ship Speed knots	Characteristic Wave Height, ft				
	0–4	4–6	6–8	8–15	> 15
5–10	0.097	0.073	0.106	0.268	0.451
10–15	0.219	0.265	0.332	0.360	0.421
15–20	0.451	0.449	0.428	0.277	0.085
20–25	0.144	0.150	0.099	0.082	0.030
25–30	0.075	0.053	0.034	0.013	0.003
> 30	0.014	0.001	0.004	0.006	0.000

*f is the fraction of all samples of size N, belonging to a distribution specified by $p(x)$, which will have at least one value of $x > x_{m_1}$.

The fractions f_2 of time that specified ranges of characteristic wave heights will experience in the North Atlantic Ocean are:

Wave Height	0–4	4–6	6–8	8–15	> 15
Value of f_2	0.24	0.22	0.17	0.27	0.10

The fractions f_3 of time that the ship will make a given heading to the sea for all operating speeds and a given wave height are:

Wave Height ft	Head Seas	Quarter-Head Seas	Beam Seas	Quarter-Following Seas	Following Seas
0–8	0.125	0.250	0.250	0.250	0.125
0-15	0.250	0.250	0.125	0.250	0.125
> 15	0.330	0.670	0	0	0

When several similar sets of test data are used in the derivation of a predicated distribution, a weighting factor f_4 is utilized. For example, if four sets of similar test data were available and were used in the derivation, f_4 would equal 0.25. The products of the weighting factors used in the calculations are given in Table 5.

The long-term distribution patterns for hull stresses and bending moments are calculated in Table 6. Similar tables were devised for use in the calculation of the long-term distribution of the ship's motions. The probabilities $(1-P)$ of exceeding given values of the variate are tabulated for all the weighted short-term distributions. The last line in the table is obtained by summing up all environmental conditions and thus gives the derived values of $(1-P)$ for the long-term distribution. The long-term distributions of hull stresses, bending moments, and motions are plotted on cumulative probability charts in Figures 6 through 9.

The straight lines shown on these charts were computed directly from the percentages represented by the plotted points, on the assumption that the long-term distribution is of the log-normal type. The fairly good fit (except in case of heave acceleration) of the computed line to the plotted points indicates that this assumption is reasonable.

The wave-induced hull girder stresses amidship have been converted to bending moments by making use of the midship section modulus which is applicable to the gage location. On SPERRY, the strain gage was located 10.1 ft above the calculated neutral axis. The section modulus applicable to this strain gage location is 7750 ft-in.^{2}

(Text continued on page 22.)

TABLE 5

Product of Weighting Factors (f_1, f_2, f_3) Applicable to Different Sets of Operating Conditions

Ship Speed		Relative Direction of Sea	Characteristic Wave Height, ft				
Knots	Class	deg	0-4	4-6	6-8	8-15	> 15
5-10	1	0	0.00291	0.00201	0.00225	0.01810	0.01485
		45	0.00582	0.00402	0.00450	0.01810	0.03022
		90	0.00582	0.00402	0.00450	0.00905	0
		135	0.00582	0.00402	0.00450	0.01810	0
		180	0.00291	0.00201	0.00225	0.00905	0
10-15	2	0	0.00658	0.00729	0.00705	0.02430	0.01389
		45	0.01315	0.01458	0.01410	0.02430	0.02821
		90	0.01315	0.01458	0.01410	0.01215	0
		135	0.01315	0.01458	0.01410	0.02430	0
		180	0.00658	0.00729	0.00705	0.01215	0
15-20	3	0	0.01353	0.01235	0.00910	0.01870	0.00281
		45	0.02705	0.02470	0.01820	0.01870	0.00570
		90	0.02705	0.02470	0.01820	0.00935	0
		135	0.02705	0.02470	0.01820	0.01870	0
		180	0.01353	0.01235	0.00910	0.00935	0
20-25	4	0	0.00433	0.00413	0.00210	0.00553	0.00099
		45	0.00865	0.00825	0.00420	0.00553	0.00210
		90	0.00865	0.00825	0.00420	0.00276	0
		135	0.00865	0.00825	0.00420	0.00553	0
		180	0.00433	0.00413	0.00210	0.00276	0
25-30	5	0	0.00225	0.00146	0.00073	0.00088	0.00010
		45	0.00450	0.00292	0.00146	0.00088	0.00020
		90	0.00450	0.00292	0.00146	0.00044	0
		135	0.00450	0.00292	0.00146	0.00088	0
		180	0.00225	0.00146	0.00073	0.00044	0
> 30	6	0	0.00043	0.00026	0.00008	0.00004	0
		45	0.00085	0.00053	0.00015	0.00004	0
		90	0.00085	0.00053	0.00015	0.00002	0
		135	0.00085	0.00053	0.00015	0.00004	0
		180	0.00043	0.00026	0.00008	0.00002	0

TABLE 6

Derivation of Predicted Distribution for Variations in Hull Stress Due to Longitudinal Bending, at Main Deck, Amidships for Wartime Service in North Atlantic Ocean

Wave Height Class ft	Operating Condition Record Number	Relative Direction of Waves to Ship	Ship Speed knots	Ship Speed Class* and Corresponding Weighting Factor	$\Sigma f_1 \cdot f_2 \cdot f_3 \cdot f_4$	Number of Variations per Hour N	Average Number of Variations per Hour Contributed by each Operating Condition $f_1 \cdot f_2 \cdot f_3 \cdot f_4 \cdot N = n$	E, Value of Mean Square Variation, kips²	Probability of Exceeding Given Magnitude of Variation (1 – P) — Given Magnitude in kips: 0.12	0.20	0.50	1.00	1.50	2.00	2.50	3.00	4.00	5.00	6.00	8.00	10.0	12.0	15.0	18.0
0-4	1	H	12	(1-2)	0.00949	584	5.542	1.850	0.992	0.978	0.873	0.582	0.296	0.115	0.0341	0.0077	0.0001							
	2	H	16	(3-4-5-6)	0.02054	720	14.789	5.390	0.997	0.992	0.954	0.830	0.658	0.476	0.3136	0.1882	0.0513	0.0096	0.0012					
	3	QH	15	(1-2-3-4-5-6)	0.06002	600	36.012	5.740	0.997	0.993	0.957	0.840	0.675	0.498	0.3365	0.2084	0.0615	0.0128	0.0018					
	4	B	9	(1)	0.00582	300	1.746	0.097	0.862	0.662	0.075													
	5	B	12	(2-3)/½	0.02010	412	8.281	5.680	0.997	0.993	0.956	0.838	0.672	0.494	0.3327	0.2050	0.0597	0.0122	0.0017					
	6	B	14	(2-3)/½	0.02010	403	8.100	3.440	0.995	0.988	0.929	0.747	0.519	0.312	0.1625	0.0730	0.0095	0.0007						
	7	B	23	(4-5-6)	0.01400	960	13.440	0.360	0.960	0.894	0.499	0.062	0.001											
	8	QF	10	(1-2)	0.01897	125	2.371	0.650	0.978	0.940	0.680	0.214	.0.031	0.002	0.0001									
	9	QF	20	(3-4-5-6)	0.04105	186	7.635	0.210	0.933	0.826	0.304	0.008												
	10	F	8	(1-2-3-4-5-6)	0.03003	398	11.952	1.250	0.988	0.968	0.818	0.449	0.165	0.040	0.0067	0.0007								
4-6	11	H	5	(1)	0.00201	530	1.065	2.120	0.993	0.981	0.888	0.623	0.346	0.151	0.0524	0.0143	0.0005							
	12	H	11	(2)/½	0.00365	435	1.588	7.500	0.998	0.994	0.967	0.875	0.740	0.586	0.4346	0.3011	0.1184	0.356	.0.0082	0.0002				
	13	H	15	(2)/½	0.00365	600	2.190	4.410	0.996	0.990	0.944	0.797	0.600	0.403	0.2423	0.1299	0.0265	0.0034	0.0002					
	14	H	17	(3)	0.01235	622	7.682	7.990	0.998	0.995	0.969	0.882	0.754	0.606	0.4573	0.3242	0.1349	0.0437	0.0110	0.0003				
	15	H	21	(4-5-6)	0.00585	764	4.469	7.650	0.998	0.994	0.967	0.877	0.745	0.592	0.4417	0.3083	0.1235	0.0380	0.0090	0.0002				
	16	QH	5	(1)	0.00402	500	2.010	1.810	0.992	0.978	0.871	0.575	0.288	0.109	0.0316	0.0069	0.0001							
	17	QH	15	(2)	0.01458	545	7.952	8.030	0.998	0.995	0.969	0.882	0.755	0.607	0.4591	0.3260	0.1363	0.0444	0.0112	0.0003				
	18	QH	16	(3-4-5-6)	0.03640	560	20.384	3.690	0.996	0.989	0.934	0.762	0.543	0.338	0.1838	0.0872	0.0130	0.0011						
	19	B	5	(1-2)	0.01860	405	7.533	2.490	0.994	0.984	0.904	0.669	0.405	0.200	0.0812	0.0269	0.0016							
	20	B	15	(3-4-5-6)	0.03640	501	18.236	2.690	0.994	0.985	0.911	0.689	0.433	0.226	0.0979	0.0352	0.0026	0.0001						
	21	QF	20	(1-2-3)	0.04330	690	29.877	7.090	0.997	0.994	0.965	0.868	0.728	0.568	0.4141	0.2810	0.1046	0.0294	0.0062	0.0001				
	22	QF	25	(4-5-6)	0.01170	556	6.505	6.790	0.997	0.994	0.963	0.863	0.717	0.554	0.3983	0.2656	0.0947	0.0251	0.0049	0.0001				
	23	F	9	(1-2-3-4-5-6)	0.02750	514	14.135	6.340	0.997	0.993	0.961	0.854	0.701	0.532	0.3731	0.2418	0.0801	0.0193	0.0034					
6-8	24	H	26	(1-2-3-4-5-6)	0.02131	763	16.260	16.400	0.999	0.997	0.984	0.940	0.871	0.783	0.8631	0.5776	0.3769	0.2177	0.1113	0.0201	0.0024	0.0002		
	25	QH	10	(1)	0.00450	592	2.664	7.600	0.998	0.994	0.967	0.876	0.743	0.590	0.4393	0.3060	0.1218	0.0372	0.0087	0.0002				
	26	QH	12	(2)/½	0.00705	622	4.385	10.200	0.998	0.996	0.975	0.906	0.802	0.675	0.5418	0.4138	0.2083	0.0862	0.0293	0.0018	0.0001			
	27	QH	15	(2)/½	0.00705	556	3.920	3.690	0.996	0.989	0.934	0.762	0.543	0.338	0.1838	0.0872	0.0130	0.0011	0.0000					
	28	QH	17	(3)	0.01820	633	11.521	4.810	0.997	0.991	0.949	0.812	0.626	0.435	0.2726	0.1539	0.0359	0.0055	0.0005					
	29	QH	25	(4-5-6)	0.00581	784	4.555	17.580	0.999	0.997	0.985	0.944	0.879	0.796	0.7008	0.5948	0.4024	0.2412	0.1290	0.0261	0.0033	0.0003		
	30	B	18	(1-2-3)	0.03680	206	7.581	5.760	0.997	0.993	0.957	0.840	0.676	0.499	0.3378	0.2096	0.0621	0.0130	0.0019					
	31	B	23	(4-5-6)	0.00581	235	1.365	4.130	0.996	0.990	0.941	0.784	0.579	0.379	0.2201	0.1131	0.0207	0.0023	0.0001					
	32	QF	9	(1)	0.00450	444	1.998	1.430	0.989	0.972	0.839	0.496	0.207	0.060	0.0126	0.0018								
	33	QF	21	(2-3-4-5-6)	0.03811	178	6.784	3.980	0.996	0.990	0.939	0.777	0.568	0.366	0.2079	0.1042	0.0179	0.0018	0.0001					
	34	F	16	(1-2-3)	0.01840	238	4.379	13.400	0.998	0.997	0.981	0.928	0.845	0.741	0.6272	0.5108	0.3030	0.1547	0.0681	0.0084	0.0005			
	35	F	23	(4-5-6)	0.00291	60	0.175	2.130	0.993	0.981	0.889	0.625	0.347	0.152	0.0531	0.0146	0.0005							
8-15	36	H	7	(1-2-3-4-5-6)1/3	0.02252	543	12.228	17.360	0.999	0.997	0.985	0.944	0.878	0.794	0.6976	0.5954	0.3978	0.2369	0.1257	0.0250	0.0031	0.0003		
	37	H	8	(1-2-3-4-5-6)1/3	0.02252	502	11.305	20.500	0.999	0.998	0.987	0.952	0.896	0.822	0.7372	0.6446	0.4581	0.2953	0.1727	0.0440	0.0076	0.0009		
	38	H	9	(1-2-3-4-5-6)1/3	0.02252	566	12.746	4.830	0.997	0.991	0.949	0.813	0.627	0.436	0.2741	0.1551	0.0364	0.0056	0.0005					
	39	QH	12	(1-2)	0.04240	557	23.617	5.670	0.997	0.992	0.956	0.838	0.672	0.493	0.3321	0.2023	0.0594	0.0121	0.0017					
	40	QH	20	(3-4-5-6)	0.02515	692	17.403	12.890	0.998	0.996	0.980	0.925	0.839	0.733	0.6157	0.4974	0.2890	0.1437	0.0612	0.0069	0.0004			
	41	B	7	(1-2-3-4-5-6) ½	0.01689	445	7.516	47.0	0.999	0.999	0.994	0.976	0.947	0.908	0.8600	0.8048	0.6797	0.5470	0.4195	0.2135	0.0895	0.0310	0.0044	0.0004
	42	B	10	(1-2-3-4-5-6)/½	0.01689	304	5.135	6.240	0.997	0.993	0.960	0.851	0.697	0.526	0.3672	0.2363	0.0769	0.0181	0.0031					
	43	QF	9	(1-2-3-4-5-6)	0.06755	313	21.143	13.630	0.998	0.997	0.981	0.929	0.847	0.745	0.6322	0.5166	0.3091	0.1597	0.0712	0.0091	0.0006			
	44	F	8	(1)	0.00905	302	2.733	4.180	0.996	0.990	0.941	0.787	0.583	0.384	0.2242	0.1161	0.0217	0.0025	0.0001					
	45	F	12	(2-3-4-5-6)	0.02472	261	6.451	11.970	0.998	0.996	0.979	0.919	0.828	0.715	0.5932	0.4714	0.2627	0.1238	0.0494	0.0047	0.0002			
over 15†	46	H	7	(1-2-3-4-5-6)	0.03364	443	14.854	23.950	0.999	0.998	0.989	0.959	0.910	0.846	0.7703	0.6867	0.5127	0.3521	0.2224	0.0691	0.0153	0.0024	0.0001	
	47	QH	7	(1-2-3-4-5-6)	0.06643	344	23.475	16.680	0.999	0.997	0.985	0.941	0.873	0.786	0.6875	0.5830	0.3831	0.2233	0.1155	0.0215	0.0024	0.0002		
Number of Variations per Hour Exceeding Given Level (Summing over all conditions)							457.687		455.2	451.1	424.5	365.5	300.5	236.2	179.5	133.1	70.74	37.25	19.46	5.148	1.413	0.424	0.068	0.008
Percentage of Variation Exceeding Given Level							100.0		99.46	98.55	92.75	79.87	65.66	51.61	39.22	29.09	15.45	8.139	4.252	1.125	0.309	0.093	0.015	0.002

*The numbers in this column shown in parentheses indicate the speed class in Table 5 to which the corresponding weighting factors are applied. The factors f_1, f_2, f_3, and f_4 are defined on page 14. Where more than one speed class is indicated, the applicable speed class weighting factor is also assumed to apply for ship speeds for which no experimental data are available.

†Conditions used for wave height range greater than 15 feet were chosen from the highest sea states observed for the head and quarter-head conditions. They are used here because waves above 15 feet were not encountered during the observation periods.

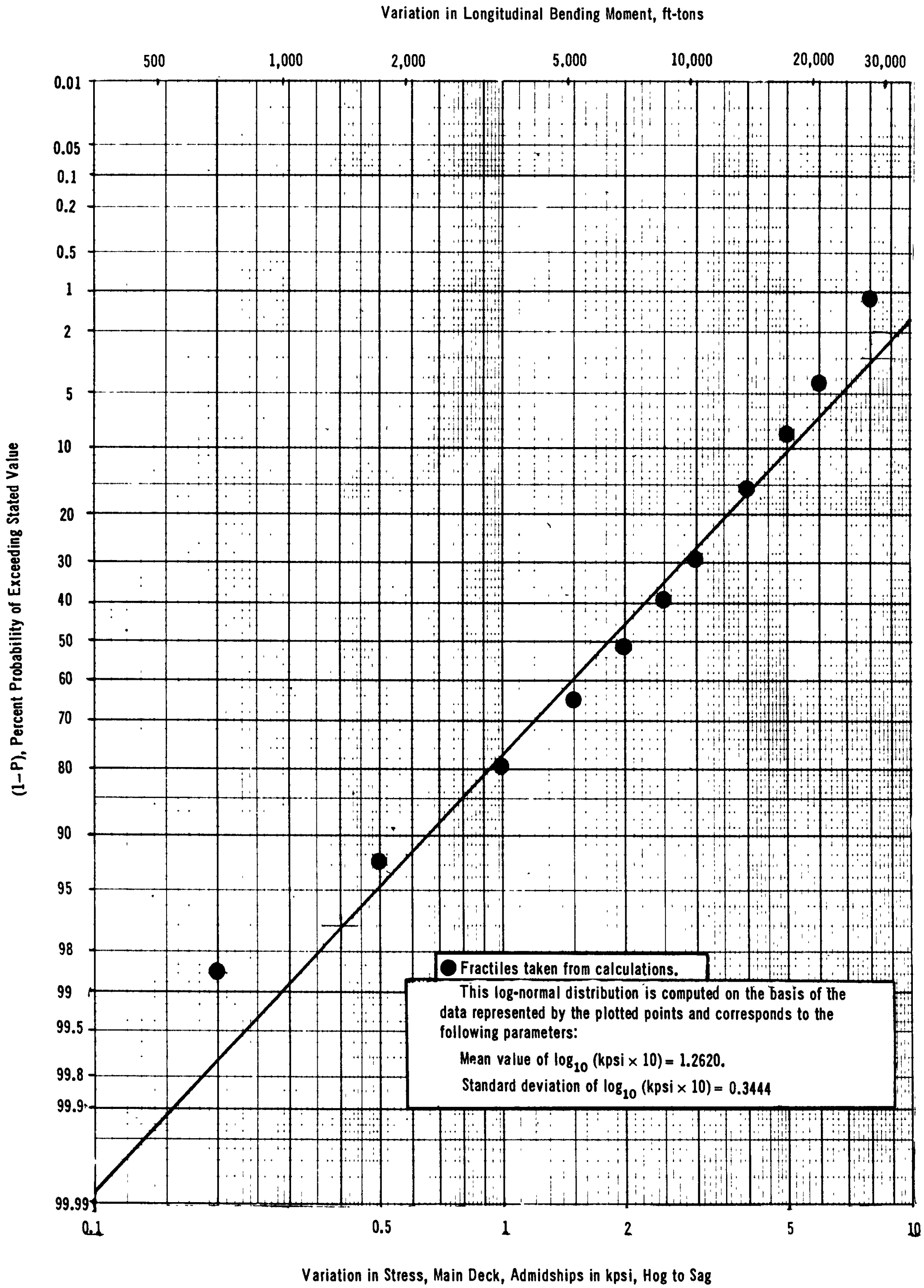


Figure 6 – Long-Term Cumulative Distribution of Longitudinal Stress and Bending Moment Amidships for Wartime Service in North Atlantic Ocean

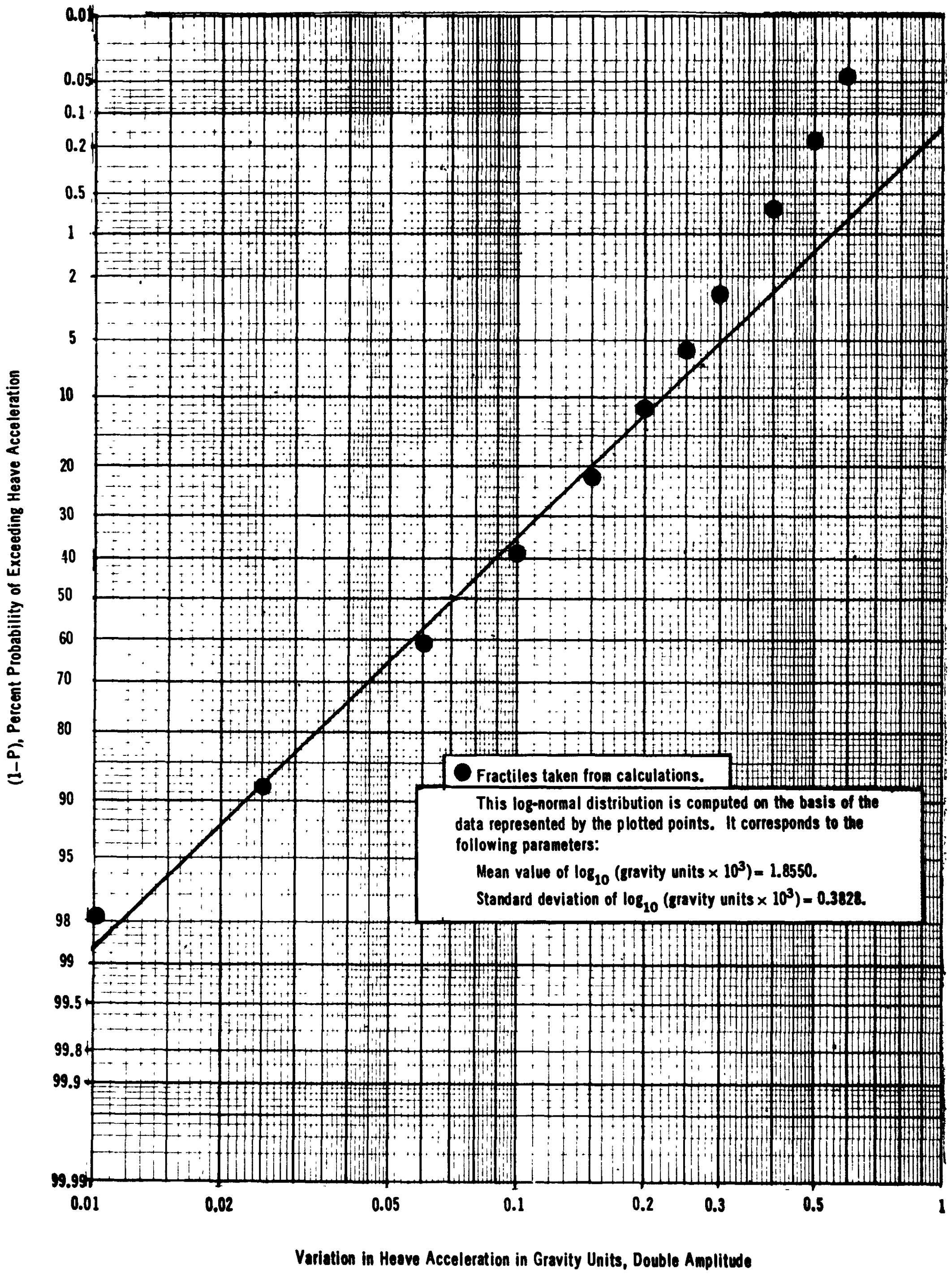


Figure 7 – Long-Term Cumulative Distribution of Heave Acceleration for Wartime Service in North Atlantic Ocean

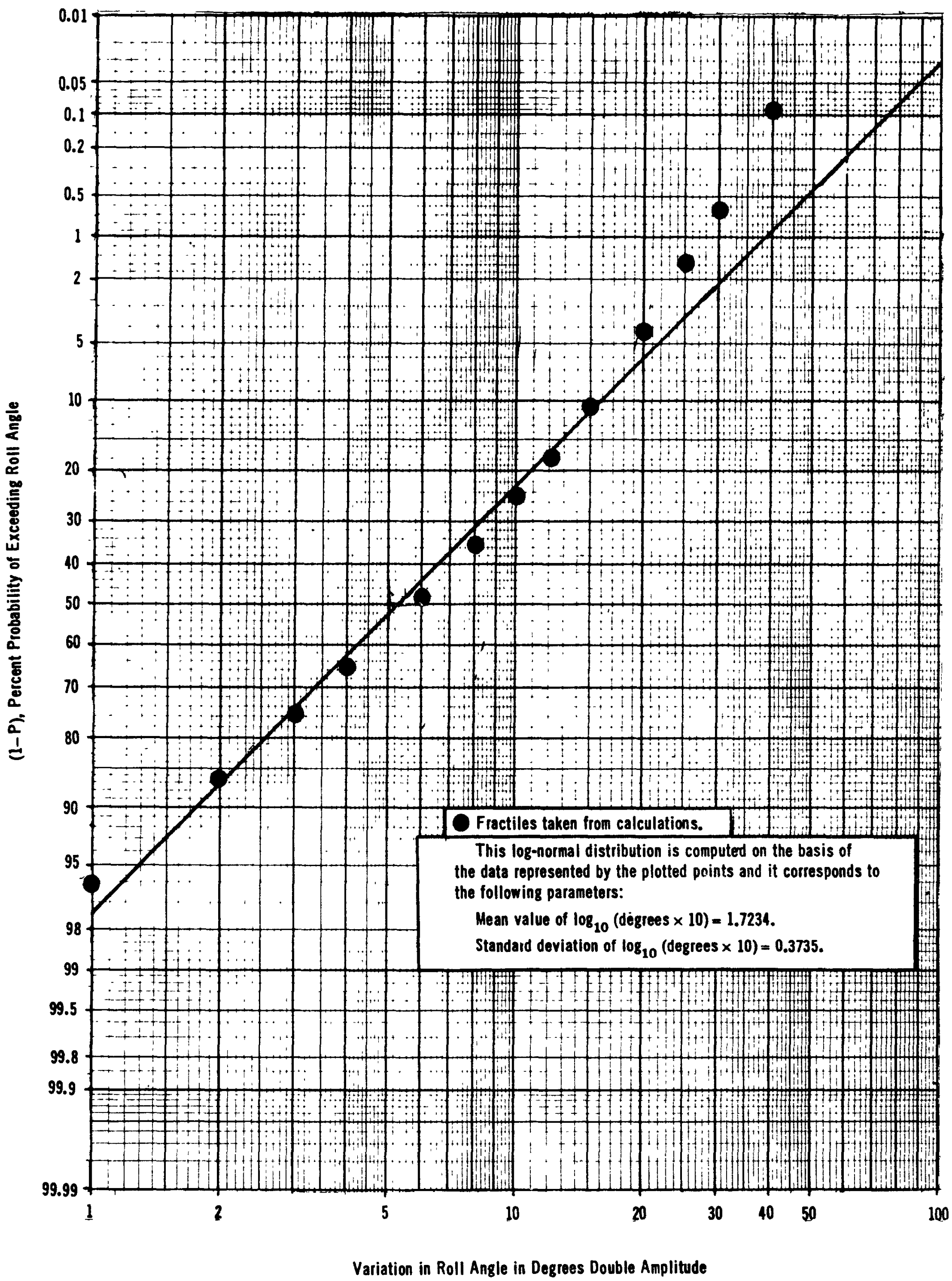


Figure 8 – Long-Term Cumulative Distribution of Roll Angle for Wartime Service in North Atlantic Ocean

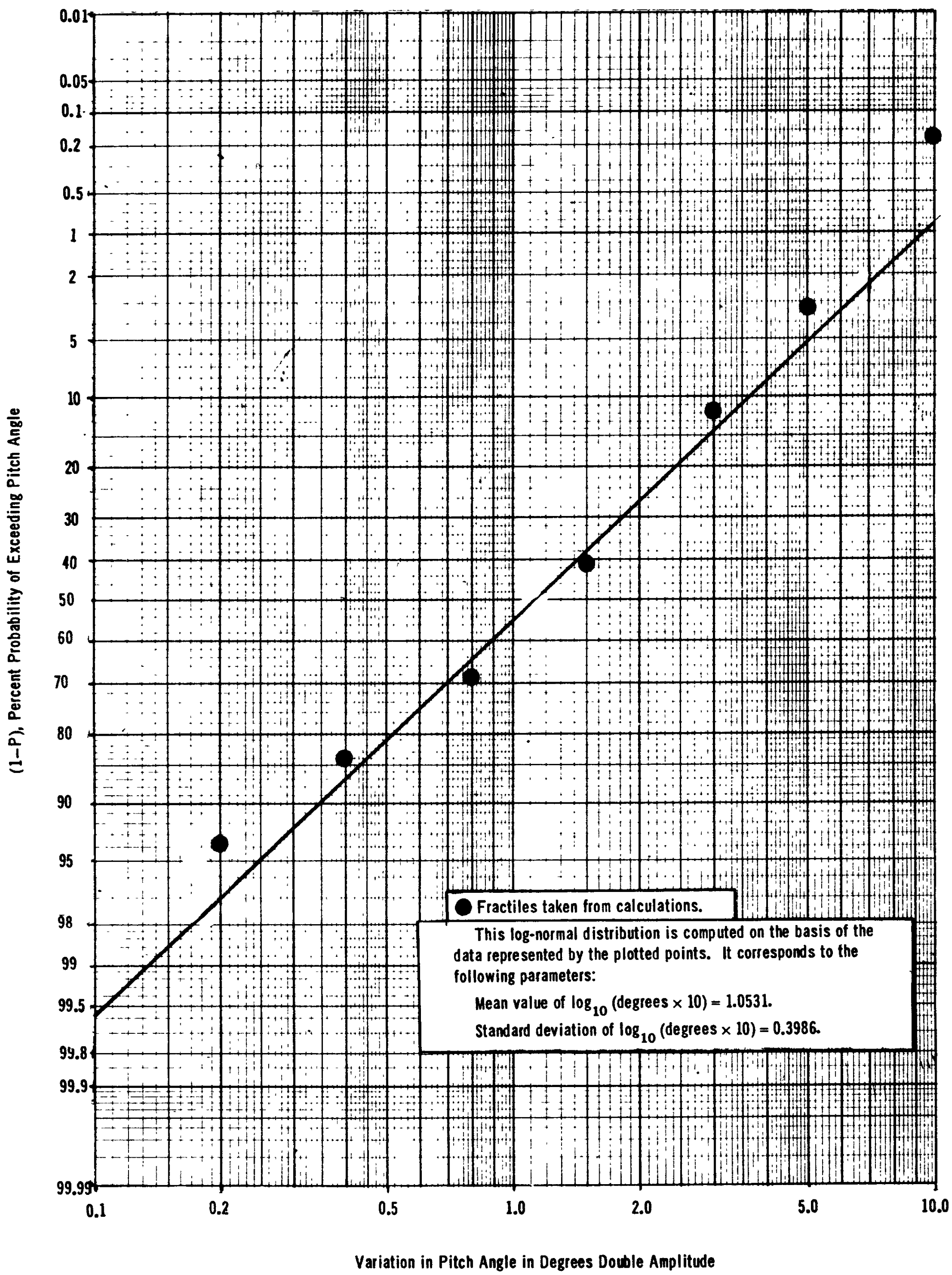


Figure 9 – Long-Term Cumulative Distribution of Pitch Angle for Wartime Service in North Atlantic Ocean

DESIGN AND OPERATIONAL DATA FOR DD 692-CLASS DESTROYERS IN WARTIME SERVICE

It has been mentioned that the distribution patterns give the probability of exceeding any given magnitude of motion or stress and that the distribution pattern can also be used as a load spectrum for calculating endurance strength. In this section design and operational specifications are suggested. They were obtained from SPERRY data and are based on the following assumptions:

1. The ship will generally be operating in the North Atlantic Ocean. The observations of sea conditions at Weather Station C are considered typical of conditions in the North Atlantic and are assumed to represent the conditions the ships will encounter in service.

2. Operating speed patterns corresponding to various sea conditions are assumed to follow those reported in the previous section.

SHORT-TERM DISTRIBUTION

Characteristic and extreme values can be predicted, and the probability of exceeding any value of a variable for a *particular* sea condition, ship speed, and heading can be easily obtained for DD 692-Class destroyers from the values of E listed in Table 4.

LONG-TERM DISTRIBUTION

The probability of exceeding and of not exceeding any value of the variable when the ship is subjected to *all* the environments for a period of years, is given in Figures 6 through 9. For example, approximately half of the pitch angle variations experienced would probably be less than 1 deg peak to peak (from Figure 9). These distributions may be considered valid up to variations corresponding to a value of $(1-P)$ equal to 1 percent.

PREDICTION OF EXTREME VALUES OF ORDINARY WAVE-INDUCED SHIP MOTIONS AND BENDING MOMENTS

To estimate the largest values of motions and bending moments for design purposes, the extreme value formula of page 12 may be used:

$$x_{m_1} = [E_m (y + \log_e N)]^{1/2}$$

It is assumed* that the worst combination of operating conditions is that which gives the largest value of E, i.e., E_m. The value of N may be estimated as follows: Assume that

*An alternate procedure is given in Appendix A.

the ship will be subjected to the worst operating conditions for a period, taken here as 4 hr, and will experience V variations during that time, and that this situation will be repeated n times during the service life of the ship. Therefore, $N = nV$.

As an example, consider the prediction of the extreme variation of longitudinal bending moment, excluding the effects of slamming. From Table 4

$$E_m = 440 \times 10^6 \, (\text{ft}^2 - \text{ton}^2); \; V = 1780$$

If the risk $f = 0.001$ is assumed, then, from Reference 10, $y = 6.9$. Therefore, with $n = 20$,

$$x_{m_1} = [440 \times 10^6 \, (6.9 + 10.47)]^{1/2} = 89{,}000 \text{ ft-ton hog to sag}$$

Maximum values for the other variables considered herein have been estimated similarly by taking $f = 0.001$ and $n = 20$. They are listed in Table 7 together with the largest values measured at any time during trials on SPERRY.

Predictions of extreme values should be used with caution because the method may break down by predicting too large values, that is, values larger than it would be possible to attain in practical operations. The extreme values listed in the last column of Table 7 are considered reasonable.

DESIGN MIDSHIP BENDING MOMENT INCLUDING WHIPPING EFFECTS*

In addition to the ordinary stress variations that occur at the frequency of wave encounter, allowance must be made for the still-water stresses and the whipping stresses that result from slamming or pounding of the ship in rough seas.

Because of the nature of these tests still-water stress data are not measured; therefore, only the vibratory or whipping and ordinary wave-induced bending moments will be considered. The ordinary wave-induced values were discussed in the previous section. Significant whipping stresses were not measured on SPERRY because the ship's speed was reduced in rough seas to prevent damage. Severe whipping stresses, however, were recorded during trials of a Dutch destroyer.[5] The oscillograms of Figures 10 and 11 show the most severe whipping stresses recorded on SPERRY and on the Dutch destroyer, respectively. The results obtained for the Dutch destroyer are used to arrive at the most severe values for the midship bending moment of DD 692-Class destroyers by assuming that the Dutch destroyer and DD 692-Class destroyers are geometrically and structurally similar and will operate in similar seas at the same Froude number. The method used is given in Appendix B. Characteristics of both ships are given on page 3.

*For an alternative approach, see Appendix A.

TABLE 7

Maximum Values of Ship Motions and Longitudinal Bending Moments for DD 692-Class Destroyer

All values refer to peak-to-peak variation and do not include effects of whipping.

Operating Condition Record Number	Quantity	Conditions for which Maximum Value Is Predicted				Number of Variations per 4-hour period N	Number of Variations Expected during Operating Life of Ship in Conditions Corresponding to E_m	Estimated Most Probable Maximum Value in One Storm (4 hr)* $E_m \log_e N$	Maximum Expected Value* during Operating Life of Ship [$f = 0.001$]	Largest Measured Variation	Recommended Maximum Allowance for Design Purposes
		Characteristic Wave Height ft	Direction of Sea Relative to Ship's Course, deg	Ship Speed (from rpm's) knots	Mean Square Value of the Variation E_m also Equals Four Times the Area under the Power Spectrum						
29	Heave Acceleration	8	045	25	0.096 g^2	2900	58,000	0.87 g	1.39 g	0.72 g	1.4 g
37	Roll Angle	10.5	Confused	8	459.2 deg^2	1600	32,400	58.2 deg	95 deg	93 deg	95 deg
41	Pitch Angle	10.5	Confused	7	41.0 deg^2	1485	29,700	17.3 deg	28.0 deg	16.2 deg	28 deg
41	Longitudinal Bending Stress Amidships	10.5	Confused	7	36.7 $(kips)^2$	1780	35,600	16.6 $(kips)^2$	25.4 $(kips)^2$	11.0 $(kips)^2$	26 $(kips)^2$
41	Longitudinal Bending Moment Amidships	10.5	Confused	7	440×10^6 ft^2- ton^2	1780	35,600	57,500 ft-tons	89,000** ft-tons	38,000 ft-tons	90,000 ft-tons

*These values are estimated on the assumption that all values are independent. This is not strictly valid and may result in a slight overestimate of the extreme value.

**This value may be compared with the maximum hog to sag bending moment of 91,800 ft-tons obtained from the standard calculation on Bureau of Ships Plan No. DD 851-025041, dated 4 April 1949.

1. The wave heights listed are the average height of the larger, well-defined waves, as determined by visual observations.
2. The conditions listed are those under which the largest values recorded at any time were obtained.
3. The measured values listed are the largest values recorded throughout seaworthiness tests on destroyers, and cover about 2 years operation at sea.
4. The stress and bending moments refer to center line, main deck, amidships. This is the ordinary wave-induced stress free of whipping stresses. The applicable section modulus = 7750 ft-in.^{2}

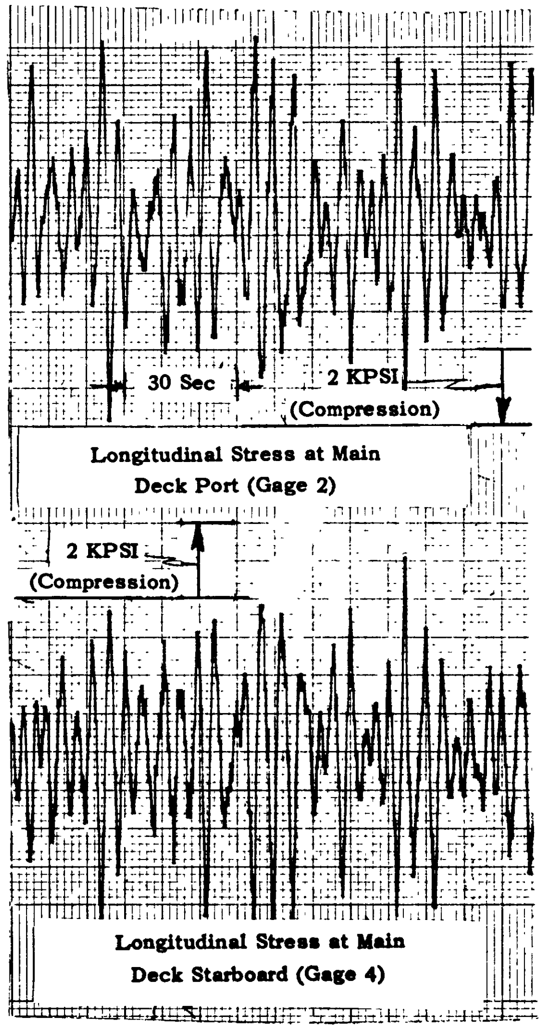
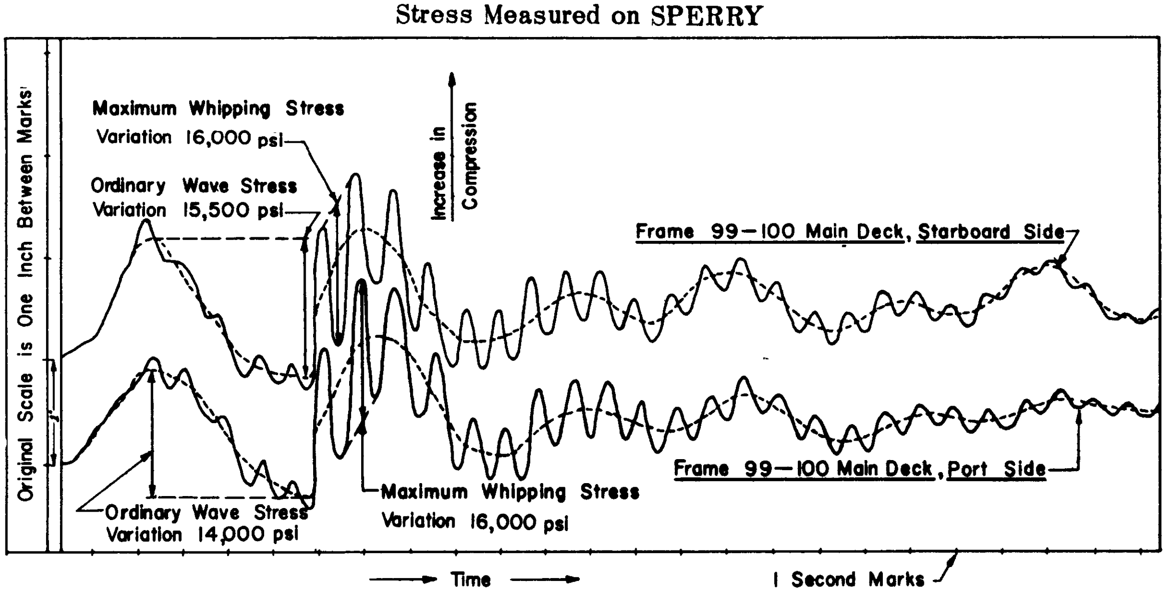


Figure 10 – Oscillogram Showing Whipping Stress Superimposed on Ordinary Wave Stress Measured on SPERRY



Notes: This is part of run labeled × 2.2 – 20-foot quarter-head seas at 17 knots.
The characteristics of this ship are listed on page 3.

Figure 11 – Maximum Whipping Stress Measured on Dutch Destroyer

The maximum vibratory bending moment, peak to peak, measured on the Dutch destroyer was 31,000 ft-tons. This leads to a value of about 40,000 ft-tons for DD 692-Class destroyers.

The expected extreme value of ordinary wave-induced bending moment variation is 89,000 ft-tons * (from Table 7). The latter value must be augmented by the vibratory bending moment incident to slamming and by the still-water bending moment in order to arrive at a recommended midship design bending moment. On the basis of whipping data from the Dutch destroyer and previous tests,[4] the total variation of the ordinary bending moment, which includes the wave-force impulse that excites whipping, may be assumed to be made up of 60-percent sag and 40-percent hog relative to the still-water bending moment. Thus, from the procedure of Reference 4, the following midship design bending moments are obtained:

$$\text{Hogging Moment} = 0.40\ (89{,}000) + 0.50\ (40{,}000) + \text{still-water moment}$$
$$= 56{,}000 \text{ ft-tons} + \text{still-water moment}$$

$$\text{Sagging Moment} = 0.60\ (89{,}000) + 0.50\ (40{,}000) + \text{still-water moment}$$
$$= 73{,}000 \text{ ft-tons} + \text{still-water moment}$$

PREDICTIONS OF MOTIONS AND BENDING MOMENTS FOR DD 931-CLASS DESTROYERS

The trials on BARRY were conducted primarily to test a new type of sonar dome. However, limited structural seaworthiness data were collected during these tests. The results were analyzed to obtain some experimental data for predicting the order of magnitude of motions and midship bending moments that may be encountered by ships of this class.

Values of the mean square variation E, applicable to the short-term or Rayleigh distribution, are listed in Table 8 with the maximum measured variations for several test conditions. The E values were derived from the maximum variation measured during relatively short test runs of approximately 50 to 100 variations for each run and are derived from the relationship stated on page 12, i.e., $x_{max} \approx k\sqrt{E}$.

The relatively few variations in the test run and the effect of correlation between successive variations introduces some error. In Reference 11 these errors are evaluated, and it is shown that, with 50 to 100 measured variations, there would be little advantage in estimating E by the direct method, particularly when the expected accuracy of the definition of operating environment is considered. Statistical predictions may be made based on the values of E listed in Table 8.

---

*The maximum hog-to-sag longitudinal bending moment obtained from the standard calculation, BuShips Plan DD 851-025041, is 91,800 ft-tons.

TABLE 8

Maximum Measured Values of Ship Motions and Longitudinal Bending Moment from DD 931-Class Destroyer Test

Test Conditions			Run* Number	Pitch Acceleration		Bow Vertical Acceleration		Amidship Vertical Acceleration		Pitch Angle		Roll Angle		Amidship Longitudinal Bending Stress		Amidship Longitudinal Bending Moment		Vertical Shear Stress At Frame 50, Neutral Axis	
Wave Height ft	Ship Speed knots	Sea Direction		Maximum rad/sec²	E** rad/sec²	Maximum g	E** g²	Maximum g	E** g²	Maximum deg	E** deg²	Maximum deg	E** deg²	Maximum kips	E** kips²	Maximum ft-ton	E** ft/ton²	M Maximum kips	E** kips²
3–5	F.P.†	Head	515 AH/AS	0.07	0.0011	0.4	0.036	0.16	0.0058	4.0	3.81	9.0	20.0	6.30	10.0	24,300	148×10^6	1.020	0.26
3–5	F.P.†	Quarter-Head	505 & 506S	0.08	0.0015	0.5	0.057	0.25	0.0142	2.0	0.95	13.0	42.0	3.75	3.5	14,500	52×10^6	1.380	0.48
3–5	F.P.†	Beam	510S	0.04	0.0004	1.2	0.327	0.60	0.084	3.0	2.14	14.0	49.0	6.75	11.4	26,000	169×10^6	1.620	0.66
3–5	F.P.†	Quarter-Following	512S	0.04	0.0004	0.8	0.145	0.20	0.0091	5.0	6.15	16.0	64.0	3.75	3.5	14,500	53×10^6	1.560	0.61
3–5	F.P.†	Following	525 15R/15L	0.03	0.0002	0.3	0.020	0.20	0.0091	3.0	2.14	11.0	30.0	8.55	18.3	33,000	275×10^6	1.560	0.61
5–8	10	Head	501S	0.08	0.0015	0.6	0.084	0.20	0.0091	3.0	2.14	8.0	16.0	5.25	6.9	20,200	100×10^6	0.960	0.23
5–8	15	Head	502S	0.06	0.0008	0.6	0.084	0.20	0.0091	3.0	2.14	13.0	42.0	3.90	3.8	15,100	57×10^6	1.560	0.61
5–8	20	Head	503S	0.08	0.0015	0.7	0.111	0.25	0.0142	3.0	2.14	7.0	12.0					1.680	0.70
5–8	25	Head	504S	0.12	0.0033	1.0	0.230	0.40	0.0364	3.0	2.14	6.0	9.0	6.30	10.0	24,300	150×10^6	1.080	0.29
5–8	F.P.†	Quarter-Head	505S	0.10	0.0023	0.6	0.084	0.30	0.0204	5.0	6.15	16.0	64.0	2.40	1.4	9,250	21×10^6	1.440	0.52
5–8	F.P.†	Following	514S	0.08	0.0015	1.6	0.580	0.30	0.0204	3.0	2.14	20.0	100.0	1.95	1.0	7,500	14×10^6	1.260	0.40
8–12	15	Head	521 35R/35L	0.16	0.0058	1.6	0.580	0.30	0.0204	7.0	11.7	28.0	200.0	14.25	51.0	55,000	760×10^6	1.020	0.26
12–20	15	Head	521A 35R/35L	0.16	0.0058	1.2	0.327	0.30	0.0204	10.0	23.8	22.0	120.0	14.25	51.0	55,000	760×10^6	1.560	0.60
12–20	25	Head	523 25R/25L 524 35R/35L	0.26	0.0154	2.2	1.11	0.70	0.111	9.0	19.3	20.0	100.0	18.75	88.0	73,000	1300×10^6	3.540	3.20

*The letter S following the three-digit number indicates a steady straight run. Fractions following the number indicate rudder angle that was applied for a short period during the run. R stands for right rudder, L left rudder. The number before R and L is rudder angle setting in degrees. AH/AS indicates a change from ahead to astern, that is, a crashback run.

**Mean square value of the variation derived from the maximum value in the test run. E also equals four times the area under the power spectrum.

†F.P. stands for full power.

☐ Boxed values are maximum measured during the test.

Since predictions of maximum values for design purposes based on the limited data alone are not justified, order-of-magnitude approximations are made by weighting the DD 931-Class data with the more complete DD 692-Class data.

Comparison of Table 4 with Table 8 indicates that the magnitudes of the rolling and heaving motions for the DD 692-Class destroyer are larger than those for the DD 931-Class ship for the same general operating conditions. The pitching motions appear to be of the same order of magnitude. Therefore, it is considered safe to assume that the maximum variations of roll, pitch, and heave for design purposes will be equal for both classes.

The expected extreme value of ordinary wave-induced midship bending moment for the DD 931 Class is taken as equal to the maximum value obtained on the DD 692 Class times the fourth power of the ship length ratio, or 130,000 ft-tons. The maximum hog-to-sag longitudinal bending moment obtained from the standard calculation on Bureau of Ships Plans 601905 and 601906 is 125,450 ft-tons. The maximum whipping midship bending moment derived by the method given in Appendix A is 57,000 ft-tons. Again, from the procedure of Reference 4, the following midship design bending moments are obtained:

$$\text{Hogging Moment} = 0.40\,(130{,}000) + 0.50\,(57{,}000) + \text{still-water moment}$$
$$= 80{,}000 \text{ ft-tons} + \text{still-water moment}$$

$$\text{Sagging Moment} = 0.60\,(130{,}000) + 0.50\,(57{,}000) + \text{still-water moment}$$
$$= 107{,}000 \text{ ft-tons} + \text{still-water moment}$$

Maximum allowance for design purposes for the other quantities, based on the limitations and assumptions stated above, for DD 931 Class are as follows:

Quantity	Recommended Maximum Allowances for Design Purposes*
Heave Acceleration	1.4 g
Roll Angle	95 deg
Pitch Angle	28 deg

*All values refer to peak-to-peak variation

DISCUSSION

The data presented in this report tend to substantiate the usefulness of the Rayleigh and log-normal distributions for presentation of ship motion and stress data as well as for statistical estimates of expected extreme and characteristic values. The comparison of predicted and measured maximum values in samples taken under time-stationary conditions shows rather good agreement and tends to substantiate further the applicability of the Rayleigh distribution for predicting ship response (except for severe roll motions) to waves under time-stationary conditions. Limited data analysis suggests that the long-term distribution of E values is approximated by the log-normal distribution.

The data given in Table 4, together with suitable scaling laws and weighting factors, may be utilized to predict motions and bending moments of geometrically similar ships. The extreme design bending moments may be compared with present design bending moments to evaluate the strength of the ship structure. For the DD 692 Class, the maximum dynamic main deck stress amidship expected, corresponding to the predicted maximum sag moment of 73,000 ft-tons, is 21,000 psi. The main deck should have sufficient buckling strength to withstand this stress plus the still-water stress. For the DD 931 Class, the maximum expected dynamic values are 107,000 ft-tons sag moment and 27,000 psi stress in the main deck amidships. The alternative method of predicting extreme values, given in Appendix A, will need further study before it can be considered of general applicability.

The emphasis given to the vibratory whipping stresses is in order since these stresses are not presently considered in hull structure design.

The vibratory stresses measured during tests on DD 692- and DD 931-Class destroyers were not large. However, the tests illustrate that the whipping stress will be large if certain severe conditions are encountered. It is not possible at this time to define those conditions quantitatively. However, from Figure 10 of Reference 12, an empirical relationship for ESSEX-Class carriers may be deduced between the threshold of conditions conducive to the generation of severe vibratory stresses equal to or exceeding the ordinary wave-induced stress, and the wave height and ship's speed. When the ship is operating in head or quarter-head seas whose characteristic wave height exceeds 15 feet, the threshold of severe whipping is reached when the sum of the characteristic wave height in feet and ship speed in knots exceeds approximately 38 (feet + knots). This "critical" value is deduced from 39 hr of tests data obtained in head and quarter-head seas with various characteristic wave heights and ship speeds that ranged from 15 to 31 feet and 8 to 25 knots, respectively. In this period the threshold value, obtained by averaging over consecutive 4-hr periods, varied between 38 and 42 (feet + knots). (Severe whipping did not occur when the ship operated for several hours under conditions where the sum was 35 or less.) The maximum whipping stress measured on a Dutch destroyer (Figure 11) occurred when the ship was operating in quarter-head seas with characteristic wave heights of 20 feet at a speed of 17 knots for a sum of 37 (feet + knots). Sufficient data are not available to estimate a "critical" value for destroyers.

Vibration tests on merchant cargo ships made by the Taylor Model Basin have shown that it is more difficult to excite ship vibrations in the loaded condition. It has also been noted that the fundamental mode of vertical hull vibration is more readily excited by ordinary hydrodynamic action of the water when the ship is in the light rather than loaded condition. It might be inferred, therefore, that the whipping response to slamming loads would also be more severe for the "light" condition; however, sufficient data to support this hypothesis are not available, and the load variations of naval ships may not be large enough to be significant under the usual operating conditions.

Theoretical investigations of the slamming (whipping) mechanism, including the calculation of the forces and the elastic response of the ship thereto, are being made. The results indicate that bow-flare immersion is predominantly responsible for the generation of sudden bow forces in naval ships and the resultant severe whipping response. Experimental data from USS ESSEX (CVA 9) and a Dutch destroyer are available to evaluate the usefulness of the results of these studies.

The fact that heavy confused seas were the conditions under which the maximum motions and stresses were measured on SPERRY, illustrates that it is not always possible to ease the rigid-body motions of a ship by simply changing course. The ship changed course several times in an unsuccessful attempt to ease the ship's motions. The confused sea condition was such that speed and course adjustment did not result in an acceptable level of ordinary wave-induced ship motions. However, vibratory slamming motions are always lessened by slowing down to low speed in rough seas.

The largest measured roll angle variation of 93 deg measured on SPERRY was considered unusually extreme when the data were analyzed because it was 90 percent higher than the value that would be predicted from the corresponding E value. This variation may indicate a nonlinear condition or it may be a very rare extreme value, statistically predictable. Correspondence with the Commanding Officer of SPERRY elicited the information that his ship had experienced this order of magnitude of rolling motion several times, leading to the conclusion that a nonlinear condition exists for large rolling angles on DD 692-Class destroyers. The fact that the sea direction was confused when this value was recorded may have been a contributing factor. The second highest rolling angle recorded on SPERRY was 66 deg. This value approximates the estimated most probable maximum value listed in Column 9 of Table 7.

CONCLUSIONS

1. Comparison of the measured and predicted extreme values tends to substantiate further the applicability of statistical methods for predicting ship response.

2. Scaling laws may be used to predict ordinary wave-induced motions and bending moments for geometrically similar ships.

3. In the rational derivation of the specification for design hull bending moments, the vibratory whipping stresses should be considered in addition to the statistical prediction of the ordinary wave-bending moment.

4. A relationship appears to exist between the threshold of conditions conducive to the generation of severe vibratory stresses equal to or exceeding the ordinary wave-induced stress and the wave height and ship's speed.

5. In heavy confused seas, speed and course adjustment may not always ease the ordinary wave-induced motions. However, vibratory motions are always reduced by slowing down.

ACKNOWLEDGMENTS

The excellent cooperation received from the Commanding Officer and personnel of SPERRY made it possible to collect the test data. The cooperation of Mr. L.A. Becker of the Structures Division and Mrs. M.D. Bledsoe of the Seaworthiness and Fluid Dynamics Division in providing data from the BARRY and Dutch destroyer trials is greatly appreciated. Mr. R. Dominic assisted in analysis and evaluation of the great volume of SPERRY data. Installation of trial gear and collection of trial data was greatly expedited by the expert assistance of the Instrumentation Division personnel, particularly Mr. M. Graybill and Mr. W.E. Smith.

APPENDIX A*

EXPECTED EXTREME BENDING MOMENT ESTIMATED FROM LONG-TERM DISTRIBUTION OF CHARACTERISTIC PARAMETER $E^{1/2}$

In this report the expected extreme bending moment has been based on the assumption that the most severe operating condition (and the resultant ship response defined by the parameter E_s) actually experienced during the sea trials is the worst to be expected during the ship's life.

Another, more general approach would be to estimate the expected extreme value of $E_s^{1/2}$ (rms bending moment or stress) on the basis of a known distribution of the parameter. Thus far the distribution of $E_s^{1/2}$ (or E_s) for hull girder bending had not been studied. Extensive studies of the corresponding parameter for ocean waves $E_W^{1/2}$ (actually of significant wave height)[2, 13] indicate that this parameter has a log-normal distribution. It would not be unreasonable to expect the rms value of ship response to wave action to follow the same type of distribution. Accordingly, an attempt was made to fit the log-normal distribution to the values of $E_s^{1/2}$ for hull bending moment (stress). The E_s values and corresponding probabilities were taken from Columns 9 and 6, respectively, of Table 6. The resulting distribution, shown in Figure 12, approximates a log-normal distribution. A similar study was made for a carrier; the results are also shown in Figure 12.

Let us devise a method for prediction of expected extreme bending moment on the basis of:

1. A known long-term distribution of bending moment, Figure 12.

2. A known long-term distribution of sea conditions (in terms of characteristic wave heights and wave lengths).**

For each ship an "extreme sea state" is postulated which is defined as a sea state** in which

1. The characteristic wave lengths† L_W are less than $\sqrt{2}\ L_s$ and larger than $(1/\sqrt{2})\ L_s$, where L_s is the length between perpendiculars of the ship (because ships are known to respond primarily to waves of the order of ship length).

2. The characteristic wave height H_w is equal to or greater than the most probable wave height for a wave of length equal to the length of the ship. This height may be read from Curve C, Figure 2, of Reference 14. For ships of length larger than 300 ft, a most probable wave height H_w of 23 ft is correct within ± 3 ft.

---

*The method given here was proposed by Dr. N.H. Jasper.

**A more meaningful and satisfactory description of the severe sea condition would be given in terms of that power spectrum of the waves which gives most severe ship response.

†The wave length may be calculated from the wave period T_W usually reported by shipboard observers by the relationship $L_W = 3.4\ T_W^2$.

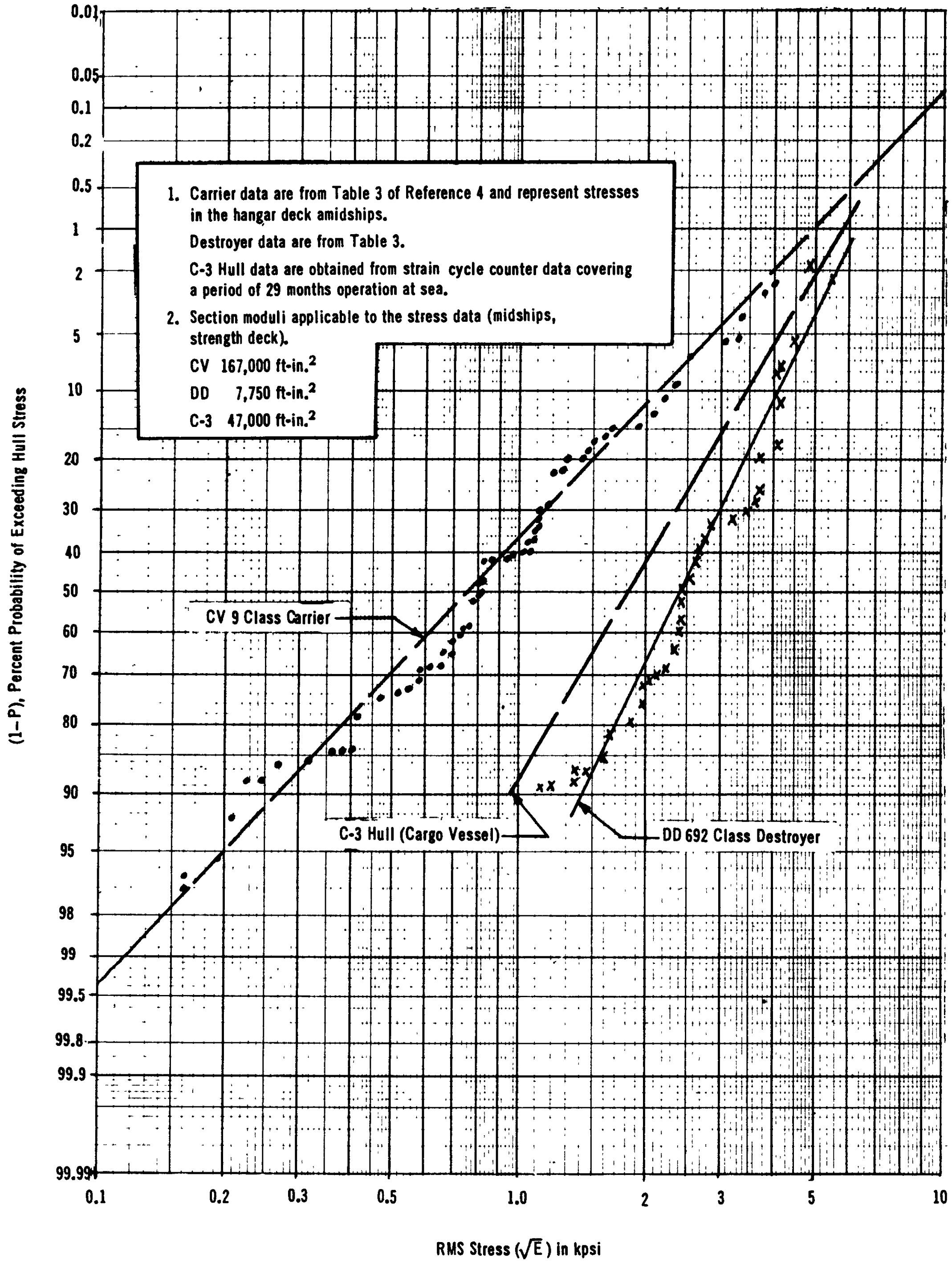


Figure 12 – Distribution of $E^{1/2}$ Values for Hull Stress

The percent of time (1 − P) that the ship will be exposed to the extreme sea state can be read from a statistical joint distribution of wave height and length such as prepared by Dr. Roll,[15] corresponding to the particular values of L_W and H_W.

The rms value $E_s^{1/2}$ corresponding to (1 − P) determined as described above may then be read from the long-term distribution of $E_s^{1/2}$, such as shown in Figure 12. The most probable extreme value of stress (or bending moment) corresponding to an exposure of (1 − P) to the extreme sea state may then be calculated in the usual manner as illustrated in the following example for a DD 692-Class destroyer:

Length between perpendiculars = 369 ft

Extreme sea state: $255 < L_W < 500$ ft

$8.6 < T_W < 11.8$ sec

Characteristic Wave Height: $H \gtrsim 23$ ft

Section modulus: $Z = 7750$ ft-in^2 (main deck)

1. Percentage of exposure to extreme sea state (1 − P) = 2.16 percent, from Reference 15. (Similar wave data covering 8 yr of observation are available from the U.S. Weather Bureau.)

2. Rms value of stress corresponding to (1 − P) = 2.16 percent is, from Figure 12, $\sqrt{E_s}$ = 5.5 kpsi; rms bending moment = $\sqrt{E_m} = Z\ \sqrt{E_s}$ = 19,000 ft-tons.

3. Number of stress variations experienced during exposure to extreme sea state (assume ship is at sea 100 days per year)

$$N = \frac{20 \text{ yr } (100 \text{ days})(24 \text{ hr})(3600 \text{ sec})(1 - P)}{\frac{1}{2}(8.6 + 11.8) \text{ sec}}$$

$N \approx 365{,}000$ cycles

4. Most probable extreme bending moment* = $\sqrt{E_m}\ \sqrt{\log_e N}$

M = 68,000 ft-tons, hog to sag

5. Assuming 60-percent sag and 40-percent hog

M_{sag} = 0.6 (68,000) + 0.50 (40,000) + still-water bending moment

M_{hog} = 0.4 (68,000) + 0.50 (40,000) + still-water bending moment

M_{sag} = (61,000 + still-water bending moment) ft-tons

M_{hog} = (47,000 + still-water bending moment) ft-tons

Corresponding stresses in the main deck amidship are − 17,600 psi + still-water stress
+ 13,600 psi + still-water stress

As noted previously, the BuShips design bending moment variation was 91,800 ft-tons, hog to sag.

*If it is desired to estimate the extreme bending moment which is expected to be exceeded by only a fraction f of all ships, use the formula $M = [E_m(\gamma + \log N)]^{1/2}$; see page 12 of this report.

APPENDIX B

METHOD FOR SCALING DYNAMIC BENDING MOMENT RESPONSE*

The problem is to estimate the vibratory hull bending moment due to slamming from the known response of a similar ship of different size. It will be assumed that both ships will operate in geometrically similar waves at the same Froude number.

Let $P(\bar{x}, t) = f_1(\bar{x})\, f_2(t)$ be the maximum slamming force per unit length at a selected reference station; the force is to be determined for both the reference ship, denoted by the subscript R, and the ship under consideration. The forces P and P_R are to be calculated on the *assumption that the length of the ship under consideration is equal to that of the reference ship*, P will then be modified by factors to correct for the effect of ship size. The development to follow will make use of Frankland's response factors[16] and of scale factors.

The static deflection y_0 for a linear elastic system of generalized stiffness k and mass M, subjected to a generalized load Q, is $y_0 = \frac{Q}{k}$. The dynamic deflection y under dynamic application of this load distribution is $y = y_0\,(u)$, where u is Frankland's response factor. It is assumed that the time-load variation is similar for both ships and that the ratio of intensities is $\frac{P}{P_R}$ everywhere. For a given mode of response, the stress and bending moments are proportional to the deflection. Let the spatial mode function be $X(x)$. Then, for the ship,

$$y_0(x, t) = \frac{Q(t)\, X(x)}{k}, \text{ where } Q = Q_0 \cdot f_2(t)$$

and

$$y(x, t) = \frac{Q(t)\, X(x)}{\omega_n^2 M_n}\, u(t)$$

where ω_n is natural frequency of the mode considered.

$$y(x) = \frac{X \int_0^L PX\, dx}{\omega_n^2 \int_0^L \rho X^2\, dx}(u)$$

where ρ is the mass of ship per unit length at x. The bending moment

$$M = EI\frac{d^2 y}{dx^2} = \frac{EIu \int_0^L PX dx}{\omega^2 \int_0^L \rho X^2 dx}\left[\frac{d^2 X}{dx^2}\right]$$

For two ships of *different* size, the ratio of the bending moments may be calculated on the assumption that the ratios of the external forces $\frac{P}{P_R}$, of the masses $\frac{\rho}{\rho_R}$, and of the mode

*This method was proposed by Dr. N.H. Jasper.

shapes X are the same all along the ship. Then, for operation at the same Froude number,

$$M = M_R \left(\frac{u}{u_R}\right)\left(\frac{EI}{EI_R}\right)\left(\frac{P}{P_R}\right)\left(\frac{\omega_R}{\omega}\right)^2 \frac{\Delta_R}{\Delta} \lambda$$

Similarly

$$y = y_R \left(\frac{u}{u_R}\right)\left(\frac{P}{P_R}\right)\left(\frac{\omega_R}{\omega}\right)^2 \left(\frac{\Delta_R \lambda^3}{\Delta}\right)$$

where λ is the scale ratio $\frac{L}{L_R}$, and Δ, Δ_R denote the displacements of the two ships of length L and L_R, respectively. The time ratio $\left(\frac{\text{duration of load}}{\text{natural period of vibration}}\right) = \tau$ applicable to the load P, for the *reference-sized* ship must be multiplied by the factor $\lambda^{-1/2}$ to obtain the time ratio needed to determine the load factor u applicable to the full-size ship, i.e.,

$$\tau \text{ (ship of length } L) = \tau \text{ (ship of length } L_R) \; \lambda^{-1/2}$$

The above method was applied in this report to scale the whipping responses measured on a Dutch destroyer to the DD 692- and DD 931-Class destroyers, assuming that $u = u_R$ and that $P = P_R$.

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