Chapter 5

WAVE-PRODUCED MOTION OF MOORED SHIPS

Robert T. Knapp
Professor of Hydraulic Engineering
California Institute of Technology
Pasadena, California

SCOPE OF PAPER

This paper presents a brief description of some ship motion measurements made in Los Angeles Harbor in conjunction with the model study of inner mole at that location. It also includes the description of the battery of recording instruments which was developed as the result of the difficulties encountered in making the ship motion measurements by conventional means.

NEED FOR INFORMATION CONCERNING MOTION OF MOORED SHIPS

Knowledge of the characteristics of motion of moored ships is of considerable importance to several phases of harbor engineering. For example, it is a very important factor in general harbor design. It is becoming well recognized that wave motion and the resulting ship motion vary quite widely in different parts of a given harbor. Also the maximum acceptable motion of a moored ship depends upon the type of ship-to-shore operation that has to be carried out. For example, passenger and light cargo loading and unloading can be carried on successfully even though ship motions of relatively large amplitude are present. On the other hand, major operations at outfitting and repair docks and the operation of drydock gates require that ship motion be very small. Unfortunately, little quantitative information exists concerning either the maximum acceptable ship motions for the different types of harbor operation or the magnitude and other characteristics of the wave motion which will produce a given ship motion under a specified system of mooring.

The quantitative knowledge of ship motion is also of importance to the detailed design of all waterfront structures involving ship mooring since the maximum loading applied to such structures by the ship will commonly be as a result of the ship motion produced by wave action.

COMPONENTS OF SHIP MOTION

A moored ship generally has a very complicated pattern of motion. A convenient set of axes for analyzing this motion consists of a horizontal axis parallel to the pier or other mooring, a similar axis perpendicular to the pier, and a vertical axis, all passing through the center of gravity of the ship. When the various components of this motion are examined critically, it is found that they are not all of equal significance. Of the three linear components, the longitudinal and lateral are the most important since the vertical or "heaving" motion is nearly always of much smaller amplitude than the other two. Of the three angular motions, pitch seems to be the least important for the moored ship; whereas, roll and yaw may both cause considerable trouble. Pitching and heaving are primarily induced by the vertical components of the wave motion. The other ship motions are the result of the horizontal water motion. It thus becomes obvious that the horizontal water motion is the fundamental cause of the significant components of motion of moored ships. The reason for this is that major ship motion is induced only by waves whose length is at least a large fraction of the ship length. The amplitude of the horizontal water motion of such waves is much greater than that of the vertical; hence, the horizontal motion of the moored ship is much greater than the vertical.

Unfortunately, the conventional method of measuring wave activity is by use of a water stage or wave height recorder. This measures only the vertical component and period of the wave motion. For long period waves this is a particularly insensitive method of measuring horizontal water motion. An added disadvantage is that the amplitude of the short period "wind chop" waves may be much greater than that of the long period waves that cause the ship motion. Thus, unless the wave height recorder is properly damped, its records may be meaningless. The wave height recorder suffers from still another disadvantage. A single instrument gives no information concerning the direction of travel of the waves. Due to the complicated nature of the wave patterns existing under natural conditions, it is often extremely difficult to determine the direction of wave travel from the simultaneous records of three wave height recorders spaced in a triangular pattern. However, if ship motion is to be correlated with water motion, it is necessary to know the direction of the horizontal motion of the water.

SUMMARY OF PROBLEM

To summarize the problem, it consists of two parts. The first part is to determine the linear and angular components of motion of moored ships and to evaluate the maximum amplitudes of the different components that can be tolerated for various types of harbor activities. The second part is to determine the magnitude and direction of the horizontal water motions and to correlate these measurements with the resulting ship motion for various types of ships under various mooring conditions. The harbor designer already has at his disposal at least two methods of predicting in considerable detail the horizontal water motion over an entire area of a proposed harbor. Many large harbors are designed with the help of model studies. If undistorted scale models are used, reliable measurements can be obtained of the horizontal water motion in various parts of the harbor. Furthermore, methods have been developed and are being improved constantly for the calculation of the wave pattern within harbors due to the wave energy entering through the breakwater openings. The missing links in the chain of design are the correlation of water motion with ship motion and the values of the allowable ship motion for the different operations.

SHIP MOTION OBSERVATIONS

Observations of ship movements at outfitting piers were made in the spring of 1944 as a part of the model study of the inner mole for the Naval Operating Base at Terminal Island in Los Angeles Harbor. The measurements were made as follows: large rectangular targets were fasten-

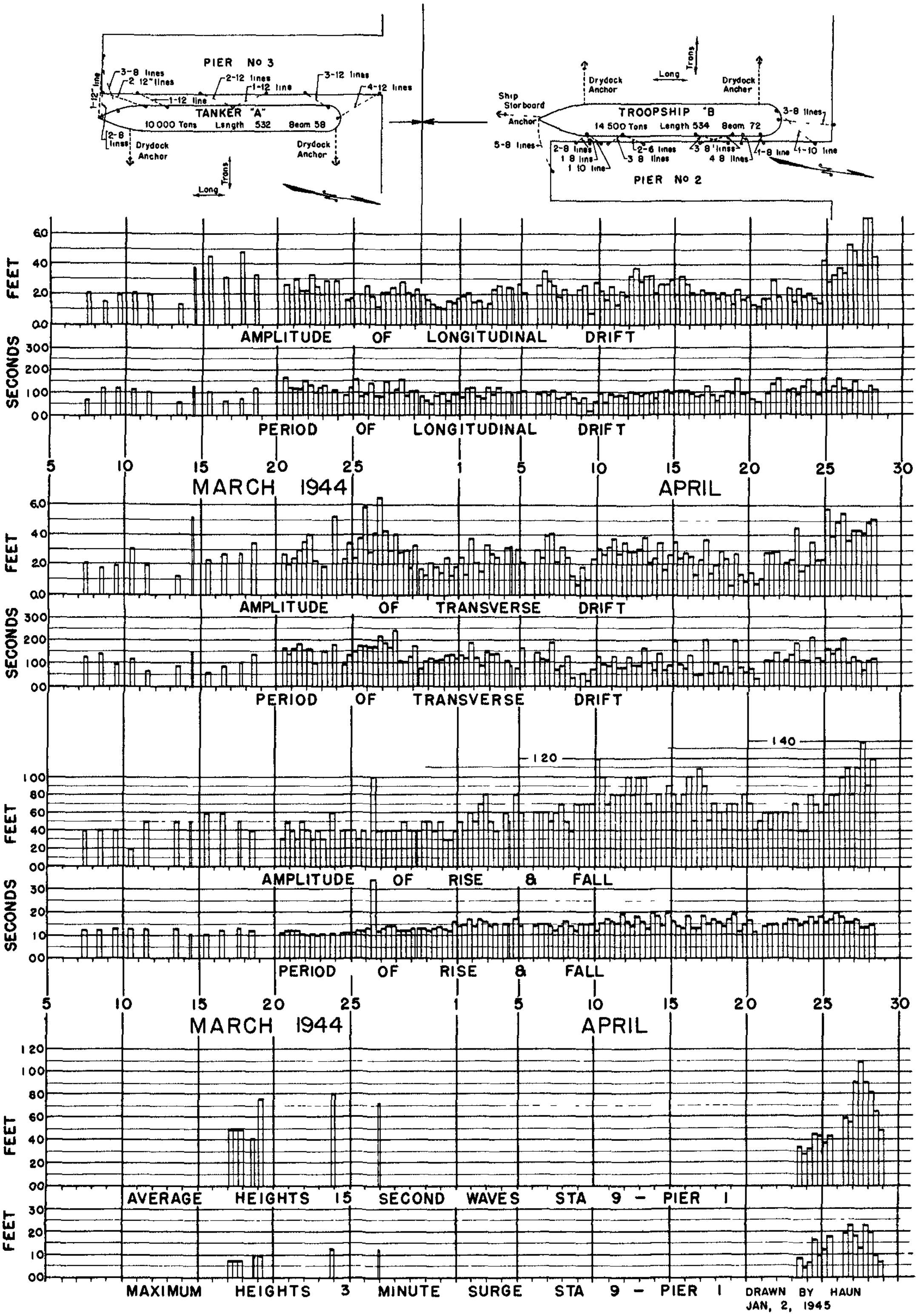


Fig. 1. Observed ship and wave motions of tanker and troop ship.

ed to the bow and stern of the ship to be studied. These targets were subdivided into numbered squares which were in turn subdivided into four labelled quarters. Two surveyors levels were mounted in fixed positions on the pier, one for each target. Determination of ship motion was made hourly. The two targets were read simultaneously at very short intervals until enough data had been obtained for the calculation of the amplitudes and periods of the lateral, longitudinal, and vertical motions of the ship. These three components were obtained from the original data through the use of a plotting board and movable templates. This method proved to have a satisfactory accuracy and be much faster than direct calculation.

These observations were continued over a period of about three months and included nine different ships whose displacements varied between 10,000 and 14,500 tons. Most of the measurements were of little value because the ship motion was too small to cause any difficulty in the operation. However, on two ships, Tanker A and Troop Ship B, the measuring period included some moderately high activity. Fig. 1 shows the observed ship motion during these two sets of measurements together with the wave height measurements as recorded by a float type wave height recorder operating in a stilling well.

GENERAL CHARACTERISTICS OF SHIP MOTION

At the top of Fig. 1 will be found a sketch showing the method of mooring used for each ship. This figure requires detailed study. The first thing to be noticed is that the wave height recorder shows two types of waves, the normal 10-to-15 sec wind waves, and a long wave having a period of approximately three minutes. The maximum observed wave heights for the three minute waves is just slightly over .2 of 1 ft, whereas the maximum height of the 15-sec waves was over 1 ft. During much of the time the record indicates zero wave height. This does not mean that there were no waves in the harbor, but simply that the wave height records were not sufficiently accurate to detect a small amplitude wave. The determination of the heights of the 15-sec waves was complicated by the presence of wind chop. It proved to be very difficult to get a satisfactory damping of the stilling well which would make it possible to see the 15-sec waves and at the same time eliminate the motion due to wind chop. Thus about .3 ft was the lowest 15-sec wave that could be detected. It proved possible to measure heights of the 3-min waves somewhat more accurately, but here .05 ft was about the minimum. These facts explain the ship motion shown on the record during times in which no wave motion is indicated.

If the measurements of the vertical ship motion are next examined, it will be seen that they correlate quite closely with both the period and the amplitude of the 15-sec waves. (In this connection it should be noted that throughout the diagram the word "amplitude" is used to mean the double amplitude or total excursion of the ship.)

The transverse and longitudinal motions are in striking contrast to the vertical. Both of these horizontal motions show large amplitudes and long periods. Their periods are seen to average between 100 and 150 sec, which is a reasonable correlation with the so-called 3-minute waves.

It may be concluded tentatively from these measurements that medium and large-sized ships move vertically with the same amplitude and period as the wave, provided that the wavelength is about equal to the ship length, or greater. It also may be concluded that the horizontal motion of such ships does not follow that of a short period wave, at least for wave heights of under 1 1/2 ft, but it does respond to the long-period waves.

HEIGHT OF WAVE PRODUCING DAMAGE

Fig. 2 is a record of the four days, April 23, 24, 26, 27, 1944, during which time there were periods of damage to ships and piers. The damage was all traceable to the horizontal motion of the ship. It will be observed that the periods of damage correlate well with those of the high amplitude 3-min. waves. Thus a similar record indicated that damage was present whenever the 3-min waves had a height of .2 of a ft or over. Rough calculations indicated that in the depth of the water existing at the piers, a 3-min wave with a .2 ft wave height would have a horizontal water oscillation of approximately 8 to 10 ft. This agrees very well with the observed longitudinal and transverse motions of the ship in spite of the fact that a relatively elaborate system of mooring had been used in an endeavor to minimize the motion.

Unfortunately, little can be said concerning the maximum tolerable movement at the outfitting piers. This is principally because at the time these measurements were taken, no means had been established for getting a reliable estimate of the effect of the motion on the work. There is one bit of evidence in that there was no complaint concerning the effect of the surge on April 23 and 24, whereas on April 26 the surge did interfere with the work. Thus it might be concluded that the horizontal motion of three to five feet, with a period of approximately 3 min, is about the upper limit of tolerance for general work.

INSTRUMENT DEVELOPMENT

The manual measurements described in the previous paragraphs were tedious, expensive, and not too satisfactory. Four men, two instrument men and two recorders, were required to take the simultaneous readings of the motion of the targets. For continuous readings, this meant a crew of 12 men for the three shifts. Despite this large crew, it was physically impossible to take enough readings to obtain the complete history of the ship movement. The work was also very discouraging to the crew because most of the time the ship motion was trivial. On the other hand, it was necessary to take the measurements continuously since the surge occurred without warning and often lasted only a few hours, which was too short a time to organize a crew and start taking measurements after the surge was first noted. Because of this situation, it was recommended in the report on the Terminal Island study that an effort be made to develop a battery of recording instruments which could operate with only infrequent service. The Bureau of Yards and Docks approved this recommendation and entered into a contract for the development of such a battery of instruments.

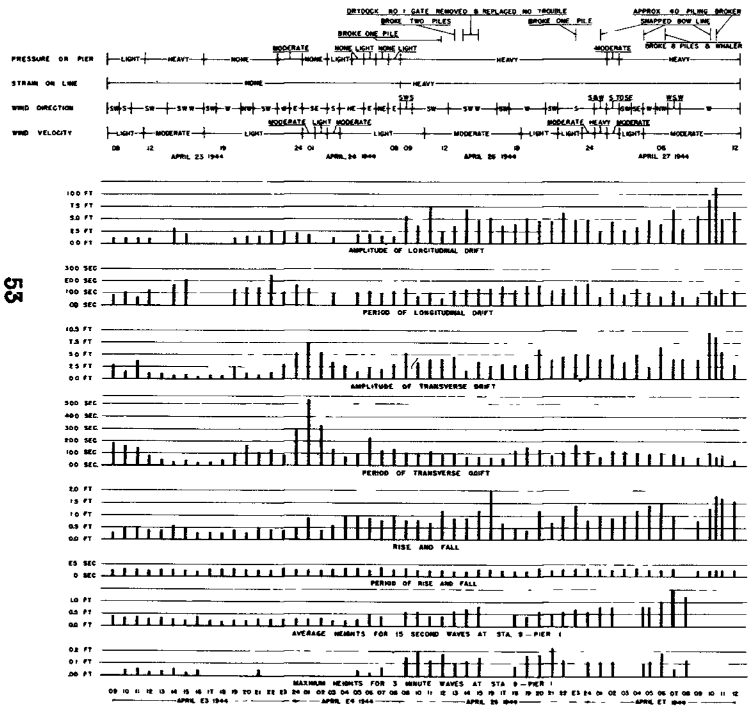


Fig. 2
Observed motion of waves and of troopship "B" before and during period of damaging ship motion.

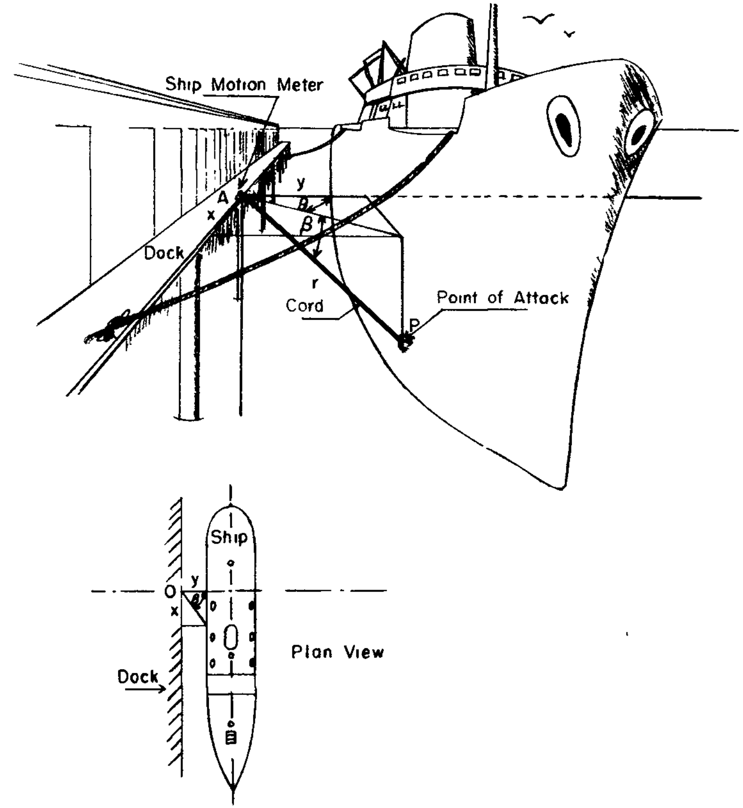


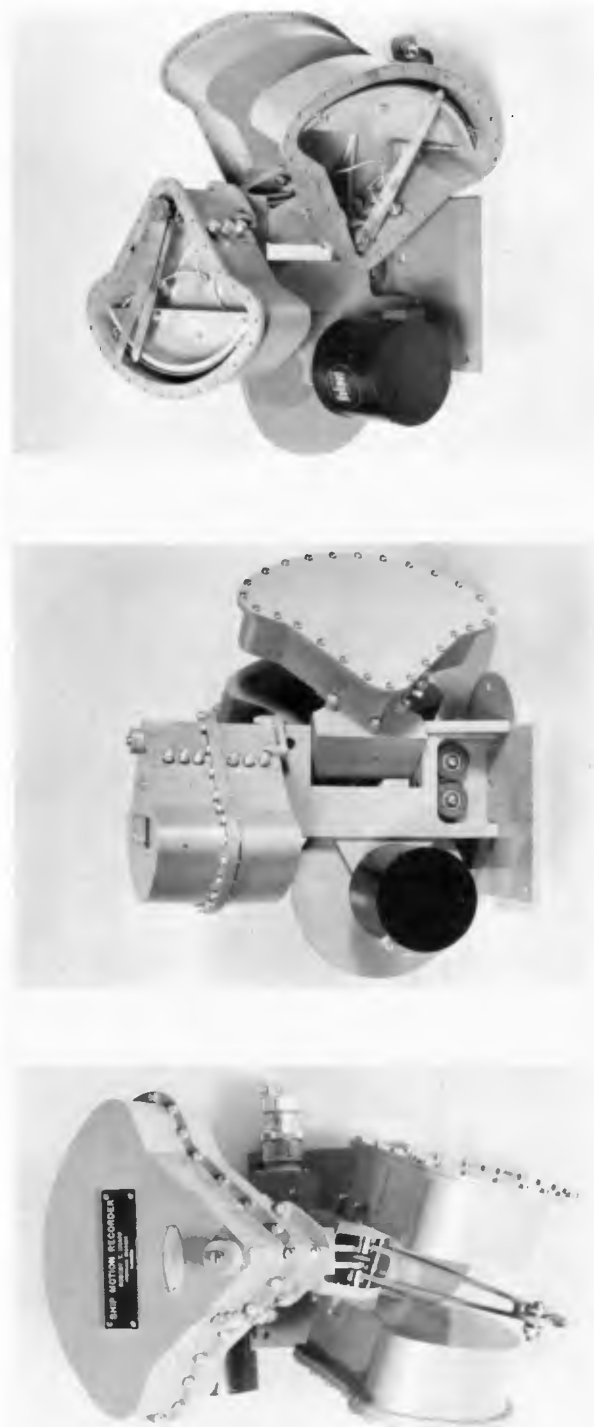
Fig. 3
Schematic installation of ship motion recorder.

COMPONENTS OF INSTRUMENT BATTERY

As the result of the experience gained in the study just described, it was decided that the primary effort in the development of a ship motion meter should be to obtain measurements of the longitudinal and lateral motion of a ship with respect to the pier. The measurement of roll and yaw was considered to be desirable as a secondary objective. It was decided not to attempt to measure pitch. The close correlation between the vertical water motion of the waves and that of the ship found in the previous study indicated that a satisfactory solution would be to record the vertical water motion, but to omit attempting to measure the vertical motion of the ship. The set of measurements considered to be of equal importance to the determination of the horizontal component of the ship motion was that of obtaining the magnitude and direction of the horizontal water motion. Since the correlation of ship and water motions is one of the most important features of this type of study, it was decided that all of the measurements should be recorded simultaneously on a single record. The battery finally developed to meet these objectives consists of a ship motion meter which measures directly the longitudinal and lateral motions; an auxiliary attachment to this meter, which indicates roll and yaw; a bottom pressure recorder, which measures the vertical amplitude of the waves and surges and effectively eliminates the fluctuations due to wind chop; a current meter, which indicates magnitude and direction of the horizontal water motion; and a multiple element recording galvanometer.

Ship Motion Meter. Fig. 3 is a sketch showing the general scheme of the Ship Motion Meter. The meter itself is installed on the pier in a convenient location, either above or below the dock. It is connected to the ship by a very light cable (1/16-in dia.). An effort is made to locate the point of attachment to the side of the ship on a horizontal line running through the center of gravity of the ship and normal to the longitudinal axis. The line may be secured to the ship either by welding on a lug or by use of a small powerful permanent magnet. This latter method proved quite satisfactory since the force required to operate the instrument is very small. Fig. 4 shows three views of this instrument. The instrument consists basically of four potentiometers that are operated by the motion of the cable. The output of the linear potentiometer varies directly with the changing length of line connecting the instrument to the ship. The other three potentiometers are operated by the changing angle which the cable makes with the pier. The potentiometer cards are wound to give outputs proportional to the trigometric functions of the angle. Two of the potentiometers, one sine and one cosine, move with the horizontal angle that the line makes with the normal to the pier. Another cosine potentiometer measures the vertical angle that the line makes with this normal. The outputs of these four potentiometers are interconnected so as to give two outputs, one of which varies linearly with the longitudinal motion of the ship and the other varies linearly with the lateral motion.

The roll and yaw indicator is shown in Fig. 5. When this unit is used, it must be mounted on the ship in place of the simpler cable attachment. It consists of two more potentiometers, but in this case the output varies directly with the angle rather than with the trigonometric function. Fig. 6 shows a schematic diagram of the roll and yaw installa-



a. Front view. b. Side view. c. Cover plates removed.

Fig. 4. Ship motion recorder.

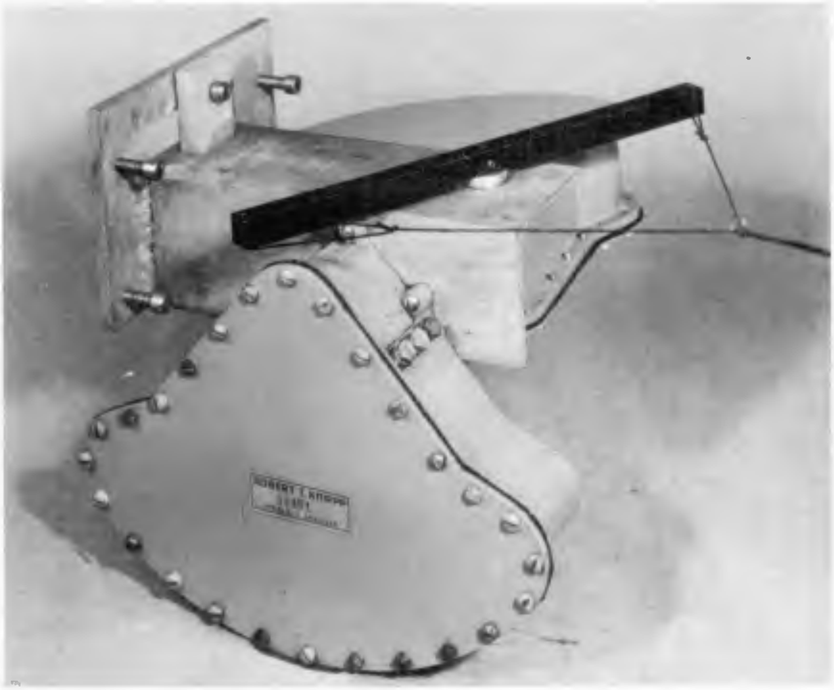
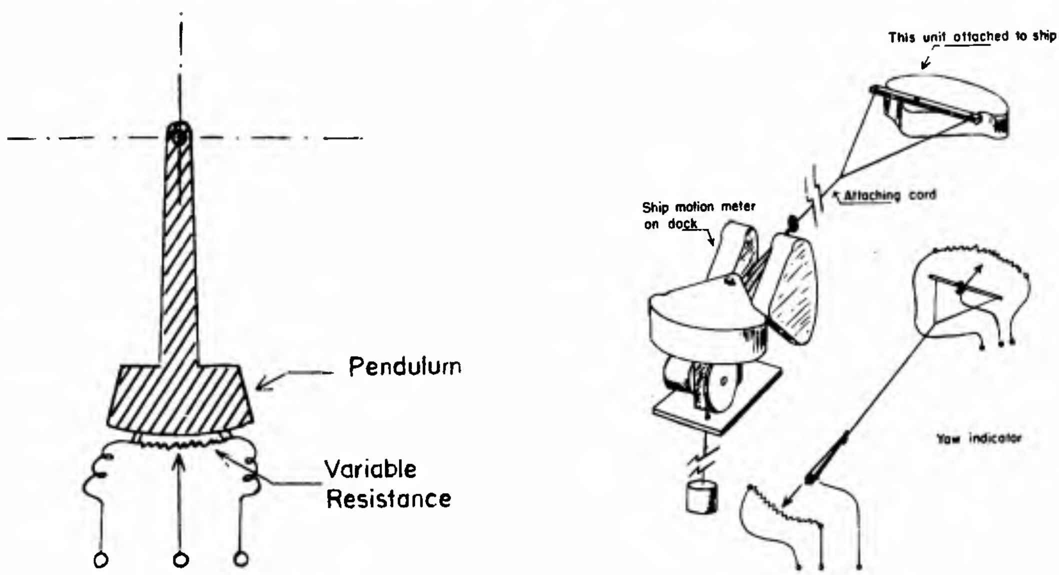


Fig. 5. Roll and yaw indicator.



a. Roll indicator. **b. Yaw indicator.**

Fig. 6. Schematic diagrams of roll and yaw indicator.

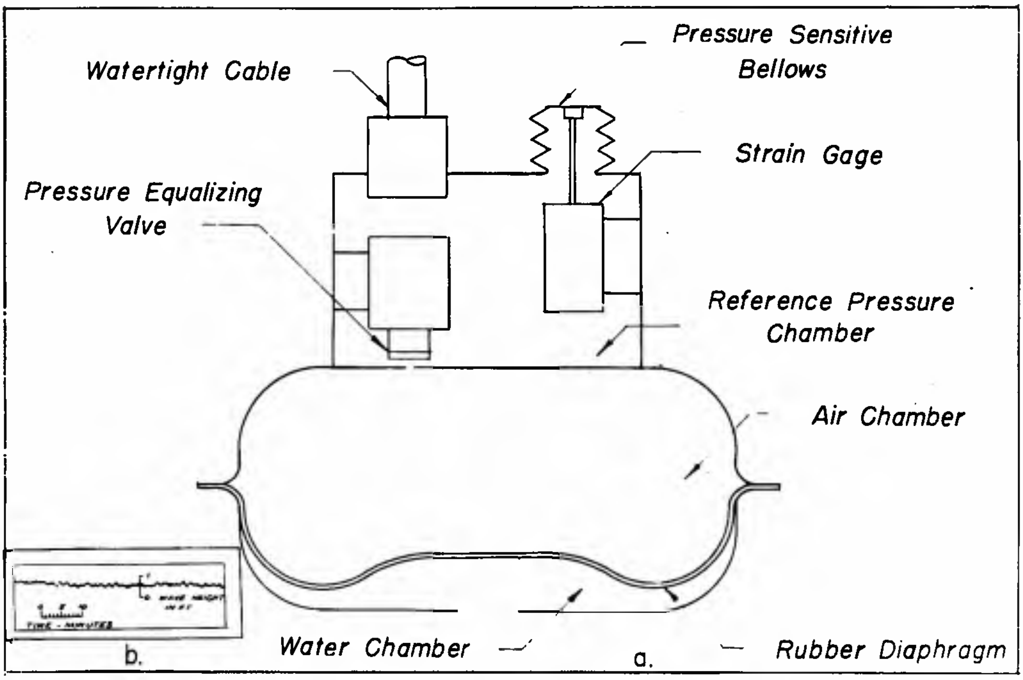


Fig. 7
Bottom pressure recorder, (a) schematic diagram, (b) record made by recorder.

Fig. 8. Current meter mounted in leveling tripod.

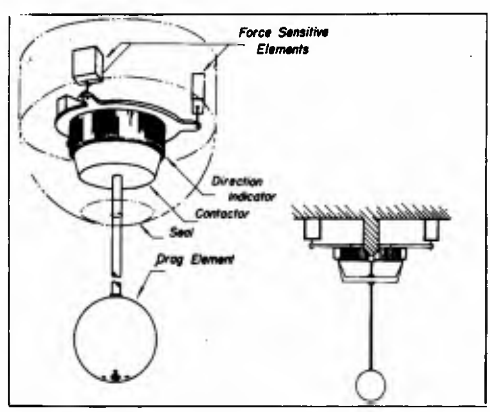


Fig. 9. Diagrammatic sketch; construction of current meter.

tion. It is seen that the roll potentiometer is operated by a simple pendulum. The yaw indicator requires an additional potentiometer to be installed in the ship motion meter. This is also wound so that its output is directly proportional to the angle. The two yaw potentiometers, the one on the ship and the one on the pier, are connected electrically so that the output is proportional to the difference between the two angles. The output of the ship yaw potentiometer is proportional to the angle between the instrument line and the ship, which is the sum of the angle between the instrument line and the pier and the yaw angle of the ship with respect to the pier. The output of the pier yaw potentiometer is proportional to the angle of the instrument line with the pier. Thus when this is subtracted from the ship potentiometer output, the remaining output is proportional to the ship yaw angle.

Bottom Pressure Recorder. The Bottom Pressure Recorder is seen in Fig. 7. The reason for designing a new instrument, rather than employing one of the existing wave height recorders, was basically to obtain an instrument whose electrical output would be the same type as that from the other instruments of the battery so that the same recorder could be used. Furthermore, a relatively high sensitivity was desired so that low amplitude, long period waves could be recorded, while at the same time the instrument was required to be undamaged by operation in water of widely varying depth. The instrument is very simple, both in principle and in operation. Fig. 7 shows a sectional diagram of the instrument. It will be seen that it consists essentially of an air chamber, on one end of which is a flexible metal bellows open on the inside to the air chamber and surrounded by the water on the outside. This bellows is restrained from moving in response to the pressure fluctuations in the water by a rod which is connected to a wire-wound uncemented strain gage. The output of this strain gage is thus directly proportional to the pressure difference between the air chamber and the water. The air chamber is in two parts, the upper, or working chamber, and the lower, or depth compensating chamber. The upper chamber has a constant volume, but the bottom of the lower chamber is a very flexible rubber diaphragm which is directly in contact with the water. There is a single connection between the two chambers through a pressure-equalizing valve. This is a solenoid valve which is normally held tightly closed by spring pressure and is opened only when the solenoid is energized. It will be seen that when the equalizing valve is open, the pressure in the working chamber will be that of the surrounding water. During installation of the instrument in a new location, the equalizing valve is held open while the instrument is being lowered to its operating location. The valve is then closed and the instrument immediately begins to function, indicating the difference in pressure between the working air chamber and the surrounding water as the latter fluctuates due to the passage of the waves.

Horizontal Current Meter. The current meter, together with its leveling tripod, shown in Fig. 8, is designed to give a record of the magnitude and direction of the horizontal water motion. Since the record is continuous, it also indicates the period of the oscillations. The actuating element of the meter consists of a sphere suspended below the case by means of a rod. The rod is pivoted within the case. The freedom of motion required for operation is obtained by means of a flexible rubber unit which also acts as a seal. The force of the water moving past the ball tends to cause the upper end of the rod to rotate in-

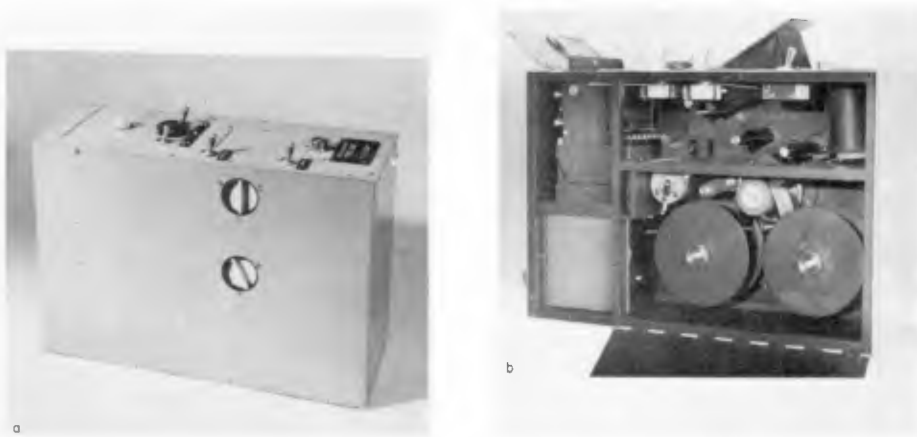


Fig. 10. 35 mm. recording galvanometer; (a) closed, (b) open.

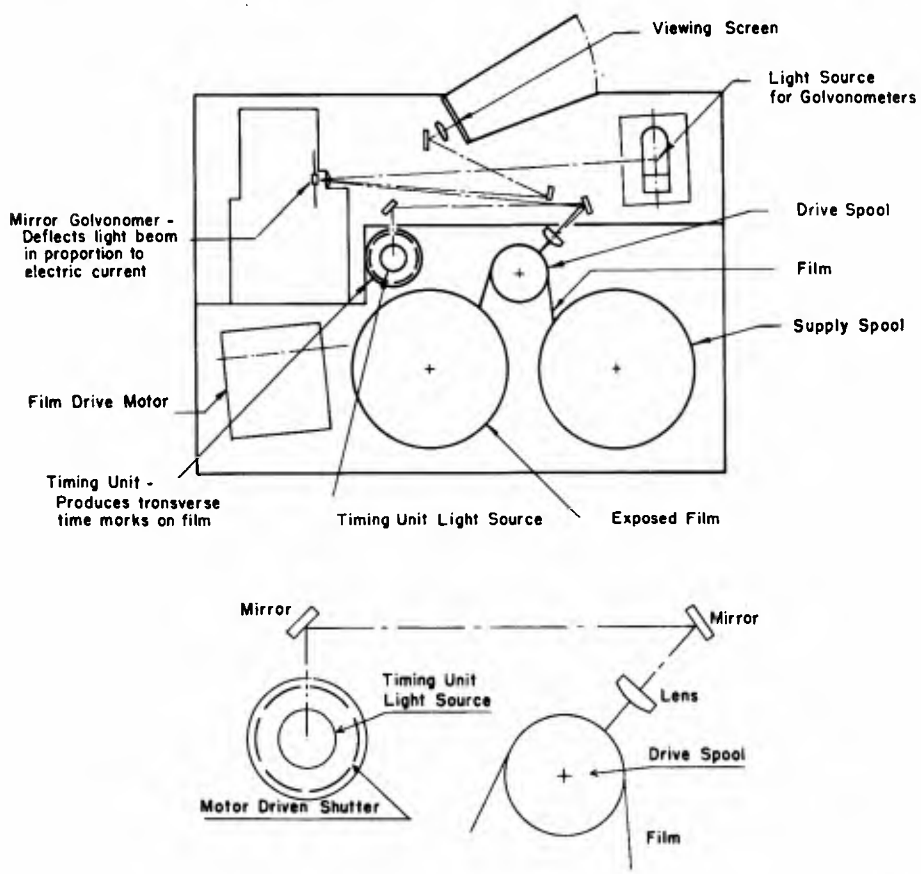


Fig. 11. Diagram of internal construction of recording galvanometer.

side the case. This rotation is prevented by a battery of three wire-wound, unbonded strain gages similar to the one used in the Bottom Pressure Recorder. These gages are connected electrically so that their combined output is proportional to the horizontal force on the ball independent of the direction from which this force is applied. Interposed between the rods and the set of strain gages is a 360° wire-wound potentiometer. A rigid disc carrying a special ring contact is fastened to the rod. The diameter of the ring contact is that of the potentiometer winding, and as the rod starts to move under the influence of the water force the ring makes contact with the potentiometer at one point on the circle. Since this point is determined by the direction from which the water force comes, the potentiometer output is proportional to the direction of the water motion. The instrument operates completely filled with oil and the case is provided with a small rubber bellows which equalizes the pressure with that of the surrounding water. Thus the instrument is capable of operating at any depth without modification. Fig. 9 is a diagrammatic sketch of the internal construction of the current meter. Since it was proposed to install this meter on the natural harbor bottom, a special mounting tripod was designed to support it. It is desirable to have the ball hang vertically below the meter so that the readings of the meter will be proportional to the horizontal water motion. Therefore, a leveling device was incorporated in the tripod head. Furthermore, if the meter is lowered in open water, it is necessary to know the orientation of it with respect to the cardinal directions. Therefore, an aircraft type transmitting compass was installed on the tripod in addition to the leveling mechanism. The installation was completed by the addition of an electrically operated level indicator.

The Recording Galvanometer. Although several excellent multiple-element recording oscillographs are available commercially, they are all designed primarily for use in investigating relatively high speed phenomena. Although it is possible to reduce the film speed considerably, it is difficult to accomplish the very large reduction that would be required to obtain a three-week continuous record without reloading, which was the goal established for this application. Also it was felt desirable to use 35 mm film in place of the much wider recording material normally employed in the standard oscillographs. Therefore, a special recording galvanometer was constructed utilizing a standard 9-element galvanometer block from one of the commercial oscillographs. Fig. 10 shows two views of the completed instrument and Fig. 11 a diagram of the internal arrangements. The timing unit gives a two-minute timing line on the film. This film is standard, unperforated, dye-backed microfile film which permits daylight loading and unloading and operates for three weeks on a 100-ft spool.

OPERATION OF THE INSTRUMENT BATTERY

The instruments described were completed and operated individually and as a battery for sufficient time to demonstrate their satisfactory performance. Unfortunately, however, it had not yet been possible to inaugurate a program of study with them, either to determine the limits of tolerable motion for various harbor activities or to ascertain the correlation between ship and water motion for various systems of mooring. These are both extremely important steps and it is hoped that this work can be continued along these lines.

ADDITIONAL INFORMATION NEEDED

There is still another step that needs to be taken to complete the information necessary for the design of waterfront structures to which ships are moored. This is to determine the forces produced on waterfront structures by the motion of moored ships. A program of direct measurement does not seem to be indicated for this step, or at least not until a great deal more information is available concerning the correlation of water and ship motion. The basic reason for this statement is that there are so many variables that affect the actual forces between the pier and the ship that it would require a very large and lengthy program of field measurements to cover enough different cases to make such empirical information useful and reliable. On the other hand, it may not be necessary to determine these forces by direct measurements after a thorough understanding has been obtained concerning the ship motion produced by given waves. When this information is available, it should be possible to calculate the resulting forces with reasonably good accuracy and by methods which would take into account the geometric and dynamic characteristics of the ship as well as the system of mooring and the wave characteristics at the location of the given structure.

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