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AN UNMANNED SYSTEM FOR RECORDING STRESSES AND ACCELERATIONS ON SHIPS AT SEA

SSC-150

BY

D. J. FRITCH AND F. C. BAILEY

SHIP STRUCTURE COMMITTEE

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3 June 1963

Dear Sir:

One of the most critical needs in ship design is to learn the actual long-term stress history of ships. 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. The initial phase of this study involved the development and performance testing of the data recording system.

Herewith is a copy of the first progress report, SSC-150, An Unmanned System for Recording Stresses and Accelerations on Ships at Sea by D. J. Fritch and F. C. Bailey.

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

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

Sincerely yours,

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

Serial No. SSC-150

First Progress Report
on
Project SR-153

to the

SHIP STRUCTURE COMMITTEE

on

AN UNMANNED SYSTEM FOR RECORDING STRESSES AND ACCELERATIONS ON SHIPS AT SEA

by

D. J. Fritch and F. C. Bailey
Lessells and Associates, Inc.

under

Bureau of Ships
Department of the Navy
Contract NObs-77139

transmitted through

Committee on Ship Structural Design
Division of Engineering and Industrial Research
National Academy of Sciences-National Research Council

under

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Washington, D. C.
U. S. Department of Commerce, Office of Technical Services

3 June 1963

ABSTRACT

In order to obtain long-term statistical data on wave-induced bending moments, two dry-cargo ships have been equipped with stress transducers and automatic magnetic-tape recording instrumentation. One of these ships has also been equipped with accelerometers to provide information on seaway-induced loads on cargo. The transducers and their installation are described, as well as the data conditioning units, the tape recorder, and the programmer which allows sampling of the data at pre-selected intervals and continuous recording when pre-set stress levels are exceeded.

The system has performed beyond expectation; data have been obtained on 36 round-trip voyages representing almost three ship-years of operation. Versatility of the unit in handling a variety of data inputs and adapting to various data reduction methods has been demonstrated. In addition, the data tapes are available for future analysis in a broad spectrum of naval design applications. Experience gained to date will permit future installations to be handled expeditiously and at minimum expense, with a high degree of reliability of the unit assured in service.

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INTRODUCTION

The rational design of ship structures must be based on knowledge of the magnitudes and combined effects of the loads to which the ship is subjected in service. Some of these loads arise from locked-in stresses, diurnal temperature variations, local heating or cooling, still-water cargo loading, low-frequency wave-bending load, slamming, and local vibratory effects. Rather than attempt a simultaneous study of the combined effects of all of the above loads, and because of the statistical nature of some of them, it is most convenient to investigate each type of loading in detail and then establish the effects of combined loadings.

This project deals specifically with the determination of low-frequency wave-bending loads. The approach is aimed at establishing information on maximum attainable wave-induced bending moments for various types of ships operating on a number of routes. This immediately implies a comparatively "long range" program. By contrast, one could approach the problem by simultaneously studying a larger number of variables such as bending moment loads, wave proportions, cargo loading, speed and ship motions on extensively instrumented ships. Problems of instrumentation and data reduction dictate that studies of this type be "short range" in nature, and of value primarily in establishing interrelations between the recorded parameters as opposed to establishing knowledge of the probable range of, say, bending moment, under most operating conditions.

In all structural response studies, it is desirable to obtain simultaneous information on cause and effect. Using the full-scale ship as a moving instrument platform, as well as the structure under investigation, it is quite convenient to measure seaway loads in terms of their effect on the ship, but quite difficult, as yet, to simultaneously determine the environment. Consequently, information of value can be obtained, but an important link in prototype ship structural research still is missing.

The present objective of this project is:

"To obtain statistical records of vertical longitudinal wave bending moments experienced by various types of ships operating on different trade routes, with the emphasis being placed on extreme values of external loads. The purpose is to provide information for (a) the direct use of the ship designer, and (b) to test methods of predicting bending moments." This is based largely on the recommendation for a project on "Statistical Studies of Seaway Loads Aboard Ship," which was made in the report edited by Professors E. V. Lewis and G. Gerard and entitled A Long-Range Research Program in Ship Structural Design.[1] The complete recommendation is reproduced in Appendix A.

After Project SR-153 had been active for some time, the Army Transportation Corps (ATC) expressed interest in the program as it might relate to a study of loads imposed on delicate cargo as a result of seaway-induced accelerations. Although the interest of ATC was directed at completing a broad survey of cargo loads encountered in all modes of transportation, and consequently had little or no bearing on the initial objectives of the Ship Structure Committee program, it became apparent that substantial economies would be effected by sharing of recording and data reduction systems.

This report will describe the instrumentation systems developed, and in use, to obtain bending moment and acceleration data. The basic recording systems have now accumulated almost three ship-years of operating time, and some manual data analysis has been undertaken. The theoretical and practical aspects of the data reduction and analysis, and preliminary results, will be discussed in subsequent reports.

BASIC SYSTEM REQUIREMENTS

General

At the time this project was initiated, several investigations had been completed, or were under way,[2-4] which required instrumentation of the general type needed for this study. It was essential, therefore, that decisions regarding choice of system be based on a clear understanding of the capabilities of existing instrument designs. Any proposed system had to be assessed in the light of the anticipated complexity, and inherent flexibility, of data reduction and analysis systems (external to the recording system) which could be utilized. This evaluation was complicated by the fact that most of the more elaborate existing systems presupposed certain statistical relationships in the wave-induced data and actually accomplished some data reduction prior to recording.

Early in the program, the following general requirements were established and existing equipments reviewed in this light:

1. Cyclic bending moment only will be studied.

2. A sampling device, as opposed to one which records continuously, is to be preferred, in view of the data storage problem.

3. "Unmanned" operation for periods of up to a month is desirable.

4. "Good" reliability.

5. High accuracy (2%).

6. Adapted to shipboard environment.

7. Low cost (initial, maintenance, and data reduction).

8. Immunity to the intentional or accidental ministrations of untrained, unauthorized, personnel.

Previous Work

The principal investigations in the general field had been sponsored by the David Taylor Model Basin (DTMB), the Society of Naval Architects and Marine Engineers (SNAME), The Swedish Shipbuilding Research Foundation (SSRF) and the British Shipbuilding Research Association (BSRA). Both SNAME and SSRF used Model Basin instruments for their work, but SNAME had, in addition, sponsored a program to develop a different type of unit.

One recording technique common to all investigations, to a greater or lesser extent, was the use of strain-gage transducers, and straightforward, manned, oscillographic recording equipment. A large proportion of the published data has been obtained by this method. All future discussion will be limited to units which have the capability of unmanned operation.

The DTMB Gages and Counters

Over a period of years, DTMB developed a series of gage and counter systems which could be used to record strain, motions, or other cyclic wave-induced phenomena. The mechanical strain-cycle gage and counter[5] consisted of a mechanical strain gage having a gage length of ten inches, with mechanical magnification through a lever system by a factor of 10. As strains were induced in the unit, successive zone level and amplitude contacts were made which activated numerical counters. The logic in this unit was so constructed as to permit deduction of mean strain levels and peak-to-peak strain amplitudes from the number of counts shown for each preselected range.

A later adaptation of this instrument[6] introduced considerably more flexibility into the choice of transducer. The output of an accelerometer or strain-gage bridge, suitably amplified, was fed to a potentiometric recorder-controller which had been modified by the addition of contactors to the slide wire. These moving contactors intercepted fixed contacts, the outputs of which were fed to a relay logic unit and then to electro-magnetic counters which recorded the number of times the peak-to-peak signal had exceeded the range represented by the counter. This unit was used successfully in the SSRF program[4] while the mechanical unit described briefly above was used in the SNAME investigation.[7]

The BSRA Gage and Counter

BSRA has for some years sponsored work on the measurement of wave-induced loads on merchant ships. Unfortunately, little has been published on the results of these programs, but the nature of the BSRA statistical gage is known.[8] Basically, this unit consists of a 100 inch mechanical strain gage. Strain in the gage element is transformed to rotary motion, and a system of rotating and fixed contacts energizes counters at a remote location. Strain-gage bridges have been incorporated into several of the units to obtain analogue records in oscillograph form.

Other Systems

A device has been designed by the French[9] specifically for the measurement of strains aboard ships. This "Statistical Extensometer" again combined a mechanical strain gage

(11.8 inch gage length) with mechanical amplification, electrical contacts and counters.

Other systems designed for the measurement of aircraft loads and motions were reviewed. These covered a number of well-known units and several relatively new proprietary devices. In general, analog recording was used on a variety of tape materials using hot stylus, magnetic, or scratch recording. A general disadvantage of these units was the relatively short recording time and the elaborate specialized playback equipment required which was, of course, justified when a large number of recording units were to be used.

At the conclusion of this general phase of the investigation, it was apparent that the state of development of electromechanical strain-cycle counters was such as to permit the design and construction of a relatively inexpensive unit with a high probability of achieving long life and reliable operation. All that remained was to weigh this type of unit against the other possibilities.

Basis for Selection of Tape Recorder System

Despite the attractions of an electromechanical strain-cycle counter (straightforward design, relatively low cost, possibility of no vacuum tubes, simple data reduction), several disadvantages are quite apparent. Since a large part of the data analysis is accomplished by the unit, it is not possible, after the fact, to review or reanalyze the basic strain data by alternate methods. Furthermore, instantaneous correlation of strain data with other information (wave height, accelerations, motions, etc.) is not possible.

Implicit in the statement of the objective of the present project is the necessity, at some point, of obtaining simultaneous bending moment and wave height information. This would then permit the data from full-scale ships to be used in correlations with model data. A number of shipborne wave-measuring systems are available or under development, but none of these have advanced to the point where they can be considered for this investigation from the viewpoint of cost, accuracy, and reliability. However, the desirability of obtaining simultaneous information on the load-producing element (the seaway) and the resultant bending moment cannot be overemphasized. It is recognized that this must await the development of a suitable shipborne wave-height sensor.

The decision was therefore reached that the instrumentation system be based on use of a multi-channel, magnetic-tape recording unit, in spite of higher initial costs. The specific features favoring this type of system were:

1. Standard magnetic-tape recording systems were available which, with slight modification, could provide 160 hours of continuous recording of one channel of information on a single tape.

2. The system would be versatile with regard to the number of data channels which could be utilized.

3. A complete, permanent, analog record of the desired information would be available at the completion of each voyage.

4. Type, method, and scheduling of analysis would not be restricted.

5. All seaway-induced stresses would be recorded, including slamming (whipping) stresses which result from longitudinal vibration of the hull at its lowest natural frequency. (Although these stresses are not of primary interest on this project, other investigators are pursuing this problem.)

6. A variety of high-speed automatic data reduction techniques would be available.

In addition, the contemplated tape-recording system, as initially installed, or with slight modification, could obtain data of interest to a number of other active or suggested research programs. Some of these are listed below. (Project numbers are those used in Lewis and Gerard, pages 220 and 221.)[1]

Project No.	Title and Comment
3	Routine Collection and Dissemination of Synoptic Wave Data (Deduction of sea spectra by analysis of ship response and use of transfer function).
11	Long Range Determination of Expected Sea Conditions for Ship Design Purposes (sea data from ship response using

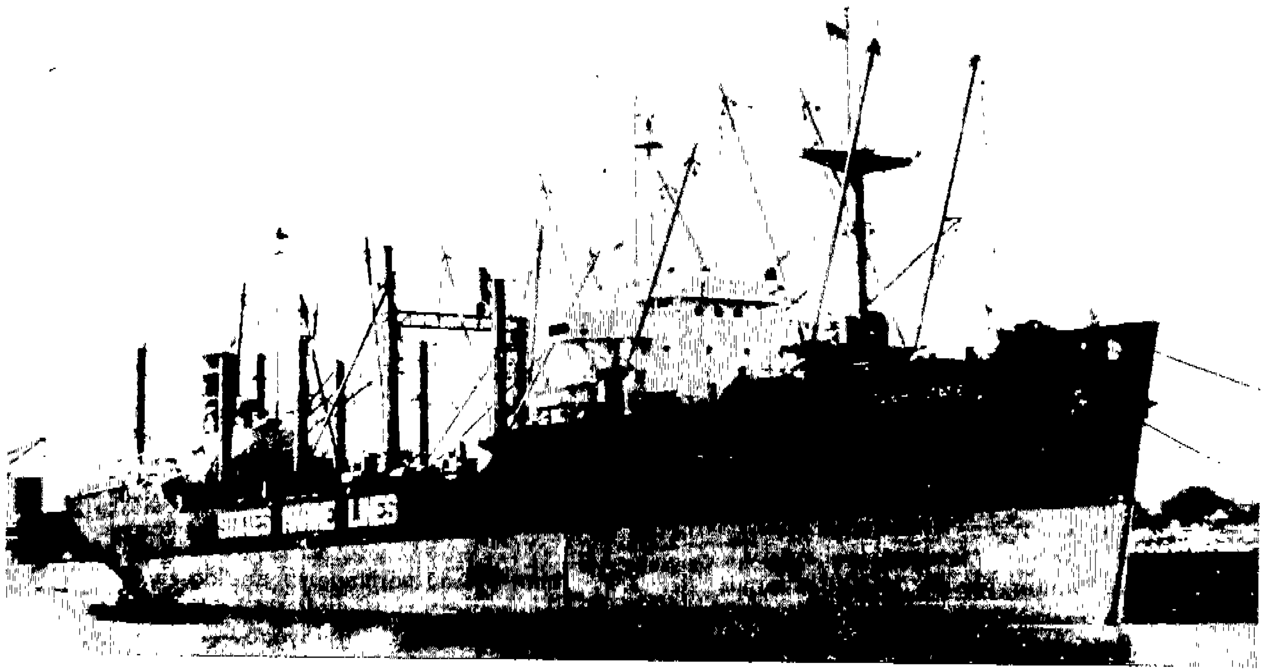


FIG. 1. S. S. HOOSIER STATE

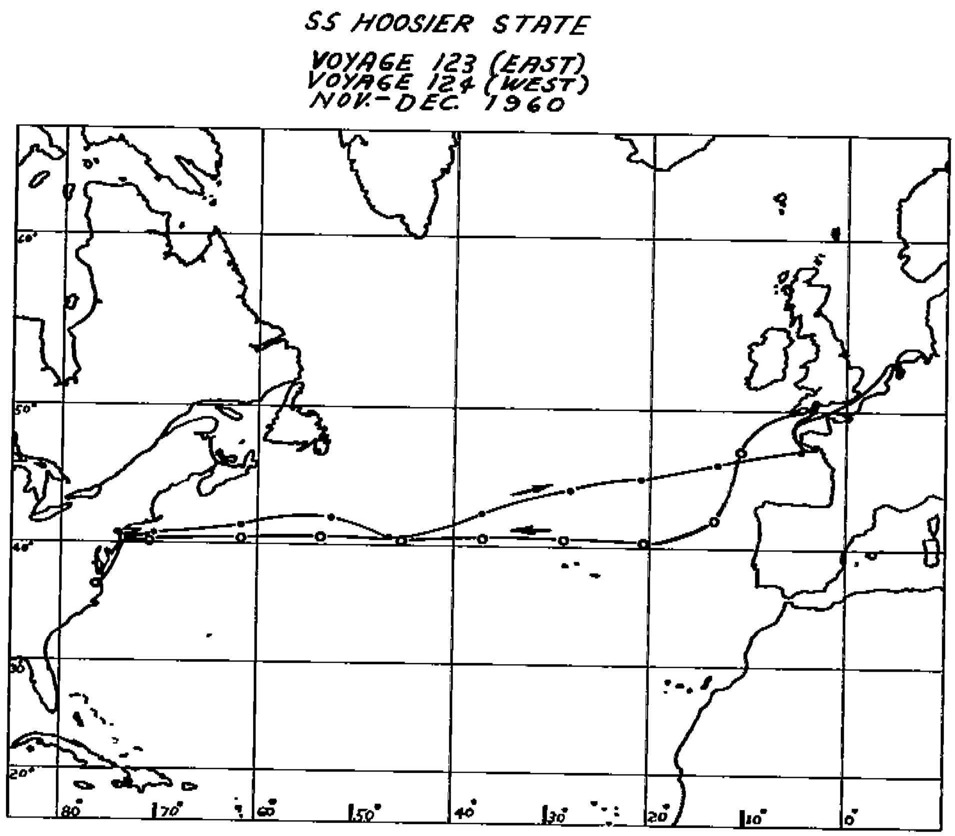


FIG. 2. S. S. HOOSIER STATE: VOYAGE 123 (EAST); VOYAGE 124 (WEST); NOV.-DEC. 1960.

DATA LOG

SHIP____________________

VOYAGE________________ FROM________________ TO____________________ DATES____________ TO____________

			SHIP							WIND			
			Noon Position			Avg. Speed Knots	Avg. Engine R.P.M.						
Index No.	Date (M, D, Y) Time (GMT)	Time Meter Rdg.	Lat.	Long.	Course	(Past four hours)		Sea Temp.	Air Temp.	Knots Wind Speed	True Wind Dir.	Weather	Initials

FIG. 3. DATA FORM FOR RECORDING SHIP SPEED AND WEATHER CONDITIONS.

DATA LOG

	Sea							
Index No.	Beaufort Sea State Number	True Direction of Advance	Avg. Wave Height Ft.	Avg. Wave Period Sec.	Avg. Wave Length Ft.	Estimate Average Length in Feet & True Direction of Swell	Barometer Reading & Sea Photo Number	Remarks (Changes of Course, Changes of Speed, Changes of Ballasting, Slamming, Rewind Recorder)

FIG. 4. DATA FORM FOR RECORDING SEA STATE CONDITIONS.

Project No.	Title and Comment
	transfer function.)
18	Case Studies of Seaway Loads aboard Ship. (Same basic recording system; additional transducers required.)
19	Correlation of Full-Scale Bending Loads with Model and Theoretical Predictions.
21	Trends of Bending and Shear Loads in Irregular Seas.
26	Transverse Bending Loads (Rearrangement of strain-gage bridge connections.)
27	Loads Resulting from Motions of Internal Liquids.
34	Observation of Slamming Loads at Sea (Data already available on tape.)
39	Compiling Data and Observing Sea and Air Temperatures and Solar Radiation on Various Trade Routes (Extensive log data now recorded; all information could be placed on a single channel of tape.)
41	Statistical Data on Extreme Temperature gradients in Ship Hulls (Diurnal thermal stress variations can be observed on magnetic tape records.)

Specific details of the complete magnetic-tape system follow.

DESCRIPTION OF SYSTEM

General

At the present time two instrumentation systems are in operation on dry-cargo vessels in the North Atlantic service. One ship has been instrumented for the unmanned recording of wave-induced stresses on magnetic tape. The instrument aboard the second ship includes channels for recording wave-induced accelerations in addition to stresses. The ships are the S.S. HOOSIER STATE and the S.S. WOLVERINE STATE, two C4-S-B5 cargo vessels, operated by States Marine Lines. Figure 1 is a photograph of the S.S. HOOSIER STATE docked in Bremerhaven, Germany. The selection of the two sister ships was based on the willing cooperation of States Marine Lines and the desirability of collecting a large quantity of data on a given ship type and trade route within the shortest possible elapsed time.

The ships operate between East Coast U. S. ports and Northern European ports. The route of a typical voyage is illustrated in Fig. 2.

The ship's watch officers maintain a data log book for the project which includes concurrent data on ship position operating conditions, local weather and sea conditions. The log entries can later be related to given samples of the reduced data. The officers also rewind and replace the data tapes on the magnetic-tape recorder.

The States Marine Line ships participate in the collection of data for the U. S. Weather Bureau. The watch officers are therefore accustomed to gathering the type of weather and sea-state data which are included in the log sheets. Samples of the data log sheets are provided in Figures 3 and 4. The first column, "Index Number, " ties together the data on the two pages which correspond to a given watch period. The "Time Meter Reading" is obtained from an indicator associated with the magnetic tape recorder and serves to identify the corresponding data record on the magnetic tape. The other column headings are self-explanatory.

Figure 5 illustrates in block diagram form the complete system for recording ocean-wave-induced stress which has been placed aboard the S.S. HOOSIER STATE. It is also representative of the stress channel of the expanded stress and acceleration recording system on board the S.S. WOLVERINE STATE.

Figure 6 is a functional block diagram representing one channel typical of the seven acceleration recording channels of the S.S. WOLVERINE STATE SYSTEM.

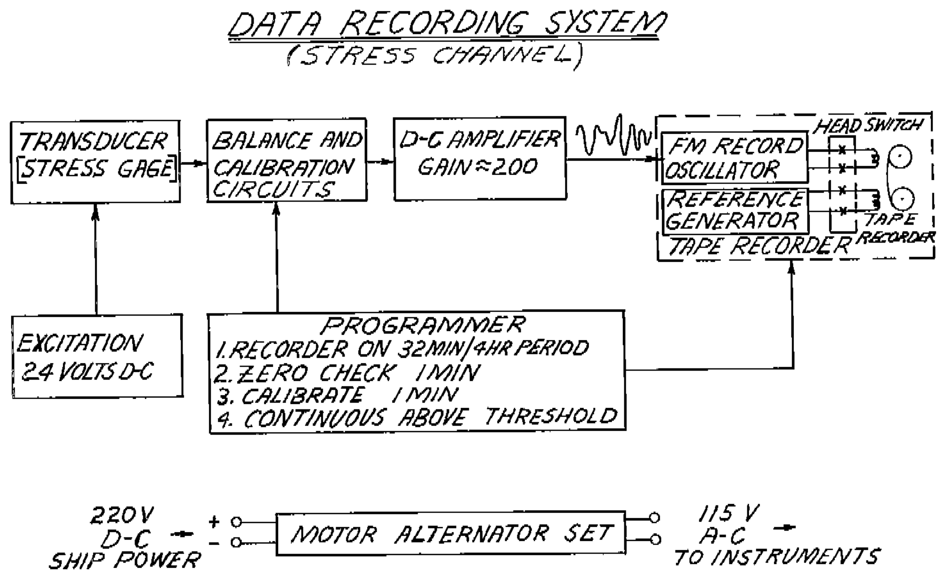


FIG. 5. DATA RECORDING SYSTEM (STRESS CHANNEL)

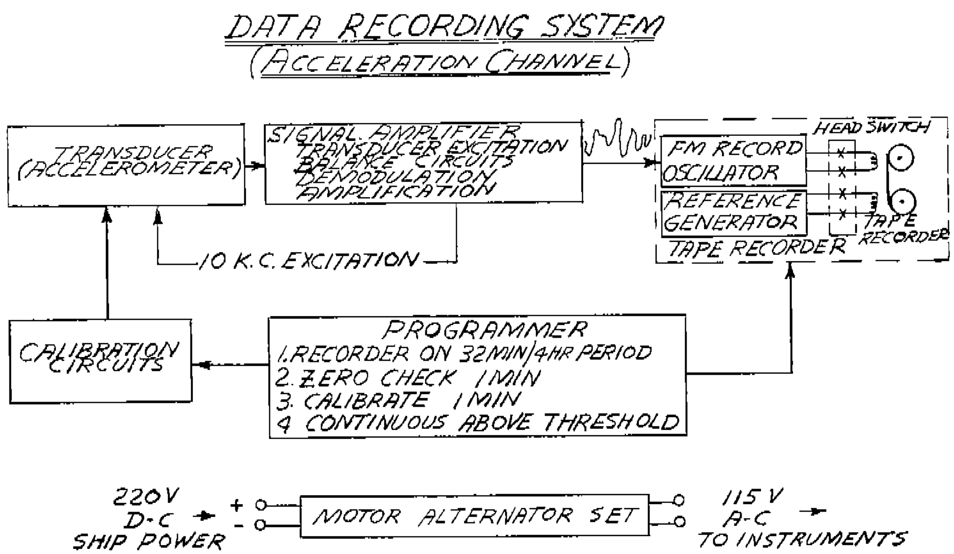
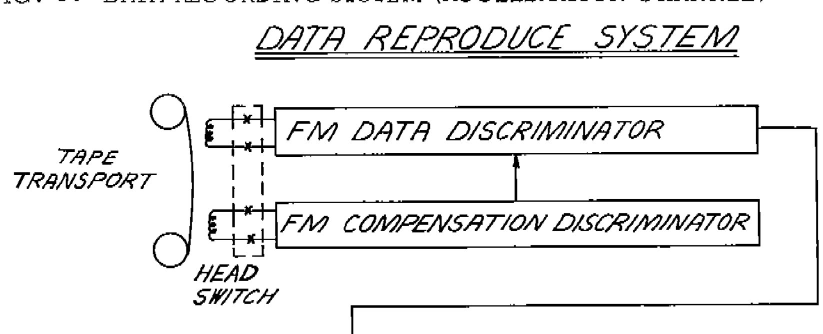


FIG. 6. DATA RECORDING SYSTEM (ACCELERATION CHANNEL)



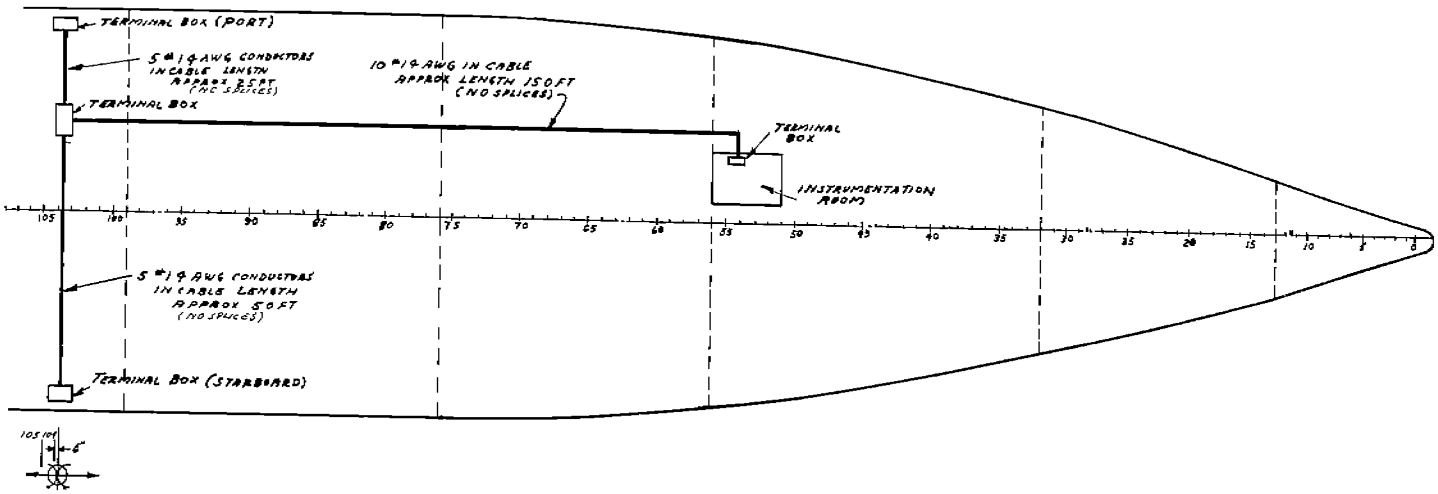


FIG. 8. WIRING LAYOUT STRAIN GAGE CIRCUITS.

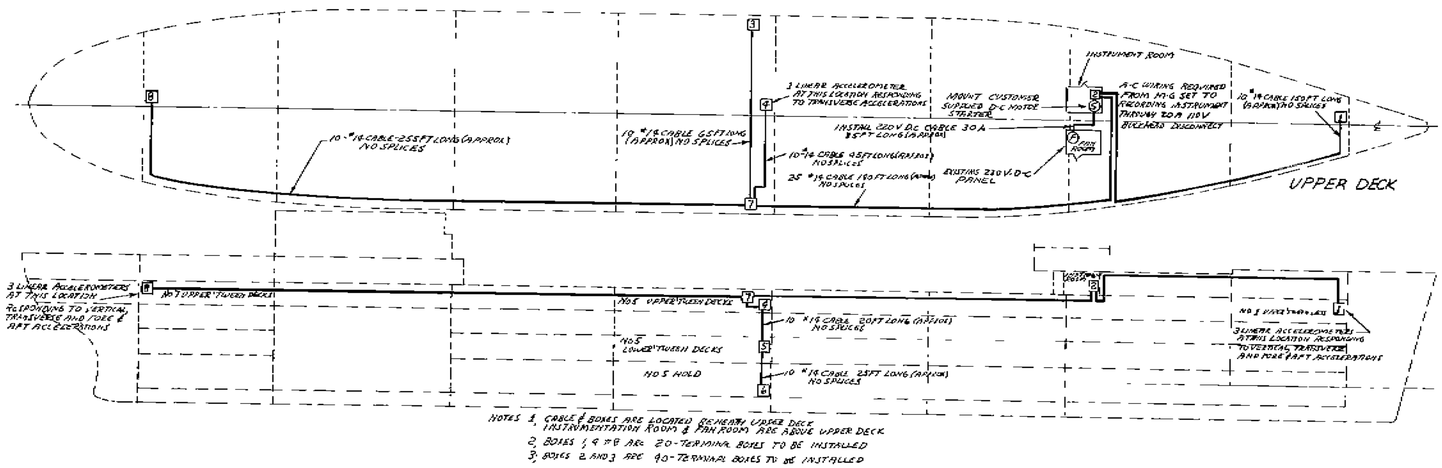


FIG. 9. INSTRUMENTATION CABLE AND TERMINAL BOX LAYOUT. S. S. WOLVERINE STATE.

electrical signals suitable for graphical recording or subsequent analysis.

Figure 8 indicates the transducer cabling which was added to the S.S. HOOSIER STATE. It shows the general location of the port and starboard stress transducers with respect to the instrumentation room in which the recording equipment was located.

Figure 9 indicates the transducer cabling which was installed on the S.S. WOLVERINE STATE and shows the location of the acceleration transducers at the bow, stern, and amidships. The port and starboard stress gages are located near junction boxes 3 and 7 respectively.

The following sections of this report contain descriptions of the various components of the data collection system. Detailed specification on the individual components are included in the Appendix.

Transducers and Data Conditioning Units

Stress Channel

Stress Gage. A stress measuring transducer was developed by cementing etched-foil electrical strain gages to the inside of the ship's side plates six inches below the weather deck. Plating thickness was 0.90 inches; transverse frames are 30 inches apart at this section. A similar stress gage was placed amidships on both the port and starboard sides of the ship. The gages were oriented to respond only to the longitudinal component of the bending stress. The outputs of the two stress gages were combined electrically to form a full bridge circuit in which horizontal components cancel so that only the vertical components of the longitudinal bending stress appear in the output. Figure 10 illustrates the completed installation of one of the stress gages in the midship cargo spaces.

Tatnall Metal Film Strain Gages Type C6-181 were used in the S.S. HOOSIER STATE installation. Eight gages were used to form the four-arm bridge circuit. The active arms of the bridge, on opposite sides of the ship, consisted of two gages electrically connected in series and positioned against the side plate to form a vee-shaped dyadic stress gage[10] with the centerline of the vee oriented

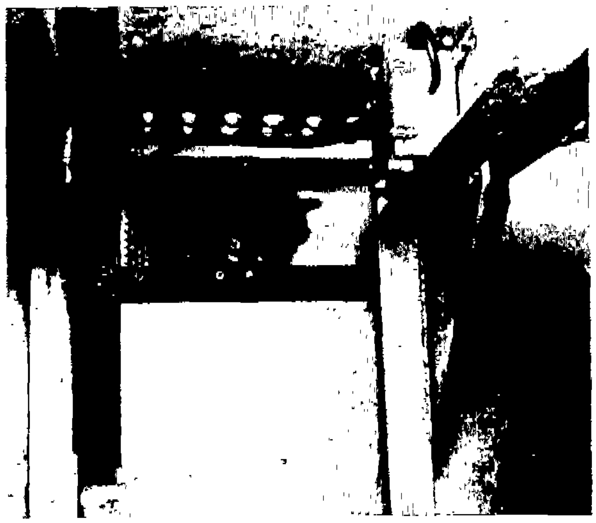


FIG. 10. STRESS GAGE INSTALLATION IN MIDSHIP CARGO SPACE.

in the fore and aft direction. The angle of the vee is selected to compensate for the Poisson effect in the steel side plate. A Poisson ratio of 0.26 was used for the mild ship steel.

Baldwin-Lima-Hamilton Stress-Strain gages, type FAB28-S6 were used in the S.S. WOLVERINE STATE installation. These were a new development which had just become available in the fall of 1961, at the time the second shipboard installation took place. These units combine two axial-strain-sensing elements, having different electrical resistance and oriented at right angles, into a single unit to provide a measurement of true stress along the principal gage axis. These units are designed to compensate for a Poisson's ratio of 0.28 for mild steel.

The temperature compensating (inactive) bridge arms consist of an electrical strain gage or pair of strain gages identical to that which was used in the active arms. These compensating gages are cemented to blocks of mild-steel ship plate which are held by spring loading against the ship's side plate. The blocks are thus exposed to the same side plate temperatures as the active gages, but to none of the forces which act on the side plates.

The stress gages are protected in place by a steel housing. Fig. 11 illustrates the protective housing with strain gages, strain-gage connectors, and compensating block in place. The housing consists of a steel ring and a cover with O-ring seals between the open

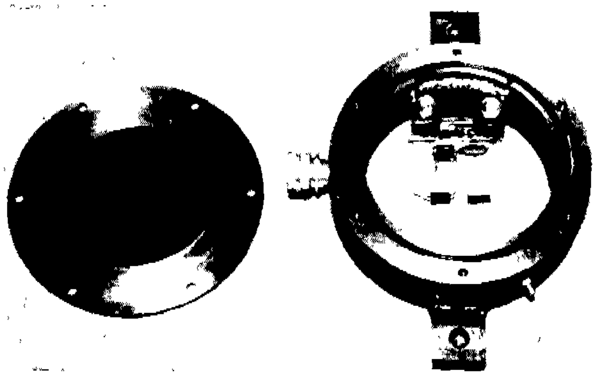


FIG. 11. COMPONENT PARTS FOR STRESS GAGE INSTALLATION.

bottom of the ring and the ship's side plates and the top of the ring and the cover. The housing is supported in place between two frames of the ship by means of the angle-iron structure shown in Fig. 10. A flex-link connection is used between frames and angle-iron structure to insure that the structure does not provide a load path parallel to the side shell plating on which the transducer is mounted. A metal screen protects the electrical cable which is attached to the housing.

After final assembly the housing is filled with Dow Corning Compound Number 3, a silicone grease which provides electrical insulation and protection against moisture, and is harmless to natural and synthetic rubber cables. Then sufficient silicone grease is pumped in through a grease fitting to produce a slight positive pressure which excludes air and moisture from the housing.

Since the strain gage is located on one face of the side shell plating, any local bending effects would be additive to the basic center thickness longitudinal stress. Inspection shows no initial unfairness of the plating in this region. This, coupled with the general location of the gages near the gunwale angle, the plating thickness, and transverse stiffener spacing (30 inches), lead to the conclusion that local bending effects will result in negligible error in the recorded stresses. This will be established, insofar as possible, by static "calibration" of the vessel throughout the anticipated seaway induced stress range.

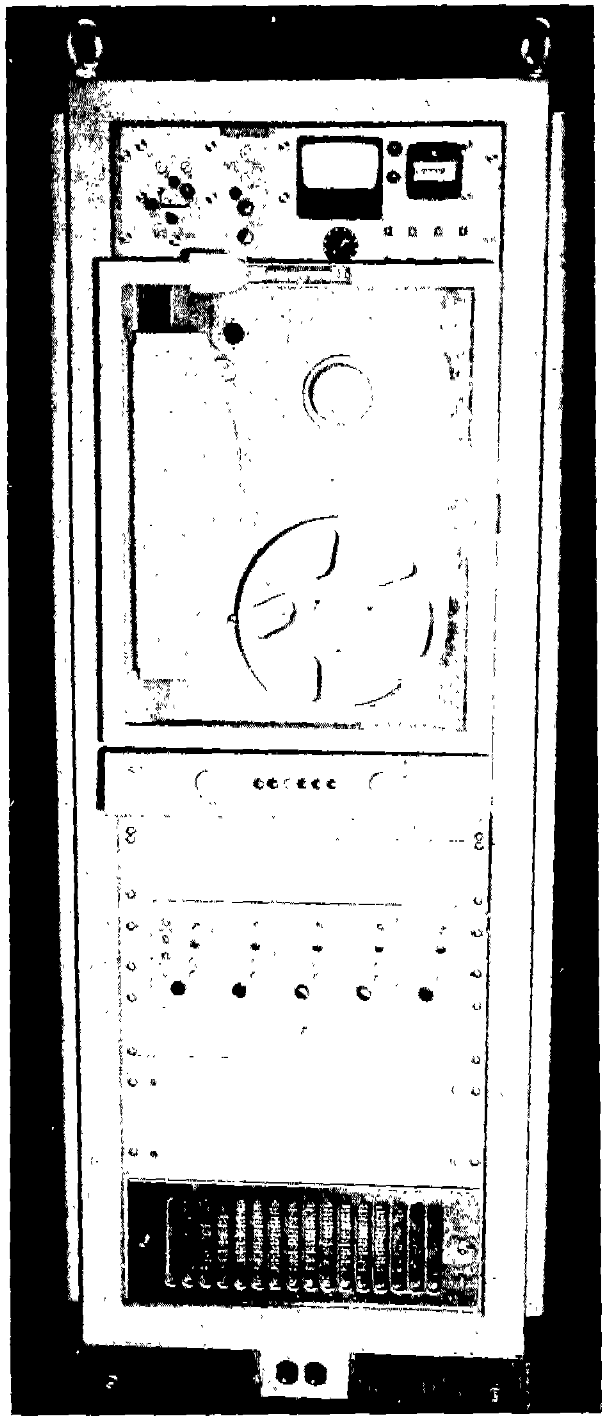


FIG. 12. AUTOMATIC DATA RECORDING UNIT

Strain Gage Module. A compact, strain-gage module, type SRB200RCH, which contains a solid-state regulated 24-volt d-c bridge excitation power supply, bridge balancing and calibration circuits was purchased from Video Instruments Incorporated of California (now a division of Endevco Corporation). The calibration portion of the unit can be remotely operated from the system programming unit described later. This module includes the blocks marked EXCITATION 24 VOLTS D-C and BALANCE AND CALIBRATION CIRCUITS of Fig. 5. It appears as the left-hand unit in the upper panel of the recording system shown in Fig. 12.

Strain Gage Amplifier. A chopper-stabilized, transistorized d-c amplifier (Video Instruments Division, Endevco Corporation Model 602A) has been incorporated in the system to raise the low level output signals from the strain gage module to a level which matches the input requirements of the tape recorder. This amplifier has the highly desirable characteristics of low noise and very good long-term gain and zero-stability. The strain-gage amplifier appears as the second unit in from the left-hand side on the top panel of the complete recording system, as shown in Fig. 12.

Stress Meter. At the center of the top panel of the recording system, Fig. 12, is a meter which monitors the output of the strain gage amplifier. The meter is an Assembly Products, Inc. contact making meter-relay with adjustable high- and low-limit contacts.

The meter is used during the voyage as an indicator of satisfactory system operation, since it swings to the left and right of center scale as the wave-induced stresses vary from a positive to negative value with respect to their still water value. The limit contacts can be positioned on the meter scale so that the recording system will be turned on when the wave-induced stresses exceed selected pre-set values. In this manner extra data samples will be gathered during periods of rough sea conditions.

The meter is also used during the routine equipment checkout visit, at the end of each voyage, to indicate satisfactory calibration and balance of the various data channels of the system. For this purpose, the stress channel and each of the acceleration channels can be fed in turn through the strain-gage amplifier by means of a selector switch on the programming unit.

Acceleration Channels

The data recording system on board the S.S. WOLVERINE STATE utilizes seven additional tape recorder channels to record the output of seven linear accelerometers at various locations on the ship. Three accelerometers are located at the bow oriented to measure linear accelerations in the vertical, transverse (athwartship), and fore-and-aft directions. Three accelerometers having the

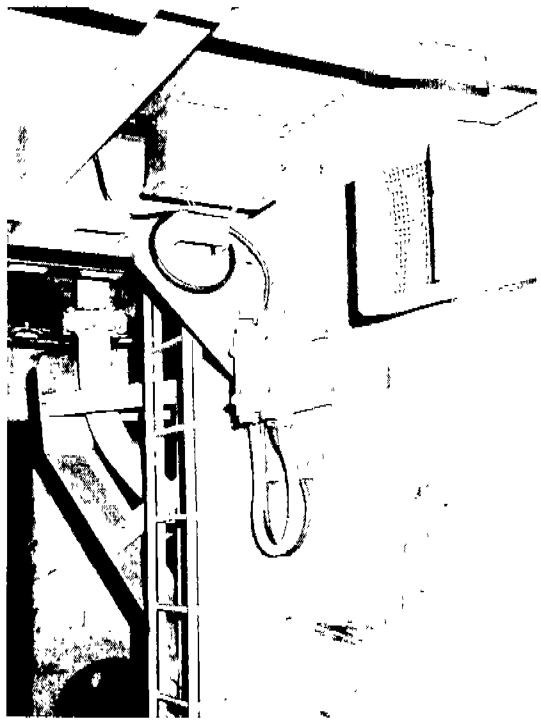


FIG. 13. COMPLETED INSTALLATION OF A MOISTURE-PROOF BOX CONTAINING STRAIN-GAGE ACCELEROMETERS.

same orientation are located at the stern. A single accelerometer measuring transverse accelerations is mounted amidships. All accelerometers are located on the center line of the ship and at the same level in the ship, just below the midship weather deck.

Accelerometers. Unbonded strain-gage linear accelerometers (Statham Instruments, Inc. Model A3) having a range of ± 2.5 g and a natural frequency of 55 cycles per second have been used in all accelerometer locations. Strain-gage accelerometers were selected because of the very low frequencies encountered in wave-induced accelerations. The useful frequency range of these accelerometers is from 0 (d-c) to 33 cycles per second. The accelerometers are calibrated electrically in the same manner as an electrical resistance strain-gage bridge, that is, by shunting one arm of the strain-gage bridge with a calibration resistor of the proper value. Figure 13 illustrates the completed installation of a moisture-proof box containing strain-gage accelerometers, their associated signal amplifiers, and remotely operated calibrating circuits. The boxes are bolted to steel plates that have previously been welded to the overhead.

Figure 14, provides an interior view of the accelerometer housing. In the center is seen a machined steel block with three mutually perpendicular sides to which are attached the three linear accelerometers. Through bolts attach this block firmly to the steel plate previously mentioned so that the accelerometers are in intimate contact with the ship's structure. The accelerometer signal amplifiers are located in front of the accelerometer mounting block and the remote calibration relay is seen at the rear of the box.

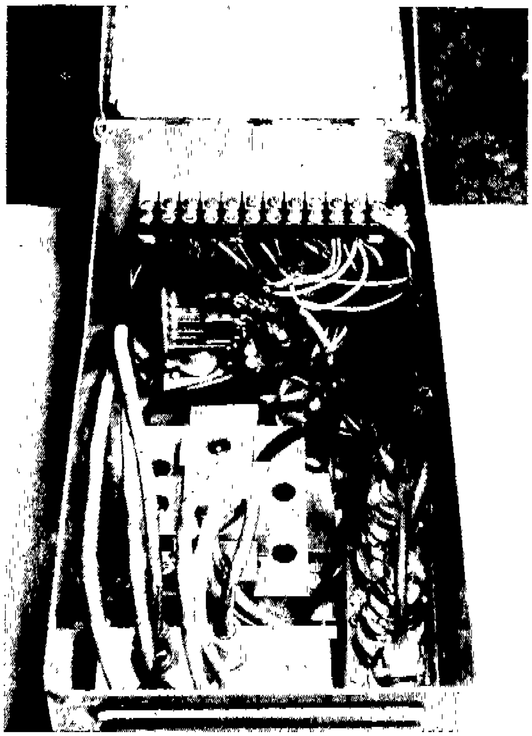


FIG. 14. INTERIOR VIEW OF THE ACCELEROMETER HOUSING.

Accelerometer Amplifiers. Transistorized accelerometer signal amplifiers (Statham Instruments, Inc. Model CA9-56) are employed to supply excitation to the strain-gage accelerometers and amplify the transducer output to a level which matches the input requirements of the tape recorder.

The accelerometers are used in a carrier system. Ten kilocycle per second carrier excitation is supplied by the amplifier unit to the strain-gage bridge in the accelerometer. The accelerometer bridge output is then demodulated in the amplifier unit and amplified to the proper level. Since the amplifier units are located adjacent to the accelerometers, only the d-c power required to operate the amplifier and the low-frequency signals from the accelerometers are carried by the shipboard instrumentation cables.

Recording System

The shipboard magnetic-tape data-recording system is illustrated in the system block diagrams, Fig. 5 and 6, and the photograph Fig. 12. The cabinet is 27 x 27 x 70 inches. The system is based on the Model 3168 tape transport manufactured by Minneapolis-Honeywell Regulator Company of Denver, Colorado. The system uses 10 1/2 inch reels of one inch wide magnetic tape having a 1-mil (0.001") mylar backing. A 14-track IRIG standard magnetic recording head permits the recording of up to 14 channels on the one inch wide tape, and provides compatibility for playback of the tapes on other standard machines. A tape speed of 0.3 inches per second permits the recording of forty hours of data on a single pass of the tape. The frequency modulation recording technique is used to provide a system frequency response 0 (d-c) to 50 cycles per second. (The IRIG standard center frequency at 0.3 inches per second is 270 cycles per second.)

Because of the very slow tape speed, the system incorporates electronic compensation for the noise resulting from irregularities of tape motion. A constant frequency is recorded on one of the tracks of the tape. During playback, variations in the frequency which is recorded on this track, resulting from motion irregularities (flutter and wow), produce signals which are subtracted from the outputs of the data channels to improve the overall system signal-to-noise ratio.

The recording system aboard the S.S. HOOSIER STATE records one channel of data and the compensation signal during each pass of the tape. At the end of each pass, the ship's Second Officer rewinds the tape and switches the two active recording channels to the next pair of recording heads. This action

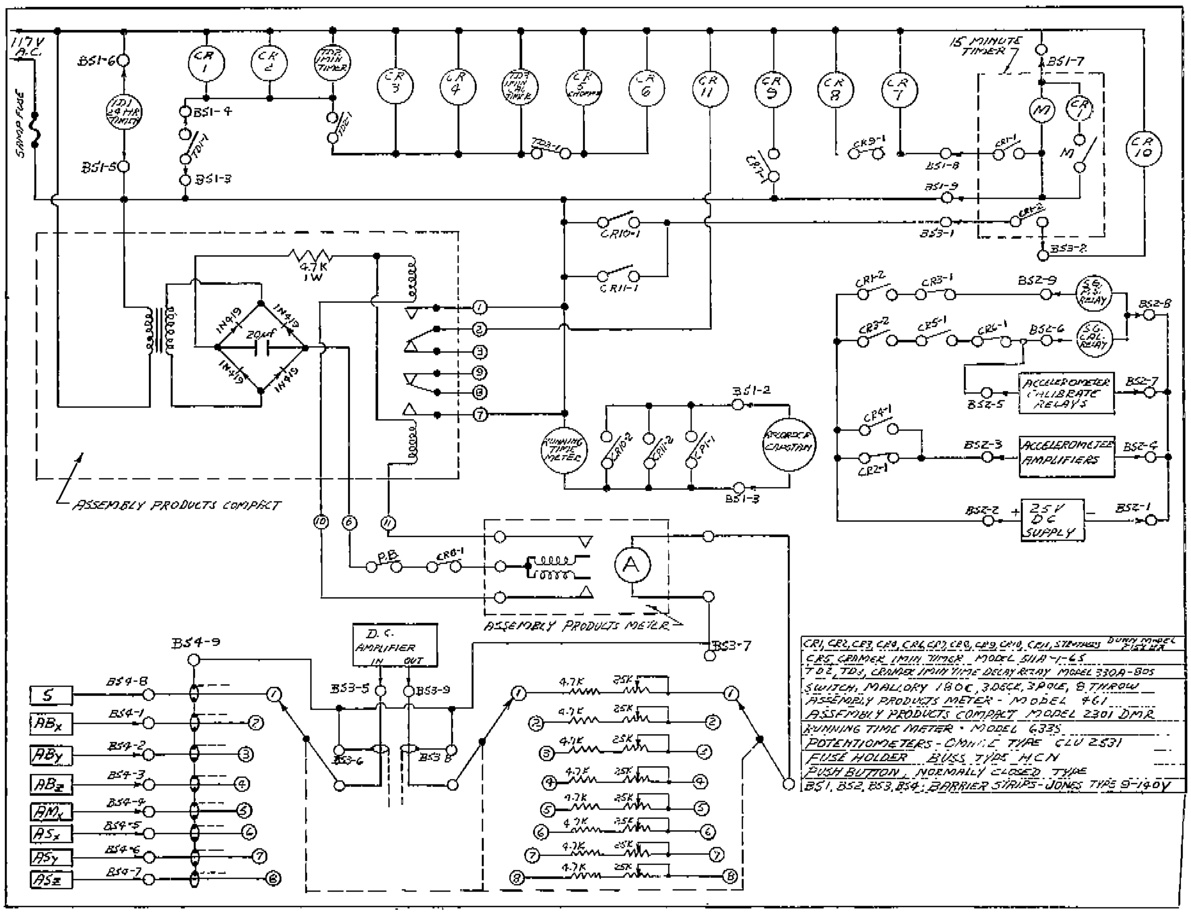


FIG. 15. PROGRAMMER WIRING SCHEMATIC S. S. WOLVERINE STATE.

can be repeated four times to produce eight tracks on a single reel of tape, recorded two at a time, for a total data record of 160 hours total elapsed time.

The recording system on board the S.S. WOLVERINE STATE utilizes 10 of the 14 available tracks (one stress channel, seven acceleration channels, one compensation channel, and one spare channel). At the end of each forty hours of record the ship's Second Officer rewinds the tape and replaces it with a new reel.

Programming Unit

A programming unit developed by the investigators has been incorporated to provide the automatic operation of the shipboard recording system. The functions of this unit are indicated in the system block diagrams, Fig. 5 and 6. A schematic diagram of the programming unit aboard the S.S. WOLVERINE STATE is included as Fig. 15. The front panel of the programming unit appears at the top of the complete recording system cabinet, see photograph, Fig. 12. This panel includes the Strain-Gage Module, the Strain-Gage Amplifier, the Stress Meter, and an elapsed-time meter which serves as a tape footage counter.

The fundamental purpose of the programming unit is to turn the recording system on regularly at four-hour intervals to obtain a data record of thirty minutes duration. At the beginning of each of these records the unit performs a calibration sequence. The power is removed from all transducers for a one-minute system zero-check. Then, during a second minute, calibration resistors are alternately shunted and removed from across one arm of the strain gage bridge in each transducer. The calibration sequence provides checks on system zero drift and calibration

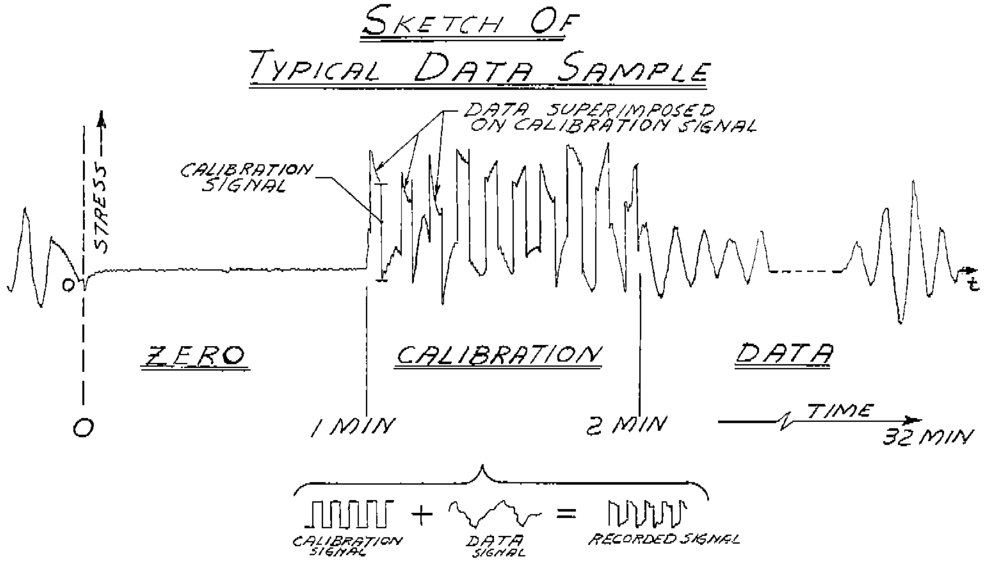


FIG. 16. SKETCH OF TYPICAL DATA SAMPLE.

changes, and also provides timing markers along the tape record since the sequence is repeated at regular four-hour intervals. A sketch of a typical interval of data record is shown in Fig. 16. As noted in this figure and in Fig. 17 (a) and (b), stress and acceleration signals are superimposed upon the calibration signals. The change of level occurring at the beginning and end of the calibration pulses serve to indicate the calibration level. The stress channels are calibrated for a stress change of 10,000 psi. The acceleration channels are calibrated for an acceleration change of 0.5 g.

In addition to obtaining regular records of fixed length and providing calibration signals, the programming unit will also obtain extended records of data when the sea conditions are extremely bad. Adjustable contact on the Stress Meter can be set to selected threshold values at which the programming unit can be triggered to turn on the recorder and obtain records in fifteen minute increments in addition to the regular records of one-half hour duration. A stress level attained above the preset threshold will turn the recorder on. An automatic timer will turn the recorder off at the end of fifteen minutes unless stresses continue above the preset level.

Auxiliaries

Shipboard Cables. Prior to the actual installation of the recording systems aboard ship, cabling from the instrumentation room to the transducer locations, and from the instrumentation room to the source of shipboard 220-volt d-c power was added to each ship. Since it was required that this wiring meet Coast Guard approval, the wiring was installed by marine contractors under the supervision of the investigators. Figures 8 and 9 illustrate the instrumentation cabling which was added to each ship. The power to operate the recording system, about 1500 watts, was drawn from the lines to the forward quarters ventilation system.

Motor-Alternator Set. A conversion device was needed to convert the 220-volt d-c shipboard power to 110-volt 60-cycle a-c power to operate the recording system. Surplus shipboard motor-alternator sets with the required starting and protective circuits were purchased and installed aboard each of the ships. The motor-alternator sets were conservatively rated for increased reliability. A 4KVA unit was installed aboard the S.S. HOOSIER STATE and a 7.5KVA unit was installed aboard the S.S. WOLVERINE STATE. The function of these units is indicated in the system block diagrams, Fig. 5 and 6.

Remote Indicating Instruments for Ship Chart Room. As part of the data log maintained for this project, the officer on watch records the reading from an elapsed time meter. This provides the total time that the recorder has recorded data during the previous four hours,

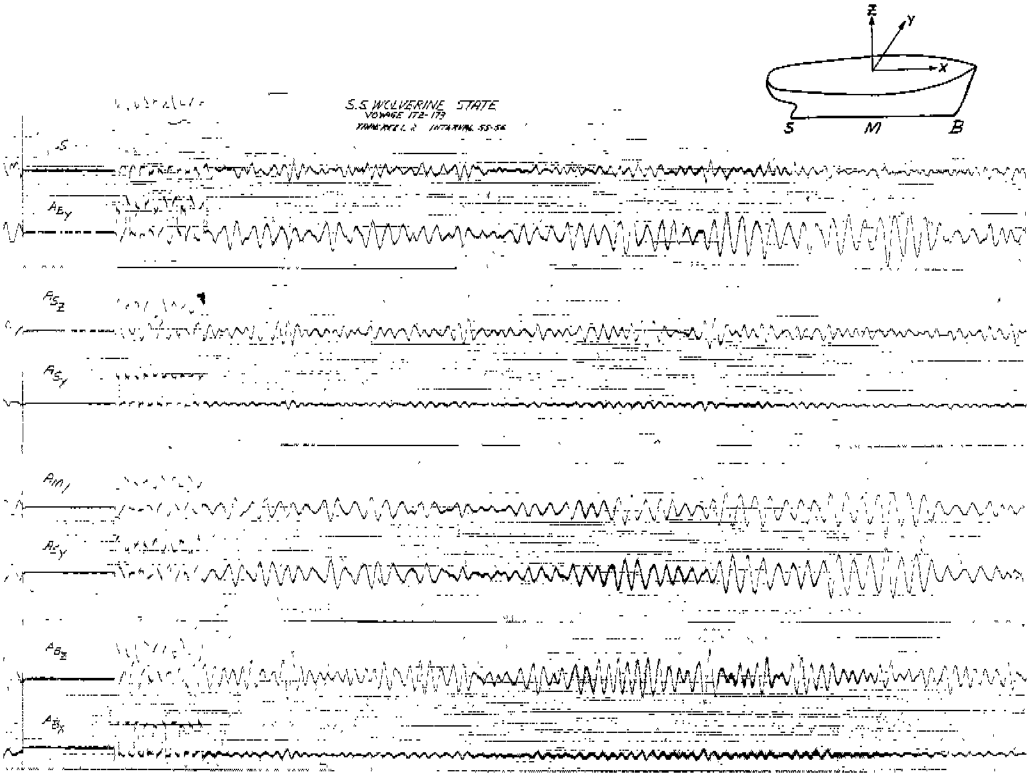


FIG. 17 (a). VISUAL RECORD OF STRESS AND ACCELEROMETER SIGNALS.

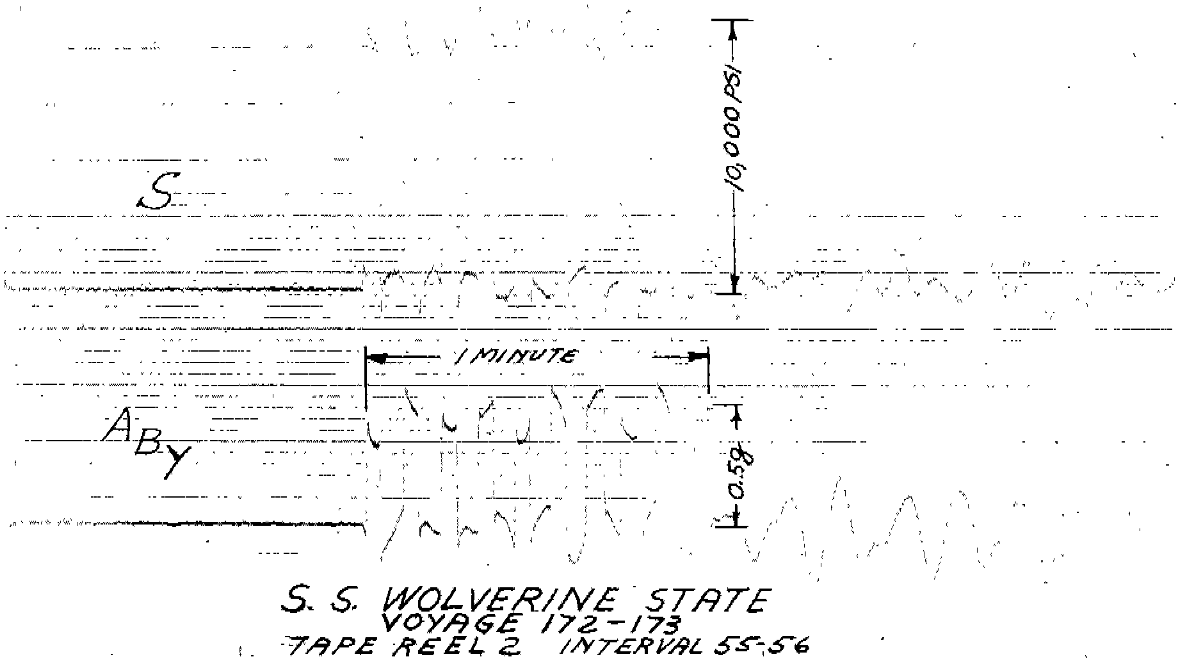


FIG. 17 (b). ENLARGED VIEW OF CALIBRATED SECTION.

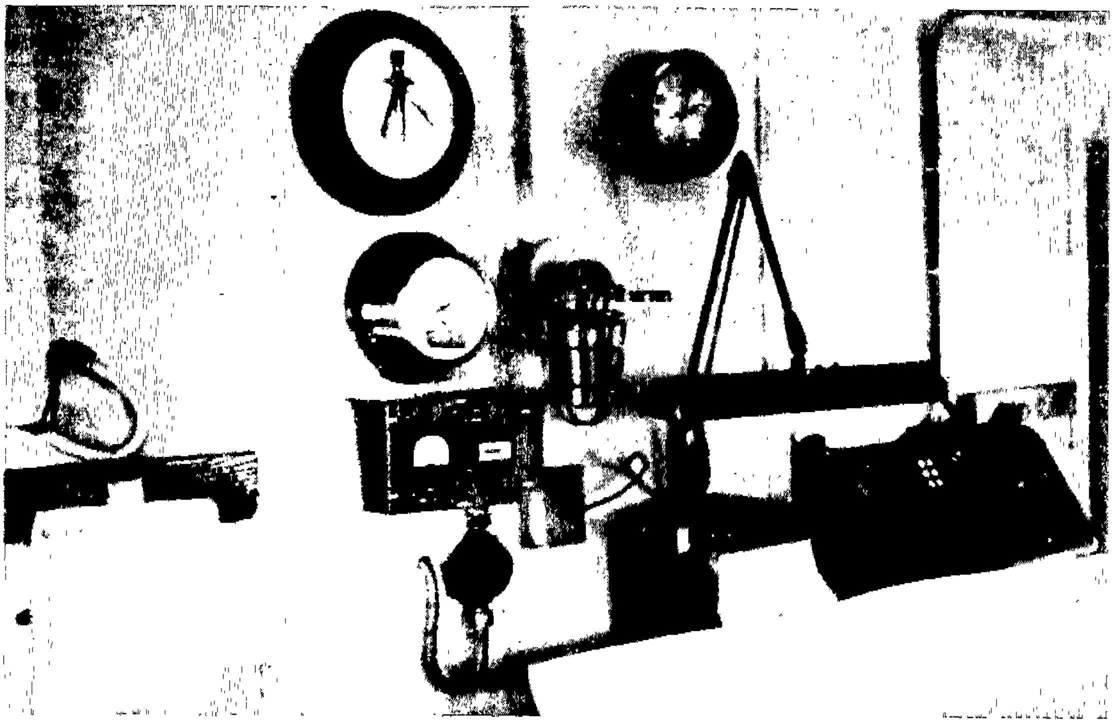


FIG 18. INDICATORS IN CHART ROOM.

and serves to tie the tape record to the data log. To observe this meter, the watch officer must leave the bridge and go two decks below to the recording equipment. Because of this inconvenience, the Second Officer of the S.S. HOOSIER STATE requested that a remote indicating meter be located in the Chart Room.

The investigators agreed that a remote indicating running time meter would be installed in the Chart Room. It was also decided, since the additional cost was slight, to include a remote indicating stress meter. The ship electrician installed a four-conductor cable between the recording equipment and the Chart Room during the tenth voyage so that the instruments could be installed when the ship returned. The resulting installation is pictured in Fig. 18.

The ship personnel were instructed to take their time meter readings from this remote running time meter in the Chart Room, and to reset it to zero when tape is rewound to agree with the meter on the recording equipment.

A similar remote indicator has been assembled for installation aboard the S.S. WOLVERINE STATE in the near future.

Tape Playback System. A system for playing back the data tapes is located in the investigators' laboratory. This system is compatible with the shipboard recording units in that it accommodates 10 1/2 inch reels of one-inch-wide magnetic tape which have been recorded using frequency modulation techniques in the standard 14-track IRIG configuration. The purpose of this system is to reconstruct the originally recorded data in the form of electrical signals which can be used as inputs to graphical recorders or automatic data analysis systems. Figure 7 is a functional block diagram illustrating the operation of reproducing a typical channel of magnetic-tape recorded data.

PERFORMANCE OF EQUIPMENT

General

The original installation was made aboard the S.S. HOOSIER STATE in November of 1960. The second installation was made aboard the S.S. WOLVERINE STATE in December 1961. Up to October 1962, useful data have been obtained from 17 out of the 20 round-trip voyages of the S.S. HOOSIER STATE and from 8 out of 9 round-trip voyages of the S.S. WOLVERINE STATE.

A regular maintenance check is made aboard each ship, approximately once a month, at the completion of a round-trip voyage. During these visits the operation of the recording system and the condition of all transducers is checked; any needed repairs are made; and routine preventative maintenance is performed.

After the initial two months of operation, moisture entered the stress-gage housings aboard the S.S. HOOSIER STATE. Corrosion then caused the compensation strain gages on both sides of the ship to develop short circuits. The result was an overload which damaged the strain-gage amplifier and, by a chain reaction, damaged the F-M recording oscillator in the tape recorder. Because of delays in shipping schedules and the need for sufficient time to renew the transducer installation, the system was inoperative for nearly three months.

After removal of the stress gage, the protective housing was filled with Dow-Corning No. 3 compound (silicone grease) under slight pressure to exclude moisture, and a "dike" of electrical direct-sealing compound was formed around the outside of the housing adjacent to the ship's side plate. In the original installation the housing was hard packed with the silicone grease and reliance was placed upon the O-ring seal between the housing and the ship side plate.

Since the repair, the stress gages on the S.S. HOOSIER STATE have operated satisfactorily for 16 months. The revised installation techniques were employed on the S.S. WOLVERINE STATE stress gages. These have been operated satisfactorily with no evidence of deterioration during the nine months of operation since they were installed.

There have been some minor system difficulties from time to time, but these have either occurred toward the end of a voyage or have not been of a serious enough nature to cause the loss of a significant quantity of data. Examples of these difficulties would include several failures of the strain gage amplifiers, a relay failure in one of the tape recorders, and failure of the motor-alternator speed control aboard the S.S. HOOSIER STATE.

Bending Moment Calibration

It is desirable to obtain a direct bending moment vs. stress calibration for each stress-gage installation. To date, it has been possible to obtain only one such calibration on the S.S. HOOSIER STATE and none on the S.S. WOLVERINE STATE.

The S.S. HOOSIER STATE calibration was accomplished during night bunkering in Brooklyn, N. Y., in November of 1960. A total of 1369.1 tons of fuel were taken aboard in the three midship double-bottom tanks, resulting in a calculated bending-moment change at the gage cross section of 35,666 ft-tons (sag). Using the section modulus at the gage location (43,120 in.^{2}-ft), the computed stress change at the gages was -1,853 psi. This compared to a stress of -1,750 psi measured at the recorder, a difference of only 5.5 percent. It should be noted that the addition of riveted deck straps to the vessel, subsequent to the calibration, increased the section modulus at the gages to 47,365 in.^{2}-ft.

It was possible to observe stress changes in the S.S. WOLVERINE STATE during drydocking. The change in stress from the still water condition prior to drydocking, to the drydocked condition (on blocks, dock pumped) was -9000 psi. This compares to the maximum observed (to date) seaway-induced peak-to-peak stress value of 8300 psi.

CONCLUDING REMARKS

The performance of the two "unmanned" tape recording systems to date has been excellent. The versatility of the unit has been demonstrated by the ease with which additional transducer inputs were handled in the case of the S.S. HOOSIER STATE. The acquisition of data reduction and analysis equipment will result in a completely integrated system for acquisition of data from a number of units, with analysis being performed at a central facility.

In order that the objectives of the project may be fully realized, it is necessary that information be obtained on a number of ship types operating on a variety of routes. It is to be hoped that, with satisfactory instrumentation now available, sufficient interest will be exhibited to permit equipping other ship types. For example, it would seem desirable that one or more C-4 MARINER class vessels, operating on the northern trans-Pacific run, be instrumented. These are relatively fast ships operating on one of the more unpleasant routes, as regards weather and sea conditions. At some point in the near future, a large tanker, operating on as unfriendly a route as possible, should be studied.

The data tapes are being stored at the investigators' facility. Inquiries relative to these tapes, or to shipboard installations, can be directed either to the investigators or to the Secretary, Ship Structure Committee, U. S. Coast Guard Headquarters, Washington 25, D. C.

ACKNOWLEDGEMENTS

This project is sponsored by the Ship Structure Committee and is under the guidance of an advisory committee of the Committee on Ship Structural Design of the National Academy of Sciences-National Research Council. The wholehearted cooperation and continuing assistance of the States Marine Lines, and in particular of Messrs. E. P. Bainbridge, Neil Miller, and the officers and men of the S.S. HOOSIER STATE and the 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 deeply appreciated.

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APPENDIX A

Project 22: Statistical Studies of Seaway Loads Aboard Ship

Objective: To obtain statistical records of vertical longitudinal wave bending moments experienced by various types of ships operating on different trade routes, with the emphasis being placed on extreme values of external loads.

Program: Carry out a long-range statistical study of longitudinal wave bending moments on approximately 15 to 20 ships of different sizes, speeds and types operating on important routes. Sea and weather data should be compiled concurrently. Reports of accumulated results in tabular and graphical form should be issued periodically. Statistical studies should be made, leading primarily to information on distributions of extreme load values. (Short-range case studies entailing more complete seaway load measurements and measurement of wave patterns are covered in Project 18.)

Suggested Techniques: Two strain gage installations mounted on the strength deck amidships, one port and one starboard, should be installed on all ships. They should be temperature-compensated and connected in series in order to give a mean reading. Calibration of each ship in terms of vertical longitudinal bending moment would be obtained by filling and emptying ship tanks in calm water to provide known bending moments. Records at sea would be obtained by suitable instruments designed to require a minimum of attention, such as strain-cycle counters, automatic sampling recorders, or instruments for recording average and maximum values during fixed time intervals. The instruments should be designed so as not to respond to high-frequency strain variations caused by slamming, engine vibration, etc., for such effects should be considered separately under another project.

Statistical analysis should be made of all load data; in particular, "extreme value" theory should be applied to the study of trends of maximum values. (See also Project 23.) If sufficient data are obtained, analysis of trends should also be obtained in the manner of Jasper.[10]

Research in Progress: Some stress data are being obtained by the Hull Structure Committee of the SNAME (Panel S-10), DTMB, British Shipbuilding Research Association, the Swedish Ship Research Institute, the Laboratory for Ship Structure Research, Delft Technical University, and the Association Technique Maritime et Aeronautique, France (de Leiris[53]). The Ship Structure Committee has initiated a project (SR-153) with Lessells and Associates, Inc., for a portion of this study.

Results Expected: Further supporting data on statistical trends of hull bending moments. After five or more years, statistically valuable information on extreme loads for different services and different ship types should emerge.

Taken from Reference 1.

APPENDIX B

Detailed Specifications on System Components

1. Transducers

   a. Stress Gages

      i. Budd/Tatnall Metalfilm Strain Gage, Type C6-181 (See Reference No. 9 for stress gage configuration)
      Manufacturer: The Budd Company, P. O. Box 245, Phoenixville, Pennsylvania
      Resistance: 120 ± 0.2 ohms
      Gage Factor: 2.01 ± 0.5%
      Temperature Compensation: compensated for use on mild steel
      Gage Length: 0.5 inches
      Gage Width: 0.5 inches
      Overall Length: 1.005 inches
      Overall Width: 0.5 inches
      Resistance Material: Advance
      Backing Material: Epoxy

      ii. Baldwin-Lima-Hamilton Stress-Strain Gage Type FAB28-S6
      Manufacturer: Baldwin-Lima Hamilton, Waltham, Massachusetts
      Resistance: Element 1: 350 ohms
      Element 2: 98 ohms
      Material Poisson Ratio: .28
      Material Coef. of Expansion: 6 micro inch/inch/°F (Mild Steel)
      Gage Material: Resistance Foil
      Backing Material: Phenolic

   b. Strain Gage Cement

      Manufacturer: Armstrong Products Company, Argonna Road, Warsaw, Indiana
      Type: Armstrong Adhesive A-1
      Epoxy resin formulation with inorganic filler and amine type catalyst

   c. Dow Corning 3 Compound (Silicone Grease)

      Manufacturer: Dow Corning Corporation, Midland, Michigan
      A non-melting silicon dielectric and lubricant. Effective from 40 to 400°F

   d. Accelerometers

      Manufacturer: Statham Instruments, Inc., 12401 Olympic Boulevard, Los Angeles 64, California
      Model: A3-2.5-350
      Range: ±2.5g
      Nominal Bridge Resistance: 350 ohms
      Maximum Excitation: 11 volts d-c or a-c (rms)
      Full Scale Output (open circuit): ±20 mv.
      Approximate Natural Frequency: 55cps
      Damping (Viscous Fluid): 0.7 ± 0.1 critical at room temperature
      Direction of Sensitivity: Perpendicular to base
      Overload: Three times rated range
      Transverse Acceleration Response: 0.02g per g up to rated range
      Nonlinearity and Hysteresis: Less than ±1% of full scale output
      Weight: Approximately 2 1/2 ounces

2. Strain Gage Conditioning Equipment

   Manufacturer: Video Instruments Division, Endevco Corporation, 161 East California Boulevard, Pasadena, California
   Model: SRB-200RCH Strain Gage Module
   Output for Bridge Excitation: 0-24 volts d-c
   Current Range: 0-200ma
   Output Impedance: Less than 0.2 ohm
   Line Regulation, 95-135V. a-c: 0.1%
   Load Regulation, 0-Full Load: 0.1%
   Ripple, 95-135V. a-c: 1 mv. rms
   Input Power: 115 ± 20V. a-c 50-400 cps
   Unit contains controls for calibration, bridge balance and excitation level. Internal relays permit removal of transducer excitation and operation of calibration circuits by remote control.

3. Amplifiers

   a. Strain Gage Amplifier

      Manufacturer: Video Instruments Division, Endevco Corporation, 161 East California Boulevard, Pasadena, California
      Model: 602A Solid State Amplifier
      Input: Differential or single ended

Input-Cases Isolation, ohms, 10,000 Meg.
Output: Single ended, isolated from input and ground
Output-Case Isolation, ohms: 100 Meg.
Gain Range: 1-1,000
Gain Steps: 7
Gain Vernier: Variable between steps
DC Gain Accuracy: 1%
Gain Stability: .04% 24 hrs.
Gain Temperature Coeff., %/°F: .02
Zero Stability: .04% F.S. 24 hrs.
Zero Temperature Coeff., %F.S./°F: .005
D.C. Linearity, F.S.: .05
Input Impedance, ohms: 1 Meg.
Max. Safe Input Signal, Volts: ±10
Max. Source Impedance: 1K
Max. Source Unbalance: 10K
D.C. Common Mode Rejection, db: 160
60 CPS Common Mode Rejection, db: 120
Max. Safe Common Mode Signal, Volts: ±200
Bandwidth, Relative to D.C. output: 10 ~ 1%; 100 ~ 3db
Max. Overload Recovery Time: 1/2 Sec.
Total Output Noise, Wide Band, Including Chopper Ripple, at Max. Gain, mv Rms: 3
Full Scale Output Volts: ±10
Max. Output Current: 200
Max. D.C. output Impedance, ohms: .5
Max. Capacitive Load, Wide Band: Infinite up to rated output current.
Operating Temperature Range, °F: +40 to +120
Power Requirement: 115 ± 10% VAC, 50-400 ~ 40 watts

b. Accelerometer Amplifier

Manufacturer: Statham Instruments, Inc., 12401 West Olympic Boulevard, Los Angeles 64, California
Model: CA9-56 Strain Gage Signal Amplifier
Power Requirements: 30 millamperes at 28 volts DC ±10%
Output: -2.5 to +2.5 DC
Transducer excitation: 4.5 to 5.5 volts peak-to-peak (square wave)
Frequency: 10 kc
Frequency response: Flat ±5% (referenced to DC), from zero to 2000 cps
Ripple: Less than 0.15% rms.
Sensitivity: Designed to operate with transducers with rated sensitivity from 1.5 mv/v to 10 mv/v
Balance control: From -2.5 to +2.5 volts d-c
Gain Stability: ±0.4% over a period of 8 hours after 15 minute warm-up
Input Impedance: Designed to operate with transducers with bridge resistance greater than 200 ohms and less than 500 ohms
Output Impedance: Less than 4,000 ohms (100K ohms minimum recommended load)
Non-Linearity and Hysteresis: Less than ±0.3% of full scale
Temperature range: Operating -65°F to +180°F; Non-operating -75°F to +230°
Thermal coeff. of sensitivity: 0.015% per degree F
Thermal zero shift ±0.005% of full scale output per degree F
Vibration tolerance: Constant displacement of 0.75 double amplitude from 5 to 30 cps. Constant acceleration of 35g from 30 to 2,000 cps. Vibration applied along any major axis
Static acceleration: 100g along any major axis

4. Tape Recording System

Manufacturer: Minneapolis-Honeywell Regulator Company, Heiland Division, 4800 East Dry Creek Road, Denver 10, Colorado
Tape Transport: Type 3167, 0.3 and 0.6 ips tape speed, for 1 inch tape, 10 1/2 reels
Recording Head: IRIG Standard record head stack assembly (2 heads interleaved, 14 tracks per inch) 14 tracks.
Recording Oscillator: Dual FM Recording Oscillator, Type 4206, 0.27 kc center frequency
System Performance:
  Input Level: 0.5 to 25 volts rms for ±40 percent carrier deviation. Adjustable by means of front panel control
  Input Impedance: 10,000 ohms, unbalanced to ground
  Frequency Response and Signal/Noise

Ratio: DC - 50 cps, 0.27kc, 36 (compensation improves S/N ratio by 20db)
Total Harmonic Distortion: Less than 2%
DC Linearity: No more than 0.5% deviation from best straight line (±40% deviation system)
Drift Sensitivity: Less than ±0.2% of full scale in six hours after 1/2 hour warmup
DC Drift: No more than 0.2% of full scale per hour warmup (±40% deviation system)
Output Level: 4 volts peak maximum for full scale deviation
Output Current: 30 milliamps maximum (standard output)
Output Impedance: Less than 1 ohm
Output Characteristics: Balance, short-circuit proof; can be operated with one side grounded. Output returns to zero with no input signal present (squelch) or with overmodulation (adjustable from ±50% deviation) for oscillograph galvanometer protection.
Low Pass Filters: Type 5232, Flat Frequency Response: dc to maximum specified cutoff frequency, ±0.5 db. overshoot unspecified.

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