SSC-164

Results From Full-Scale Measurements of Midship Bending Stresses on Two C4-S-B5 Dry-Cargo Ships Operating in North Atlantic Service

by

D. J. FRITCH
F. C. BAILEY
and
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ADDRESS CORRESPONDENCE TO:

SECRETARY
SHIP STRUCTURE COMMITTEE
U. S. COAST GUARD HEADQUARTERS
WASHINGTON 25, D. C.

September 1964

Dear Sir:

The Ship Structure Committee is currently sponsoring a project at Lessells and Associates, Inc., that is measuring the vertical bending moments on ocean-going ships.

Herewith is a copy of the fourth progress report, SSC-164, Results from Full-Scale Measurements of Midship Bending Stresses on Two C4-S-B5 Dry-Cargo Ships Operating in North Atlantic Service by D. J. Fritch, F. C. Bailey and N. S. Wise.

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

Please address any comments concerning this report to the Secretary, Ship Structure Committee.

Sincerely yours,

John B. Oren

John B. Oren
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

SSC-164

Fourth Progress Report
of
Project SR-153
"Ship Response Statistics"

to the

Ship Structure Committee

RESULTS FROM FULL-SCALE MEASUREMENTS OF MIDSHIP BENDING STRESSES ON TWO C4-S-B5 DRY-CARGO SHIPS OPERATING IN NORTH ATLANTIC SERVICE

by

D. J. Fritch
F. C. Bailey
and
N. S. Wise

Lessells and Associates, Inc.
Waltham 54, Massachusetts

under

Department of the Navy
Bureau of Ships Contract NObs-88349

Washington, D. C.
National Academy of Sciences-National Research Council
September 1964

ABSTRACT

Records of wave-induced midship bending stresses have been obtained on magnetic tape during the past three years using an unmanned instrumentation system. The reduced data cover thirty-four round trip voyages of two instrumented C4-S-B5 (machinery aft) dry-cargo vessels on the North Atlantic trade route. The data represent about 12,000 hours at sea out of five ship-years of operation. Each data point is based on a one-half hour record representing four hours of ship operation. According to past experience, better than 80% effectiveness can be expected from the unattended data collecting system. An automatic Probability Analyzer is used in the reduction of data.

All available data have been reduced and are presented as plots of rms stress variation and maximum peak-to-peak stress variation vs. sea state (Beaufort Wind Scale). Statistical methods are presently available for the prediction of extreme loads from the data.

The data have been shown to be representative of a class of ships exposed to sea states corresponding to Beaufort Numbers 3-7. More data are needed at the higher sea states, on other ship types, and other trade routes.

The reduced data and tapes are available to interested groups through the Investigators or the Secretary, Ship Structure Committee.

CONTENTS

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I. INTRODUCTION

A. General

This report represents the completion of the second phase of Ship Structure Committee Project SR-153: Statistical Studies of Seaway Loads Aboard Ship. Phase two has involved the recording, reduction, and preliminary analysis of midship bending stresses from two C4-S-B5 dry-cargo vessels* in North Atlantic service. During the period from November 1960 to January 1964, the averaged output of electrical resistance stress gages mounted amidship on the port and starboard gunwales has been recorded on a single channel of a magnetic tape recorder aboard each ship. Data are automatically recorded for thirty minutes each four hours, and continuously whenever stresses exceed a preset level.

The recorded signal results from a combination of bending moments produced by still water loading, waves, slamming, and diurnal temperature variation. During reduction of the data, all components are removed by filtering except the signal representing the stress in the fore and aft direction induced at the gage location by the vertical component of the wave-induced longitudinal bending moment; i.e., the stresses resulting from hogging and sagging.

At the end of 1963, after approximately five ship-years of operation on the two instrumented ships, the collected data represented about 12,000 hours of ship operation. At this point, the instrumentation was removed from one of the ships (S. S. HOOSIER STATE) for reinstallation aboard a different type of dry-cargo vessel, and the equipment remaining aboard the second vessel (S. S. WOLVERINE STATE) was converted to record the outputs of the port and starboard stress gages separately. The port and starboard records may then either be combined during data reduction, to simulate the previous data, or examined individually. Thus, a relationship between the averaged stress and the individual port and starboard stresses may be determined.

Because of the above mentioned change of ship type and the change in the data recording practice on the remaining C4, this would seem an opportune time to report on the experience and results of data collection and reduction to date.

The first phase of this project, covering the period from May 1959 to November 1960, involved the development and installation of an unmanned system for recording stresses aboard ship. It has been documented in Ship Structure Committee Report SSC-150 (1).**

A second Ship Structure Committee Report, SSC-153 (2) reports some early experience in employing manual reduction techniques on the taped data.

A third Ship Structure Committee Report SSC-159 (3) covers a period, May 1961 to June 1963, during which the Office of the Chief of Transportation, Department of the Army, participated in an extension of

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* The particulars of C4-S-B5 vessels are presented in Table 7.(appendix)

** See List of References, Section VI

the project to record wave-induced accelerations at several locations on one of the C4 Vessels (S. S. WOLVERINE STATE) for the purpose of determining seaway-induced loads on shipborne cargo.

B. Background

Studies of the seaway loading on ships have been pursued intermittently since the beginning of iron and steel shipbuilding. However, the present project, SR-153, represents the first systematic long-range study of seaway loading on operating merchant dry-cargo vessels of the United States. Similar studies on a more limited basis have been performed in other countries - notably in England, France, Japan, and Sweden. An attempt is being made to integrate the programs and results of these studies through The Committee on Response to Wave Loads of the International Ship Structures Congress (4).

The irregular character of the seaway has dictated a statistical approach to the analysis of ship response to seaway loads and the prediction of extreme values of loads on ship structures. The first major step in the statistical interpretation and analysis of seaway loads was the result of the work of Dr. Norman H. Jasper in the early and middle 1950's while he was at the David Taylor Model Basin (5).

In order to provide background data for the application of these statistical methods, data must be collected over a long period of time. To meet this requirement, Dr. Jasper and the David Taylor Model Basin developed equipment which simultaneously measured and analyzed the wave stresses into number of occurrences at preset stress levels right on the ship.

It was expected that Project SR-153 would continue with the collection of analyzed data by applying Dr. Jasper's method and equipment, which had previously been used mainly with naval and Coast Guard vessels, to operating commercial vessels on various trade routes. However, in determining the philosophy under which the project would operate, it was recognized that the data should be recorded in analog form so that as new analysis techniques developed, they could be applied to the data without requiring another long-term program. Magnetic tape recording offered a means of accomplishing the desired result. It provided means of recording and storing data in a convenient form which would be accessible in the future for digital computer and power spectrum analysis if these types of analysis should become appropriate.

An American Bureau of Shipping project currently active at Webb Institute of Naval Architecture (6) has provided the first opportunity for application of the collected and reduced data. The reduced data have been furnished to the Webb group as they become available.

The work of R. Bennet of Sweden at Webb Institute during the fall of 1962 and the spring of 1963 (9, 10) has represented the first extensive application of full-scale ship data, including that from Project SR-153, in the prediction of extreme values of seaway loads. In Bennet's approach, presented in detail in Reference (9), data collected on a given ship type operating on a specified trade route may be used to derive the response of the same ship operating on any other trade route for which statistical data on seaway conditions are available. Utilizing the stress and seaway data collected aboard ship on the given trade route, a generalized statistical response characteristic is developed. This characteristic represents the average response of the ship to each sea state on the Beaufort Wind Scale.* Combining this generalized response characteristic with the observed statistical distribution of sea conditions for another trade route provides an overall response characteristic for the same ship operating on the other trade route. The derived characteristic thus permits expected extreme values of seaway loads to be determined for the given ship operating on any specified trade routes.

The investigators have cooperated with The Society of Naval Architects and Marine Engineers in their efforts to encourage the operators of ocean-going tankers [7, 8] and Great Lakes ore carriers to participate in the collection of long-term data on seaway loading of these types of vessels.

During 1963, all available data were reduced using the Sierra Research Probability Analyzer which became operational early in the year. The method of data reduction utilizing the Probability Analyser is described in the Appendix.

As a result of the work at Webb Institute and at the Swedish Shipbuilding Research Foundation it became apparent early in 1963 that a simple and direct method of handling bending moment data would involve correlations between the root-mean-square stress variation** representative of each data interval and sea state encountered during the interval. All data from both ships were placed in this form (see Figures 1-6) and the patterns observed were generally similar to those found for several Swedish ships studied in a like manner [11]. The total data represented 4968 hours at sea for the S.S. HOOSIER STATE and 6828 hours at sea for the S. S. WOLVERINE STATE.

Data reduction and presentation will continue. An investigation of digital computer techniques is under way to determine the applicability of these techniques to the calculations involved in the final stages of data reduction after the basic output is obtained from the Probability Analyzer, and the compilation of these results with pertinent information from the data logs for use in future analysis. If the results of this investigation are satisfactory, the investigators plan to switch to the use of machine computations with a resultant saving in man-hours and an expected increase in accuracy over present manual calculations. An added advantage is that the accumulated reduced data will then be available in punched card form for various analysis techniques which can be performed rapidly on a generalized digital computer.

** The term stress variation is defined as the vertical distance from crest to adjacent trough or trough to adjacent crest on an oscillographic record of stress signals. See Reference [2].

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* The use of the term sea state throughout the remainder of this report will refer to numbers on the Beaufort Wind Scale (see Table 6). (appendix)

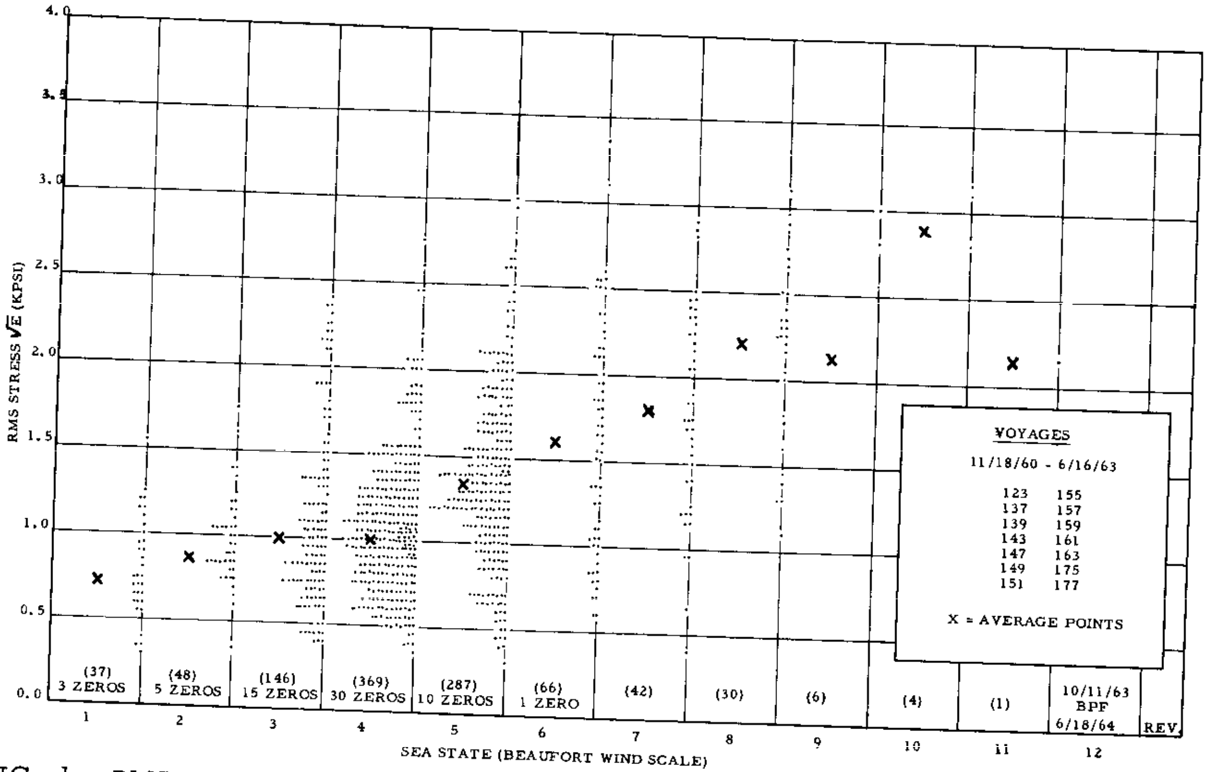

FIG. 1. RMS STRESS VERSUS SEA STATE (S. S. HOOSIER STATE)

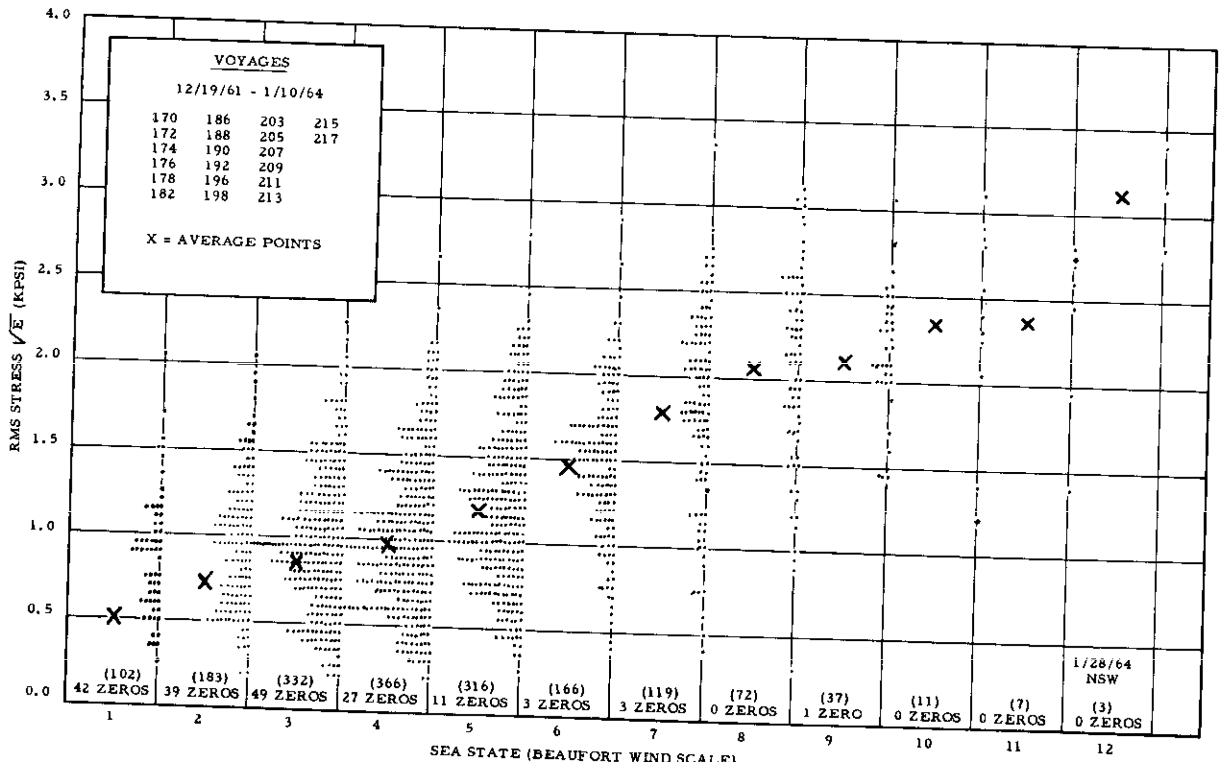

FIG. 2. RMS STRESS VERSUS SEA STATE (S. S. WOLVERINE STATE)

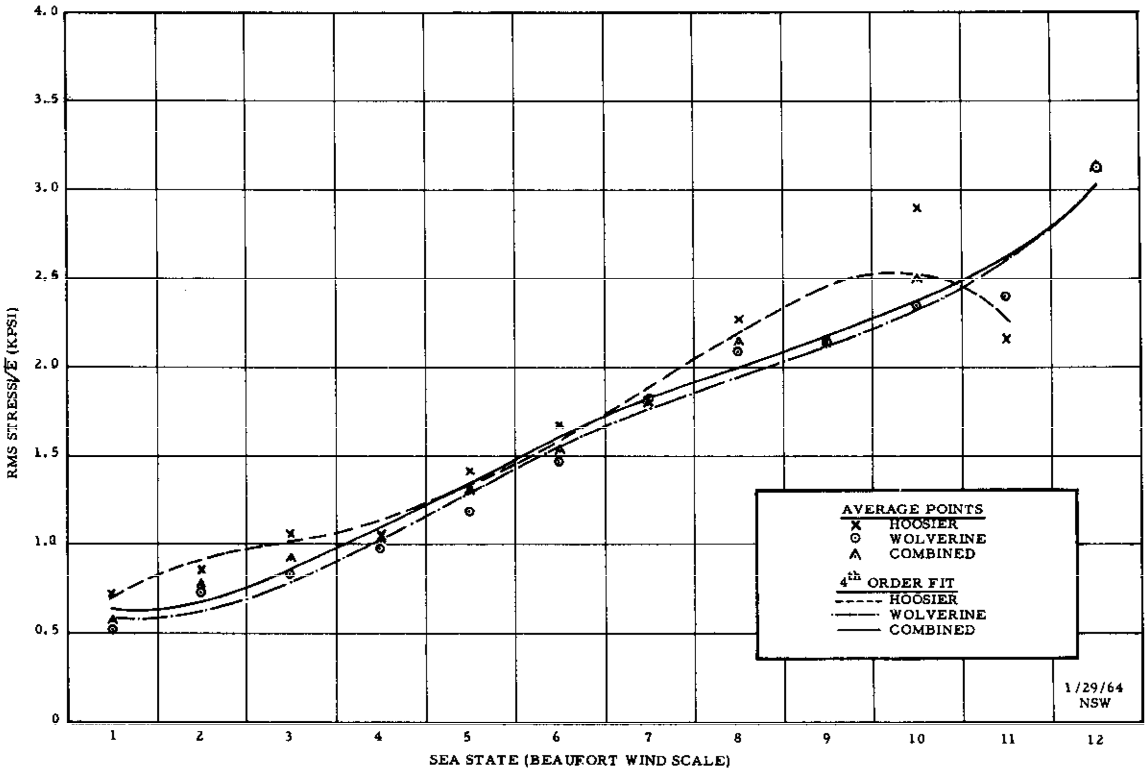

FIG. 3. RMS STRESS VERSUS SEA STATE (COMPARISON OF 4TH ORDER CURVES FOR EACH SHIP AND COMBINATION OF BOTH)

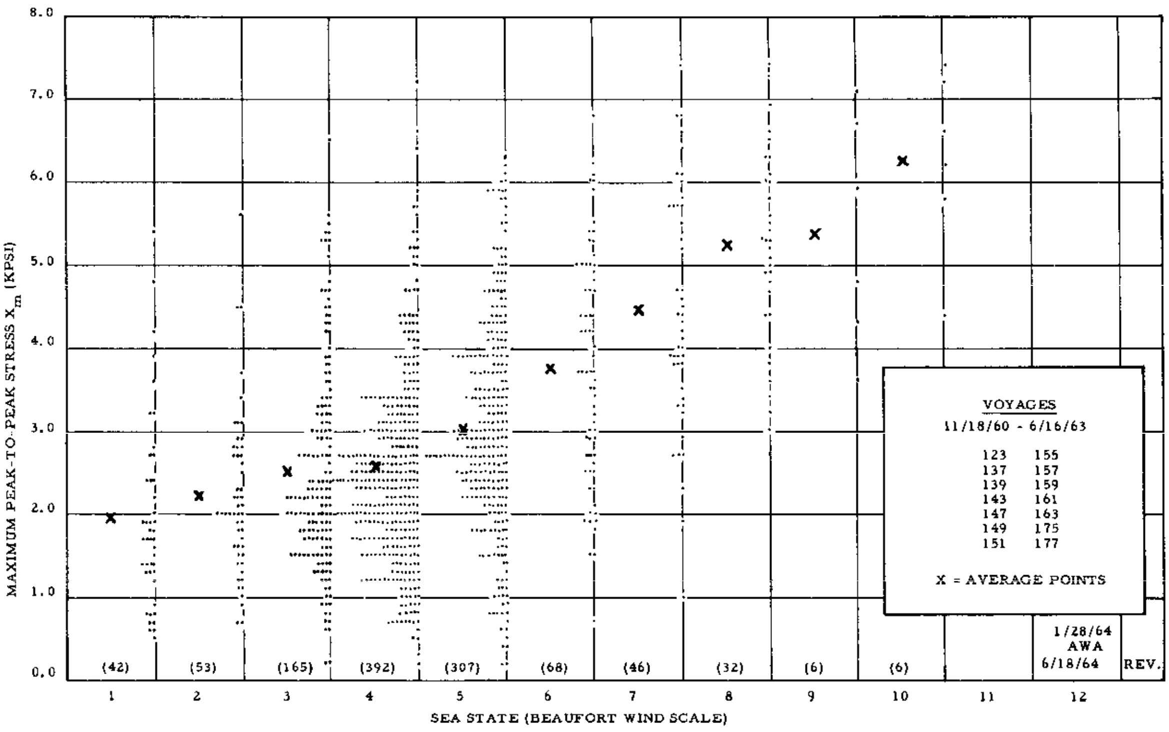

FIG. 4. MAXIMUM PEAK-TO-PEAK STRESS VS. SEA STATE (S.S. HOOSIER STATE)

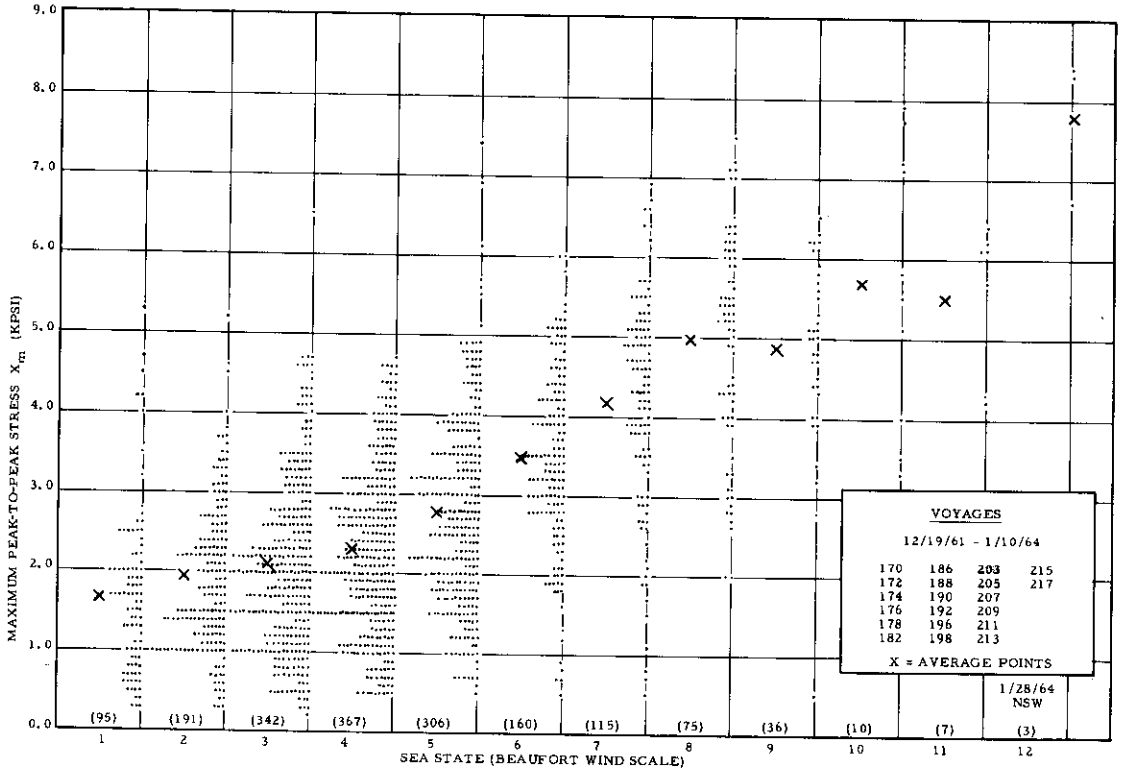

FIG. 5. MAXIMUM PEAK-TO-PEAK STRESS VS. SEA STATE (S.S. WOLVERINE STATE)

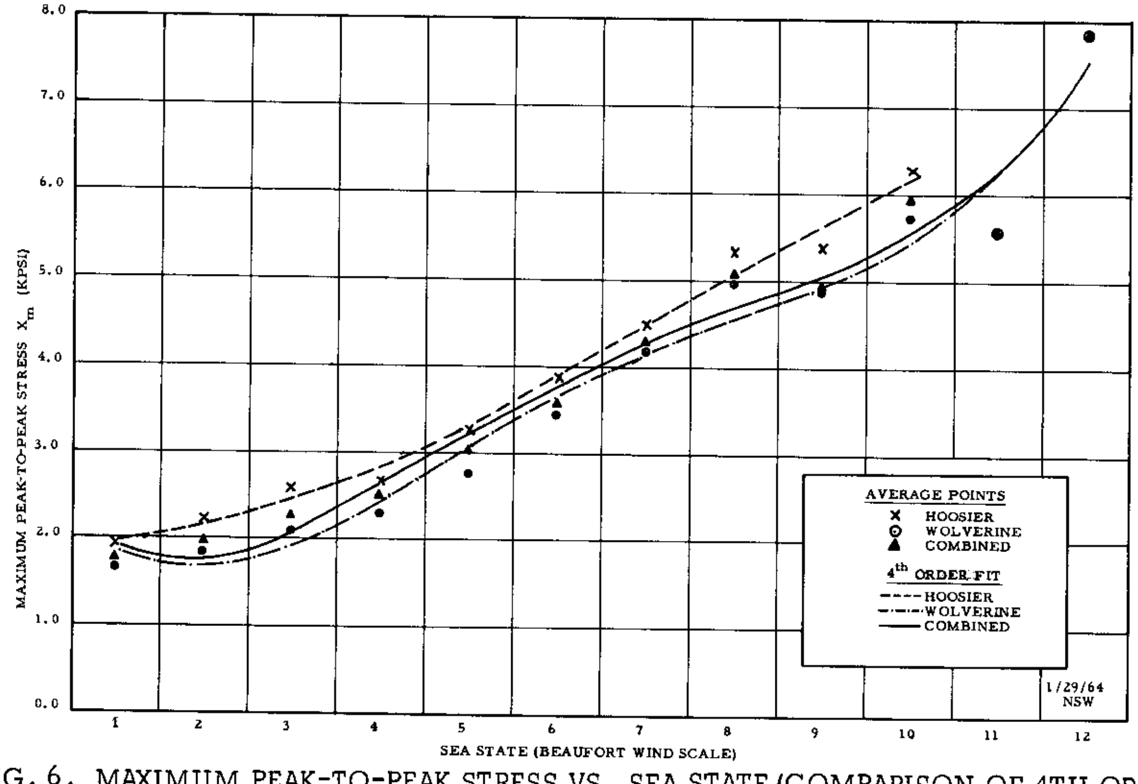

FIG. 6. MAXIMUM PEAK-TO-PEAK STRESS VS. SEA STATE (COMPARISON OF 4TH ORDER CURVES FOR EACH SHIP AND COMBINATION OF BOTH)

II. RESULTS OF DATA REDUCTION

Reduced data which have been collected during approximately five ship-years of operation of C4 (Machinery-aft) vessels in North Atlantic service are now available. The data cover fourteen round-trip voyages of the S. S. HOOSIER STATE between November 1960 and June 1963 and twenty round-trip voyages of a sister ship, the S. S. WOLVERINE STATE between December 1961 and January 1964. Tables 1 and 2 entitled "Current Tape Data" indicate the disposition of the reels of magnetic data tape recorded aboard each of the ships.

The results of data reduction have been accumulated by the Investigators on work sheets similar to Figure 17. These work sheets also include selected information on ship operation, weather, and sea conditions from a data log maintained for the project by the ship's officers. The parameters of particular interest for each reduced interval (one half-hour record for each four hours of ship operation) are the rms stress variation ($\sqrt{E}$) and the maximum recorded peak-to-peak stress variation (X_m). These quantities are particularly useful for the prediction of extreme values of seaway loading when plotted against sea state in a procedure proposed by R. Bennet of Sweden (9). Figures 1 and 2 present all available rms stress data from each ship vs. sea state. Figures 4 and 5 present all available maximum peak-to peak stress data vs. sea state. Each point on these figures corresponds to the reduced data from a half-hour record representative of four hours of ship operation. The average values of all the data points within each sea state have been calculated and are shown on the plots.

Curves of the best fourth order least square polynominal fit to these average values were determined in a digital computer study. The resulting curves for the individual ships and for the combined data from both ships are presented in Figures 3 (rms stress) and 6 (maximum peak-to-peak stress). The average points for each ship and for the combined data are indicated on these figures.

A similar fourth order plot, Figure 13, was made earlier in the project of data from an approximately equal number of voyages of both ships.

Figures 7 and 8 are combined plots representing the best visual fit through calculated average values of rms stress variation and maximum stress variation respectively as a function of sea state under different ship headings based on data from 11 voyages of the S. S. WOLVERINE STATE.

Figures 9 and 10 are graphs indicating the distribution of the time spent by each ship in various sea states during the total time represented by the reduced data (4,964 hours of operation of S. S. HOOSIER STATE, 6,828 hours of S. S. WOLVERINE STATE). Figures 11 and 12 give similar data on time spent at various ship speeds.

III DISCUSSION OF RESULTS OF DATA REDUCTION

The reduction and preliminary analysis of the tape recorded data take place in the Investigators' Laboratory using the equipment pictured in Figure 14. The data tapes consist of half-hour samples of bending stress signals recorded once during each four hours of ship operation at sea with extended records during heavy sea conditions.

(Manuscript continued on pg. 15)

TABLE 1. CURRENT TAPE DATA (S.S. HOOSIER STATE)

Instrument Voyage No.	SML Voyage No.	Reel No.	Log Book No.	Date Start	Date Finish	Record Head Tracks	Tape Data	and Remarks
1	123/124	123H	1	11/18/60	12/19/60	8	OK	
		124H	2				OK	
2	125/126	No Tapes	3	12/25/60	1/19/61	8	NG	FM OSC Failure. No data; had tape degaussed 3/3/61
3	127/128	No Tapes	4	1/31/61	3/5/61	8	NG	Stress Xducr trouble early in voyage. No data (10 hours).
4	129/130	129-130H	None	3/8/61	5/7/61	8	NG	Could not repair Xducr until return 5/7. (Corroded compensation gages.)(5/8-5/9 Xducr repairs.)
5	131/132	No Tapes	None	5/12/61	6/14/61	8	NG	15 min. timer trouble. Data to Norfolk (no valve) ran continuously. Officers shut down system.
6	133/134	No Tapes	5	6/16/61	7/10/61	8	NG	No data. No calibration. Fuse failure SGM two days before arrival New York City.
7	135/136	No Tapes		7/11/61	8/11/61	8	NG	Relief man, M-G set trouble (overspeed). Speed control resistor open 8/8/61. Repaired resistor replaced strain gage amplifier. Installed transistor elec. and 14 track head.
8	137/138	137-138H	9	8/16/61	9/8/61	14	OK	
9	139/140	139-140H	10	9/15/61	10/10/61	14	OK	
10	141/142	141-142H	8 & 11	10/17/61	11/8/61	14	NG	Noise, missing calibration. Data on Ch 1-2 only, few good intervals but cannot match log.
11	143/144	143-144H	12	11/12/61	12/6/61	14	OK	Installed new Video Instruments Amplifier Model 602A, Serial Number 189.
12	145/146	145-146H	13	12/12/61	1/5/62	14	NG	Noise, carrier cutting out.
13	147/148	147-148H	22	1/10/62	2/8/62	14	OK	
14	149/150	149-150H	22	2/12/62	3/12/62	14	OK	Complete return trip missing.
15	151/152	151-152H	24	3/17/62	4/14/62	14	OK	
16	153/154	153-154H	25	4/19/62	5/20/62	14	NG	Data on channel 1-2 only. Noise, missing calibration; relief man; cannot match entries in log book. Not operated on return voyage.
17	155/156	155-156H	41	6/7/62	6/29/62	14	OK	
18	157/158	157-158H	31	7/7/62	7/29/62	14	OK	
19	159/160	159-160H	28	8/16/62	9/7/62	14	OK	
20	161/162	161-162H	29	9/13/62	10/10/62	14	OK	

TABLE 1. (CONTINUED)

Instrument Voyage No.	SML Voyage No.	Reel No.	Log Book No.	Date Start	Date Finish	Record Head Tracks	Tape Data and	Remarks
21	163/164	163-164H	30	10/17/62	11/13/62	14	OK	
22	165/166	165-166H	53	11/18/62	12/10/62	14	NG	Noise.
23	167/168	No Tape	54	12/12/62	1/14/63	14	NG	Diode failure, no record, tape revised.
24	169/170	169-170H	55	1/16/63	2/7/63	14	NG	Failure of port gage, noisy.
25	171/172	171-172H	67	2/15/63	3/16/63	14	NG	Noise.
26	173/174	173-174H	63	3/22/63	4/13/63	14	NG	4/15 - Installed welded gages - RPC/DJF
27	175/176	175-176H	62	4/20/63	5/15/63	14	OK	5/20 - NSW installed correct calibration resistor.
28	177/178	177-178H	64	5/22/63	6/16/63	14	OK	
29	179/180	179-180H	65	6/24/63	7/18/63	14	NG	Noise (carrier intermittent).
30	181/182	181-182H	66	7/26/63	8/19/63	14	NG	Noise, replaced chopper in Video Instruments Model 602A, Serial No. 189. Replaced 70 mfd. 25V capacitor "leaky".
31	183/184	183-184H	67	8/31/63	9/22/63	14	NG	Noise, tape transport removed at end of voyage for factory servicing.

Instrumentation system exclusive of transducers removed from ship 12/31/63.

TABLE 2. CURRENT TAPE DATA (S. S. WOLVERINE STATE)

Instrument Voyage No.	SML Voyage No.	Reel No.	Log Book No.	Date Start	Date Finish	Record Head Tracks	Tape Data	Remarks
1	170/171	170W1	In Report 666/ill(b)	12/21/61	1/14/62	14	OK	W12 No calibration signals, W15, W17 No data.
		170W2						
2	172/173	172W1	In Report 666/ill(b)	1/23/62	2/22/62	14	OK	
		172W2					OK	
		172W3					OK	
3	174/175	174W1	26, 27	2/27/62	4/6/62	14	OK	
		174W2					OK	
		174W3					OK	
		174W4					OK	
4	176/177	176W1	17	4/11/62	5/8/62	14	OK	
		176W2					OK	
		176W3					OK	W31 No calibration signals, could not analyze.
5	178/179	178W1	35	5/11/62	6/6/62	14	OK	
		178W2					OK	
		178W3					OK	
6	180/181	180W1	36	6/10/62	7/5/62	14	NG	
		180W2					NG	
		180W3					1 Track only	W36 Only usable channel, all rest no data.
7	182/183	182W1	33, 34 (one page)	7/6/62	8/14/62	14	OK	
		182W2					OK	
8	184/185	no tapes	34	8/15/62	9/10/62	14	NG	No tapes, amplifier not working, replaced with spare.
9	186/187	186W1	16, 44 (one page)	9/16/62	10/16/62	14	OK	W14 No data.
		186W2					OK	W24 No data.
		186W3					OK	W34 No data.
10	188/189	188W1	44	10/16/62	11/9/62	14	OK	
		188W2					OK	
		188W3					OK	
11	190/191	190W1	50	11/14/62	12/7/62	14	OK	
		190W2					OK	
		190W3					OK	
12	192/193	192W1	51	12/9/62	1/4/63	14	OK	
		192W2					OK	
		192W3					OK	
13	194/195	194W1	56	1/11/63	2/12/63	14	NG	W11 No calibration signals. Amplifier trouble.
		194W2					NG	W21 No calibration signals. (Replaced.)
		194W3					NG	W31 No calibration signals.
14	196/197	196W1	57	2/17/63	3/20/63	14	OK	
		196W2					OK	W2 No data at beginning and end of tape. 33 intervals in middle - all channels. Tape must be rewound before analysis.
		196W3					OK	

TABLE 2. (CONTINUED)

Instrument Voyage No.	SML Voyage No.	Reel No.	Log Book No.	Date Start	Date Finish	Record Head Tracks	Tape Data	and Remarks
15	198/199	198W1	58	3/28/63	4/19/63	14	OK	
		198W2					OK	
16	201/202	201W1	59	4/23/63	5/27/63	14	—	All new mates;unable to operate equipment. Got coastwise data only. Removed accelerometers (both statistical and strain gage).
		201W2					—	
17	203/204	203W1	70	5/28/63	6/22/63	14	OK	
		203W2					OK	
18	205/206	205W1	71	6/28/63	7/20/63	14	OK	
		205W2					OK	
19	207/208	207W1	72	7/25/63	8/21/63	14	OK	
		207W2					OK	
20	209/210	209W1	73	8/23/63	9/16/63	14	OK	
		209W2					OK	
21	211/212	211W1	74	9/21/63	10/13/63	14	OK	
		211W2					OK	
		211W3					OK	
22	213/214	213W1	75	10/19/63	11/14/63	14	OK	
		213W2					OK	
		213W3					OK	
23	215/216	215W1	76	11/30/63	12/7/63	14	OK	One reel only. Machine not operated from New York to Bremerhaven.
24	217/218	217W1	77	12/18/63	1/10/64	14	OK	Five reels used; "3M" incorrectly supplied 1.5 mil tape for 1.0 mil tape.
		217W2					OK	
		217W3					OK	
		217W4					OK	
		217W5					OK	

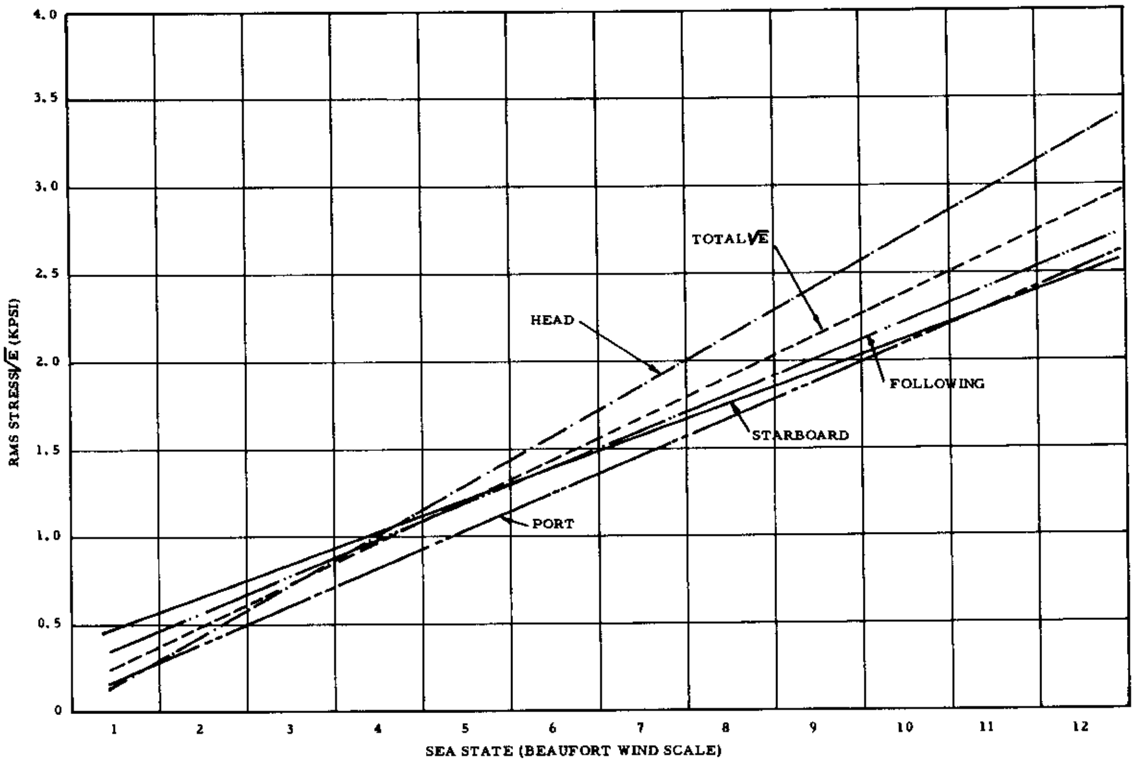

FIG. 7. RMS STRESS VS. SEA STATE (COMBINED PLOT) (S. S. WOLVERINE STATE)

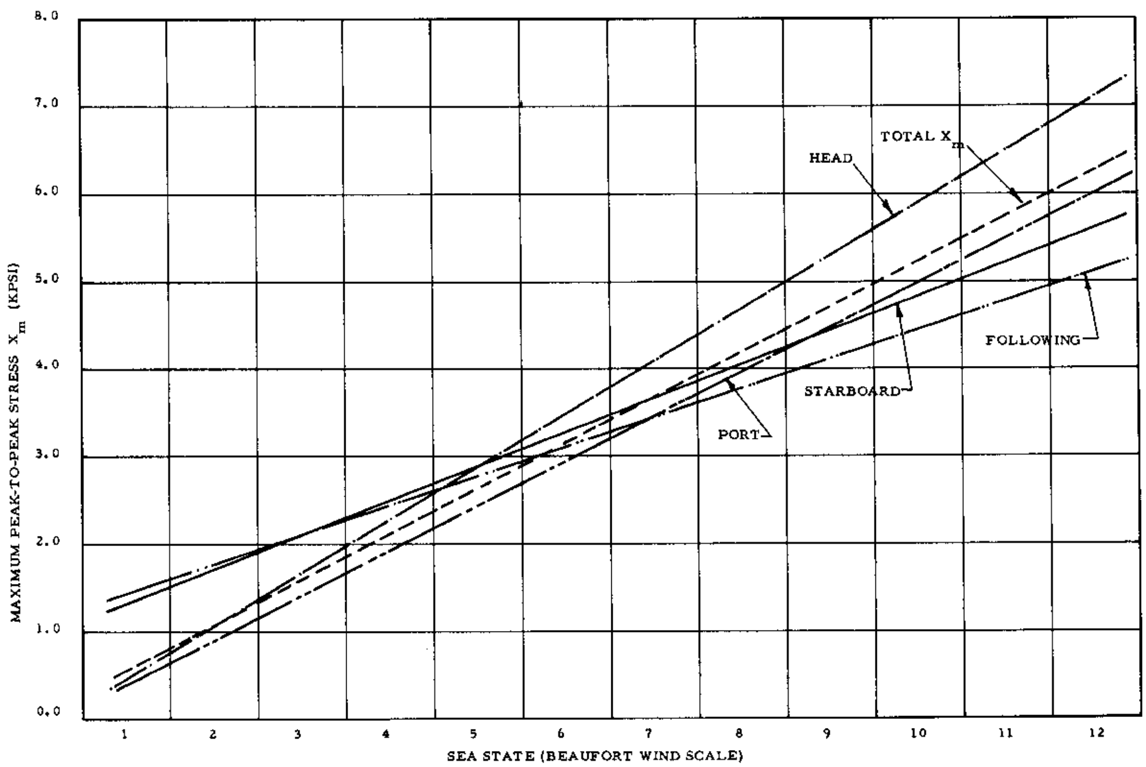

FIG. 8. MAXIMUM PEAK-TO-PEAK STRESS VS. SEA STATE (S. S. WOLVERINE STATE)

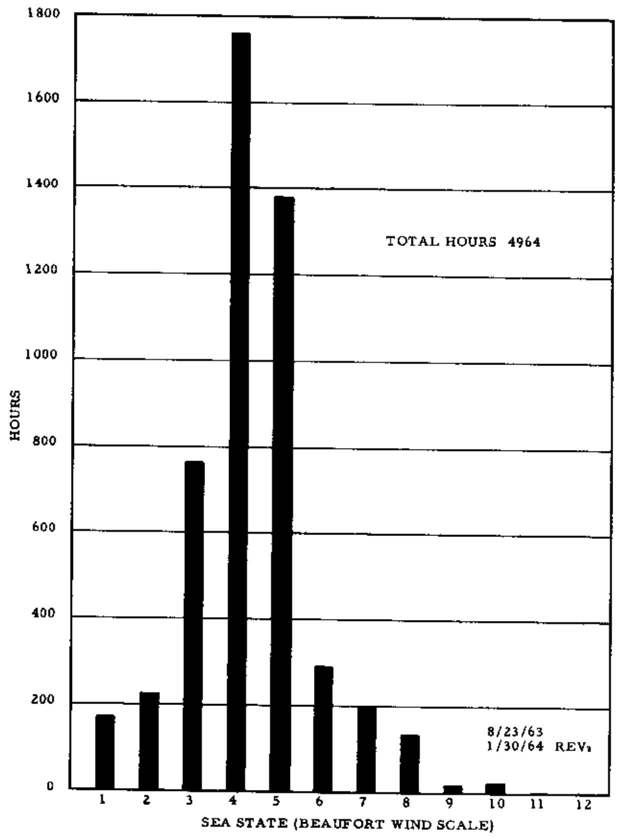

FIG. 9. NUMBER OF HOURS AT VARIOUS SEA STATES (S. S. HOOSIER STATE)

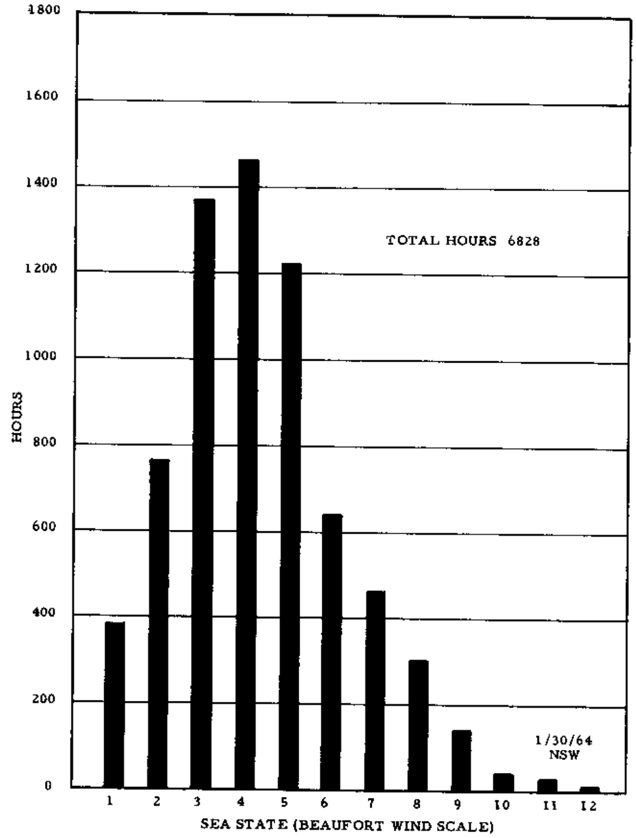

FIG. 10. NUMBER OF HOURS AT VARIOUS SEA STATES (S. S. WOLVERINE STATE)

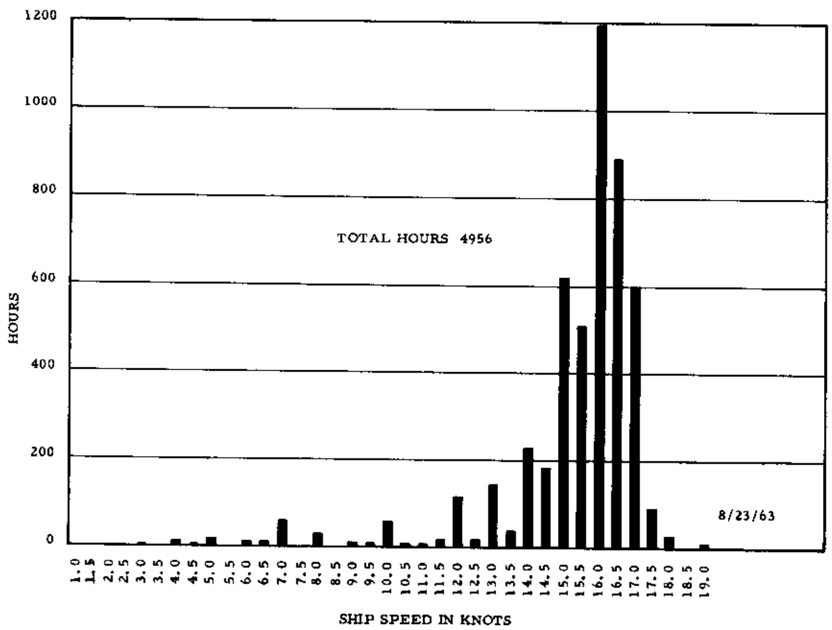

FIG. 11. SHIP SPEED VS. HOURS (S. S. HOOSIER STATE)

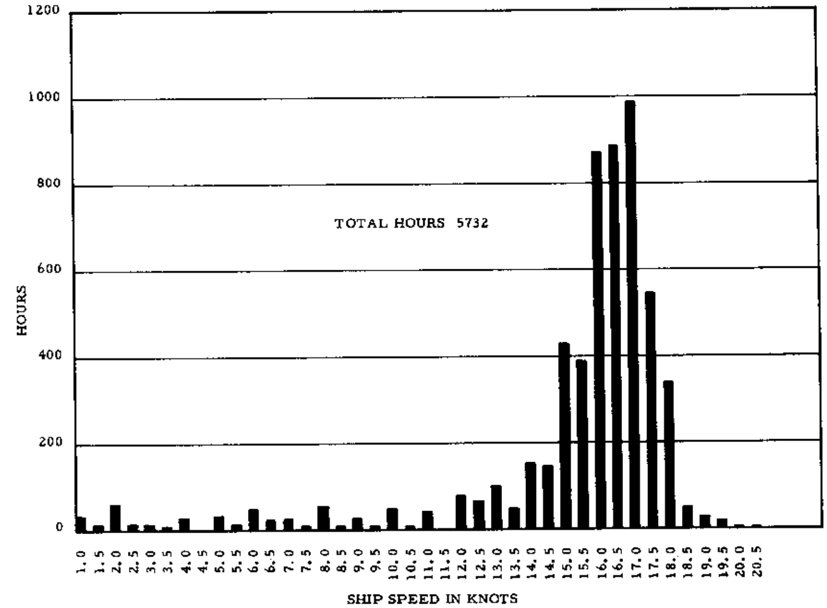

FIG. 12. SHIP SPEED VS. HOURS (S. S. WOLVERINE STATE)

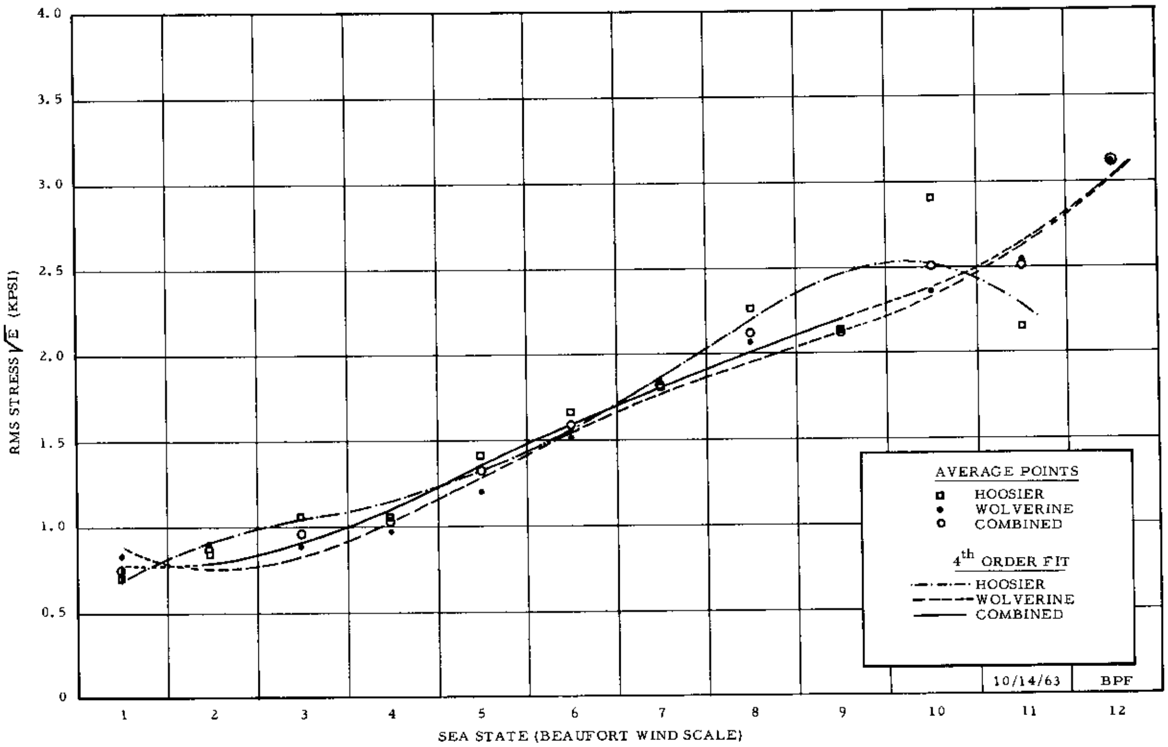

FIG. 13. RMS STRESS VS. SEA STATE (COMPARISON OF 4TH ORDER CURVES FOR EACH SHIP AND COMBINATION OF BOTH THROUGH JUNE 1963)

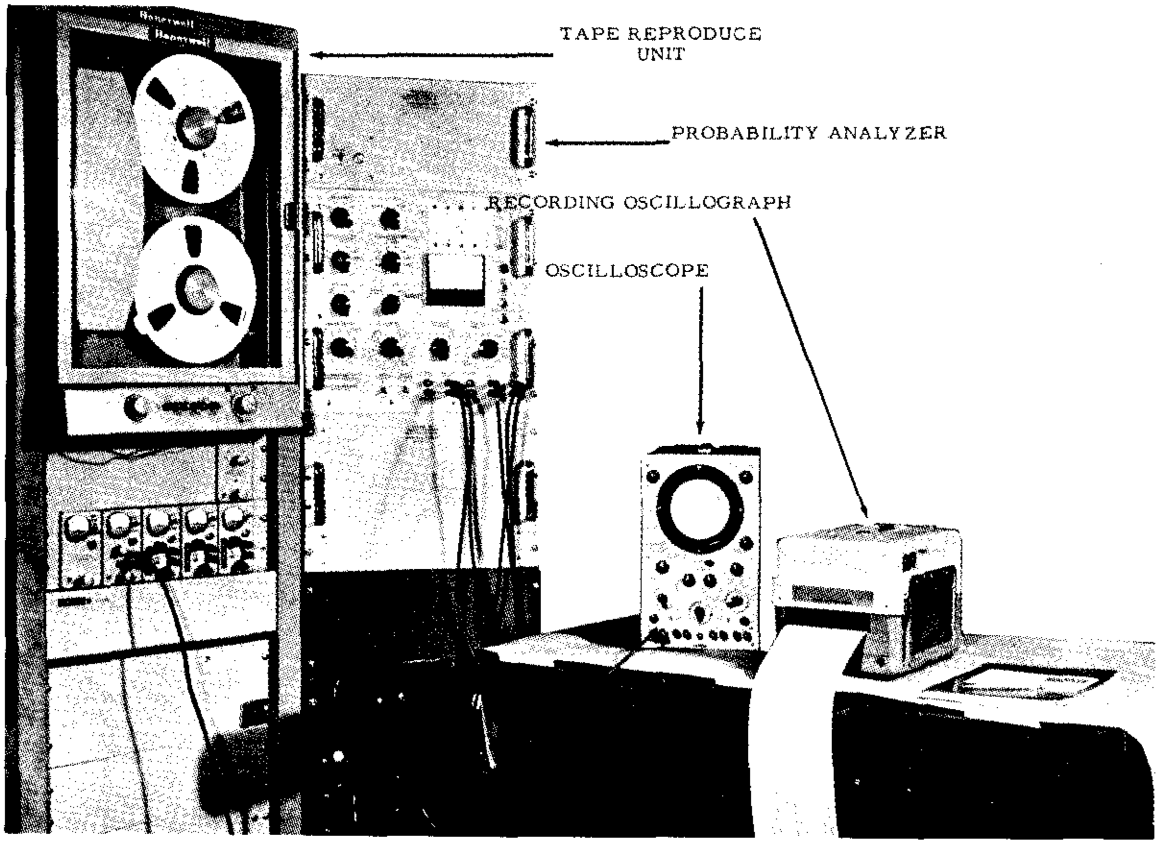

FIG. 14. PHOTOGRAPH OF DATA ANALYSIS SYSTEM

In the basic data reduction procedure, a twenty minute portion of each half-hour sample is automatically analyzed by the Probability Analyzer to provide a histogram of number of occurrences of peak-to-peak stress variations within 16 preset levels, rms stress variation ($\sqrt{E}$), average stress variation, maximum recorded peak-to-peak stress variation (X_m), and total number of stress variations which have been analyzed. The operation of the data analysis system and the technique for the reduction of each half-hour sample to tabulated values of rms and greatest peak-to-peak stress variation are presented in the APPENDIX along with samples of the Probability Analyzer output, a schematic of the data reduction procedure, and a sample work sheet for tabulating the reduced data. (See Figures 15 - 17.) Peak-to-peak variations of stress are studied in this project because of the difficulty in establishing still water stress level when the ship is away from the dockside and because the statistical procedures for analyzing peak-to-peak values of random variables are well established.

Obtaining a static load calibration on each ship has become increasingly important as more data are collected. As a practical matter, obtaining such a calibration on a dry-cargo vessel is complicated by limited time schedules and problems of inducing a large bending moment by shifting fuel oil and water ballast. Cargo handling does not usually contribute large bending moments. In the case of a tanker or bulk carrier, the situation should be considerably simplified.

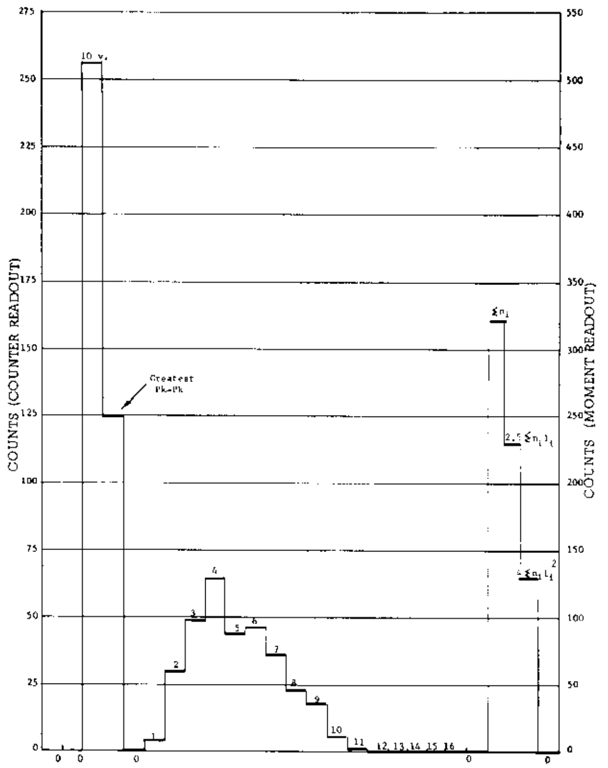

FIG. 15. TYPICAL RECORD OF PROBABILITY ANALYZER OUTPUT

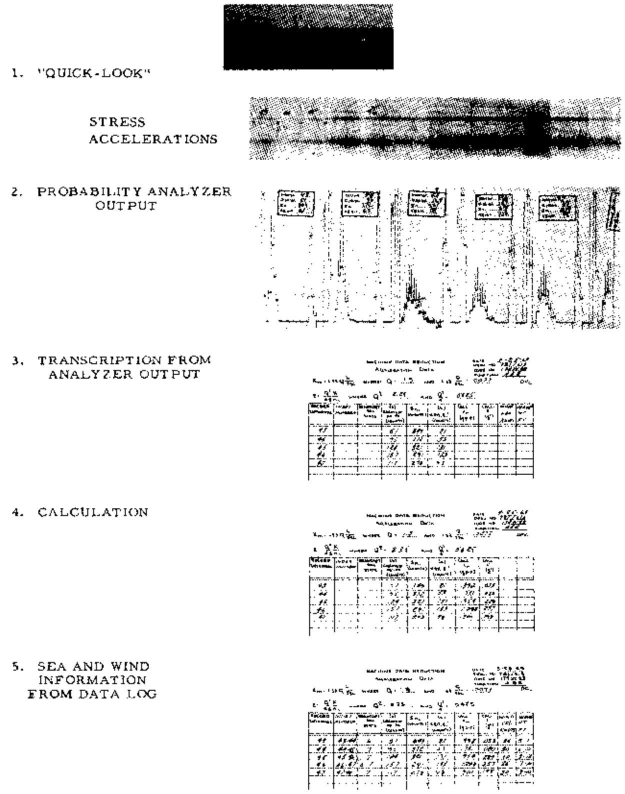

FIG. 16. SCHEMATIC OF ANALYSIS OF WAVE-INDUCED DATA

Q = 8 Kpsi   215 w11   16 Dec. '63

Voyage 215/216   S.S. Wolverine State

Record Interval	Index No.	Gpk/pk	Σn	$4\Sigma n l^2$	Calc. X_m	Calc. E	$\sqrt{E}$	Course	Ship Speed	Wind Sp.	Wind Dir.	Beaufort Sea State	Wave Dir.	Wave Ht.	Heading
1	1-2	117	291	60	4.68	4.39	2.09	244	10	30	240	7	240	8	
2	2-3	95	320	48	3.95	2.40	1.55	244	8	25	270	6	confused	8	
3	3-4	140	300	62	5.82	3.31	1.82	244	8	12	300	4	240	6	
4	4-5	68	302	22	2.83	1.17	1.08	244	7.5	10	045	3	confused	confused	
5	5-6	72	312	30	2.90	1.54	1.24	244	16.0	16	060	4	060	5	
6	6-7	77	255	31	3.20	1.95	1.40	244	16.0	26	040	5	045	7	
7	7-8	111	245	47	4.61	3.06	1.75	244	15.5	25	045	6	045	8	
8	8-9	85	255	40	3.53	2.51	1.58	244	16.6	27	024	6	024	8	
9	9-10	85	250	41	3.53	2.62	1.62	244	15.0	30	020	6	020	8	
10	10-11	80	258	31	3.32	1.92	1.39	244	15.6	30	350	6	000	8	
11	11-12	83	325	51	3.45	2.51	1.58	263	15.8	28	350	6	350	8	
12	12-13	73	280	35	3.03	2.00	1.41	263	16.0	23	350	4	000	6	
13	13-14	73	330	34	3.03	1.70	1.30	263	16.0	25	350	5	000	6	
14	14-15	73	300	30	3.03	1.60	1.26	263	15.6	16	070	3	070	3	
15	15-16	76	301	31	3.16	1.65	1.28	263	16.0	24	000	5	000	6	
16	16-17	75	270	19	3.12	1.13	1.06	Hove to	HOVE TO	25	350	5	000	6	
17	17-18	61	278	19	2.54	1.09	1.04	265	HOVE TO	20	010	5	010	6	
18	18-20	56	265	19	2.32	1.15	1.07	266	15.7	06	280	2	280	1	
19	20-21	85	301	56	3.53	2.98	1.73	263	11.0	03	280	0	NIL	0-1	
20	21-22	66	301	25	2.74	1.33	1.15	263	14.0	07	025	1	025	1	
21	22-23	58	325	20	2.41	.98	.99	263	16.0	12	090	1	045	3	
22	23-24	48	255	10	1.99	.63	.79	262	16.3	20	105	5	105	5	
23	24-25	44	224	8	1.83	.56	.75	262	16.5	18	080	5	080	6	
24	25-26	46	179	5	1.91	.36	.60	262	16.0	15	070	4	090	6	
25	26-27	40	178	7	1.66	.66	.81	262	17.5	23	340	5	340	6½	
26	27-28	50	282	12	2.08	.68	.82	262	16.5	28	005	6	005	8	
27	28-29	60	188	11	2.49	.94	.97	253	16.5	26	350	5	350	8	
28	29-30	71	202	12	2.95	.95	.97	253	16.66	27	340	5	340	8	
29	30-31	63	138	10	2.62	1.16	1.08	253	16.5	23	345	4	340	6	
30	31-32	40	95	2	1.66	.34	.58	253	16.7	21	350	4	345	6	
31	32-33	26	95	1	1.08	.17	.41	253	16.7	05	180	1	180	½	
32	33-34	32	95	1	1.33	.17	.41	253	17.0	07	220	1	220	2	

FIG. 17. TYPICAL WORKSHEET FOR CALCULATION AND REPORTING OF STRESS DATA

Reference is made to an earlier report (1) wherein calibration measurements on the S. S. HOOSIER STATE showed agreement between calculated and measured bending moment change within 5.5%. It is planned to make static load calibrations on the instrumented ships whenever the opportunity presents itself.

Each data point (in Figures 1, 2, 4, 5) is based on a twenty minute portion of the basic thirty minute sample record as was previously stated and is assumed to represent four hours of operation of the ship in the seaway. The spread of the data points is observed to run to about three times the computed average values in the lower sea states (1-5). This spread might be explained on the basis of the statistical nature of the data since the ship can operate at various headings relative to the sea and at various speeds within a given sea state. Since the reported sea state information is based on visual observations, some spread in these values as a result of individual interpretation is also likely. In addition, ship heading is not taken into account in these figures.

The number of stress variations counted during the analysis range, in general, from about 200 to 500 per record interval. The twenty minute record equals one-twelfth of the four hour period it represents. Thus, although the sample may be representative of average conditions in terms of $\sqrt{E}$, there is a probability of only one in twelve (8%) that the greatest peak-to-peak stress variation which occurs will appear in the data sample. On this basis, it is possible that actual maximum peak-to-peak stress variations may run as much as 20% higher than those appearing in the sample record. This difference is predicted from the approximate formula developed by Lonquet-Higgins ($X_m = \sqrt{E} \sqrt{\log_e N}$, where X_m is the most probable value of the maximum amplitude of stress variation for a total of N variations occurring during a period when $\sqrt{E}$, the rms stress variation, remains constant (see Section III.B. of Reference (2))) by assuming that the number of stress variations is increased by a factor of twelve.

Although there are more data available from the S. S. WOLVERINE STATE by about 30% voyage and time-wise, a comparison of the fourth order curves of Figures 3 and 6 indicates good agreement between ships expecially in the sea states 3 to 7 where most data are available. Close agreement is to be expected since the ships are of the same type operating on the same route. As data gathering continues, more information in the higher sea states will become available to reinforce the trends of the curves in this region.

A review of reduced data available from both ships was made to determine how the data from one ship compared with that from the sister ship. This study embraced 14 voyages of the S. S. HOOSIER STATE between November 1960 and June 1963 and 13 voyages of the S. S. WOLVERINE STATE between December 1961 and April 1963; that is, all available data on the HOOSIER STATE and an approximately equivalent amount of data available on the WOLVERINE STATE and taken in similar voyages. Tables 3 and 4 indicate the number of hours spent by each ship at various headings with respect to the seaway in this series of voyages, and Figures 11 and 12 show the number of hours spent by each ship at the various speeds.

TABLE 3. NUMBER OF HOURS AT VARIOUS HEADINGS (S. S. HOOSIER STATE)

Data from 14 Voyages During the Period 11/18/60 - 6/16/63		
HEADING	NUMBER OF INTERVALS	NUMBER OF HOURS
HEAD SEA	373	1492
* PORT BEAM SEA	286	1144
* STARBOARD BEAM SEA	270	1080
FOLLOWING SEA	313	1252
Total Hours		4968

* Total Hours 2224 (Beam Sea)

TABLE 4. NUMBER OF HOURS AT VARIOUS HEADINGS (S. S. WOLVERINE STATE)

Data from 11 Voyages During the Period 2/27/62 - 4/21/63		
HEADING	NUMBER OF INTERVALS	NUMBER OF HOURS
HEAD SEAS	253	1012
* PORT BEAM SEAS	200	800
* STARBOARD BEAM SEAS	291	1164
FOLLOWING SEAS	261	1044
Total Hours		4020

* Total Hours 1964 (Beam Sea)

TABLE 5. COMPARISON OF MACHINE AND MANUAL PEAK AND PEAK-TO-PEAK STRESS DETERMINATION

(X_m in KPSI pk-pk)

Record Interval (From Tape #174W31)	43 (Bft 6)			44 (Bft 7)			45 (Bft 7)		
Index Number	43 - 44			44 - 45			45 - 46		
	MACHINE		MANUAL	MACHINE		MANUAL	MACHINE		MANUAL
	Σ_n	X_m	X_m	Σ_n	X_m	X_m	Σ_n	X_m	X_m
PK/PK	305	1.83	1.69	425	4.54	4.68	334	4.95	4.70
+ PK	154	1.04	1.08	212	2.46	2.72	169	2.54	2.49
- PK	151	1.04	0.94	211	2.46	1.95	166	2.58	2.32
$\pm$ PK	307	1.04	-	430	2.50	-	331	2.54	-
(+PK + (-PK) (calculated)		2.08	2.02		4.92	4.67		5.12	4.81

NSW
15 Aug. 63

Figure 13 presents the plots of average rms stress values for the two ships individually and combined for these similar voyages and shows a very close agreement in response between the two. It was on this basis that it was decided that both ships were providing information characteristic of a class.

Table 5 summarizes a study to determine the differences which would result in the reduced data for X_m if the peak positive and peak negative stress (occurring with respect to still water value) were determined for each sample interval and added rather than considering the single

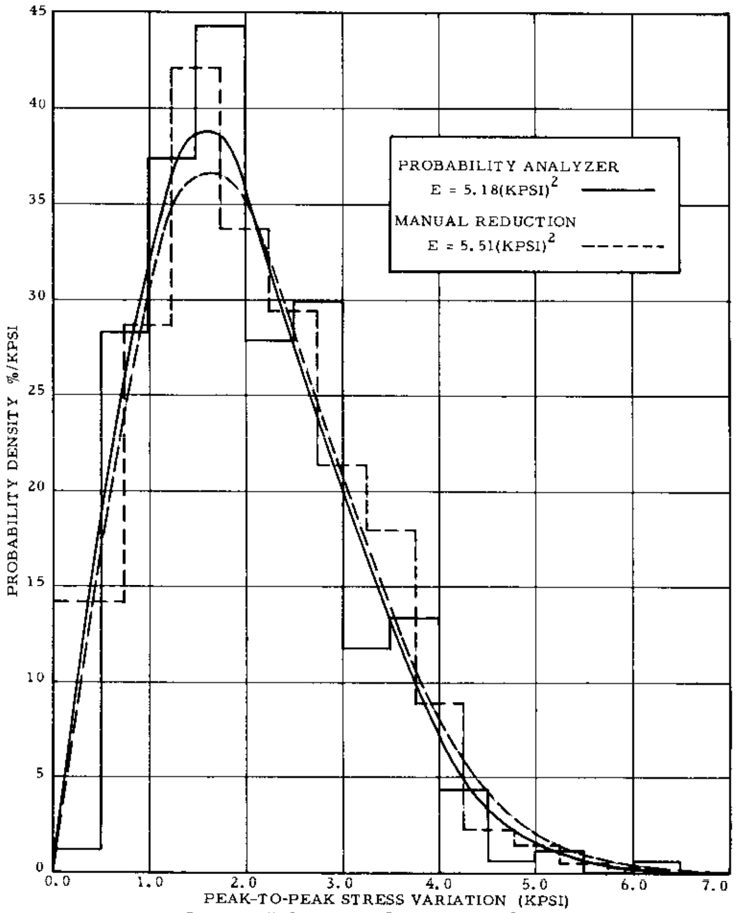

FIG. 18. HISTOGRAMS AND CORRESPONDING RAYLEIGH DISTRIBUTIONS (S. S. WOLVERINE STATE)

greatest peak-to-peak variation. The results at higher stress levels (4-5 KPSI pk-pk) were found to agree within 7-8% in the worst case and this order of difference was considered insignificant.

Figures 18 and 19 are examples of the good agreement obtained between the results of machine and manual analysis.

The techniques for data gathering and reduction have proven successful. It remains now to continue to obtain and process more information in order to increase reliability of the indicated trends, get more data in the extreme sea states, and apply the methods to additional ship types and routes.

IV. CONCLUSIONS

All available wave-induced stress data from 34 round-trip voyages of C4 (machinery aft) dry-cargo vessels operating on North Atlantic trade routes have been reduced and are available for study. The data represent about 12,000 hours at sea recorded during five ship-years of operation.

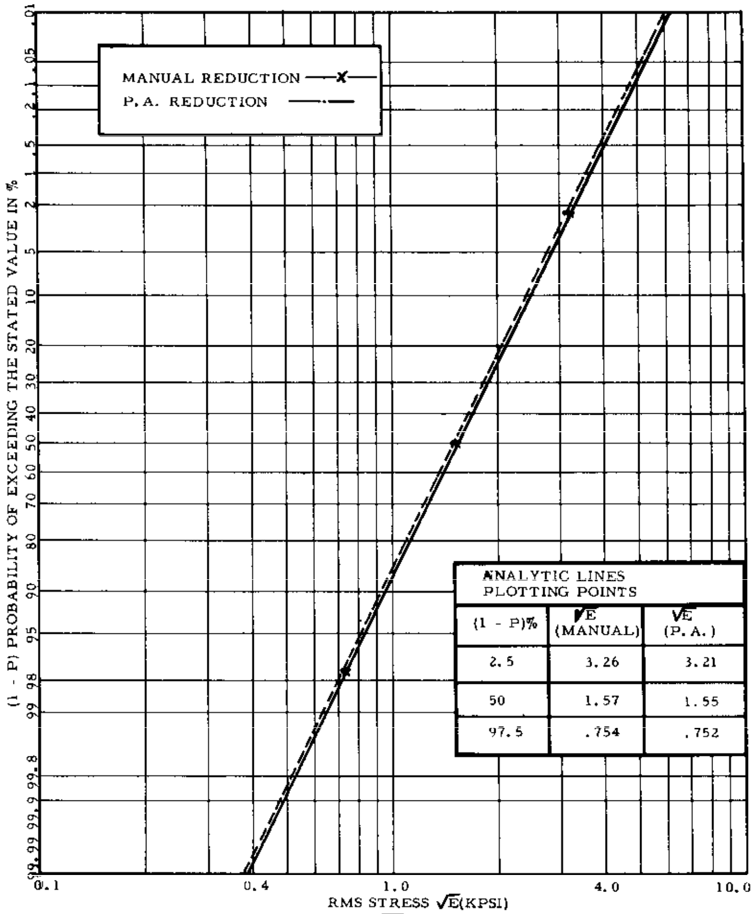

FIG. 19. LOG - NORMAL DISTRIBUTION OF $\sqrt{E}$ VALUES (S. S. WOLVERINE STATE)

In one method of analyzing these data the rms values of stress variation and the maximum peak-to-peak values were plotted against the sea state as measured by the standard Beaufort wind scale. These curves showed a consistent relationship.

The first vessel to be instrumented has provided useful data from 14 out of 31 round trip voyages (45%), whereas the second system has provided data from 20 out of 24 voyages (82.5%). Considering that the shipboard instruments are, for all practical purposes, unattended and the electronic components are operating continuously, the performance of the two shipboard units has been satisfactory. In the future, it should be possible to plan on at least 80% effectiveness of the system depending on the interval at sea between the routine maintenance checks at each East Coast turn-around.

The Sierra Research Probability Analyzer has provided a great savings in time and cost of data reduction and has permitted the project to maintain data reduction on a current basis. A comparison of the results of machine and manual reduction on several early voyages has proven the accuracy of the Probability Analyzer.

A comparison of the long-range data from the sister ships vs. sea state indicates that the data from each are typical of the class of ships over the range of conditions for which large amounts of data have been collected (Beaufort Numbers 3-7) with a trend continuing through the higher sea states where data are sparce because the ships seldom encountered these higher sea states.

The fact that the data are representative of a class of ships has permitted the system installed on the first ship to be removed for reinstallation aboard a new type of vessel with machinery amidship. The second C4 is to continue the collection of data with the emphasis on the higher sea states (9 and above).

The magnetic data tapes, data log books, and data reduction work sheets (see Figure 17) are being stored at the Investigators' facility and are available to other workers in the field. Inquiries relative to these items may be directed either to the Investigators, or to the Secretary, Ship Structure Committee, U. S. Coast Guard Headquarters, Washington, D. C.

V. ACKNOWLEDGEMENTS

This project is sponsored by the Ship Structure Committee and is under the advisory guidance of the Ship Hull Reserach Committee of the National Academy of Sciences, National Research Council. The assistance of the Project Advisory Committee with Dr. C. O. Dohrenwend as Chairman is gratefully acknowledged.

The wholehearted cooperation of States Marine Lines, and in particular, Messrs. E. P. Bainbridge, Neil Miller and the officers and men of the S. S. HOOSIER STATE AND S. S. WOLVERINE STATE has been a major factor in the success of the investigation to date. The contribution of States Marine Lines in the form of shipboard wiring and instrument installation is particularly appreciated.

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APPENDIX

DESCRIPTION OF DATA REDUCTION TECHNIQUES

A. System

The data reduction system as shown in Figure 14 consists of the Magnetic Tape Reproduce Unit, the Probability Analyzer (a special purpose computer), and a Recording Oscillograph.

The tape reproduce unit accepts the 10½ inch reels of one inch wide tape which have been recorded on the ships using FM recording techniques. The data are played back at speeds up to 200 times (60 ips) the recording speed (0.3 ips), using 14 track IRIG heads and FM demodulation techniques.

The Probability Analyzer accepts the output signals of the tape reproduce unit, changes the latter's analog signals to digital form, performs the analysis, and translates the results back to analog form for readout. In operation, the output of the tape unit is filtered by the probability analyzer's input filter. This eliminates all but the wave-induced data. These data, for a given record interval. are then sorted by magnitude and stored as counts in one of sixteen level counters. Analysis is completed at the end of a preset time interval, a predetermined number of total counts, or when the storage capacity of one of the level counters is reached. At this point, the system automatically stops the analysis and provides a readout cycle directly on the recording oscillograph. The readout provides a histogram (bar

TABLE 6. TABLE OF BEAUFORT NUMBERS

Force	Wind Speed	Description of Sea
0	Less than 1 kt	Like a mirror.
1	1-3 kt, mean 2 kt	Ripples, with the appearance of scales, are formed; but without foam crests.
2	4-6 kt, mean 5 kt	Small wavelets, still short but more pronounced - crests have a glassy appearance and do not break.
3	7-10 kt, mean 9 kt	Large wavelets. Crests begin to break. Foam of glassy appearance. Perhaps scattered white horses.
4	11-16 kt, mean 13 kt	Small waves becoming larger. Fairly frequent white horses.
5	17-21 kt, mean 18 kt	Moderate waves, taking a more pronounced long form; many white horses are formed. (Chance of some spray.)
6	22-27 kt, mean 24 kt	Large waves begin to form, the white foam crests are more extensive everywhere. (Probably some spray.)
7	23-33 kt, mean 30 kt	Sea heaps up and white foam from breaking waves begins to be blown in streaks along the direction of the wind.
8	34-40 kt, mean 37 kt	Moderately high waves of greater length, edges of crests begin to break into the spindrift. The foam is blown in well-marked streaks along the direction of the wind.
9	41-47 kt, mean 44 kt	High waves. Dense streaks of foam along the direction of the wind. Crests of waves begin to topple, tumble and roll over. Spray may affect visibility.
10	48-55 kt, mean 52 kt	Very high waves with long overhanging crests. The resulting foam in great patches is blown in dense white streaks along the direction of the wind. On the whole, the surface of the sea takes a white appearance. The tumbling of the sea becomes heavy and shock-like. Visibility affected.

TABLE 6 (Continued)

Force	Wind Speed	Description of Sea
11	56-63 kt, mean 60 kt	Exceptionally high waves. (Small and medium sized ships might be for a time lost to view behind the waves.) The sea is completely covered with long white patches of foam lying along the direction of the wind. Everywhere the edges of the wave crests are blown into path. Visibility affected.
12	64-71 kt, mean 68 kt	The air is filled with foam and spray. Sea completely white with driving spray. Visibility very seriously affected.

Note: The Beaufort Scale extends to force 17 (118 kt.), but force 12 is the highest which can be distinguished visually from the sea.

TABLE 7. TABLE OF PARTICULARS OF C4-S-B5 VESSELS

A. General

Original Name: MARINE RUNNER

Type: C4-S-B5 Machinery-Aft Dry Cargo Vessel

Builder: Sun Shipbuilding and Drydock Company
Chester, Pennsylvania

Date: September 1945

Hull Number: 359

Length Overall:	520'-0"
Length Between Perpendiculars:	496'-0"
Beam, Molded:	71'-6"
Depth, Molded:	54'-0"
Depth, Molded to Poop Deck:	52'-0"
Depth, Molded to Upper Deck:	43'-6"
Depth, Molded to Second Deck:	35'-0"
Depth, Molded to Third Deck:	26'-0"
Load Draft, Molded (Design):	30'-0"
Load Draft, Keel (Full Scantling):	32'-9 7/8"
Gross Tonnage:	10,747

TABLE 7 (Continued)

Net Tonnage:	6,657
Official Number:	248,740
Block Coefficient:	0.654 (30' Molded Design Draft) 0.61 (18' Typical Present Operation)
Prismatic Coefficient:	0.664 (30' Molded Design Draft) 0.628 (18' Typical Present Operation)
Waterplane Coefficient:	0.752 30' 0.685 18'
Midship Section Modulus (with deck straps):	45,631 in.^{2} ft. (to top of Upper Deck)

B. Light Ship

Light Ship Weight:	6,746 L.T.
Center of Gravity:	30.40 ft. above keel 24.20 ft. aft of amidships
Light Ship Drafts:	3'-7" forward 19'-9 1/2" aft 11'-8 1/4" mean
Dead Weight at 32'-9 7/8" (Cargo Capacity):	15,348 L.T.

C. Machinery

Propulsion System: Steam Turbine with Double Reduction Gear

	Normal	Maximum
H.P. Turbine, Design R.P.M.	5,358	
L.P. Turbine, Design R.P.M.	4,422	
Propeller, Design R.P.M.	85	88
Propeller, Normal Operating R.P.M.	80	
Shaft Horsepower, H.P. Turbine	4,500	
Shaft Horsepower, L.P. Turbine	4,500	
Shaft Horsepower, Total	9,000	9,900
First Reduction Gear, H.P. Turbine	9.096	
First Reduction Gear, L.P. Turbine	7.508	
Second Reduction Gear	6.93	

graph) of number of occurrences in each of the sixteen levels. In addition, the total number of data variations analyzed, the magnitude of largest stress variation, a calculated average stress value, and the mean-square value of the data record are supplied. A typical readout is shown in Figure 15.

Following the readout cycle, the machine will proceed automatically (or manually as desired) to analyze the next data interval. The specifications for the Probability Analyzer are given in Section C of this Appendix.

The recording oscillograph accepts either the analog output of the tape reproduce unit (thus reproducing the originally recorded information) or the output of the probability analyzer (the reduced data) to produce a strip chart record.

B. Techniques of Data Reduction

The steps in the reduction of data are presented in Figure 16. The tapes from the ship are played back at 200 times original speed directly onto the recording oscillograph running at slow speed. This produces a greatly compressed record with the record intervals separated by the calibration signals (Figure 16 - 1). From this "quick-look", the entire voyage may be assessed as to quality of recorded data and intervals of especial interest may be determined. In addition, the quick-look is correlated with the log book entries and the corresponding log book interval numbers are marked directly on the oscillogram. The taped data are then played through the probability analyzer. The probability analyzer output is recorded as shown in Figure 16-2. A typical interval of probability analyzer output is shown in Figure 15. Each interval, consisting of a sequence of pulses, is then marked with a sequential "record interval" number. The pulses corresponding to Greatest Peak-to-Peak Stress, Total Number of Stress Variations, and the Mean Square Value ($4\sum n_i$) for each interval are read off in terms of machine counts and entered on the work sheet (see Figures 16-3 and Figure 17). The necessary mathematical calculations are performed to transfer the machine counts into maximum peak-to-peak stress (X_m) in KPSI and mean square stress (E) in KPSI ^{2}. These values are then recorded on the work sheet (see Figure 16-4 and Figure 17). Log book intervals (Index Numbers) are correlated with machine intervals (Record Interval) and these are entered along with the pertinent data log book entries to complete the work sheet.

The completed work sheets represent a compilation of the reduced data for each voyage. The work sheets, magnetic data tapes, and data log books for each voyage are retained on file by the Investigators, and can be made available to interested parties on request to the Investigators or to the Secretary, Ship Structure Committee, U. S. Coast Guard Headquarters, Washington 25, D. C.

C. Probability Analyzer: Model PA 102

Manufacturer: Sierra Research Corporation
Post Office Box 22
Buffalo 25, New York

Specifications

GENERAL

Input Voltage	±1.v. d.c.
Input Impedance	≥1,000 ohms
FILTER — 3 Selectable Filters with a mid-band gain of 5.	High pass of about 1 cps combined with low pass of about 66 cps. High pass of about .5 cps combined with low pass of about 33 cps. High pass of about .25 cps combined with low pass of about 17 cps. High pass filter is first-order type; Low pass filter is second order, approximately 0.6 critically damped.
Output Voltage	0 to 10v. d.c. to pen recorder
Output Current	10 m.a. maximum
Frequency Range	0 to 100 cps

PEAK-ENCODER

Input	± 5v. into 5,000 ohm load
Output	7-bit binary number for (to Peak 7-bit binary number for 0 to Trough

These two encoders determine and store in binary form the greatest positive value, occurring between successive positive-going zero crossings and the most negative value, occurring between successive negative-going zero crossings.

Accuracy	± 1 count, ± 1%
Response	0 to maximum in less than .0026 seconds

PEAK TO PEAK DETECTOR

The sum of counts corresponding to the readings in the positive and negative peak-encoders are read out into the level occurrence counters at successive positive-going and/or negative-going zero crossings. This is an 8-bit binary number.

ZERO CROSSING DETECTOR

Positive and negative-going zero crossings are extracted, and are used to operate the readout into the level occurrence counters and to reset the encoders.

LEVEL-OCCURRENCE COUNTERS

Number of Counters	16
Maximum Count	255 (8-bits)
Digital to Analog Conversion	10v. full scale, ± 1% accuracy

The 16 counters will register a count when the encoded peak-to-peak values are: 1 to 11, 12 to 23, 24 to 35, 36 to 47, 48 to 59, 60 to 71, 72 to 83, 84 to 95, 96 to 107, 108 to 119, 120 to 131, 132 to 143, 144 to 155, 156 to 167, 168 to 179, and 180 to 255 respectively.

CONTROLS

Mode Switch	Peak-to-Peak Positive Peak Negative Peak (Trough) Positive and Negative Peak
Readout Gain	
Counter Readout	10v. = full scale = 32, 64, 128, 256, 512, 1024, 2048, or 4096 counts
Auxiliary Readout	10v. = full scale = 128, 256, 512, 1024, 2048, or 4096 counts
Stop Mode	Overload of any level-occurrence counter or one of the following: External command, predetermined time, predetermined number of cycles.
Readout Form	Between thresholds, below thresholds.
Analysis Duration	2, 4, 6, 8, 12, 16, 24, 32, 48, 64, 96 seconds (derived from 60 cps line.) 50, 100, 150, 200, 300, 400, 600, 800, 1200, 1600, 2400 counts into level occurrence counter.

AUXILIARY COMPUTATION

Moments	Voltages proportional to total number of counts and first and second moments are recorded. 10v. = 128, 256, 512, 1024, 2048, 4096 counts.

Greatest Peak-to-Peak Value	Encodes and stores the greatest Peak-to-Peak value during a given analysis cycle.

AUXILIARY CONTROLS

Relay	Relay Closure to Turn Tape Recorder off and Paper Recorder on at end of analysis cycle. Turn Paper Recorder off and tape recorder on after readout is completed.
Delay	Incorporate selectable delay of 1, 2, 4 seconds ± 20% after start of tape recorder and before start of analysis cycle.

DESIGN

Approximate Size	30" x 19" x 13"
Approximate Weight	100 pounds
Temperature Range	50°F to 100°F
Power Required	Approximately 70 watts, 115v ± 10% 60 cps. Panel mounted for installation in standard relay rack.

SHIP HULL RESEARCH COMMITTEE

Division of Engineering & Industrial Research
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