Report 1251

DEPARTMENT OF THE NAVY
DAVID TAYLOR MODEL BASIN

HYDROMECHANICS

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APPLIED MATHEMATICS

STATISTICAL PRESENTATION OF MOTIONS AND HULL BENDING MOMENTS OF ESSEX-CLASS AIRCRAFT CARRIERS

by

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

STRUCTURAL MECHANICS LABORATORY

RESEARCH AND DEVELOPMENT REPORT

February 1959 Report 1251

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

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22 May 1959

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To: Chief, Bureau of Ships (312) (in duplicate)

Subj: Motions and hull bending moments of Essex-Class aircraft carriers; forwarding of report on

Ref: (a) BUSHIPS ltr S29-7 (442-440-330) of 21 Jun 1948

Encl: (1) TMB Report 1251 entitled "Statistical Presentation of Motions and Hull Bending Moments of ESSEX-Class Aircraft Carriers" 22 copies

1. As requested by reference (a) the David Taylor Model Basin is conducting a long-range investigation of the strains in ships at sea for the purpose of evaluating and improving methods for the design of ship girders and structural components. Instruments have been developed and installed on various types of ships to collect information on the wave loads, stresses, and motions which ships experience in service.

2. In enclosure (1) motions and stresses measured on three essentially similar aircraft carriers are analyzed. From the measurements the motions and longitudinal hull bending moments which ships of the ESSEX Class may be expected to experience over a wide range of operating conditions are determined by statistical methods. Formulas are given for use in estimating probable extreme values of moments and motions.

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ABSTRACT

The motions and longitudinal hull bending moments which ships of the ESSEX Class may be 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 VALLEY FORGE (CVS 45) and USS ESSEX (CVA 9).

From the test results, data are derived for this type of ship for use in design and operating problems involving bending moments and ship motions. Formulas are given for use in estimating probable extreme values of moments and motions.

INTRODUCTION

The David Taylor Model Basin is conducting a long-range investigation of the strains in ships at sea[1] for the purpose of evaluating and improving methods for the design of ship girders and structural components. Instruments have been developed and installed on various types of ships to collect information on the wave loads, stresses, and motions which ships experience in service. For more complete background and discussion of this program see References 2 and 3.

Motions and stresses measured on three essentially similar aircraft carriers are analyzed in this report.* USS ESSEX (CVA 9) and USS ORISKANY (CVA 34) are conversions of the basic ESSEX Class (World War II variety); USS VALLEY FORGE (CVS 45) is an unconverted carrier of this same class. The salient characteristics of the conversion that affect hull form and weight distribution—those factors that have primary effect on bending moments—are the addition of blisters throughout the midportion of the ship and a modest (10-percent) increase in full-load displacement. Data were obtained on VALLEY FORGE** in the Atlantic Ocean from September 1955 to April 1957, on ESSEX during a passage around Cape Horn in July 1957,[4] and on ORISKANY during a rough passage around Cape Horn in June 1952.

Oscillographic recordings were made of variations of roll and pitch angle, heave accelerations (at the center of gravity of the ship), and hull strains as the ship responded to wave-induced loads. From these the following information is specified for ESSEX-Class carriers:

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[1]References are listed on page 30.

*No strains were measured on ORISKANY.

**These data were obtained during joint operations with USS C.S. SPERRY (DD 697); the SPERRY tests will be reported at a later date.

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

b. The predicted extreme values of longitudinal bending moment and motions expected during the operating life of the ship.

c. The frequency distributions of stresses and ship motions.

TEST INSTALLATION AND TEST RESULTS

Most of the data utilized in this report were measured on VALLEY FORGE. However, the most severe hull stresses and motions experienced by ESSEX and ORISKANY are used whenever they are larger than those observed on VALLEY FORGE.

Hull stresses were measured by SR-4 strain gages installed at the main deck and keel amidship on VALLEY FORGE. The roll and pitch angles were measured by a stable element, and the heave acceleration was measured by a Schaevitz accelerometer located near the center of gravity. The locations of the gages are shown in Figure 1. The measurements were recorded on a TMB automatic statistical recorder. The five channels of this instrument were utilized as follows: Channel 1 recorded the heave acceleration; Channels 2 and 3 recorded the longitudinal strain from gages located on the keel and main deck, respectively; and Channels 4 and 5 recorded the pitch and roll angles, respectively. Typical oscillograms are shown in Appendix A. In order to observe the relative magnitude of the stresses induced by transverse and longitudinal bending, strains on the port and starboard side of the main deck were recorded on a Sanborn oscillograph.

All the data on VALLEY FORGE were obtained in the course of the normal assigned operations. Measurements were made whenever operating conditions were encountered for which data had not been obtained previously.

Wave heights and wave directions for the VALLEY FORGE tests were determined by two methods. Estimates made by trained observers from the ship's aerology unit were averaged, and stereophotographs of the sea surface taken by cameras mounted on the island structure were analyzed by the U.S. Hydrographic Office. Comparison of data from these two sources indicates that the observers made reliable estimates of characteristic wave heights.[5]** During the ESSEX tests wave heights were measured with the wave height recorder developed by M.J. Tucker in Britain.

The sea conditions assumed in the calculations are those for the North Atlantic Ocean inasmuch as they probably represent the more severe continuous operating conditions that a

*All stresses given in this report were computed from measured strains. The hull bending moments are deduced from the strain measurements and the calculated section modulus applicable to the strain-gage location.

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

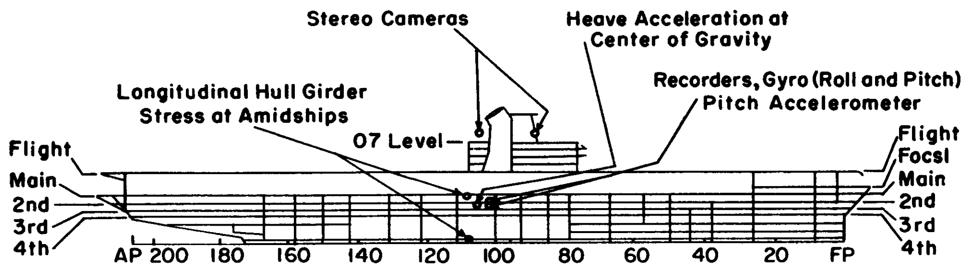

Figure 1a – Inboard Profile

The characteristics of the ship are: Length between perpendiculars, 820 ft; Beam, 92 ft; Draft, 29 ft; Displacement (full load), 41,500 tons.

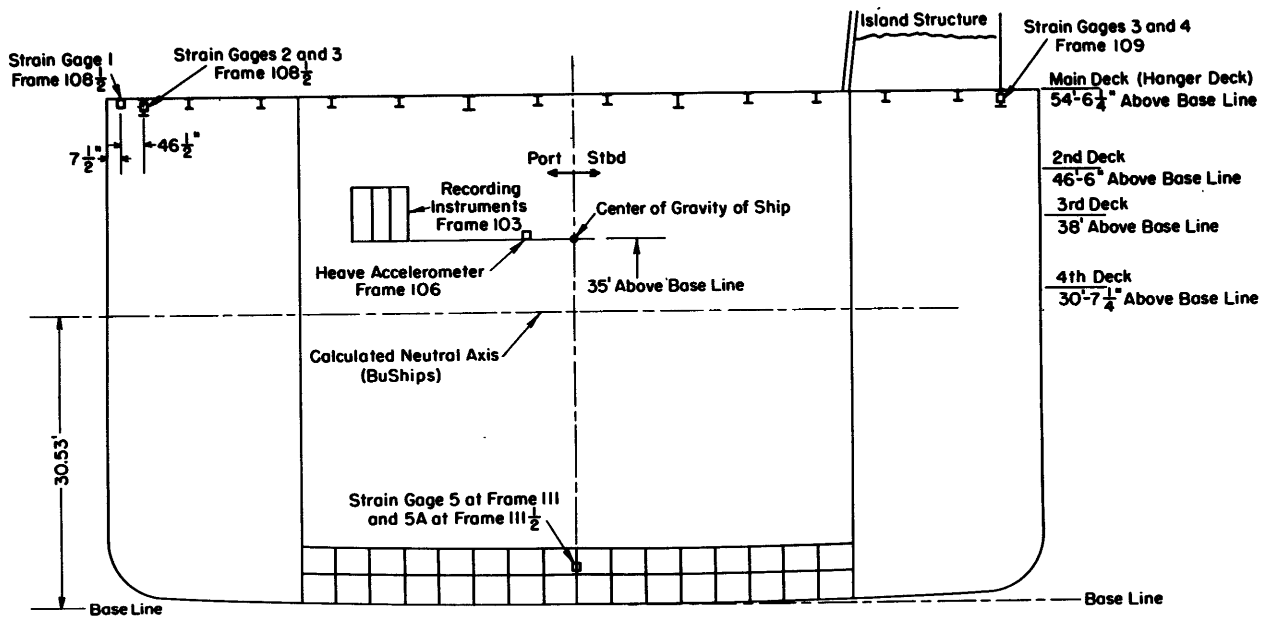

Figure 1b – Section Near Midship Looking Forward

The midship section moment of inertia is 3.96×10^6 ft^2-in^2 according to BuShips (Code 442) calculations dated 2 Oct 56. This value applies to the unconverted CVS 45 hull.

Strain gages 2, 4 measure strain in the port and starboard outboard longitudinals at the neutral axis of the plate-stiffener combination. These gages are located 23.85 ft above the neutral axis.

Strain gage 1 measures the longitudinal stress in the deck plate (dyadic stress gage). This gage is located 23.97 ft above the neutral axis.

Strain gages 3, port and starboard, are arranged to read strains due to longitudinal hull bending. These gages are located 23.76 ft above the neutral axis.

Strain gage 5 measures the longitudinal strain at the approximate location of the neutral axis of the keel-inner bottom structure.

Figure 1 – Location of Instruments on USS VALLEY FORGE (CVS 45)

ship will experience. 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 ESSEX Class. This information is given in Table 2 of Reference 6.

All recorded strain and motion data were classified according to appropriate ranges of ship speed, wave height, and ship's course relative to the wave direction.* Statistical methods were used to determine the ship's response in terms of mean square values and maximum measured values for a wide variety of operating conditions; see Table 1.

The relative magnitudes of the hull stresses induced by longitudinal and transverse bending are given in Appendix B. Stresses measured on the deck plating and on the adjacent longitudinal stiffener at the outboard edge of the main deck are compared in Appendix C. Local bending stresses were small in this area.

STATISTICAL BACKGROUND

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[7] 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.

The Rayleigh distribution of a variable x is defined by the single parameter E, the mean square value of x; i.e., $E = \overline{x^2}$. The log-normal distribution of x is defined by two parameters: the mean value of log x and the variance of log x. The statistical methods utilized here are discussed in References 7 and 8.

For illustrative purposes, consider one of the variables; for example, pitch angle. All pitch angles (peak to peak) are considered to be members of a statistical "population." The distribution indicates the relative probability $p(x)$ of encountering a pitch angle of the magnitude x. Figure 2 illustrates this distribution function. The area under the curve of Figure 2a up to a value x_i is the fraction P of all members of the population 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 $P(x) = 1 - e^{-x^2/E}$.

Both the Rayleigh (Figure 2) and log-normal distributions (Figures 3 through 6) can be represented by straight lines when plotted on special graph paper. Inasmuch as the Rayleigh distribution is applicable to a given combination of sea, speed, and heading, it will be called the "short-term" distribution whereas the log-normal distribution will be designated the "long-term" distribution.

---

*It was often difficult to define the sea and the direction of the ship relative to the sea. The description given is the best that could be made.

TABLE 1

Basic Statistical Data for ESSEX-Class Carriers

All data are for VALLEY FORGE except where noted otherwise.

Wave Height ft	Ship Speed knots	Record Number	Stereo Photo Number	Ship Speed knots	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	Heading of Sea Relative to Ship deg	Heading of Swell Relative to Ship deg	E††, ft², Mean Square Wave Height: From Stereo Data	E††, ft², Mean Square Wave Height: From Wind Data	Wind Velocity for 8 Hours Preceding Test knots
														Head Seas
0-4	20-25	30	H-060	24		3.6	2	2.7	3.7	335-345	325-335	4.6	9.2	8-18
4-6	10-15	25	G-113	10		5.7	4	5.9	5.1	015-025	355-25	10.4	20.0	12-30
4-6	10-15	67	C-418	12			3	6.0		355	355-345	12.5	24.0	14-21
4-6	15-20	19	E-071	20		6.5	6	6.0	5.9	040-060	000	9.3	18.0	10-31
4-6	20-25	18	E-064	25		6.9	3	6.1	6.9	009-013	316-319	15.8	16.0	9-20
6-8	5-10	34	H-201	10		6.5	6	6.9	6.3	015	005-015	11.9	32.0	16-33
6-8	10-15	62		12			1	7.0		330-340	332-340			8-26
6-8	10-15	61		14			1	7.0						8-26
6-8	10-15	1	C-452	15		6.6	3	8.0	8.6	010-020		17.2	32.0	17-30
6-8	10-15	2	C-466	15		8.1	3	7.7	8.2	355		17.7	24.0	24-30
6-8	15-20	16	E-062	20		7.2	3	6.1	7.1	020	350-000	11.8	16.0	11-30
6-8	20-25	69a	I-014	25		6.4	3	7.5	7.9	338-358	318-358	22.0	30.0	14-20
8-15	5-10	41	J-040	8	12.0	17.9	3	12.1		340-000	350-000	58.8	48.0	30-40
8-15	5-10	43		8			3	10.0		340-350	342-350			23-33
8-15	5-10	46		8			3	9.0		355-357	346-354			23-33
8-15	5-10	53		10			4	10.0		358-004†	353-001†			22-28
8-15	5-10	38	J-003	8	10.5	7.3	4	9.9	9.3	007	020	21.5	24.0	22-53
8-15	5-10	39	J-003	8	10.5	7.3	4	9.9	9.3	001	019	21.5	24.0	36-54
8-15	5-10	69		8	12.0					359				
8-15	10-15	4	C-495	12		5.8	6	9.0	7.0	339-342	349-356	10.7	28.0	16-19
8-15	20-25	51		25			3	10.0		358-359	349-356			22-28
> 15	5-10	72		10	14.0			18.0		014				
> 15	5-10	77*		10	20					005				
														Quarter Head Seas
0-4	10-15	24	G-049	12		5.0	5	3.7	5.0	062	068	9.1	8.0	12-17
0-4	20-25	30	H-060	24		3.6	2	2.7	3.7	335-345	325-335	4.6	9.2	8-18
0-4	20-25	31	H-100	25		3.5	3	2.8	4.5		035-040	5.2	9.2	8-18
4-6	15-20	19	E-071	20		6.5	6	6.0	5.9	040-060	000	9.3	18.0	10-31
4-6	20-25	18	E-064	25		6.9	3	6.1	6.9	009-013	316-319	15.8	16.0	9-20
6-8	5-10	60		10			1	7.0		334-341	333-340			8-24
6-8	10-15	22	F-362	10		9.2	4	6.6	6.3	304	333	15.9	20.0	15-32
6-8	10-15	23	F-365	12	7.7	8.2	1		11.0	040	050-070	15.3	20.0	15-32
6-8	10-15	9	D-085	14		4.2	5	6.2	5.4	†	033-043†	6.1	10.4	2-29
6-8	10-15	10	D-122	15		6.2	7	8.0	6.5		040-050	9.9	12.0	3-10
6-8	20-25	16	E-062	20		7.2	3	6.1	7.1	020	350-000	11.8	16.0	11-30
8-15	5-10	40	J-035	8	12.5	16.5	3	12.7	12.2	317	334	29.4	40.0	24-54
8-15	5-10	47		8			4	9.0		321-322	311-318			23-29
8-15	5-10	45		8			2	9.0		349-355	347-354			23-33
8-15	10-15	70		10				16.0		025				
8-15	15-20	5	C-500	18		6.3	3	8.8	8.8	†	330†	14.3	32.0	18-19
> 15	5-10	73		10	14			15.0		260				
> 15	5-10	78*		10	20					300				
> 15	5-10	79A**		8	24									
> 15	5-10	79**		8	24									

Response of Ship to Sea

Record Number	Heave: E, Value of Mean Square, η^2	Heave: N_h, Variations per Hour	Heave: Predicted Maximum Value in One Hour, η	Heave: Number of Variations in Sample	Heave: Maximum Measured Variation in Sample, η	Heave: Maximum Predicted Variation in Sample, η	Heave: Predicted Max / Measured Max = R	Strain, Main Deck Amidships: E, Value of Mean Square Kips Squared	Strain: N_h, Variations per Hour	Strain: Predicted Maximum Value in One Hour kips	Strain: Number of Variations in Sample	Strain: Maximum Measured Variation in Sample, kips	Strain: Maximum Predicted Variation in Sample, kips	Strain: Predicted Max / Measured Max = R
Head Seas														
30	0.00037††	480	0.057	80	0.040			0.026††	360	0.42	60	0.40		
25	0.000023††	530	0.0116	315	0.015			0.0265††	720	0.425	420	0.40		
67	0.00090††	480	0.075	112	0.065			0.73	420	2.10	98	2.00	1.83	0.92
19	0.0033	474	0.140	245	0.15	0.13	0.87	0.69	463	2.06	239	2.03	1.94	0.96
18	0.0073	600	0.210	279	0.210	0.20	0.95	4.38	696	5.31	325	4.70	5.04	1.07
34	0.000041††	480	0.016	240	0.015			0.060	602	0.62	301	0.54	0.58	1.08
62	0.00070	564	0.042	113	0.066	0.058	0.87	0.57	566	1.90	113	2.00	1.65	0.83
61	0.00060	565	0.062	254	0.063	0.058	0.92	0.48	600	1.75	260	1.65	1.63	0.98
1	0.00099	529	0.079	141	0.070	0.07	1.00	0.53	491	1.81	131	1.85	1.61	0.87
2	0.0012††	515	0.086	206	0.080			0.67	515	2.05	206	2.30	1.89	0.82
16	0.0020††	510	0.110	170	0.10			2.31††	750	3.91	250	3.65		
69a	0.0000305††	600	0.044	190	0.040			0.101††	780	0.82	250	0.75		
41	0.0061	404	0.200	404	0.21	0.19	0.90	3.72	444	4.76	444	4.50	4.76	1.05
43	0.0019††	406	0.110	210	0.10			2.05	445	3.62	230	3.68	3.34	0.91
46	0.0013	479	0.089	319	0.086	0.087	1.01	1.10	483	2.61	322	2.75	2.51	0.92
53	0.0014	488	0.093	323	0.099	0.09	0.91	1.33	488	2.90	326	2.65	2.78	1.05
38	0.0041	418	0.248	349	0.180	0.16	0.89	10.87	389	8.03	324	7.50	7.90	1.05
39	0.0061	416	0.200	381	0.200	0.22	1.10	16.55	362	9.88	332	9.80	9.80	1.00
69	0.011	408	0.258	204	0.30	0.24	0.81							
4	0.0019	413	0.107	344	0.090	0.106	1.18	0.60	290	1.71	249	1.87	1.82	0.97
51	0.00388††	600	0.157	289	0.146			4.98††	650	5.68	315	5.35		
72	0.0075	400	0.212	200	0.24	0.20	0.83	28.18	360	12.92	180	12.20	12.10	0.99
77*	0.0138	338	0.254	169	0.22	0.27	1.23							
Quarter Head Seas														
24	0.00052††	510	0.057	340	0.055			0.22	612	1.19	306	1.15	1.13	0.98
30	0.00037††	480	0.057	80	0.040			0.0152††	360	0.295	60	0.25		
31	0.00023††	384	0.015	83	0.010			0.0514††	500	0.560	109	0.49		
19	0.0033	474	0.140	245	0.15	0.13	0.87	0.69	463	2.06	239	2.03	1.94	0.96
18	0.0073	600	0.210	279	0.210	0.20	0.95	4.38	696	5.31	325	4.70	5.04	1.07
60	0.0012	499	0.086	208	0.089	0.08	0.90	0.65	475	2.01	198	2.05	1.85	0.90
22	0.0020††	495	0.110	403	0.110			1.17	495	2.66	403	3.25	2.66	0.82
23	0.0015	497	0.097	331	0.086	0.093	1.08	1.21	746	2.68	373	2.65	2.76	1.01
9	0.0037	368	0.140	276	0.140	0.14	1.00	1.31	388	2.80	291	3.35	2.74	0.82
10	0.0047††	483	0.170	387	0.170			1.62	484	3.17	387	3.51	3.11	0.89
16	0.0020††	510	0.110	170	0.10			2.31††	750	3.91	250	3.65		
40	0.0066	384	0.200	404	0.180	0.20	1.11	5.58	396	5.77	415	5.39	5.80	1.07
47	0.0079††	457	0.210	61	0.180			1.250††	465	2.78	62	2.26		
45	0.0035	465	0.150	203	0.130	0.14	1.08	1.680	460	3.20	199	3.20	2.99	0.93
70								14.75	358	9.45	178	9.00	8.80	0.98
5	0.0031	514	0.140	137	0.140	0.12	0.86	0.60	262	1.60	70	2.10	1.60	0.76
73	0.00695	428	0.187	214	0.209	0.19	0.92	9.586	390	7.60	195	6.60	7.10	1.07
78*	0.0083††	360	0.22	39	0.21									
79A**														
79**														

Record Number	Pitch: E, Value of Mean Square Degrees Squared	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: Predicted Max / Measured Max = R	Roll: E, Value of Mean Square Degrees Squared	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: Predicted Max / Measured Max = R
Head Seas														
30	0.0038††	360	0.150	60	0.125			0.340	227	1.35	34	1.40	1.09	0.78
25	0.00032††	240	0.042	140	0.040			0.0855††	240	0.68	140	0.65		
67	0.22††	420	1.10	98	1.00			0.33††	300	1.40	70	1.20		
19	0.16††	300	0.96	155	1.00			1.90	240	3.30	124	3.3	3.00	0.92
18	0.39††	696	1.57	325	1.50			1.390††	194	2.70	90	2.50		
34	0.0078††	360	0.215	180	0.20			0.280	228	1.15	114	1.40	1.15	0.82
62	0.102	521	0.80	104	0.63	0.69	1.10	0.22	521	1.17	104	1.50	1.02	0.67
61	0.118	508	0.86	229	0.75	0.80	1.07	0.49	402	1.71	174	1.90	1.60	0.84
1	0.166††	491	1.00	131	0.90			0.25	341	1.21	91	0.90	1.06	1.18
2	0.15††	515	0.98	206	0.90			0.35	339	1.46	136	1.60	1.31	0.82
16	0.035††	480	0.43	160	0.42			0.94††	210	2.24	70	2.00		
69a	0.019††	600	0.35	190	0.25			0.326††	388	1.30	123	1.25		
41	1.46	388	2.95	388	3.10	2.90	0.94	1.83	321	3.25	321	4.60	3.20	0.70
43	0.80	428	2.20	221	2.05	2.08	1.02	0.51	406	1.75	221	1.70	1.70	1.00
46	0.31	439	1.26	293	1.40	1.32	0.94	0.34	444	1.40	296	2.50	1.40	0.57
53	0.26	450	1.26	300	1.20	1.20	1.00	0.31	426	1.37	284	1.40	1.30	0.93
38	2.04	380	3.50	317	3.25	3.40	1.04	1.29	373	2.76	312	4.00	2.70	0.68
39	4.74	351	5.26	322	5.65	5.23	0.93	1.90	333	3.32	305	4.10	3.30	0.81
69														
4	0.50	290	1.71	241	1.87	1.65	0.88	5.80	225	5.60	196	5.80	5.52	0.96
51	0.48††	493	1.72	238	1.62			0.74††	210	1.99	102	1.85		
72	9.72	326	7.50	163	6.90	7.04	1.01	3.18	354	4.30	177	6.00	4.06	0.68
77*	8.132	328	6.90	164	5.40	6.40	1.20	18.52††	260	10.0	28	9.5		
Quarter Head Seas														
24	0.046††	275	0.509	240	0.50			0.630	243	1.86	162	2.60	1.80	0.70
30	0.0038††	360	0.150	60	0.125			0.340	227	1.35	34	1.40	1.09	0.78
31	0.0069††	308	0.190	67	0.17			0.410	180	1.45	45	1.30	1.25	0.96
19	0.160	300	0.960	155	1.00			1.90	240	3.30	124	3.30	3.02	0.92
18	0.390††	696	1.580	325	1.50			1.390††	194	2.70	90	2.50		
60	0.173	475	1.350	198	0.95	0.96	1.01	0.460	398	1.65	166	1.30	1.50	1.15
22	0.230††	495	1.200	403	1.20			0.350	234	1.38	191	1.40	1.35	0.97
23	0.031††	495	0.430	373	0.42			0.400	404	1.55	202	1.40	1.40	1.00
9	0.610	335	1.88	244	2.08	1.83	0.88	0.760	303	2.08	227	2.30	2.03	0.88
10	0.380	280	1.45	223	1.60	1.43	0.90	0.710	309	1.98	191	2.00	1.93	0.97
16	0.035††	480	0.43	160	0.42			0.940	210	2.24	70	2.00		
40	1.610	418	3.12	370	3.50	3.09	0.89	3.920	295	4.70	310	4.60	4.70	1.04
47	1.470††	450	2.98	60	2.45			0.550††	450	1.83	60	1.50		
45	0.690	440	2.05	190	2.25	1.92	0.85	0.400	465	1.57	200	1.70	1.50	0.88
70														
5	0.270	372	1.25	99	1.40	1.12	0.80	2.500††	185	3.60	37	3.00		
73	4.022	370	4.86	185	5.30	4.59	0.87	1.780	314	3.18	157	3.80	3.00	0.79
78*	7.628	314	6.60	157	6.00	6.20	1.03	61.00	244	18.8	122	19.0	17.30	0.90
79A**	12.8				9.50									
79**	12.8	296	8.5	148	7.50	8.00	1.07							

TABLE 1 (continued)

Wave and Speed Classification: Wave Height ft	Wave and Speed Classification: Ship Speed knots	Record Number	Stereo Photo Number	Ship Speed knots	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	Wind and Wave Data: Heading of Sea Relative to Ship deg	Heading of Swell Relative to Ship deg	E††, ft², Mean Square Wave Height: From Stereo Data	From Wind Data	Wind Velocity for 8 Hours Preceding Test knots	Heave: E, Value of Mean Square, g^2	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	$R = \frac{\text{Predicted Max}}{\text{Measured Max}}$	Strain, Main Deck Amidships: E, Value of Mean Square Kips Squared	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: E, Value of Mean Square Degrees Squared	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: E, Value of Mean Square Degrees Squared	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	$R = \frac{\text{Predicted Max}}{\text{Measured Max}}$
Beam Seas																																										
0-4	10-15	14	E-021	12		5.6	7	3.7	4.5		075-095	5.3	5.2	9-20	0.0004††	444	0.051	370	0.50			0.330	444	1.41	370	1.47	1.40	0.95	0.034††	420	0.45	350	0.60			0.470	314	1.64	262	1.70	1.62	0.96
0-4	15-20	29	H-087	20		2.9	1	2.7	3.7		080-100	3.5	9.2	8-18	0.00016††	600	0.032	250	0.030			0.072††	600	0.68	250	0.63			‡							0.480	233	1.60	97	1.65	1.48	0.90
0-4	20-25	28	H-078	25		3.8	4	2.7		100-110	080-100	3.0	9.2	8-18	0.000057††	610	0.019	225	0.018			0.0376††	446	0.48	164	0.438			0.0055††	333	0.179	121	0.162			0.970	204	2.28	85	2.50	2.02	0.81
0-4	20-25	32	H-100	25		3.5	3	2.8	4.5	265	255-265	5.2	9.2	2-13	0.00038††	540	0.049	595	0.05			0.130††	390	0.88	430	0.88			0.060††	480	0.610	530	0.630			1.000	152	2.25	186	2.40	2.30	0.96
4-6	10-15	11	D-148	15		8.5	6	5.5	5.5	080-100	070	19.6	18.0	3-14	0.0038††	420	0.150	350	0.15			0.660	434	4.00	373	2.30	1.98	0.86	0.180	223	0.99	186	1.10	0.97	0.88	1.000	179	2.28	149	1.90	2.20	1.16
4-6	15-20	20	E-074	20		7.3	3	5.9	6.5	160-180	080-098	11.3	18.0	6-30	0.0017	524	0.130	253	0.130	0.098	0.75	1.270††	134	2.50	65	2.30			0.0056††	228	0.175	110	0.162			2.320	241	3.56	116	4.10	3.30	0.81
4-6	20-25	37	I-073	25		4.3	2	4.3	6.0	220-200	090-120	10.3	10.4	14-22	0.0026††	540	0.128	225	0.120			0.590	591	1.94	246	1.81	1.81	1.00	0.190††	540	1.10	225	1.00			1.750	264	3.10	110	3.10	2.86	0.92
6-8	10-15	27	G-150	12		4.2	2	6.5	7.1	082-085†	065-068†	8.1	18.4	15-21	0.0030	447	0.109	373	0.150	0.13	0.87	0.490	437	1.76	364	1.75	1.70	0.97	0.040	385	0.49	321	1.15	1.52	1.32	0.210	392	1.12	327	1.40	1.11	0.79
6-8	15-20	13	D-199	16		6.5	3	6.9	6.3		072-083	8.9	16.0	15-26	0.0031††	450	0.138	375	0.140			0.900	497	2.36	415	2.70	2.33	0.86	0.096††	420	0.78	350	0.75			0.750	225	2.20	188	1.75	1.99	1.14
6-8	15-20	3	C-470	20		9.1	3	7.8	7.5		095	8.9	24.0	20-28	0.0050	422	0.170	218	0.170	0.17	1.00	0.300	368	1.36	190	1.35	1.26	0.94	0.450††	309	1.60	159	1.50			3.600	246	4.45	127	4.20	4.18	0.99
6-8	20-25	17	E-064	25		6.9	3	6.1	6.9	225	225-235	15.8	16.0	6-30	0.0067	484	0.210	242	0.190	0.19	1.00	2.630	524	4.20	262	4.50	3.83	0.85	0.340††	524	1.45	262	1.37			2.130	216	3.40	108	3.20	3.16	0.99
8-15	5-10	52		10			5	10.0			090			22-28	0.0033††	436	0.240	73	0.200			1.160††	472	2.68	79	2.25			0.830††	426	2.24	71	1.88			0.950††	426	2.40	71	2.35		
8-15	5-10	74		10	9			11.0			110				0.0022	398	0.115	199	0.127	0.11	0.87	2.788	320	4.03	160	4.05	3.77	0.93	0.872	336	2.25	168	2.40	2.12	0.88	1.773	370	3.22	135	3.40	2.95	0.87
8-15	15-20	5	C-500	18		6.3	3	8.8	8.0		330	14.3	32.0	18-19	0.0031	514	0.140	137	0.140	0.12	0.86	0.60	262	1.60	70	2.10	1.60	0.76	0.270	372	1.25	99	1.40	1.12	0.80	2.500††	185	3.60	37	3.00		
Quarter Following Seas																																										
0-4	10-15	15	E-034	15		5.0	7	2.3		115-125	135	8.9	5.2	8-12	0.00052††	420	0.056	350	0.055			0.170	400	1.01	332	1.22	1.00	0.82	0.043††	400	0.50	332	0.50			0.500	183	1.60	154	1.50	1.59	1.06
4-6	5-10	7	D-017	10		2.8	3	4.5	4.5		210	5.1	9.2	8-20	‡							0.160	203	0.92	88	0.95	0.86	0.91	0.0068††	203	0.195	88	0.175			0.900	202	2.18	87	2.10	2.00	0.95
4-6	10-15	21	F-344	12	4.8	5.8	4		5.1	†	220-230†	11.6	13.6	19-31	0.00061††	480	0.061	240	0.060			0.630	374	1.93	187	1.80	1.80	1.00	0.117††	374	0.83	187	0.78			1.400	250	2.78	125	2.60	2.60	1.00
4-6	10-15	63		12			1	6.0		153-158	152-158			8-26	0.00012††	450	0.027	240	0.026			0.442††	300	1.57	160	1.47			0.140††	240	0.87	128	0.82			10.100††	240	7.40	128	7.00		
4-6	15-20	8	D-017	18		2.8	3	4.4	4.5		040-044	5.1	9.2	10-31	0.00063††	450	0.062	316	0.060			0.340††	135	1.30	94	1.27			0.0515††	186	0.518	130	0.50			3.710	186	4.43	130	4.60	4.20	0.92
4-6	15-20	6	D-017	18		2.8	3	4.5	4.4		206-226	5.1	9.2	9-17	0.00017††	360	0.032	180	0.030			0.220	144	1.03	72	1.35	0.97	0.72	‡							2.740	168	3.75	84	4.20	3.48	0.83
6-8	5-10	35	I-014	10		6.4	3	7.5	7.9	213-273	223-233	22.0	30.0	19-30	0.000042††	485	0.016	216	0.015			0.150	395	0.92	178	1.07	0.89	0.83	0.040	320	0.49	144	0.45	0.45	1.00	2.900	278	4.13	125	4.35	3.75	0.86
6-8	10-15	26	G-127	15		5.5	6	6.6	6.7	109-119	119	19.8	16.8	10-31	0.00150	468	0.096	234	0.11	0.091	0.83	0.530	406	1.78	203	2.10	1.68	0.80	0.110††	406	0.81	203	0.75			3.370	244	4.30	122	5.00	4.03	0.81
6-8	15-20	68	C-500	17		6.3	3	8.8	8.0		244	14.3	32.0	12-19	0.00040††	390	0.049	150	0.045			2.120††	208	3.36	80	3.05			0.390††	208	1.43	80	1.30			15.290	217	9.0	105	9.80	8.40	0.86
6-8	20-25	17	E-064	25		6.9	3	6.1	6.9	255	225-235	15.8	16.0	6-30	0.0067	484	0.210	242	0.190	0.19	1.00	2.630	524	4.20	262	4.50	3.83	0.85	0.340††	524	1.45	262	1.37			2.130	216	3.40	108	3.20	3.16	0.99
6-8	20-25	36	I-052	25		3.8	5	7.1	6.0	225	205-255	9.7	18.4	22-35	‡							0.100	240	0.74	140	0.95	0.70	0.74	‡							0.740	161	1.94	94	2.00	1.85	0.92
8-15	15-20	71		16	12					220																			10.08	334	7.70	167	8.00	7.20	0.90							
8-15	15-20	75		16	11			11.0		210					0.00254	422	0.136	211	0.165	0.12	0.73	6.498	268	6.05	134	6.40	5.64	0.88	2.724	276	3.92	138	3.70	3.68	0.99	61.00	204	18.2	102	19.0	16.80	0.88
8-15	20-25	50		25			3	9.0		225	214-222			22-29	0.00076	510	0.043	220	0.069	0.064	0.93	1.470	251	2.85	109	3.50	2.60	0.75	0.260	365	1.16	158	1.25	1.15	0.92	4.800	212	5.06	92	5.00	4.70	0.94
Following Seas																																										
0-4	20-25	33	H-155	25		6.0	6	3.6	5.3	160-170	180-190	12.0	9.2	16-20	0.000144††	420	0.029	189	0.028			0.043††	420	0.51	189	0.475			0.0188††	415	0.33	187	0.31			0.77††	193	2.05	87	1.85		
4-6	10-15	12	D-159	12		7.1	5	5.0	6.7	160	160	13.6	9.2	3-21	0.000039††	420	0.0155	350	0.015			0.550	248	1.74	206	2.11	1.72	0.81	0.017††	248	0.31	206	0.25			2.90	196	3.95	162	3.80	3.80	1.00
4-6	10-15	63		12			1	6.0		153-158	152-158			8-26	0.00012††	450	0.027	240	0.026			0.442††	300	1.57	160	1.47			0.140††	240	0.87	128	0.82			10.100††	240	7.40	128	7.00		
6-8	0-5	56		5			2	8.0			177			29-32	0.00012	480	0.028	240	0.030	0.026	0.87	0.590	368	1.87	184	1.78	1.75	0.98	0.170	383	1.01	192	1.00	0.94	0.94	0.590	358	1.86	179	2.00	1.75	0.88
6-8	10-15	57		15			4	8.0		167†	157-177†			29-32	0.00022††	480	0.037	240	0.038			0.380	360	1.50	180	1.50	1.40	0.94	0.070	336	0.63	168	0.63	0.61	0.97	11.16	226	7.80	113	7.50	7.30	0.98
6-8	15-20	59		20			1	8.0		167	157-177			8-24	‡							0.270††	240	1.22	40	1.00			0.054††	424	0.57	106	0.50			3.80	195	4.35	48	6.10	3.85	0.64
8-15	5-10	55		10			2	9.0		167	157-177			8-24	0.00014††	420	0.029	153	0.026			0.430††	300	1.57	110	1.43			0.136††	300	0.88	110	0.80			2.950††	330	4.13	102	3.70		
8-15	10-15	42		12			4	10.0		175-185	185-195			28-31	0.00009††	480	0.023	256	0.022			1.290††	319	2.71	170	2.78	2.58	0.92	0.130	448	0.88	239	0.88	0.85	0.97	14.140	286	8.85	153	9.90	8.50	0.86
8-15	10-15	76		15	13			13.0		190					0.00162	400	0.138	200	0.138	0.092	0.67	11.347	224	7.85	112	7.65	7.30	0.95	4.52	218	4.93	109	5.10	4.62	0.91	54.77	202	16.80	101	19.0	15.90	0.84
8-15	15-20	48		20			4	9.0		180-182	170-178			23-29	0.00047††	430	0.053	100	0.046			0.930††	180	2.20	33	1.80			0.190††	300	1.03	55	0.88			10.300††	180	7.30	33	6.00		
8-15	20-25	49		25			4	9.0		186	176-186			23-26	0.00040	530	0.047	256	0.050	0.047	0.94	1.050††	312	2.46	156	2.30			0.111	348	0.81	174	0.75	0.76	1.01	8.10	176	6.50	88	7.50	6.03	0.81

*Records were obtained on ORISKANY.

**Records were obtained on ESSEX.

†These sea conditions were well defined and nearly unidirectional.

††E is based on maximum measured value.

‡Values were negligible.

‡‡For the method of computing E see TMB Report 1091 (Reference 5).

‡In cases where conditions did not permit visual estimates, estimates of wave height were made by extrapolation from earlier and later visual estimates.

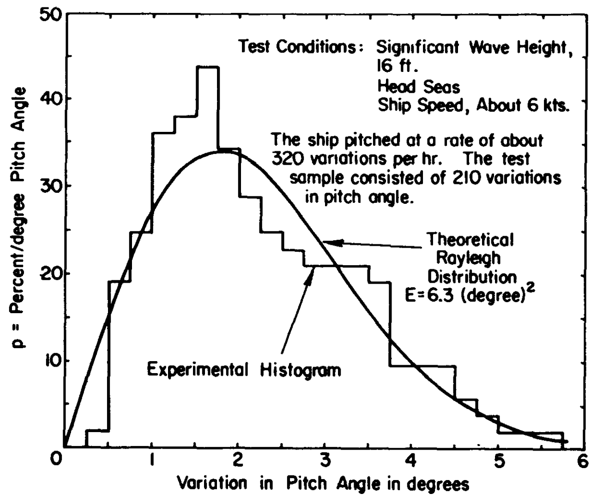

Figure 2a – Distribution of Variation in Pitch Angle

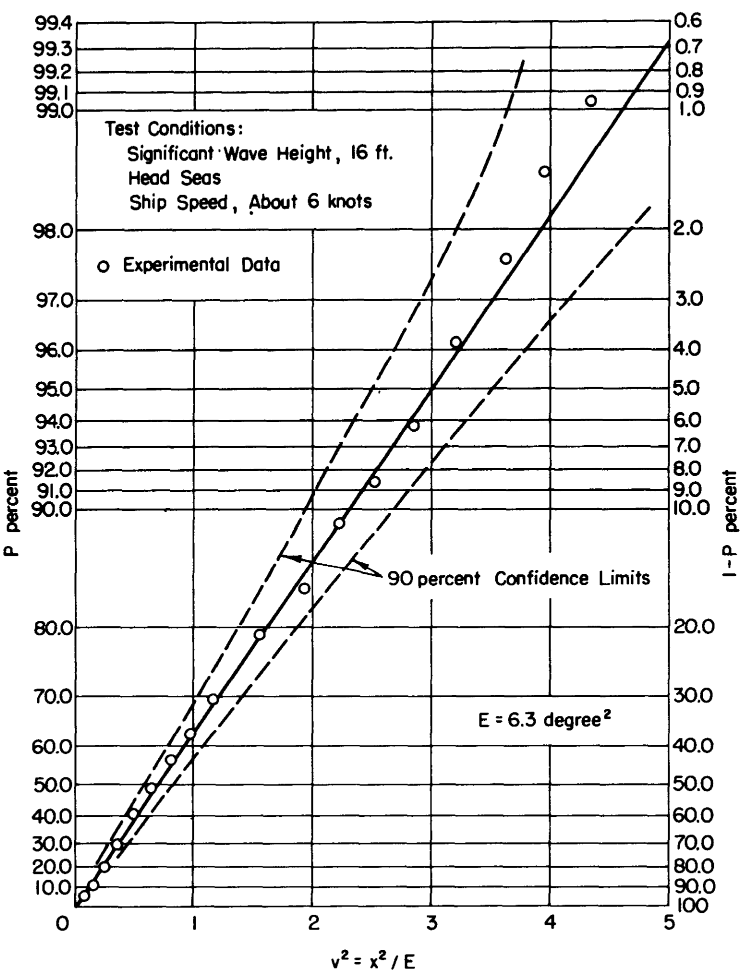

Figure 2b – Cumulative Distribution of Variation in Pitch Angle

Figure 2 – Sample of Rayleigh (Short-Term) Distributions

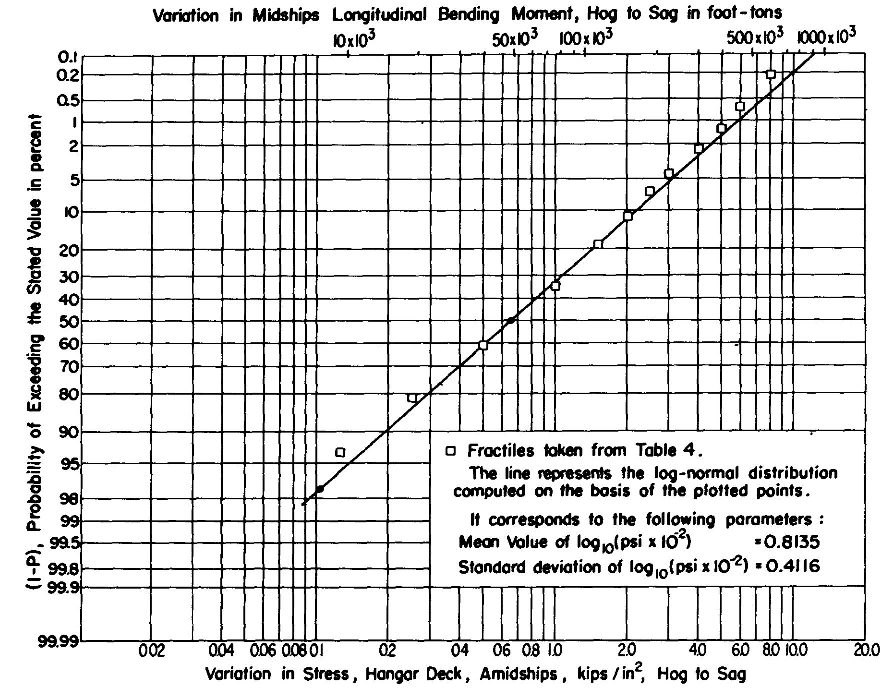

Figure 3 – Long-Term Cumulative Distribution of Longitudinal Stress and Bending Moment Amidship, for Wartime Service in North Atlantic Ocean

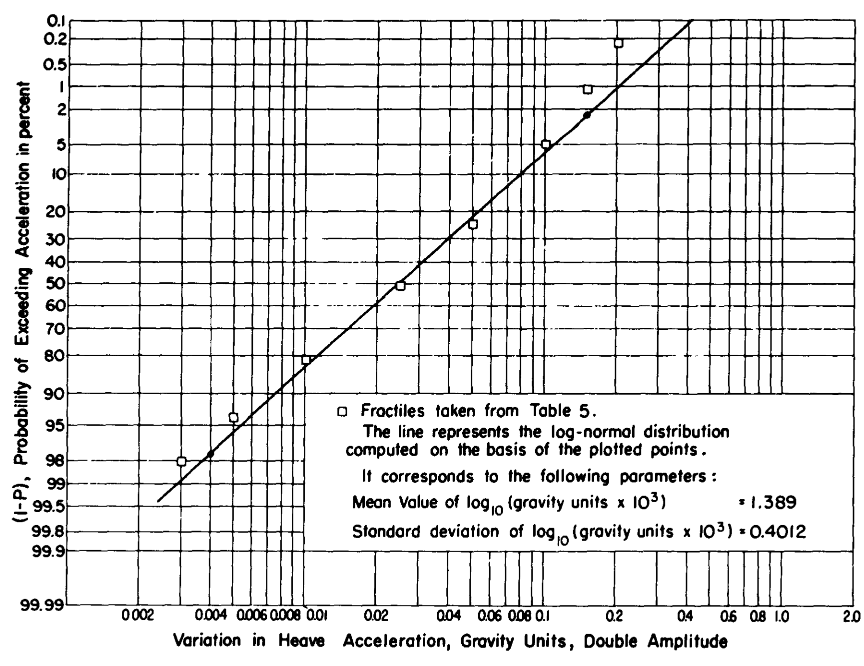

Figure 4 – Long-Term Distribution of Heave Acceleration for Wartime Service in North Atlantic Ocean

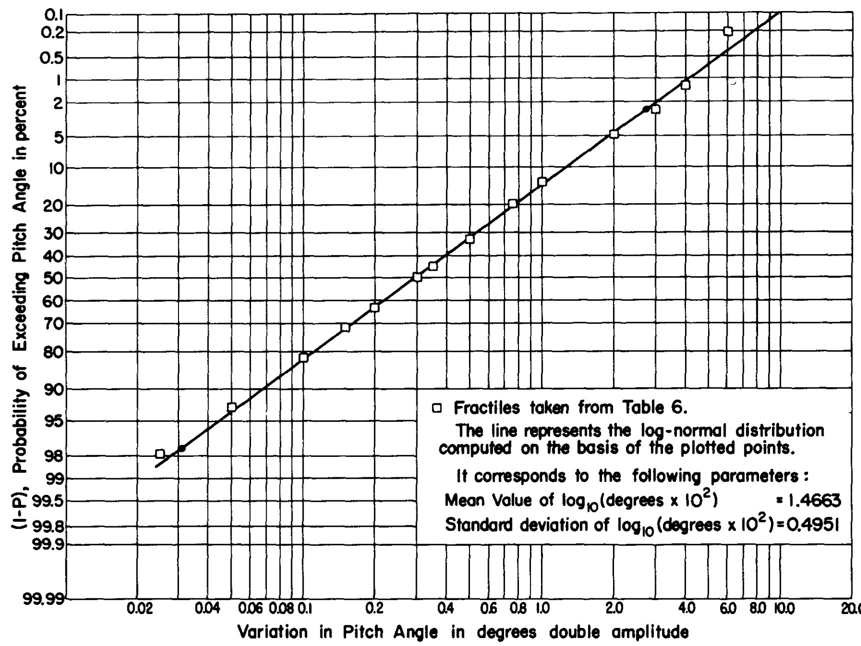

Figure 5 – Long-Term Cumulative Distribution of Pitch Angle for Wartime Service in North Atlantic Ocean

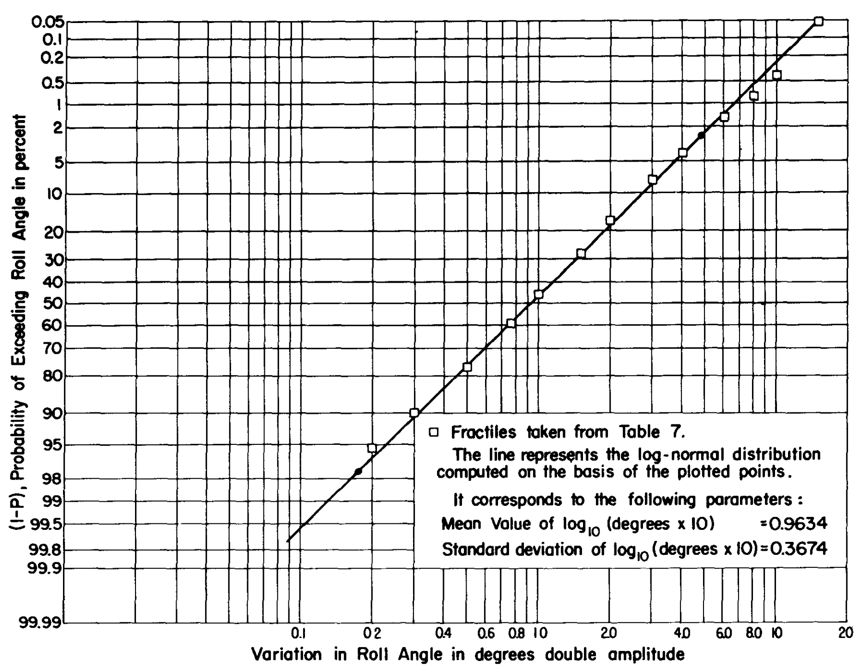

Figure 6 – Long-Term Cumulative Distribution of Roll Angle for Wartime Service in North Atlantic Ocean

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. 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]

a. The most frequent magnitude of variations* is $0.707\sqrt{E}$.

b. The average magnitude of the variations is $0.866\sqrt{E}$.

c. The most probable extreme value x_m experienced in a sample of N variations is $x_m \approx k\sqrt{E}$. For large values of N, k is approximately equal to $\sqrt{\log_e N}$.

For design purposes we may make a statistical estimate of the extreme value of the various variables as follows:

Let the value of E corresponding to the most severe 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 large.

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 $y = 7.0$.

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.

DISTRIBUTION PATTERNS OF SHIP MOTIONS AND LONGITUDINAL HULL BENDING MOMENTS

The motions and stresses (bending moments) given in this section 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.

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

**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 $x > x_{m_1}$.

SHORT-TERM DISTRIBUTION

The Rayleigh distribution corresponding to a particular set of operating conditions (sea state, speed, and course) is defined by the corresponding mean square value 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 in order to obtain the probability of exceeding any value of x from a single graph (Figure 2b) which is equally applicable to wave heights, ship motions, and hull stresses. The previous section gives formulas which may be used to estimate characteristic and expected extreme values.

LONG-TERM DISTRIBUTION

The short-term distributions, each of which is characterized by a value E, will now be be 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 will be weighted in accordance with the relative fraction of time in which carriers of this class will operate in a given sea state f_2, at a given heading to the waves f_3, and at a given ship speed f_1.

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

Speed knots	Characteristic Wave Height, feet				
	0-4	4-6	4-8	8-15	> 15
5-10	0.051	0.053	0.079	0.188	0.503
10-15	0.288	0.369	0.425	0.537	0.368
15-20	0.353	0.376	0.346	0.201	0.099
20-25	0.175	0.139	0.119	0.052	0.035
25-30	0.112	0.057	0.026	0.021	0
> 30	0.021	0.006	0.005	0	0

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

Characteristic Wave Heights, feet				
0-4	4-6	6-8	8-15	> 15
0.24	0.22	0.17	0.27	0.10

TABLE 2

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	0.00153	0.00146	0.00168	0.01270	0.01258
		± 45	0.00306	0.00292	0.00336	0.01270	0.01258
		± 90	0.00306	0.00292	0.00336	0.00635	0.00629
		±135	0.00306	0.00292	0.00336	0.01270	0.01258
		180	0.00153	0.00146	0.00168	0.00635	0.00629
10-15	2	0	0.00864	0.01015	0.00904	0.03626	0.00920
		± 45	0.01728	0.02020	0.01808	0.03626	0.00920
		± 90	0.01728	0.02020	0.01808	0.01813	0.00460
		±135	0.01728	0.02020	0.01808	0.03626	0.00920
		180	0.00864	0.01015	0.00904	0.01813	0.00460
15-20	3	0	0.01059	0.01034	0.00735	0.01358	0.0025
		± 45	0.02118	0.02068	0.01470	0.01358	0.0025
		± 90	0.02118	0.02068	0.01470	0.00679	0.0012
		±135	0.02118	0.02068	0.01470	0.01358	0.0025
		180	0.01059	0.01034	0.00735	0.00679	0.0012
20-25	4	0	0.00525	0.00383	0.00253	0.00350	0.00088
		± 45	0.01050	0.00766	0.00506	0.00350	0.00088
		± 90	0.01050	0.00766	0.00506	0.00175	0.00044
		±135	0.01050	0.00766	0.00506	0.00350	0.00088
		180	0.00525	0.00383	0.00253	0.00175	0.00044
25-30	5	0	0.00336	0.00156	0.00055	0.00142	
		± 45	0.00672	0.00312	0.00110	0.00142	
		± 90	0.00672	0.00312	0.00110	0.00071	
		±135	0.00672	0.00312	0.00110	0.00142	
		180	0.00336	0.00156	0.00055	0.00071	
> 30	6	0	0.00063	0.00016	0.00011		
		± 45	0.00126	0.00032	0.00022		
		± 90	0.00126	0.00032	0.00022		
		±135	0.00126	0.00032	0.00022		
		180	0.00063	0.00016	0.00011		

TABLE 3

Derivation of Predicted Distribution for Variations in Stress for Wartime Duty in the Atlantic Ocean

Wave Height Class ft	Characteristic Wave Height, ft Visual: Sea	Characteristic Wave Height, ft Visual: Swell	Relative Heading between Waves and Ship deg	Ship Speed Class*	Weighting Factor $\Sigma f_1 f_2 f_3 f_4$**	Number of Variations per Hour V	Average Number of Variations per Hour Contributed by Each Operating Condition $f_1 f_2 f_3 f_4 V = n$	Probability of Exceeding Given Magnitude of Variation $(1-P)$ (Magnitude in kpsi): 0.125	0.250	0.500	1.0	1.5	2.0	2.5	3.0	4.0	5.0	6.0	8.0	10.0	E Mean Square Variation
0-4		2.7	0 (±135)	4 (1, 2, 3, 5, 6)	0.0300	360.	10.800	0.555	0.090												0.0260
		3.7	±45	2 (1)	0.0204	612	12.448	0.932	0.753	0.321	0.011										0.220
		2.8	±45	4 (3, 5, 6)	0.01983	500	9.915	0.736	0.293												0.0514
		2.8	±45	4 (3, 5, 6)	0.01983	500	9.915	0.736	0.293												0.0514
		3.7	±90	2 (1)	0.02034	444	9.031	0.954	0.828	0.468	0.046										0.330
		2.7	±90	3	0.02118	600	12.708	0.805	0.420	0.031											0.0720
		2.7	±90	4 (5, 6)	0.00924	446	4.121	0.660	0.190												0.0376
		2.8	±90	4 (5, 6)	0.00924	390	3.604	0.887	0.619	0.146											0.130
		2.3	±135	2 (1, 3, 4, 5, 6)	0.0600	400	24.000	0.913	0.693	0.230											0.170
		3.6	±180	3 (1, 2, 4, 5, 6)	0.0300	420	12.600	0.696	0.235												0.0430
4-6		5.9	0	2 (1)	0.0058	720	4.176	0.559	0.099												0.0265
		6.0	0	2 (1)	0.0058	420	2.436	0.979	0.918	0.710	0.254	0.046									0.730
		6.0	0	3	0.01034	463	4.787	0.978	0.914	0.696	0.234	0.039									0.690
		6.1	0	4 (5, 6)	0.00555	696	3.863	0.997	0.986	0.944	0.796	0.598	0.402	0.240	0.128	0.026					4.38
		6.0	±45	3 (1, 2)	0.0438	463	20.279	0.978	0.914	0.696	0.234	0.039									0.690
		6.1	±45	4 (5, 6)	0.01110	696	7.726	0.997	0.986	0.944	0.796	0.598	0.402	0.240	0.128	0.026					4.38
		5.5	±90	2 (1)	0.02312	434	10.034	0.977	0.910	0.682	0.219	0.033									0.660
		5.9	±90	3	0.02068	134	2.771	0.988	0.952	0.823	0.454	0.170	0.043								1.27
		4.3	±90	4 (5, 6)	0.01110	591	6.560	0.974	0.900	0.655	0.184	0.022									0.590
		4.5	±135	1	0.00292	203	0.593	0.907	0.677	0.210											0.160
	4.8		±135	2	0.0101	374	3.777	0.976	0.904	0.673	0.204	0.028									0.630
		6.0	±135	2	0.0101	300	3.030	0.965	0.868	0.568	0.104	0.006									0.442
		4.4	±135	3 (4, 5, 6)	0.01589	135	2.145	0.955	0.834	0.480	0.056										0.340
		4.5	±135	3 (4, 5, 6)	0.01589	144	2.288	0.932	0.752	0.321											0.220
		5.0	±180	2 (1, 3, 4, 5, 6)	0.01375	248	3.410	0.972	0.894	0.635	0.162	0.017									0.550
		6.0	±180	2 (1, 3, 4, 5, 6)	0.01375	300	4.125	0.965	0.868	0.568	0.104	0.006									0.442
6-8		6.9	0	1	0.00168	602	1.011	0.771	0.353	0.016											0.0600
		7.0	0	2	0.00226	566	1.279	0.973	0.896	0.645	0.174	0.019									0.570
		7.0	0	2	0.00226	600	1.356	0.968	0.878	0.595	0.125										0.480
		8.0	0	2	0.00226	491	1.110	0.971	0.889	0.624	0.150	0.014									0.530
		7.7	0	2	0.00226	515	1.164	0.977	0.911	0.688	0.225	0.035									0.670
		6.1	0	3	0.00735	750	5.513	0.994	0.973	0.897	0.648	0.378	0.177	0.067							2.31
		7.5	0	4 (5, 6)	0.00319	780	2.488	0.857	0.540	0.084											0.101
		7.0	±45	1	0.00336	475	1.596	0.976	0.681	0.215	0.031										0.650
		6.6	±45	2 (3)	0.00656	495	3.247	0.987	0.948	0.806	0.426	0.118	0.033								1.17
	7.7		±45	2 (3)	0.00656	746	4.894	0.988	0.951	0.814	0.437	0.126	0.037								1.21
		6.2	±45	2 (3)	0.00656	388	2.545	0.988	0.954	0.827	0.466	0.150	0.047								1.31
		8.0	±45	2 (3)	0.00656	484	3.175	0.999	0.962	0.857	0.540	0.214	0.085								1.62
	7.7		±45	2 (3)	0.00656	746	4.894	0.988	0.951	0.814	0.437	0.126	0.037								1.21
		6.1	±45	4 (5,6)	0.0638	750	47.850	0.994	0.973	0.897	0.648	0.378	0.177	0.067	0.020						2.31
		6.5	±90	2 (1)	0.02144	437	9.369	0.969	0.880	0.601	0.130	0.010									0.490
		6.9	±90	3	0.00735	497	3.652	0.983	0.933	0.758	0.330	0.074	0.012								0.900
		7.8	±90	3	0.00735	368	2.704	0.949	0.812	0.435	0.359										0.300
		6.1	±90	4 (5, 6)	0.00638	524	3.343	0.995	0.978	0.684	0.425	0.219	0.093	0.033							2.63
		7.5	±135	1	0.00336	395	1.327	0.901	0.660	0.189											0.150
		6.6	±135	2	0.01808	406	7.340	0.971	0.889	0.625	0.152	0.014									0.530
		8.8	±135	3	0.01470	208	3.058	0.993	0.971	0.889	0.625	0.346	0.152	0.052	0.014						2.12
		6.1	±135	4 (5, 6)	0.00319	524	1.672	0.995	0.977	0.909	0.684	0.425	0.219	0.093	0.033						2.63
		7.1	±135	4 (5, 6)	0.00319	240	0.766	0.855	0.536	0.082											0.100
		8.0	±180	2 (1)	0.01072	360	3.859	0.960	0.849	0.519	0.072										0.380
		8.0	±180	3 (4, 5, 6)	0.01054	240	2.529	0.944	0.794	0.397	0.025										0.270
8-15		12.1	0	1	0.00212	444	0.941	0.999	0.983	0.935	0.764	0.512	0.342	0.186	0.090	0.014	0.001				3.72
		10.0	0	1	0.00212	445	0.943	0.999	0.970	0.885	0.614	0.296	0.142	0.048	0.013						2.05
		9.0	0	1	0.00212	483	1.024	0.986	0.945	0.796	0.402	0.102	0.026	0.003							1.10
		10.0	0	1	0.00212	488	1.034	0.991	0.956	0.829	0.472	0.184	0.050	0.009	0.001						1.33
		9.9	0	1	0.00212	389	0.825	0.999	0.999	0.977	0.912	0.795	0.692	0.563	0.438	0.230	0.100	0.036	0.002		10.9
		9.9	0	1	0.00212	362	0.767	0.999	0.999	0.985	0.941	0.860	0.785	0.686	0.580	0.380	0.220	0.114	0.021		16.6
		9.0	0	2	0.03626	290	10.515	0.974	0.900	0.660	0.189	0.024									0.600
		10.0	0	4 (3, 5, 6)	0.0185	650	12.025	0.997	0.987	0.951	0.819	0.637	0.447	0.285	0.164	0.040					4.98
		12.7	±45	1 (2)	0.01632	396	6.463	0.999	0.988	0.956	0.836	0.638	0.488	0.326	0.200	0.062					5.58
		9.0	±45	1 (2)	0.01632	465	7.589	0.988	0.951	0.819	0.450	0.136	0.041								1.25
		9.0	±45	1 (2)	0.01632	460	7.507	0.991	0.964	0.862	0.551	0.262	0.093	0.024							1.68
		8.8	±45	3 (4, 5, 6)	0.01850	262	4.847	0.974	0.900	0.660	0.189	0.024									0.600
		10.0	±90	1 (2)	0.02448	472	11.554	0.987	0.948	0.807	0.422	0.144	0.032								1.16
		8.8	±90	3 (4, 5, 6)	0.00925	262	2.424	0.974	0.900	0.660	0.189	0.024									0.600
		9.0	±135	4 (1, 2, 3, 5, 6)	0.06746	251	16.932	0.990	0.959	0.844	0.507	0.217	0.066	0.014							1.47
		9.0	±180	1	0.00635	300	1.905	0.964	0.865	0.098											0.430
		10.0	±180	2	0.01813	319	5.783	0.988	0.952	0.824	0.461	0.175	0.045								1.29
		9.0	±180	3	0.00679	180	1.222	0.984	0.935	0.765	0.341	0.089	0.014								0.930
		9.0	±180	4 (5,6)	0.00246	312	0.768	0.986	0.942	0.788	0.386	0.117	0.022								1.05
> 15	14.0	18.0	0	1 (2, 3, 4, 5, 6)	0.02516	360	9.058	0.999	0.999	0.999	0.965	0.940	0.867	0.801	0.726	0.642	0.500	0.278	0.101	0.029	28.2
	14.0	15.0	±45	1	0.01258	390	4.906	0.999	0.999	0.975	0.902	0.790	0.658	0.520	0.390	0.188	0.076	0.026			9.59
		16.0	±45	2 (3, 4, 5, 6)	0.01258	358	4.504	0.999	0.999	0.983	0.935	0.859	0.762	0.654	0.338	0.183	0.084	0.013	0.001		14.8
			±90	1 (2, 3, 4, 5, 6)	0.01253	320	4.010	0.999	0.978	0.914	0.698	0.446	0.238	0.104	0.038						2.79
			±135	3 (1, 2, 4, 5, 6)	0.1258	268	3.371	0.999	0.999	0.962	0.857	0.708	0.540	0.372	0.250	0.085	0.021				6.50
			±180	2 (1, 3, 4, 5, 6)	0.01253	224	2.807	0.999	0.999	0.978	0.916	0.820	0.702	0.578	0.452	0.244	0.110	0.044	0.003		11.4
Number of variations per hour exceeding given level (summing all conditions)							436.50	407.51	353.27	264.75	148.84	81.96	48.56	30.00	18.98	10.21	5.87	2.94	0.94	0.26	
Percentage of variations exceeding given magnitude							100 percent	93.4	80.9	60.7	34.1	18.8	11.1	6.87	4.34	2.3	1.3	0.67	0.21	0.06	

*The numbers in parentheses in column 4 represent ship speeds for which no data are available and for which the experimental data corresponding to the indicated speed class is assumed to apply for the purposes of the table.

**The factors f_1, f_2, f_3 are defined on pages 11 and 17. The factor f_4 is a weighting factor used when several similar sets of test data are utilized. For example, if 4 sets of similar test tata were available and were utilized in the table, then $f_4 = 0.25$.

TABLE 4

Derivation of Predicted Distribution for Variations in Heave Acceleration for Wartime Duty in the Atlantic Ocean

Wave Height Class ft	Characteristic Wave Height, ft Visual		Relative Heading between Waves and Ship deg	Ship Speed Class*	Weighting Factor $\Sigma f_1 f_2 f_3 f_4$**	Number of Variations per Hour N	Average Number of Variations per hour Contributed by each Operating Condition $f_1 f_2 f_3 f_4 N = n$	Probability of Exceeding given Magnitude of Variation $(1-P)$ (Magnitude in units of gravity)									E Mean Square Variation
	Sea	Swell						0.003	0.005	0.01	0.025	0.05	0.1	0.15	0.2	0.25	
0-4		2.7	0	4 (1, 2, 3, 5, 6)	0.0300	480	14.400	0.976	0.932	0.760	0.184	0.001					0.000370
		3.7	±45	2 (1)	0.0204	510	10.373	0.983	0.950	0.826	0.300	0.008					0.000520
		2.7	±45	4 (3, 5, 6)	0.01983	480	9.5184	0.976	0.932	0.760	0.184	0.001					0.000370
		2.8	±45	4 (3, 5, 6)	0.01983	384	7.614	0.962	0.890	0.647	0.066						0.000230
		3.7	±90	2 (1)	0.02034	444	9.031	0.978	0.938	0.779	0.210	0.002					0.000400
		2.8	±90	3	0.02118	600	12.708	0.945	0.853	0.535	0.020						0.000160
		2.7	±90	4 (5, 6)	0.00924	610	5.636	0.854	0.645	0.174							0.0000570
		2.8	±90	4 (5, 6)	0.00924	540	4.990	0.977	0.935	0.770	0.190	0.001					0.000380
		2.3	±135	2 (1, 3, 4, 5, 6)	0.0600	420	25.200	0.983	0.950	0.826	0.300	0.008					0.000520
		3.6	±180	3 (1, 2, 4, 5, 6)	0.0300	420	12.600	0.940	0.838	0.500	0.013						0.000144
4-6		6.0	0	2 (1)	0.00580	530	3.074	0.688	0.352	0.015							0.0000230
		6.0	0	2 (1)	0.00580	480	2.784	0.999	0.970	0.890	0.500	0.064					0.000900
		6.0	0	3	0.01034	474	4.901	0.999	0.999	0.970	0.835	0.460	0.049				0.00330
		6.1	0	4 (5, 6)	0.00555	600	3.330	0.999	0.999	0.986	0.918	0.710	0.252	0.047	0.004		0.00730
		6.0	±45	3 (1, 2)	0.04380	474	20.761	0.999	0.999	0.970	0.835	0.460	0.049	0.001			0.00330
		6.1	±45	4 (5, 6)	0.01110	600	6.660	0.999	0.999	0.986	0.918	0.710	0.252	0.047	0.004		0.00730
		5.5	±90	2 (1)	0.02312	420	9.710	0.999	0.999	0.974	0.854	0.520	0.074	0.003			0.00380
		5.9	±90	3	0.02068	524	10.836	0.999	0.986	0.943	0.693	0.230	0.003				0.00170
		4.3	±90	4 (5, 6)	0.01110	540	5.994	0.999	0.999	0.962	0.786	0.382	0.021				0.00260
	4.8		±135	2 (1)	0.01156	480	5.549	0.985	0.960	0.849	0.353	0.017					0.000610
		6.0	±135	2 (1)	0.01156	450	5.202	0.928	0.814	0.435	0.005						0.000120
		4.4	±135	3 (4, 5, 6)	0.01589	450	7.150	0.986	0.961	0.854	0.372	0.019					0.000630
		4.5	±135	3 (4, 5, 6)	0.01589	360	5.720	0.949	0.866	0.555	0.025						0.000170
		5.0	±180	2 (1, 3, 4, 5, 6)	0.01375	420	5.775	0.977	0.528	0.068							0.0000390
		6.0	±180	2 (1, 3, 4, 5, 6)	0.01375	450	6.188	0.928	0.814	0.435	0.005						0.000120
6-8		6.9	0	1	0.00168	480	0.806	0.978	0.542	0.088							0.0000410
		7.0	0	2	0.00226	564	1.275	0.987	0.975	0.866	0.410	0.028					0.000700
		7.0	0	2	0.00226	565	1.277	0.985	0.959	0.853	0.351	0.016					0.000600
		8.0	0	2	0.00226	529	1.196	0.999	0.975	0.904	0.532	0.080					0.000990
		7.7	0	2	0.00226	515	1.164	0.999	0.980	0.920	0.594	0.124					0.00120
		6.1	0	3	0.00735	510	3.748	0.999	0.987	0.951	0.732	0.286	0.006				0.00200
		7.5	0	4 (5, 6)	0.00319	600	1.914	0.975	0.489	0.057							0.0000305
		7.0	±45	1	0.00336	499	1.677	0.999	0.980	0.920	0.594	0.124					0.00120
		6.6	±45	2 (3)	0.00656	495	3.247	0.999	0.987	0.951	0.732	0.288	0.007				0.00200
	7.7		±45	2 (3)	0.00656	497	3.260	0.999	0.984	0.936	0.660	0.190					0.00150
		6.2	±45	2 (3)	0.00656	368	2.414	0.999	0.999	0.973	0.848	0.510	0.067	0.002			0.00370
		8.0	±45	2 (3)	0.00656	483	3.168	0.999	0.999	0.979	0.875	0.587	0.119	0.008			0.00470
	7.7		±45	2 (3)	0.00656	497	3.260	0.999	0.984	0.936	0.659	0.188	0.001				0.00150
		6.1	±45	4 (5, 6)	0.00638	510	3.253	0.999	0.987	0.951	0.731	0.288	0.007				0.00200
		6.5	±90	2 (1)	0.02144	447	9.584	0.999	0.999	0.967	0.814	0.434	0.036				0.00300
		6.9	±90	3	0.00735	450	3.307	0.999	0.999	0.969	0.817	0.448	0.040				0.00310
		7.8	±90	3	0.00735	422	3.102	0.999	0.999	0.984	0.885	0.606	0.136				0.00500
		6.1	±90	4 (5, 6)	0.00638	484	3.088	0.999	0.999	0.985	0.911	0.688	0.224				0.00670
		7.5	±135	1	0.00336	485	1.630	0.979	0.556	0.092							0.0000420
		6.6	±135	2	0.01808	468	8.460	0.999	0.984	0.936	0.659	0.188	0.001				0.00150
		8.8	±135	3	0.01470	390	5.733	0.978	0.890	0.647	0.066						0.000400
		6.1	±135	4 (5, 6)	0.00638	484	3.088	0.999	0.999	0.985	0.911	0.688	0.224	0.035	0.003		0.00670
		8.0	±180	2 (1, 3, 4, 5, 6)	0.02126	480	10.205	0.960	0.893	0.636	0.068						0.00022
8-15		12.1	0	1	0.00181	408	0.738	0.999	0.999	0.999	0.945	0.796	0.402	0.129	0.026		0.0110
		12.1	0	1	0.00181	404	0.731	0.999	0.999	0.984	0.905	0.664	0.194	0.024	0.001		0.00610
		10.0	0	1	0.00181	406	0.7348	0.999	0.987	0.949	0.720	0.268	0.005				0.00190
		9.0	0	1	0.00181	479	0.867	0.999	0.981	0.926	0.618	0.196					0.00130
		10.0	0	1	0.00181	488	0.883	0.999	0.983	0.932	0.640	0.168					0.00140
		9.9	0	1	0.00181	418	0.757	0.999	0.999	0.976	0.859	0.544	0.088				0.00410
		9.9	0	1	0.00181	416	0.753	0.999	0.999	0.984	0.902	0.664	0.194	0.025	0.001		0.00610
		9.0	0	2	0.03626	413	14.975	0.999	0.987	0.949	0.720	0.268	0.005				0.00190
		10.0	0	4 (3, 5, 6)	0.01850	600	11.100	0.999	0.999	0.975	0.851	0.525	0.076				0.00388
		12.7	±45	1 (2)	0.01632	384	6.266	0.999	0.999	0.985	0.910	0.685	0.220	0.033	0.002		0.00660
		9.0	±45	1 (2)	0.01632	457	7.458	0.999	0.999	0.988	0.924	0.728	0.280	0.068	0.006		0.00790
		9.0	±45	1 (2)	0.01632	465	7.589	0.999	0.999	0.972	0.837	0.490	0.058				0.00350
		8.8	±45	3 (4, 5, 6)	0.01850	514	9.509	0.999	0.999	0.969	0.817	0.448	0.040				0.00310
		10.0	±90	1 (2)	0.02448	436	10.673	0.999	0.999	0.988	0.933	0.758	0.330	0.082	0.012		0.00900
		8.8	±90	3 (4, 5, 6)	0.00925	514	4.754	0.999	0.999	0.969	0.817	0.448	0.040				0.00310
		9.0	±135	4 (1, 2, 3, 5, 6)	0.06746	510	34.484	0.987	0.968	0.876	0.440	0.038					0.000760
		9.0	±180	1	0.00635	420	2.667	0.938	0.836	0.490	0.012						0.000140
		10.0	±180	2	0.01813	480	8.702	0.900	0.758	0.330	0.001						0.0000900
		9.0	±180	3	0.00679	430	2.920	0.981	0.948	0.808	0.262	0.005					0.000470
		9.0	±180	4 (5, 6)	0.00246	530	1.304	0.978	0.939	0.779	0.210	0.002					0.000400
> 15		20.0	0	1 (2, 3, 4, 5, 6)	0.02516	338	8.504	0.999	0.999	0.999	0.956	0.834	0.485	0.196	0.060	0.011	0.0138
	14.0	15.0	±45	1 (2, 3, 4, 5, 6)	0.02516	428	10.768	0.999	0.999	0.986	0.914	0.698	0.238	0.039	0.003		0.00695
			±90	1 (2, 3, 4, 5, 6)	0.01253	398	4.987	0.999	0.989	0.956	0.752	0.322	0.010				0.00220
			±135	3 (1, 2, 4, 5, 6)	0.02516	422	10.618	0.999	0.999	0.961	0.782	0.368	0.020				0.00254
			±180	2 (1, 3, 4, 5, 6)	0.01253	400	5.012	0.999	0.985	0.940	0.680	0.214					0.00162
Number of variations per hour exceeding given level (summing all conditions)							466.19	457.3	438.1	381.8	239.1	115.6	25.4	4.99	0.96	0.13	
Percentage of variations exceeding given magnitude							100 percent	98.1	94.1	81.9	51.3	24.8	5.4	1.07	0.21	0.03	

*The numbers in parentheses in column 4 represent ship speeds for which no data are available and for which the experimental data corresponding to the indicated speed class is assumed to apply for the purposes of the table.

**The factors f_1, f_2, f_3 are defined on pages 11 and 17. The factor f_4 is a weighting factor used when several similar sets of test data are utilized. For example, if 4 sets of similar test data were available and were utilized in the table, then $f_4 = 0.25$.

TABLE 5

Derivation of Predicted Distribution for Variations in Pitch Angle for Wartime Duty in the Atlantic Ocean

Wave Height Class ft	Characteristic Wave Height, ft Visual: Sea	Characteristic Wave Height, ft Visual: Swell	Relative Heading between Waves and Ship deg	Ship Speed Class*	Weighting Factor $\Sigma f_1 f_2 f_3 f_4$**	Number of Variations per Hour N	Average Number of Variations per Hour Contributed by each Operating Condition $f_1 f_2 f_3 f_4 N = n$	Probability of Exceeding given Magnitude of Variation $(1-P)$ (Magnitude in degrees): 0.025	0.05	0.100	0.150	0.200	0.300	0.350	0.500	0.750	1.00	2.00	3.00	4.00	6.00	E Mean Square Variation
0-4		2.7	0	4 (1, 2, 3, 5, 6)	0.300	360	10.800	0.848	0.518	-0.074												0.00380
		3.7	±45	2 (1)	0.02034	275	5.594	0.987	0.947	0.805	0.614	0.420	0.142	0.70								0.0460
		2.7	±45	4 (3, 5, 6)	0.01983	360	7.139	0.848	0.518	0.074												0.00380
		2.8	±45	4 (3, 5, 6)	0.01983	308	6.108	0.914	0.696	0.234	0.039											0.00690
		3.7	±90	2 (1)	0.02034	420	8.543	0.982	0.929	0.746	0.516	0.309	0.072									0.0340
		2.8	±90	4 (3, 5, 6)	0.01983	480	9.518	0.989	0.959	0.847	0.687	0.514	0.222	0.130	0.016							0.0600
		2.7	±90	4 (3, 5, 6)	0.01983	333	6.603	0.894	0.634	0.162	0.016											0.00550
		2.3	±135	2 (1, 3, 4, 5, 6)	0.0600	400	24.000	0.985	0.944	0.792	0.592	0.394	0.124	0.0680								0.0430
		3.6	±180	3 (1, 2, 4, 5, 6)	0.0300	415	12.450	0.966	0.870	0.574	0.286	0.108										0.0180
4-6		6.0	0	2 (1)	0.00580	240	1.392	0.140														0.000320
		6.0	0	2 (1)	0.00580	420	2.436	0.999	0.989	0.956	0.906	0.834	0.664	0.573	0.320	0.078	0.015					0.220
		6.0	0	3	0.01034	300	3.102	0.999	0.985	0.939	0.869	0.779	0.570	0.464	0.210	0.030	0.002					0.160
		6.1	0	4 (5, 6)	0.00555	696	3.863	0.999	0.999	0.975	0.944	0.903	0.794	0.730	0.526	0.236	0.077					0.390
		6.0	±45	3 (1, 2)	0.04380	300	13.140	0.999	0.985	0.939	0.871	0.779	0.570	0.464	0.210	0.030	0.002					0.160
		6.1	±45	4 (5, 6)	0.01110	696	7.726	0.999	0.999	0.975	0.944	0.903	0.794	0.730	0.526	0.236	0.077					0.390
		5.5	±90	2 (1)	0.02312	223	5.156	0.999	0.986	0.947	0.885	0.800	0.606	0.506	0.250	0.044	0.004					0.180
		5.9	±90	3	0.02068	228	4.715	0.895	0.640	0.168												0.00560
		4.3	±90	4 (5, 6)	0.0110	540	5.994	0.999	0.987	0.949	0.888	0.820	0.624	0.524	0.268	0.054	0.005					0.190
		4.5	±135	1	0.00292	203	0.593	0.913	0.692	0.230												0.00680
	4.8		±135	2	0.01010	374	3.777	0.999	0.979	0.918	0.825	0.710	0.464	0.350	0.118	0.008						0.117
		6.0	±135	2	0.01010	240	2.424	0.999	0.983	0.931	0.854	0.750	0.526	0.418	0.168							0.140
		4.4	±135	3 (4, 5, 6)	0.03178	186	5.907	0.988	0.953	0.826												0.0515
		5.0	±180	2 (1, 3, 4, 5, 6)	0.01375	248	3.410	0.964	0.865	0.556	0.266	0.094										0.0170
		6.0	±180	2 (1, 3, 4, 5, 6)	0.01375	240	3.300	0.999	0.982	0.931	0.854	0.750	0.526	0.418	0.168	0.018						0.140
6-8		6.9	0	1	0.00168	360	0.605	0.923	0.726	0.278												0.00780
		7.0	0	2	0.00226	521	1.177	0.999	0.976	0.907	0.804	0.676	0.414	0.300	0.86							0.102
		7.0	0	2	0.00226	508	1.148	0.999	0.979	0.919	0.826	0.712	0.466	0.354	0.120	0.009						0.118
		8.0	0	2	0.00226	491	1.110	0.999	0.985	0.940	0.870	0.780	0.572	0.465	0.212	0.030	0.002					0.161
		7.7	0	2	0.00226	515	1.164	0.999	0.984	0.936	0.860	0.766	0.555	0.442	0.188	0.024						0.150
		6.1	0	3	0.00735	480	3.528	0.982	0.931	0.750	0.526	0.318	0.077									0.0350
		7.5	0	4 (5, 6)	0.00319	600	1.914	0.968	0.878	0.590	0.306	0.112										0.0190
		7.0	±45	1	0.00336	475	1.596	0.999	0.986	0.944	0.878	0.794	0.594	0.492	0.236	0.039	0.003					0.173
		6.6	±45	2 (3)	0.00656	495	3.247	0.999	0.989	0.958	0.905	0.840	0.676	0.586	0.348	0.0	0.013					0.230
	7.7		±45	2 (3)	0.00656	495	3.247	0.980	0.923	0.724	0.484	0.274	0.060									0.0310
		6.2	±45	2 (3)	0.00656	335	2.198	0.999	0.999	0.980	0.957	0.925	0.839	0.786	0.612	0.332	0.140					0.510
		8.0	±45	2 (3)	0.00656	280	1.837	0.999	0.999	0.974	0.943	0.900	0.790	0.724	0.518	0.228	0.72					0.380
	7.7		±45	2 (3)	0.00656	495	3.247	0.980	0.923	0.724	0.484	0.276	0.060	0.019								0.0310
		6.1	±45	4 (5, 6)	0.0638	480	3.062	0.982	0.931	0.750	0.526	0.318	0.077	0.030								0.0350
		6.5	±90	2 (1)	0.02144	385	8.254	0.985	0.940	0.780	0.570	0.370	0.106	0.047								0.0400
		6.9	±90	3	0.00735	420	3.087	0.999	0.974	0.901	0.790	0.660	0.391	0.278	0.078	0.003						0.0960
		7.8	±90	3	0.00735	309	2.271	0.999	0.999	0.978	0.951	0.915	0.819	0.762	0.574	0.286	0.109					0.450
		6.1	±90	4 (5, 6)	0.00638	524	3.343	0.999	0.999	0.971	0.936	0.889	0.768	0.697	0.480	0.192	0.056					0.340
		7.5	±135	1	0.00336	320	1.075	0.985	0.940	0.780	0.570	0.370	0.106	0.047								0.0400
		6.6	±135	2	0.01808	406	7.340	0.999	0.999	0.981	0.959	0.927	0.844	0.794	0.624	0.346	0.150					0.110
		8.8	±135	3	0.01470	208	3.058	0.999	0.999	0.975	0.944	0.872	0.794	0.730	0.526	0.236	0.077					0.390
		6.1	±135	4 (5, 6)	0.00638	524	3.343	0.999	0.999	0.971	0.936	0.889	0.768	0.698	0.480	0.192	0.056					0.340
		8.0	±180	2 (1)	0.01072	336	3.601	0.999	0.965	0.866	0.725	0.564	0.276	0.174	0.028							0.0700
		8.0	±180	3 (4, 5, 6)	0.01054	424	4.468	0.989	0.955	0.831	0.660	0.476	0.190	0.104	0.010							0.054
8-15		12.1	0	1	0.00212	388	0.822	0.999	0.999	0.999	0.999	0.975	0.940	0.920	0.844	0.680	0.504	0.084				1.46
		10.0	0	1	0.00212	428	0.907	0.999	0.999	0.988	0.972	0.951	0.893	0.858	0.732	0.495	0.286	0.007				0.800
		9.0	0	1	0.00212	439	0.931	0.999	0.999	0.968	0.930	0.878	0.750	0.674	0.458	0.162	0.040					0.310
		10.0	0	1	0.00212	450	0.954	0.999	0.999	0.962	0.917	0.857	0.708	0.624	0.382	0.116	0.022					0.260
		9.9	0	1	0.00212	380	0.806	0.999	0.999	0.999	0.999	0.981	0.957	0.943	0.888	0.763	0.618	0.142				2.04
		9.9	0	1	0.00212	351	0.744	0.999	0.999	0.999	0.999	0.999	0.981	0.975	0.949	0.888	0.810	0.430	0.150	0.034		4.74
		9.0	0	2	0.03626	290	10.515	0.999	0.999	0.980	0.956	0.922	0.835	0.781	0.606	0.326	0.134					0.500
		10.0	0	3 (4, 5, 6)	0.01850	493	9.120	0.999	0.999	0.986	0.968	0.944	0.878	0.837	0.698	0.420	0.234					0.480
		9.0	±45	1 (2)	0.01632	450	7.344	0.999	0.999	0.999	0.999	0.973	0.941	0.920	0.844	0.682	0.506					1.47
		9.0	±45	1 (2)	0.01632	418	6.822	0.999	0.999	0.999	0.999	0.975	0.945	0.927	0.856	0.706	0.536	0.086				1.61
		9.0	±45	1 (2)	0.01632	440	7.181	0.999	0.999	0.986	0.968	0.944	0.878	0.837	0.696	0.420	0.234	0.003				0.690
		8.8	±45	3 (4, 5, 6)	0.01850	372	6.882	0.999	0.999	0.964	0.920	0.862	0.718	0.635	0.396	0.124	0.024					0.270
		10.0	±90	1 (2)	0.02448	426	10.428	0.999	0.999	0.988	0.973	0.953	0.897	0.866	0.740	0.506	0.300	0.008				0.830
		8.8	±90	3 (4, 5, 6)	0.00925	372	3.441	0.999	0.999	0.964	0.920	0.864	0.718	0.636	0.396	0.124	0.024					0.270
		9.0	±135	4 (1, 3, 5, 6)	0.06746	365	24.623	0.999	0.999	0.962	0.917	0.858	0.708	0.624	0.382	0.116	0.022					0.260
		9.0	±180	1	0.00635	330	2.0955	0.999	0.999	0.999	0.999	0.987	0.970	0.959	0.919	0.832	0.713	0.256	0.047			2.95
		10.0	±180	2	0.01813	448	8.122	0.999	0.980	0.926	0.840	0.736	0.500	0.390	0.146	0.010						0.130
		9.0	±180	3	0.00679	300	2.037	0.999	0.987	0.949	0.888	0.810	0.622	0.524	0.268	0.053						0.190
		9.0	±180	4 (5, 6)	0.00246	348	0.856	0.999	0.978	0.914	0.817	0.698	0.446	0.330	0.105	0.006						0.111
< 15	14.0	18.0	0	1 (2, 3, 4, 5, 6)	0.02516	326	8.202	0.999	0.999	0.999	0.999	0.999	0.999	0.980	0.975	0.944	0.904	0.662	0.396	0.192	0.025	9.72
			±45	1 (2, 3, 4, 5, 6)	0.02516	296	7.447	0.999	0.999	0.999	0.999	0.999	0.999	0.999	0.981	0.957	0.925	0.732	0.496	0.284	0.061	12.8
	9.0	11.0	±90	1 (2, 3, 4, 5, 6)	0.01253	336	4.210	0.999	0.999	0.988	0.975	0.955	0.904	0.868	0.750	0.524	0.318	0.010				0.872
	12.0		±135	3 (1, 2, 4, 5, 6)	0.01258	334	4.201	0.999	0.999	0.999	0.999	0.999	0.999	0.988	0.976	0.946	0.906	0.672	0.408	0.204	0.028	10.1
	11.0	11.0	±135	3 (1, 2, 4, 5, 6)	0.01258	276	3.472	0.999	0.999	0.999	0.999	0.985	0.967	0.956	0.913	0.813	0.692	0.230	0.037			2.72
	13.0	13.0	±180	2 (1, 3, 4, 5, 6)	0.01253	218	2.732	0.999	0.999	0.999	0.999	0.999	0.981	0.973	0.946	0.886	0.801	0.400	0.136	0.029		4.52
Number of variations per hour exceeding given level (summing all conditions)							361.32	353.5	336.0	296.3	258.0	228.2	179.8	160.4	116.7	70.7	48.0	17.8	9.4	4.6	0.77	
Percentage of variations exceeding given magnitude							100 percent	97.8	93.0	82.0	71.4	63.1	49.8	44.3	32.3	19.6	13.3	4.9	2.6	1.3	0.2	

*The numbers in parentheses in column 4 represent ship speeds for which no data are available and for which the experimental data corresponding to the indicated speed class is assumed to apply for the purposes of the table.

**The factors f_1, f_2, f_3 are defined on pages 11 and 17. The factor f_4 is a weighting factor used when several similar sets of test data are utilized. For example, if 4 sets of similar test data were available and were utilized in the table, then $f_4 = 0.25$.

TABLE 6

Derivation of Predicted Distribution for Variations in Roll Angle for Wartime Duty in the Atlantic Ocean

Wave Height Class ft	Characteristic Wave Height, ft Visual: Sea	Characteristic Wave Height, ft Visual: Swell	Relative Heading between Waves and Ship deg	Ship Speed Class*	Weighting Factor $\Sigma f_1 f_2 f_3 f_4$**	Number of Variations per Hour N	Average Number of Variations per Hour Contributed by Each Operating Condition $f_1 f_2 f_3 f_4 N = n$	0.200	0.300	0.500	0.750	1.00	1.500	2.00	3.00	4.00	6.00	8.00	10.0	15.0	Mean Square Variation
								Probability of Exceeding Given Magnitude of Variation $(1-P)$ (Magnitude in degrees)													
0-4		2.7	0	4 (1, 2, 3, 5, 6)	0.0300	227	6.810	0.889	0.768	0.480	0.192	0.052									0.340
		3.7	±45	2 (1)	0.0204	243	4.957	0.939	0.867	0.673	0.410	0.204	0.028	0.002							0.630
		2.7	±45	4 (3, 5, 6)	0.01983	227	4.501	0.889	0.768	0.480	0.192	0.052									0.340
		2.8	±45	4 (3, 5, 6)	0.01983	180	3.569	0.908	0.806	0.594	0.254	0.088									0.410
		3.7	±90	2 (1)	0.02034	314	6.387	0.919	0.826	0.588	0.302	0.118									0.470
		2.8	±90	3	0.02118	233	4.935	0.920	0.829	0.594	0.310	0.124									0.480
		2.7	±90	4 (5, 6)	0.00924	204	1.885	0.960	0.911	0.773	0.560	0.356	0.100	0.016							0.970
		2.8	±90	4 (5, 6)	0.00924	152	1.404	0.961	0.914	0.780	0.570	0.380	0.106	0.018							1.00
		2.3	±135	2 (1, 3, 4, 5, 6)	0.0600	183	10.980	0.923	0.835	0.608	0.324	0.136	0.011								0.509
		3.6	±180	3 (1, 2, 4, 5, 6)	0.0300	193	5.790	0.949	0.890	0.722	0.482	0.272	0.058	0.005							0.770
4-6		6.0	0	2 (1)	0.0058	240	1.392	0.626	0.324												0.0855
		6.0	0	2 (1)	0.0058	300	1.740	0.886	0.716	0.468	0.182	0.050									0.330
		6.0	0	3	0.01034	240	2.482	0.979	0.954	0.877	0.744	0.590	0.306	0.122	0.009						1.90
		6.1	0	4 (5, 6)	0.00555	194	1.077	0.972	0.937	0.836	0.666	0.488	0.200	0.057							1.39
		6.0	±45	3 (1, 2)	0.04380	240	10.512	0.979	0.954	0.877	0.744	0.590	0.306	0.122	0.009						1.90
		6.1	±45	4 (5, 6)	0.01110	194	2.152	0.972	0.937	0.836	0.666	0.488	0.200	0.057							1.39
		5.5	±90	2 (1)	0.02312	179	4.138	0.961	0.914	0.786	0.570	0.355	0.106	0.018							1.00
		5.9	±90	3	0.02068	241	4.984	0.983	0.962	0.898	0.784	0.650	0.380	0.168	0.021						2.32
		4.3	±90	4 (5, 6)	0.01110	264	2.930	0.978	0.950	0.867	0.726	0.566	0.276	0.101	0.005						1.75
		4.5	±135	1	0.00292	202	0.590	0.957	0.904	0.758	0.536	0.330	0.084	0.012							0.900
	4.8		±135	2	0.0101	250	2.525	0.972	0.938	0.837	0.670	0.440	0.200	0.064							1.40
		6.0	±135	2	0.0101	240	2.424	0.999	0.999	0.975	0.946	0.905	0.800	0.674	0.406	0.204	0.028	0.002			10.1
		4.4	±135	3 (4, 5, 6)	0.01589	186	2.956	0.989	0.976	0.935	0.860	0.764	0.544	0.340	0.088	0.013					3.71
		4.5	±135	3 (4, 5, 6)	0.01589	168	2.670	0.985	0.968	0.913	0.814	0.694	0.440	0.232	0.038	0.003					2.74
		5.0	±180	2 (1, 3, 4, 5, 6)	0.01375	196	2.695	0.986	0.969	0.918	0.824	0.708	0.460	0.250	0.045	0.004					2.90
		6.0	±180	2 (1, 3, 4, 5, 6)	0.01375	240	3.300	0.999	0.999	0.975	0.946	0.905	0.800	0.674	0.406	0.204	0.028	0.002			10.1
		6.9	0	1	0.00168	228	0.383	0.867	0.725	0.434	0.134	0.028									0.280
		7.0	0	2	0.00226	521	1.177	0.834	0.664	0.322	0.078	0.011									0.220
		7.0	0	2	0.00226	402	0.909	0.922	0.834	0.600	0.318	0.130	0.010								0.490
		8.0	0	2	0.00226	341	0.771	0.854	0.698	0.370	0.106	0.018									0.250
		7.7	0	2	0.00226	339	0.766	0.894	0.774	0.490	0.200	0.058									0.359
		6.1	0	3	0.00735	210	1.543	0.959	0.909	0.766	0.550	0.344	0.091	0.014							0.940
		7.5	0	4 (5, 6)	0.00319	388	1.238	0.885	0.758	0.464	0.178	0.047									0.326
6-8		7.0	±45	1	0.00336	398	1.337	0.917	0.824	0.580	0.294	0.114									0.460
		6.6	±45	2 (3)	0.00656	234	1.535	0.894	0.774	0.490	0.200	0.064									0.350
	7.7		±45	2 (3)	0.00656	404	2.650	0.905	0.800	0.535	0.244	0.084									0.400
		6.2	±45	2 (3)	0.00656	303	1.988	0.949	0.889	0.720	0.478	0.268	0.054								0.760
		8.0	±45	2 (3)	0.00656	309	2.027	0.945	0.881	0.704	0.454	0.244	0.044								0.710
	7.7		±45	2 (3)	0.00656	404	2.650	0.905	0.800	0.535	0.244	0.084									0.400
		6.1	±45	4 (5, 6)	0.00638	210	1.339	0.958	0.832	0.766	0.550	0.346	0.091	0.014							0.940
		6.5	±90	2 (1)	0.02144	392	8.404	0.834	0.651	0.304	0.069										0.210
		6.9	±90	3	0.00735	225	1.654	0.948	0.887	0.716	0.472	0.262	0.050								0.750
		7.8	±90	3	0.00735	246	1.808	0.988	0.957	0.933	0.855	0.758	0.536	0.328	0.084						3.60
		6.1	±90	4 (5, 6)	0.00638	216	1.378	0.981	0.959	0.888	0.765	0.626	0.350	0.151	0.015						2.13
		7.5	±135	1	0.00336	278	0.934	0.986	0.970	0.918	0.828	0.708	0.460	0.251	0.045	0.004					2.90
		6.6	±135	2	0.01808	244	4.412	0.988	0.973	0.928	0.846	0.743	0.514	0.305	0.068	0.009					3.37
		8.8	±135	3	0.01470	217	3.190	0.999	0.999	0.984	0.964	0.936	0.864	0.768	0.555	0.350	0.093	0.015	0.0014		15.3
		6.1	±135	4 (5, 6)	0.00319	216	0.689	0.982	0.959	0.889	0.768	0.626	0.350	0.151	0.015						2.13
		7.1	±135	4 (5, 6)	0.00319	161	0.514	0.948	0.886	0.712	0.468	0.258	0.048								0.740
		8.0	±180	2 (1)	0.01072	226	2.423	0.999	0.999	0.978	0.951	0.914	0.818	0.698	0.446	0.238	0.040	0.003			11.2
		8.0	±180	3 (4, 5, 6)	0.01054	195	2.055	0.999	0.977	0.937	0.865	0.768	0.554	0.358	0.094	0.015					3.80
8-15		12.1	0	1	0.00212	321	0.681	0.978	0.952	0.872	0.736	0.578	0.292	0.112	0.007						1.83
		10.0	0	1	0.00212	406	0.861	0.925	0.838	0.612	0.332	0.190	0.012								0.510
		9.0	0	1	0.00212	444	0.941	0.889	0.768	0.480	0.192	0.056									0.340
		10.0	0	1	0.00212	426	0.903	0.879	0.750	0.448	0.162	0.040									0.310
		9.9	0	1	0.00212	373	0.791	0.970	0.933	0.824	0.648	0.460	0.174	0.045							1.29
		9.9	0	1	0.00212	333	0.706	0.979	0.953	0.877	0.744	0.590	0.306	0.121							1.90
		9.0	0	2	0.03626	225	8.159	0.999	0.985	0.958	0.908	0.842	0.678	0.500	0.211	0.066					5.80
		10.0	0	4 (3, 5, 6)	0.0185	210	3.885	0.947	0.885	0.714	0.468	0.258	0.048								0.740
		12.7	±45	1 (2)	0.01632	295	4.814	0.999	0.977	0.939	0.873	0.775	0.564	0.360	0.100	0.018					3.92
		9.0	±45	1 (2)	0.01632	450	7.344	0.930	0.849	0.635	0.360	0.161	0.018								0.550
		9.0	±45	1 (2)	0.01632	465	7.589	0.905	0.800	0.535	0.244	0.081									0.400
		8.8	±45	3 (4, 5, 6)	0.01850	185	3.422	0.984	0.965	0.905	0.798	0.670	0.406	0.200	0.028	0.002					2.50
		10.0	±90	1 (2)	0.02448	426	10.428	0.959	0.910	0.768	0.554	0.350	0.096								0.950
		8.8	±90	3 (4, 5, 6)	0.00925	185	1.711	0.984	0.965	0.905	0.798	0.670	0.406	0.200	0.028	0.002					2.50
		9.0	±135	4 (1, 2, 3, 5, 6)	0.06746	212	14.302	0.999	0.982	0.949	0.889	0.814	0.626	0.154	0.035						4.80
		9.0	±180	1	0.00635	330	2.095	0.987	0.970	0.919	0.826	0.713	0.258	0.047							2.95
		10.0	±180	2	0.01813	286	5.240	0.999	0.999	0.983	0.961	0.933	0.855	0.758	0.536	0.330	0.085	0.012	0.001		14.1
		9.0	±180	3	0.00679	180	1.222	0.999	0.999	0.976	0.947	0.908	0.808	0.678	0.418	0.212	0.031				10.3
		9.0	±180	4 (5, 6)	0.00246	176	0.433	0.999	0.989	0.970	0.933	0.888	0.755	0.610	0.330	0.139	0.012				8.10
15	14.0	18.0	0	1 (2, 3, 4, 5, 6)	0.02516	354	8.907	0.988	0.972	0.925	0.838	0.730	0.492	0.284	0.068						3.18
	14.0	15.0	±45	1 (2, 3, 4, 5, 6)	0.02516	314	7.900	0.978	0.951	0.869	0.730	0.557	0.282	0.106							1.78
	9.0	11.0	±90	1 (2, 3, 4, 5, 6)	0.01253	370	4.636	0.978	0.951	0.869	0.730	0.557	0.282	0.106							1.77
	11.0	11.0	±135	3 (1, 2, 4, 5, 6)	0.02516	204	5.132	0.999	0.999	0.999	0.999	0.984	0.964	0.937	0.866	0.770	0.554	0.350	0.194	0.025	61.0
	13.0	13.0	±180	2 (1, 3, 4, 5, 6)	0.01253	202	2.531	0.999	0.999	0.976	0.947	0.908	0.808	0.678	0.418	0.212	0.031	0.002			54.8
Number of variations per hour exceeding given level (summing all conditions) 254.10								242.21	228.0	193.94	150.6	115.6	71.27	41.60	19.03	10.16	3.97	1.93	1.02	0.13	
Percentage of variations exceeding given magnitude							100 percent	95.3	89.7	76.3	59.3	45.5	28.0	16.4	7.5	4.0	1.56	0.76	0.40	0.051	

*The numbers in parentheses in column 4 represent ship speeds for which no data are available and for which the experimental data corresponding to the indicated speed class is assumed to apply for the purposes of the table.

**The factors f_1, f_2, f_3 are defined on pages 11 and 17. The factor f_4 is a weighting factor used when several similar sets of test data are utilized. For example, if 4 sets of similar test data were available and were utilized in the table, then $f_4 = 0.25$.

The *fractions of time* f_3 that the ship will make a given heading* to the sea for all operating speeds and for all characteristic wave heights not exceeding 15 feet are:

Head Seas	Quarter Head Seas	Beam Seas	Quarter Following Seas	Following Seas
0.125	0.25	0.25	0.25	0.125

For characteristic heights greater than 15 ft, the values in the table are modified such that f_3 is taken 0.125 for beam seas and 0.25 for head seas.

The weighting factors f_1 and f_3 are based on estimates made by the commanding officers of a number of ships of the ESSEX Class, as reported in Table 2 of Reference 6. The factors f_2 have been taken from the frequency distribution of wave heights shown in Figure 13 of Reference 7 and are applicable to Ocean Station *C* in the North Atlantic Ocean. The products of the weighting factors used in the calculations are given in Table 2.

The distribution patterns are calculated in Tables 3 through 6, where the probabilities $(1 - P)$ of exceeding given values of the variable are tabulated. The last line in each table is obtained by summing up all environmental conditions and thus gives the derived values of $(1 - P)$ for the long-term distributions. The latter values are plotted on the cumulative probability charts in Figures 3 through 6.

The straight lines shown on these charts have been 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 rather good fit of the computed line to the plotted points indicates that this assumption is reasonable.

The wave-induced hull girder stresses have been converted to bending moment amidships by making use of the midship section modulus which is applicable to the gage location. On VALLEY FORGE the strain gage was located 54.3 ft above the baseline and 23.76 ft above the calculated location of the neutral axis. The section modulus applicable to this strain-gage location is 167,000 ft-in.[2]

DESIGN AND OPERATIONAL CONDITIONS FOR WARTIME SERVICE

It has been pointed out 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 calculations of endurance strength. In this section, design and operational

*In this report the heading ϕ of the ship relative to the wave direction is defined as follows: For head seas, $\phi = 0$ deg; for quarter head seas, $\phi = \pm 45$ deg; for beam seas, $\phi = \pm 90$ deg; for quarter following seas, $\phi = \pm 135$ deg; for following seas, $\phi = 180$ deg.

conditions for wartime service will be determined on the basis of the following assumptions:

1. The vessel will generally be operating in the North Atlantic Ocean. The observations of sea conditions at Weather Station *C* (52 deg N 37 deg W), see Figure 13 of Reference 7, 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 last section.

3. All headings of the ship relative to the predominant wave direction are assumed equally probable, except that seas coming approximately off the beam are considered unlikely for combinations of high speeds and rough seas, as previously indicated.

LONG-TERM DISTRIBUTIONS

Figures 3 through 6 give the probability of exceeding and of not exceeding given values, if all the motions and stresses are considered to which the ship is subjected over a period of years. For example, only 3 percent of all variations in roll angle would, on the average, exceed a value of 4.5 deg port to starboard; see Figure 6. These distributions may be considered valid up to variations corresponding to a value of $(1 - P)$ equal to 1 percent.

PREDICTION OF EXTREME VALUES

In order to estimate the largest values of motions and bending moments for design purposes, the extreme value formula discussed on page 10 may be used:

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

It will be assumed that the worst combination of operating conditions is that which gives the largest value of E, E_m. The value of N may be estimated as follows: Assume that the ship will be subject to the worst operating conditions for a period, here taken as 4 hours, 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 of the prediction of an extreme, consider the maximum variation of longitudinal bending moment, excluding the effects of slamming. From Table 7

$$E_m = 0.156 \times 10^{12} \text{ (ft-ton)}^2, \ V = 1440$$

If we take $f = 0.001$, then Reference 10 gives $y = 7.0$. Therefore, with $n = 20$,

$$x_{m_1} = [0.156 \times 10^{12} (7.0 + 10.27)]^{1/2}$$

$$= 1{,}640{,}000 \text{ ft-tons hog to sag}$$

TABLE 7

Maximum Values of Ship Motions and Longitudinal Bending Moments for ESSEX-Class Carriers

All values given refer to peak-to-peak variation.

Quantity	Ship	Location of Test Area	Conditions for Which Extreme Value is Predicted (2)			Mean Square Value of the Variation, E_m – also Equals Four Times the Area under Power Spectrum	Number of Variations per 4-hr Period	Number of Variations Expected during Operating Life of Ship Corresponding to E_m	Estimated Most Probable * Maximum Value in One Storm (4-hr Operation)	Maximum Expected Value* during Operating Life of Ship [f = 0.001]	Largest Measured Variation (3)	Maximum Variation for Design Purpose
			Characteristic Wave Height ft (1)	Direction of Seas Relative to Ship's Course	Ship Speed (from RPM's) knots							
Roll Angle	ORISKANY	Cape Horn	> 15	Quarter Head	10	61.0 deg^2	980	19,500	19.6 deg	32 deg	19 deg	32 deg
Pitch Angle	ESSEX	Cape Horn	24	Quarter Head	8	12.8 deg^2	1180	23,700	9.5 deg	14.9 deg	9.5 deg	15 deg
Heave Acceleration	ORISKANY	Cape Horn	20	Head	10	0.014 g^2	1350	27,000	0.32 gravity units	0.49 gravity units	0.3 g (USS VALLEY FORGE)	0.5 gravity units
Longitud'l (4) Bending Stress	VALLEY FORGE	North Atlantic	> 18	Head	10	28.2 (kpsi)^2	1440	28,800	14.5 kpsi	22.3 kpsi	12.2 kpsi	22 kpsi
Longitud'l (4) Bending Moment ⊠	VALLEY FORGE	North Atlantic	> 18	Head	10	0.156×10^{12} ton^2 ft^2	1440	28,800	1,070,000 ft-tons	1,640,000 ft-tons	910,000 ft-tons	1,600,000 ft-tons
Bending (5) Moment Due to Whipping ⊠	ESSEX	Cape Horn	20	Quarter Head	17	-	52 cycles per minute when whipping occurs		-	-	1,230,000 ft-tons	1,850,000 ft-tons

(1) This is the average height of the larger, well-defined waves, as determined by visual observations.

(2) These are the conditions under which the largest values recorded at any time were obtained (peak-to-peak variation).

(3) These are the largest values recorded throughout seaworthiness tests on carriers, and cover about 2 years operation at sea.

(4) Stress, c.l. main deck, amidships. This is the ordinary wave-induced stress free of whipping stresses. The applicable section modulus = 167,000 ft-in^2.

(5) This bending moment is superimposed on the ordinary bending moment. The bending moments were computed from the stress by use of the design midship section moment of inertia, as calculated by Bureau of Ships.

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

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 the rough sea trails of ESSEX, VALLEY FORGE, and ORISKANY.

Predictions of extreme values should be used with caution because the method may break down by predicting too extreme a value. The extreme values listed in the last column of Table 7 are regarded as reasonable.

DESIGN MIDSHIP BENDING MOMENT

The midship bending moment just calculated must be augmented by the vibratory bending moment incident to slamming and by the still-water bending moment. It is, furthermore, desirable to estimate the parts of the total variation due to hogging and sagging. The still-water bending moment will vary with the ship's loading and can readily be computed by routine methods. Therefore, only the contributions of the vibratory and the ordinary wave-induced moments will be considered.

The most severe hull stresses experienced* by ESSEX occurred when the ship encountered a wave 26 ft high and 1028 ft in apparent length (821 ft real length) at a ship speed of 16 knots. The oscillogram, Figure 5a of Reference 4, indicates that the ordinary stress variation at the frequency of wave encounter was made up of approximately 60-percent sag and 40-percent hog relative to the still-water stress. A large, higher-frequency stress variation, corresponding to the two-noded mode of vertical whipping vibration, was superimposed on the ordinary wave stress.

The midship bending moment variations** corresponding to the most severe stresses measured during the passage of a single wave 26 ft high were: 515,000 ft-tons (60-percent sag, 40-percent hog) for the ordinary wave-induced stress, and 1,230,000 ft-tons for the whipping stresses. The stress may be expected to increase roughly as the wave height.[4] If, for design purposes, a wave 39 ft high is assumed† rather than the 26-ft wave actually experienced, the bending moment (corresponding to the ordinary wave-induced and to the whipping stresses) would be expected to be increased by 50 percent; i.e., the moments become 773,000 ft-tons and 1,850,000 ft-tons, respectively.

The midship design bending moment may then be calculated as follows, on the assumption that a 39-ft wave will be encountered.

---

*Measured at the centerline of the hangar deck (Gage 3). The maximum stress value including ordinary wave-induced and vibratory whipping stresses was 13,500-psi sag and 10,000-psi hog.

**Midship section modulus applicable to the location of Gage 3, 54.69 ft above the baseline, is 158,000 $in.^2$ ft.

†Figure 2, Reference 11, indicates that, for waves of apparent length nearly equal to the ship's length, a height of 26 ft will certainly be encountered and a height of 43 ft will be experienced rarely or never. The assumed value of 39 ft is considered a conservative, realistic compromise.

Method 1 (Without Use of Statistical Methods)

$$\text{Hogging Moment} = 0.40\ (773{,}000) + 0.50\ (1{,}850{,}000) + \text{still-water moment}$$
$$= 1.23 \times 10^6 \text{ ft-tons} + \text{still-water moment}$$

$$\text{Sagging Moment} = 0.60\ (773{,}000) + 0.50\ (1{,}850{,}000) + \text{still-water moment}$$
$$= 1.39 + 10^6 \text{ ft-tons} + \text{still-water moment}$$

Method 2 (Statistical Prediction of Ordinary Wave-Induced Bending Moment)

Expected design extreme value of ordinary wave-induced bending moment variation is 1,600,000 ft-tons (from Table 7). The maximum variation in bending moment incident to whipping (for the 39-ft wave) is 1,850,000 ft-tons.

$$\text{Hogging Moment} = 0.40\ (1{,}600{,}000) + 0.50\ (1{,}850{,}000) + \text{still-water moment}$$
$$= 1.57 \times 10^6 \text{ ft-tons} + \text{still-water moment}$$

$$\text{Sagging Moment} = 0.60\ (1{,}600{,}000) + 0.50\ (1{,}850{,}000) + \text{still-water moment}$$
$$= 1.89 \times 10^6 \text{ ft-tons} + \text{still-water moment}$$

It should be noted that the bending moment calculations are based on the midship section modulus which is computed on the assumption that the ship structure above the hangar deck does not contribute to the section modulus. It is suggested that the bending moments computed by Method 2 be used for hull structural design. It should not be necessary to apply a safety factor to these design values. For ships geometrically similar to ESSEX, the design bending moment may be assumed to vary roughly as the fourth power of the length.

DISCUSSION

The reader will readily appreciate that many operating difficulties make it impossible to obtain as complete and accurate data as desired. For example, the sea state is the most difficult variable to assess. Ship operations allowed test runs for only a few combinations of ship speed and heading for a continuous period of time when sea conditions were fairly constant. Consequently, it was necessary to take data for the missing combinations when approximately the same sea state was again encountered. These difficulties can be overcome by model testing rather than full-scale testing. Moreover, model testing can be accomplished more economically and for a wider variety of operating conditions. Furthermore, the general method of synthesis used in this report is equally applicable to model test data.

The statistical methods described in this report are sufficiently general that, together with the basic data in Table 1, they can be applied to predict motions and bending moments of

ESSEX-Class carriers or geometrically similar ships for a wide variety of different missions or types of operations. For example, a high-speed, nuclear-powered carrier similar in form to ESSEX might be treated. For this ship, the weighting factors should be adjusted to allow much more time of operation at higher speeds than ESSEX.

ACKNOWLEDGMENTS

The cooperation received from the commanding officers and personnel of VALLEY FORGE and ESSEX was of the highest order and made it possible to obtain realistic operational data that have long been needed. Assistance in analysis of the great volume of data was given by Mr. R.J. Dominic. Installation of trial gear was greatly expedited by the expert assistance of engineers and technicians of the Instrumentation Division.

APPENDIX A

SAMPLE OSCILLOGRAMS

Samples of typical oscillograms, obtained by the TMB automatic statistical recorder on VALLEY FORGE, are given in Figures 7 through 10. Each oscillogram is identified by the record number which corresponds to that given in Table 1; Table 1 also gives the pertinent environmental and operating conditions. On these oscillograms Channel 1 measured heave acceleration at the ship's center of gravity, Channel 2 (Gage 5) measured longitudinal strain in the keel, Channel 3 (Gage 3) measured longitudinal strain in the hangar deck, and Channels 4 and 5 measured pitch and roll angle, respectively. Strain-gage locations are shown in Figure 1.

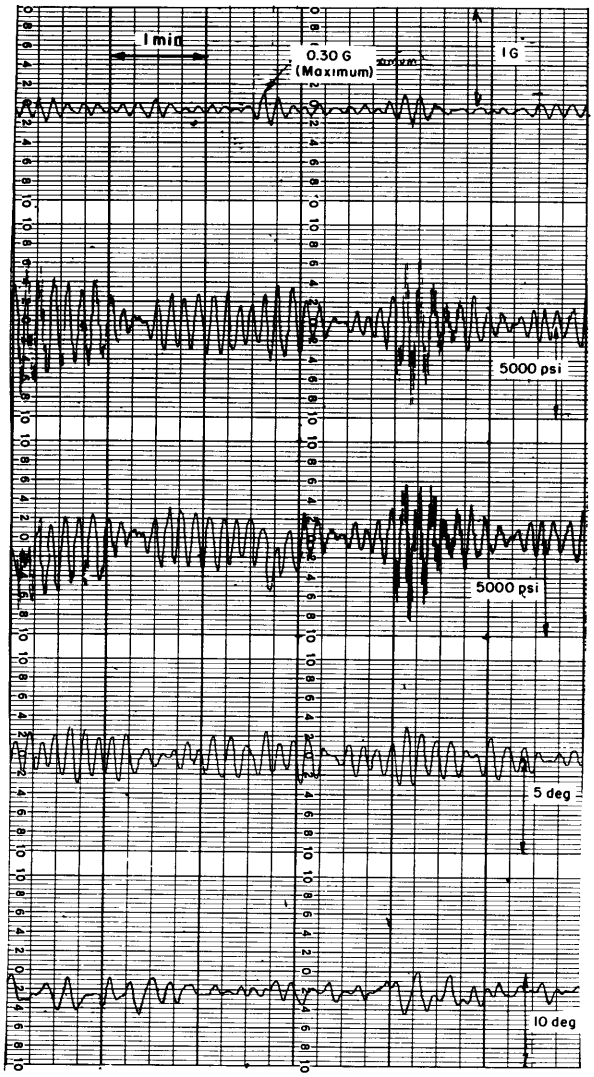

Figure 7 – Oscillogram Showing Maximum Heave Acceleration Record Number 69 on VALLEY FORGE

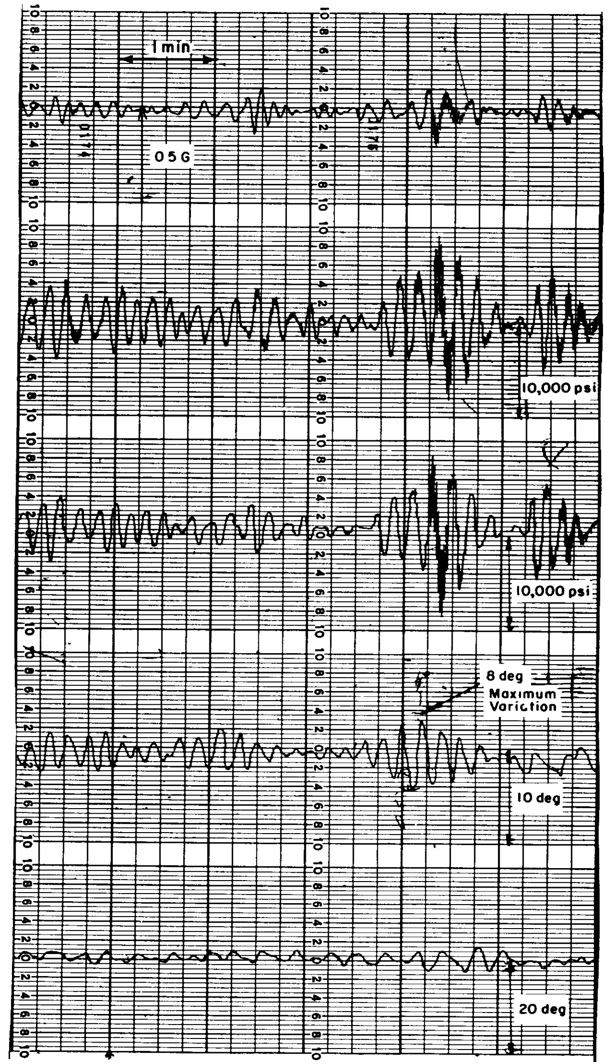

Figure 8 – Oscillogram Showing Maximum Pitch Angle Record Number 71 on VALLEY FORGE

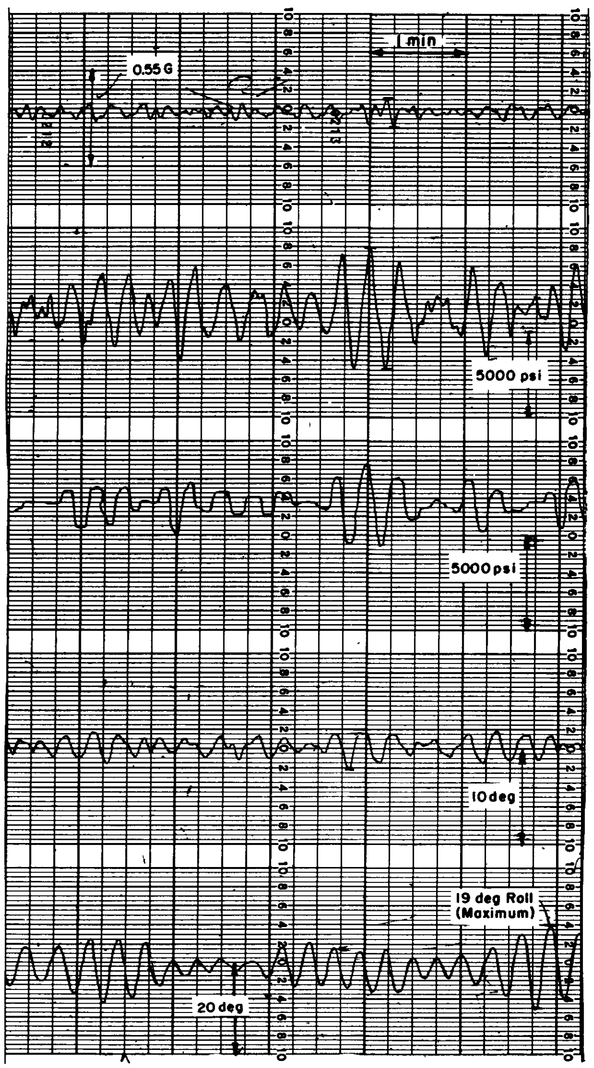

Figure 9 – Oscillogram Showing Maximum Roll Angle Record Number 75 on VALLEY FORGE

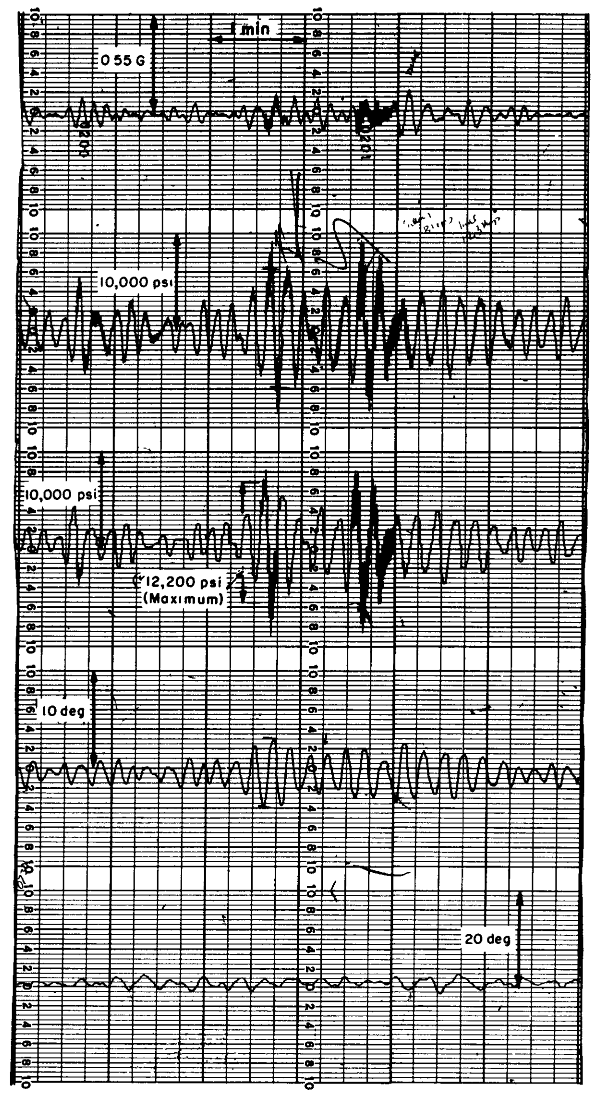

Figure 10 – Oscillogram Showing Maximum Longitudinal Stress Amidships Record Number 72 on VALLEY FORGE

APPENDIX B

COMPARISON OF LONGITUDINAL AND TRANSVERSE BENDING STRESSES

Longitudinal and transverse hull bending stresses (hangar deck amidships) are compared in Table 8. Stress variations obtained during the passage of a single wave are given for those occasions on which transverse bending made an appreciable contribution to the stresses. Figure 11 shows a sample record in which the strains on the port and starboard sides differ appreciably due to transverse bending.

It is apparent that for some operational conditions transverse bending moments* are appreciable; viz., for beam seas. However, the most severe bending stresses are experienced in head seas when transverse bending is relatively small.

TABLE 8

Comparison of Longitudinal and Transverse Bending Stresses for Occasions at which Transverse Bending Was Appreciable

Measurements were obtained on USS VALLEY FORGE.

Date	Ship Speed knots	Characteristic Wave Height ft	Relative Heading Ship to Waves	Stress, kpsi				Transverse Stress / Longitudinal Stress
				Gage 2	Gage 4	Longitudinal Bending	Transverse Bending	
9 Dec 55	10	10	Quarter Head	5	7.5	6.3	1.3	0.21
10 Dec 55	8	14	Quarter Head	6.7	3.1	4.9	1.8	0.37
9 Dec 55	10	–	–	4.0	6.7	5.4	1.4	0.26
9 Dec 55	10	–	–	2.5	5.7	4.1	1.6	0.39
9 Dec 55	10	–	–	3.0	8.3	5.7	2.7	0.47
1 Oct 55	10	9	Beam	1.4	2.7	2.1	0.65	0.31
1 Oct 55	10	9	Beam	1.0	4.0	2.5	1.5	0.60*
1 Oct 55	10	9	Beam	4.2	9.0	6.6	2.4	0.36
1 Oct 55	10	9	Beam	5.0	10.0	7.5	2.5	0.33
1 Oct 55	10	9	Beam	1.1	5.5	3.3	2.2	0.67**

*See instant marked a in Figure 11.

**See instant marked b in Figure 11.

*It should be noted that, at the midship section, the effective area moment of inertia for transverse bending is much larger than the moment of inertia for longitudinal bending.

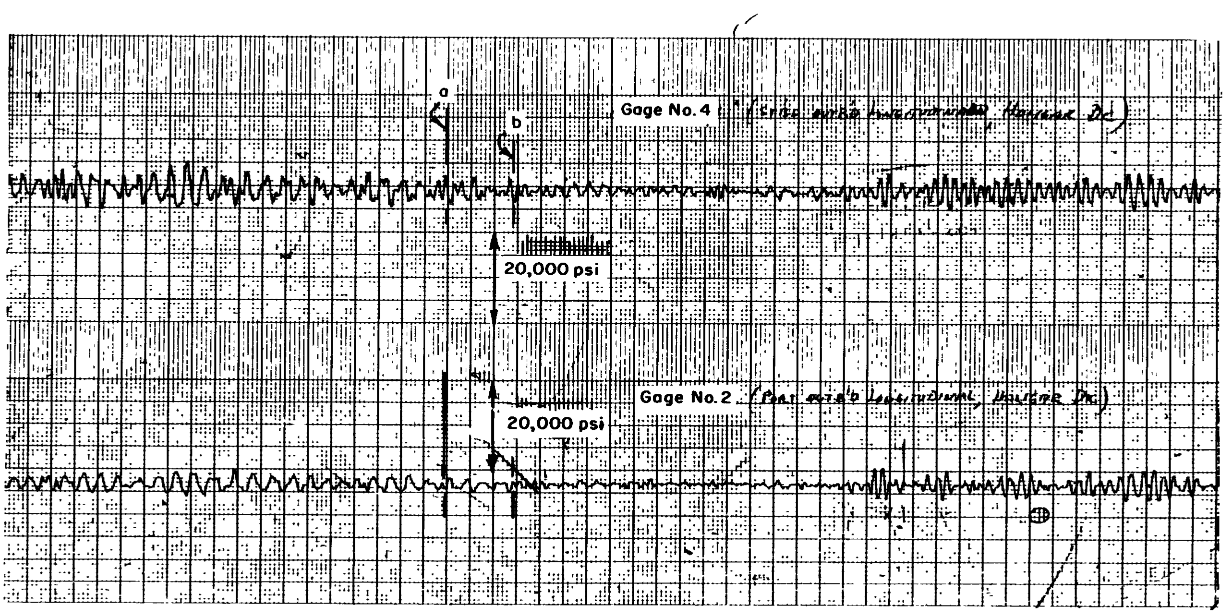

Figure 11 – USS VALLEY FORGE Sample Oscillogram

Date of test, 1 Oct 1955; zone time, 13:40–14:00; ship speed, 10 knots; beam sea; characteristic wave height, 9 ft.

Original chart scale: Smallest division equals 1 mm, chart speed is 0.25 mm/second.

APPENDIX C

COMPARISON OF STRAINS ON STRINGER PLATE AND ON LONGITUDINAL

On VALLEY FORGE a strain-gage bridge (Gage 1) was installed on the hangar deck 7½ in. inboard of the shell, and a single gage (Gage 2) was installed on the longitudinal stiffener closest to Gage 1. Both gages were oriented to measure strains in the longitudinal direction. Gage 1 consisted of a series of gages connected so as to give a signal proportional to longitudinal stress.

The purpose of Gages 1 and 2 was to determine whether a strain gage mounted directly on the deck plate, close to the shell, will be free of *local* plate bending stresses. Gage 2, on the longitudinal, was free of these local stresses and was subject to longitudinal strains only.

Gage signals are compared in Figure 12 for various magnitudes of strain variations. The two stresses are proportional, but Channel 1 indicates a magnitude about 10 percent greater than Channel 2. This difference may be due in part to the contribution of transverse bending.

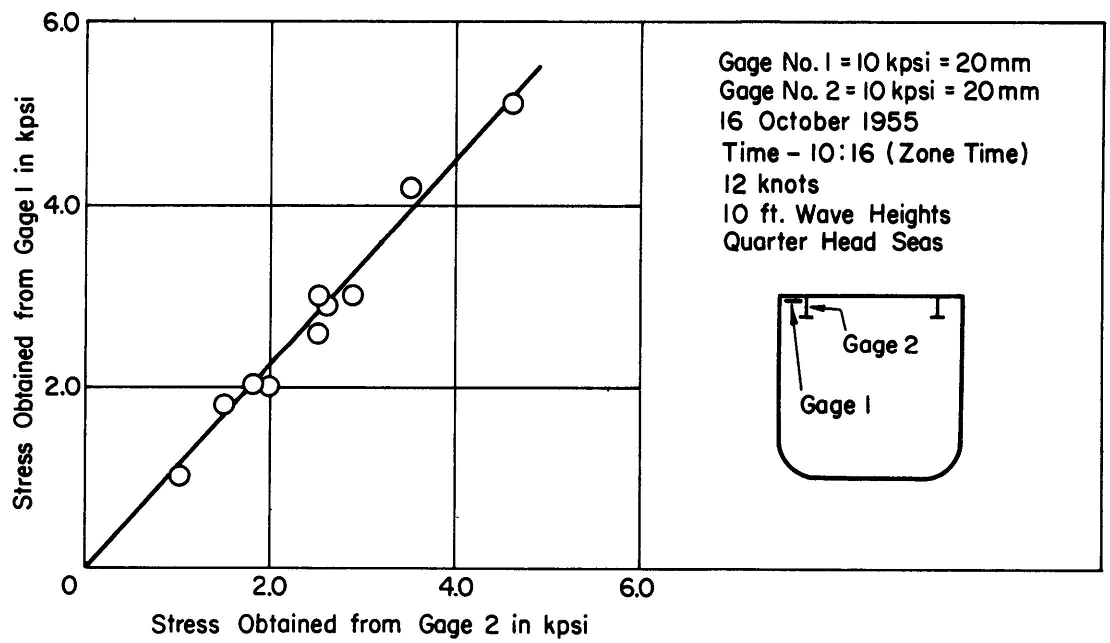

Figure 12 – Comparison of Longitudinal Stress Measured on Stringer Plate and on Longitudinal

(USS VALLEY FORGE)

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From the test results, data are derived for this type of ship for use in design and operating problems involving bending moments and ship motions. Formulas are given for use in estimating probable extreme values of moments and motions.

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The motions and longitudinal hull bending moments which ships of the ESSEX Class may be 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 VALLEY FORGE (CVS45) and USS ESSEX (CVA9).

From the test results, data are derived for this type of ship for use in design and operating problems involving bending moments and ship motions. Formulas are given for use in estimating probable extreme values of moments and motions.

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