UNIVERSITY OF MINNESOTA
ST. ANTHONY FALLS HYDRAULIC LABORATORY
LORENZ G. STRAUB, Director

Technical Paper No. 11, Series B

A Capacitive Wave Profile Recorder

by

JOHN M. KILLEN

October, 1952
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ABSTRACT

Research studies at the St. Anthony Falls Hydraulic Laboratory necessitated the development of a device for measuring and recording the profile of surface waves. The initial phase of these studies involved waves with periods ranging from 1/3 to 1 sec and with heights ranging from 1/2 to 3 inches. Existing methods of measuring and recording the profiles of these waves were considered to be not entirely satisfactory.

A method has been developed whereby wave heights are measured electrically with a recording oscillograph; the deflections correspond to the depths of submergence of an insulated wire into the water. This insulated wire acts as a small capacitor whose capacity varies directly with the wetted area of the wire.

The system has a linear calibration. Thus, accurate and continuous wave profiles can be recorded. Hysteresis effects due to surface tension are about 0.003 ft. A sensitivity up to 1/2 cm pen deflection per 0.001-ft variation in water level is possible.

The method may be used for greater wave heights, however some adjustment in oscillator frequency may be required in extreme instances.

C O N T E N T S

		Page
Abstract		ii
List of Illustrations		iv
I.	INTRODUCTION	1
II.	PRINCIPLE OF THE CAPACITIVE WAVE PROFILE RECORDER	2
III.	THE COMPOSITE INSTRUMENT	3
IV.	OPERATING CHARACTERISTICS	4
V.	RANGE OF APPLICATION	6
Acknowledgment		6
Appendix - Figures 1 to 10		7

L I S T O F I L L U S T R A T I O N S

Figure		Page
1	Capacitive Wave Profile Recorder	8
2	Wave Profile Recorder, Block Diagram	9
3	Wave Profile Recorder, High-Frequency Amplifier	10
4	Wave Profile Recorder, Driver Amplifier	11
5	Wave Profile Recorder, Oscillator	12
6	Wave Profile Recorder, Power Supply	13
7	Sample Calibration Curve for Wave Profile Recorder	14
8	Sample Records Showing Capillary Waves Reflected from Bow Support and Superimposed on Primary Wave	15
9	Sample High-Speed Records of Wave Profiles Recorded with Spring-Mounted Wire	15
10	Sample Slow-Speed Records of (a) Unstable Waves and (b) Stable Waves	16

A CAPACITIVE WAVE PROFILE RECORDER

I. INTRODUCTION

Research studies sponsored by the Office of Naval Research at the St. Anthony Falls Hydraulic Laboratory have necessitated the development of a device for measuring and recording the profile of surface waves in water. The initial phase of these studies was conducted in a channel 6 in. wide and 15 in. deep, using waves with periods ranging from 1/2 to 1 sec and with heights from 1/2 to 3 inches. Other tests are to be undertaken in a channel 9 ft wide and 6 ft deep with correspondingly larger waves.

In some instances, information on the height, length, and period of the waves was considered adequate. At other times it was necessary to obtain information on the wave profile and its phase relationship with respect to recordings of instantaneous forces exerted on a test object by the waves.

Present methods of measuring wave heights or profiles were considered inadequate from the standpoint of stability, accuracy, or both. Most wave meters can be classified as underwater, surface, or aerial types.[1] The pressure-type meter is the only one of the underwater types that would seem to be applicable. In this method, measured pressure variations at a known depth are transcribed into surface variations by wave-theory relationships. This is an indirect method and would require the preparation of special charts for reference purposes. There is also evidence that wave heights computed from the customary equations are too low.[2]

Surface types include various resistance gages and surface point and float gages. The resistance type depends for its operation on the change of electrical resistance between a partially submerged wire and the water at various degrees of wire submergence. The resistance to the flow of electric current from the wire into the water varies with the variation in wetted area of the wire, which is determined in turn by wave heights. The current flow

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[1] "An Ocean Wave Measuring Instrument," Department of the Army, Corps of Engineers Beach Erosion Board Technical Memorandum No. 6, October 1948.

[2] Snodgrass, F. E., "Wave Recorders and Wave Data," Institute of Coastal Engineering Conducted by the University of California at Long Beach, California, October 11-13, 1950.

can be calibrated as a function of wave heights. The electrical resistance, however, is also a function of water resistivity (which may vary considerably in natural waters), of water temperature, and of electric current density flowing from the wire. These additional factors affect stability and linearity of the calibration. An improvement on this method uses electrical contacts equally spaced along a staff and connected together by a network of resistors. Upon submergence, each contact conducts current of a value determined principally by the resistance network. It would seem difficult to place contacts sufficiently close together for accuracy in many model studies. In addition to the above deficiencies, the resistance types have errors caused by the disturbance of the wave, by the presence of the wire or staff, and by surface tension pulling the water away from the true surface adjacent to the staff. These effects are present but quite small when a single wire is used.

A method developed in France utilizes a vibrating electrical point gage which is positioned to the mean water level by means of a servo-mechanism.[3] It is difficult to achieve a sufficiently rapid response of this complex mechanical system to measure waves of the high frequencies occurring in models.

The aerial stereoscopic method has few, if any, advantages for laboratory application in the present program.

II. PRINCIPLE OF THE CAPACITIVE WAVE PROFILE RECORDER

The form of the sensing element is identical with the resistance type and, consequently, it retains the convenience and simplicity of that type. The electric current, however, is dependent only on the wetted area of the wire; consequently, the device possesses both linearity of calibration and high stability.

Wave heights are measured electrically by the deflection of an oscillograph galvonometer corresponding to the depth of submergence into the water of an insulated wire. The insulated wire acts as a small capacitor whose capacity varies directly with the wetted area of the wire; a high-frequency alternating current (10,000 cps) flowing in the wire will vary in a linear manner with changes in depth.

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[3]Gridel, H., "The Accurate Measuring and the Recording of Stable or Fluctuating Water Levels by Means of Continually Vibrating Limnimetric Points," La Houille Blanche, No. Special "B," November 1950, pp. 709-715 (in French).

The insulated wire surrounded by water of reasonable conductivity is equivalent to a resistor in series with a concentric cylinder condenser. The capacity of the cylindrical condenser depends on the characteristic of the insulation (k), the length of the wire, and the logarithm of the ratio of the diameter of the insulation (b) to the diameter of the wire (a).

The capacity per unit length is

$$C = \frac{k}{2 \log b/a}$$

The capacitive reactance can be made quite high compared to the equivalent resistance of natural waters, and thus the electric current flow is determined almost entirely by the capacitance of the circuit.

III. THE COMPOSITE INSTRUMENT

The sensing element used in the model wave channel is a 6-in. length of No. 32 heavy Formvar-enameled wire. The original mounting was in a bow constructed from a 3/16-in. Lucite rod similar to a hack saw. For calibration the assembly was mounted on a rack and pinion from an ordinary point gage. It was noticed that small capillary waves were reflected from the bow support rod and caused interference at the wire. An alternative mounting was developed, consisting of an overhead-support rack and pinion, with a spring attached to the channel floor to hold the wire taut and vertical. This method permits calibration and eliminates the effect of surface waves from the adjacent bow support.

The basic auxiliary apparatus consists of a 10,000-cycle oscillator, a low distributed-capacity transformer, and a current-measuring device. The original laboratory setup for static measurement, assembled from standard commercial components, is shown in Fig. 1a. The final composite instrument with the spring-mounted wire is shown in Fig. 1b.

The instrument circuit described in this report is one of many that might be used successfully to amplify the weak currents flowing in the probe to a magnitude sufficiently great to drive an inkwriting oscillograph.

A block diagram of the circuit is shown in Fig. 2. It contains a 10,000-cycle RC oscillator capable of delivering about 15 volts rms regulated output. This oscillator feeds energy to the probe through a General Radio bridge transformer, type 528A, shown as isolation transformer in Fig. 2, and T_3 in Fig. 3. This isolation transformer must be located close to the probe to minimize the effect of lead capacity. The current from the probe is coupled through a 270-ohm resistor, R_1, to the cathode of a three-stage, resistance-coupled amplifier labeled "balance and amplifier" in Fig. 2, and V_1, V_2, and V_3 in Fig. 3. A signal is fed through a simple phase-shifting network to the grid of V_1 in Fig. 3 to balance out the steady probe current at some arbitrary probe submergence. The output of the resistance-coupled amplifier is fed to a phase-sensitive detector (see Fig. 2, and V_4 in Fig. 3) which converts the high-frequency modulated output of the resistance-coupled amplifier to low-frequency fluctuation corresponding in magnitude and direction to wave heights above or below the static level. The detector is coupled to the inkwriter by a low-gain, chopper-type driver amplifier (Fig. 2, and V_5, V_6, and V_7 in Fig. 4). The oscillator[4] and power supply circuits are shown in Figs. 5 and 6, respectively.

IV. OPERATING CHARACTERISTICS

The wave profile recorder is readily calibrated by means of the rack and pinion, which has a scale graduated in 0.001-ft increments. The gage factor for the instrument in terms of centimeters pen deflection per foot wave height may be determined at any time by changing the calibrated rack and pinion position an arbitrary increment and noting the corresponding pen deflection. The most satisfactory procedure is to move the rack a few hundredths of a foot in order to introduce a constant surface-tension error, and then move the rack an arbitrary additional distance in the same direction. The linearity of the instrument over a wide range makes possible this simple calibration.

The galvonometer may be set at zero deflection for any depth of submergence of the probe by adjusting the balance control, R_2, located in the center of the panel instrument.

Phase balance should be checked occasionally by depressing S_1 on the instrument panel and at the same time alternately adjusting R_2 and the screw-driven adjustment, R_3, for minimum deflection from zero of the oscillograph pen. This adjustment of R_3 is not critical. The sensitivity control, R_4,

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[4] Sulzer, P. G., "Wide Range RC Oscillator," Electronics, September 1950, pp. 88-89.

is located on the left of the control panel and gives increasing sensitivity with clockwise rotation up to 1/2 cm pen deflection per 0.001-ft variation in height.

The circuit was calibrated in distilled water of high resistancy in a laboratory experiment; then salt was added to the water to form a 2 per cent salt solution of low resistivity. No change in calibration could be noted between these two solutions. The experiment was repeated at temperatures of 70° F and 120° F with no variation in calibration detectable. A sample calibration at a specific gain setting is shown in Fig. 7.

The long-time stability of the instrument has not been checked for periods greater than three days where drift was found to be within 0.003 ft.

A large drift of 0.03 ft is observed when a new Formvar-insulated wire is installed in the probe. This drift is due, probably, to the change in dielectric constant of the insulation by absorption of water. A stable condition is reached in about 6 hours. This condition can be avoided by use of plain enameled wire, however the greater strength of the Formvar insulation makes it the more desirable.

The fine wire produces negligible disturbance of a flowing water surface and has only a small surface tension error. The error of the instrument under static condition is less than 0.003 ft for a reversal of direction. The dynamic error is assumed to be of this order for low flow velocities.

The frequency response of the meter is considered to be very satisfactory. That higher-frequency components are recorded is indicated in Fig. 8. This record was taken with the original bow-type support and shows the reflected capillary waves superimposed on the primary wave. A sample wave profile recorded with the alternate spring-mounted wire illustrated in Fig. 1 is shown in Fig. 9.

In laboratory studies of waves, a high degree of stability of the waves is desirable; i.e., all waves in a wave train should be similar in shape and size. Thus, it is necessary that a wave meter be capable of indicating the stability or instability of these waves. A wave profile recorder does this very satisfactorily, whereas some wave height meters indicate only the mean or maximum height of a series of waves. Figure 10 shows sample records of both stable and unstable waves.

V. RANGE OF APPLICATION

The recorder will operate with a wide variation in sensing element size and length, consequently the instrument may be used for a very wide variation in wave height, from a few hundredths of a foot in model studies to many feet in nature. Some adjustment, however, would possibly be required in oscillator frequency in order to accommodate the extremes.

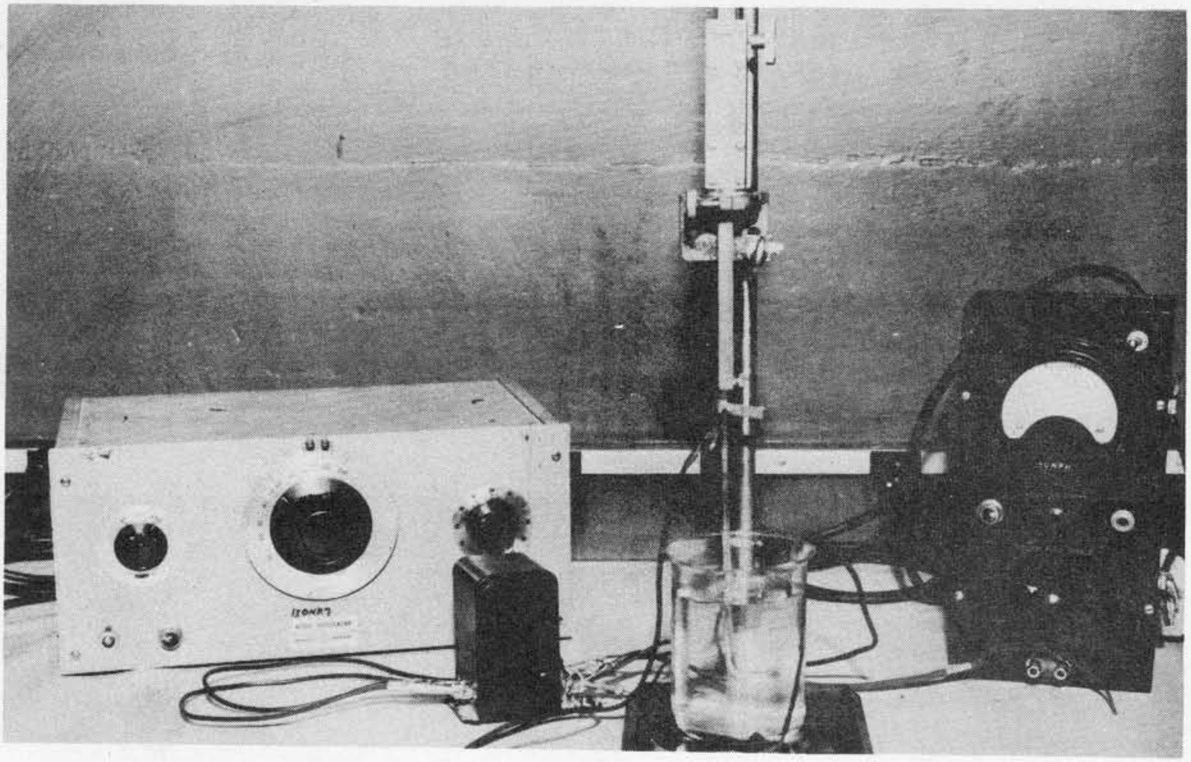
The instrument described will measure wave amplitude and frequency, and with an additional sensing element, wave length may be measured.

Acknowledgment

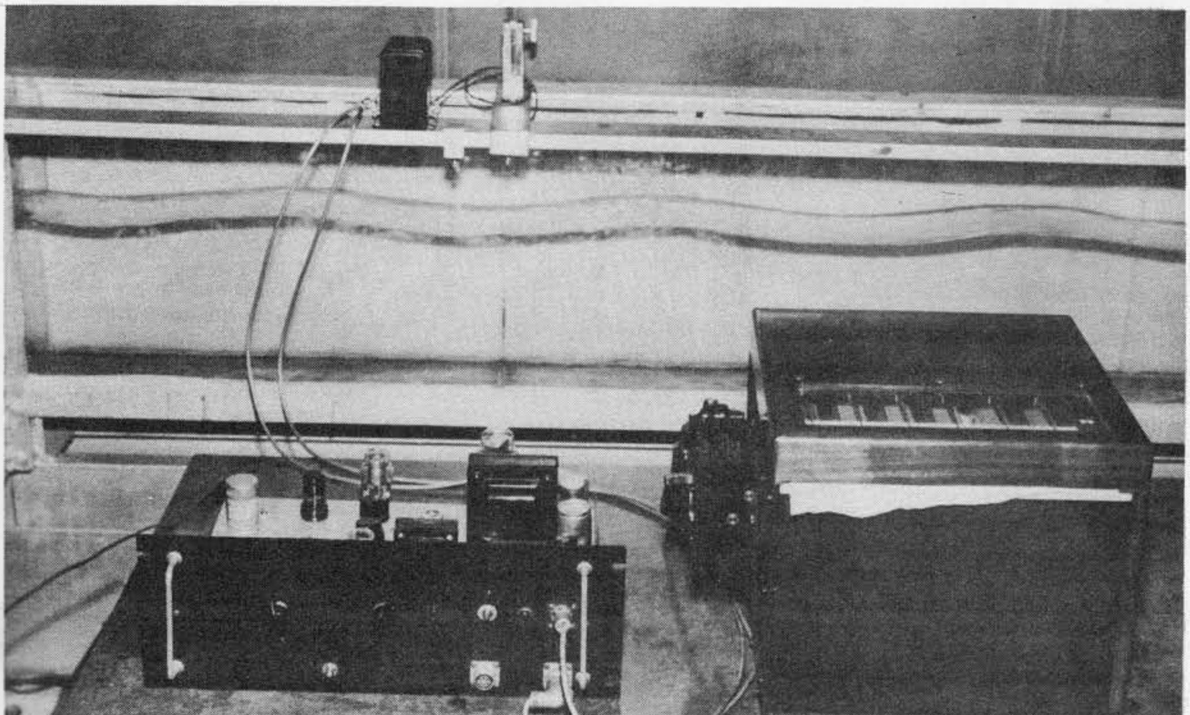
The instrument described in this paper was developed in the course of studies sponsored by the Office of Naval Research under Contract No. Nonr 710(04). The development program was carried out by John M. Killen under the general direction of Dr. Lorenz G. Straub, Director of the St. Anthony Falls Hydraulic Laboratory. Reuben M. Olson critically reviewed the written material and co-authored the final manuscript. Editing, arrangement, and preparation for publication were responsibilities of Marilyn F. Larson and Loyal A. Johnson.

A P P E N D I X

FIGURES 1 to 10



(a) Original Setup with Bow-Mounted Probe



(b) Completed Instrument with Spring-Mounted Probe

Fig. 1 – Capacitive Wave Profile Recorder

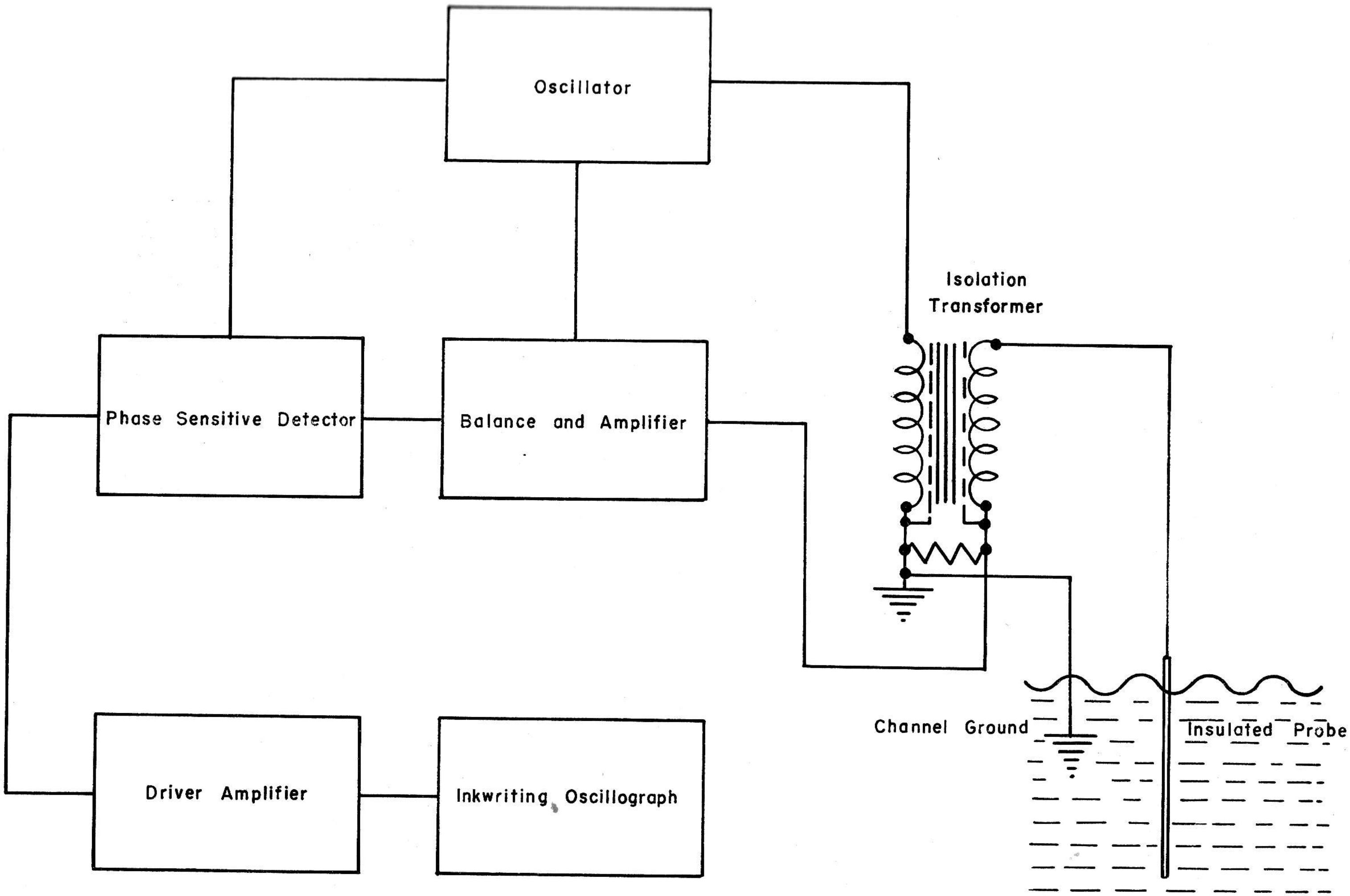


Fig.2 - Wave Profile Recorder
Block Diagram

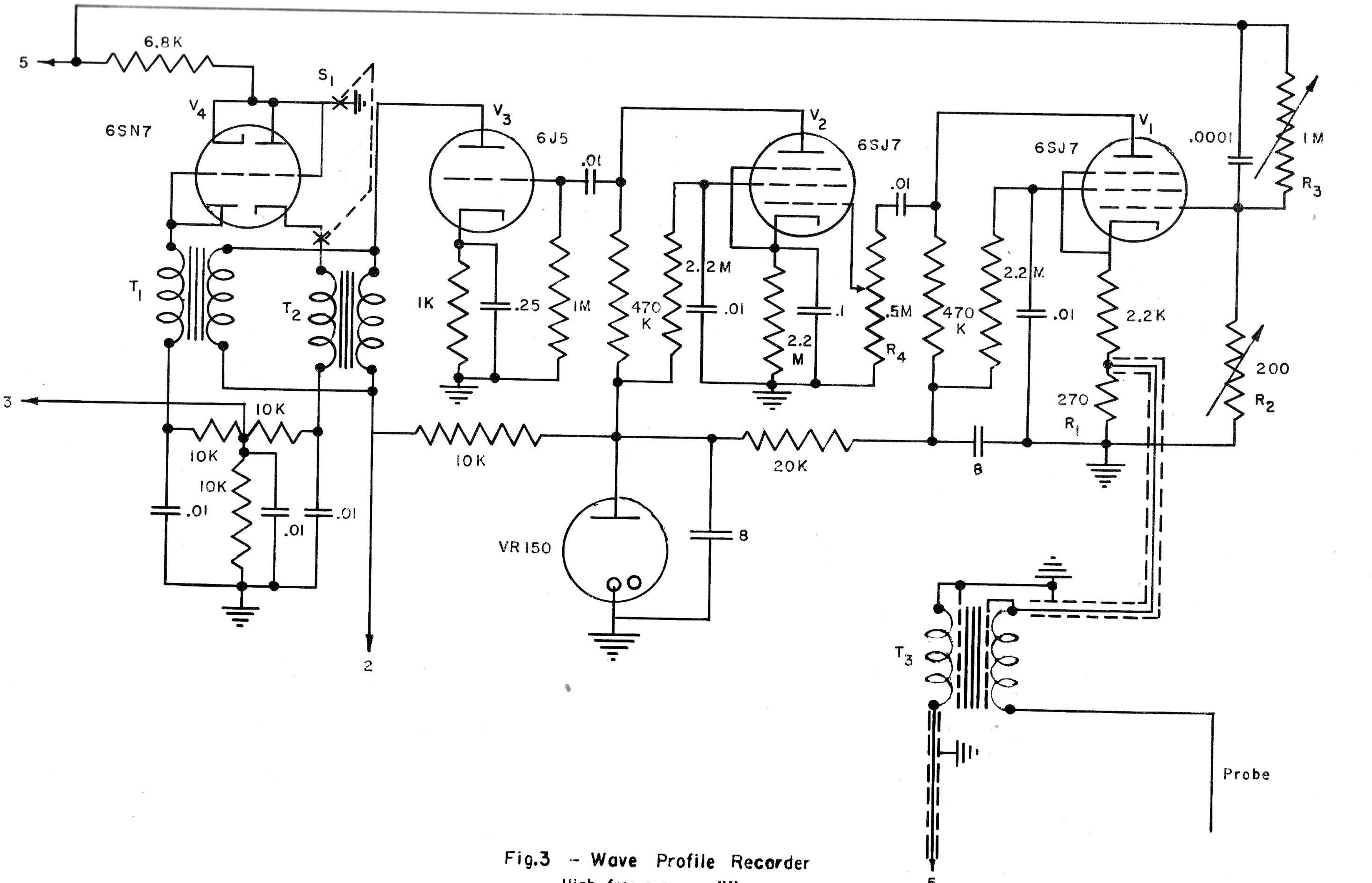


Fig.3 - Wave Profile Recorder
High-frequency amplifier

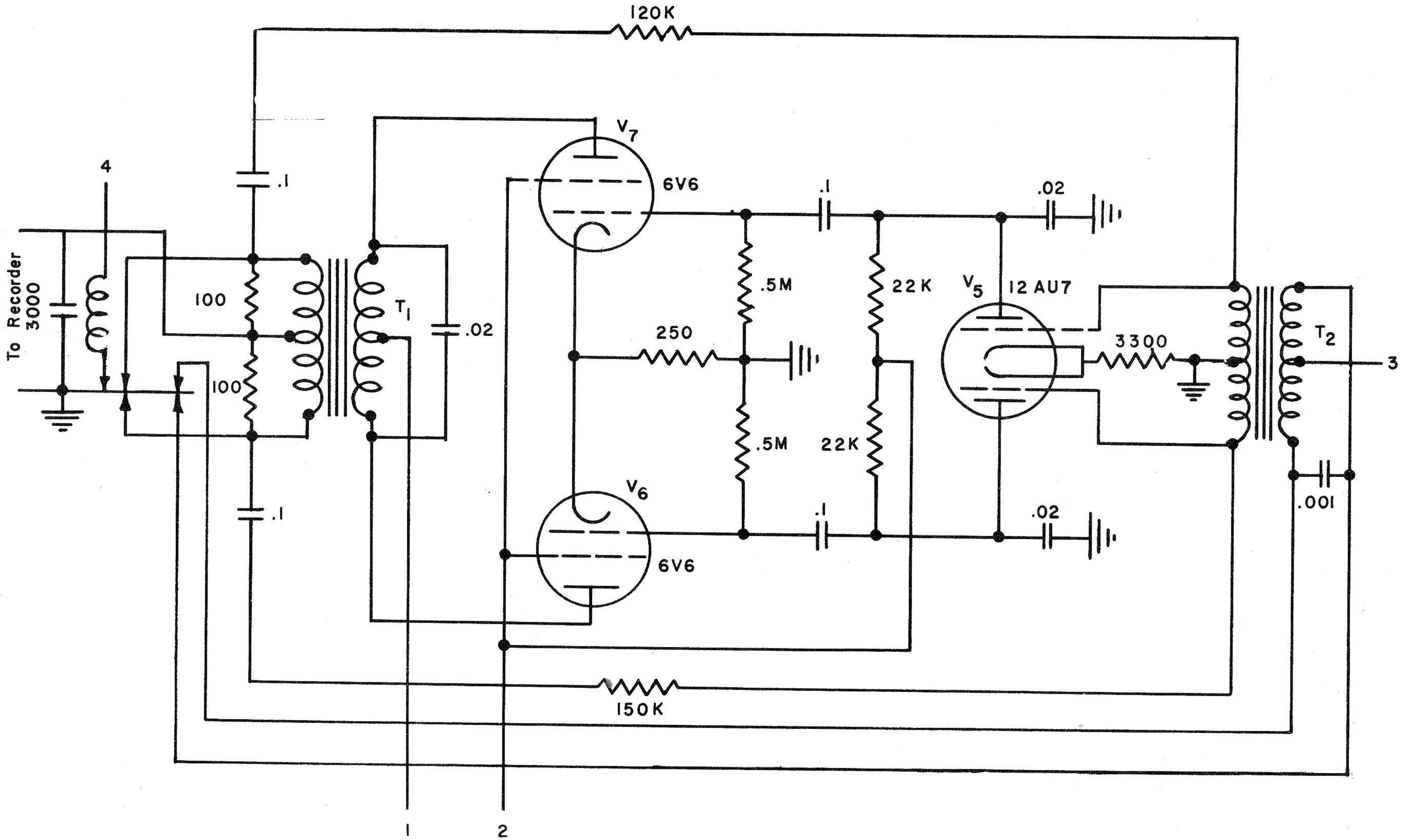


Fig. 4 - Wave Profile Recorder
Driver amplifier

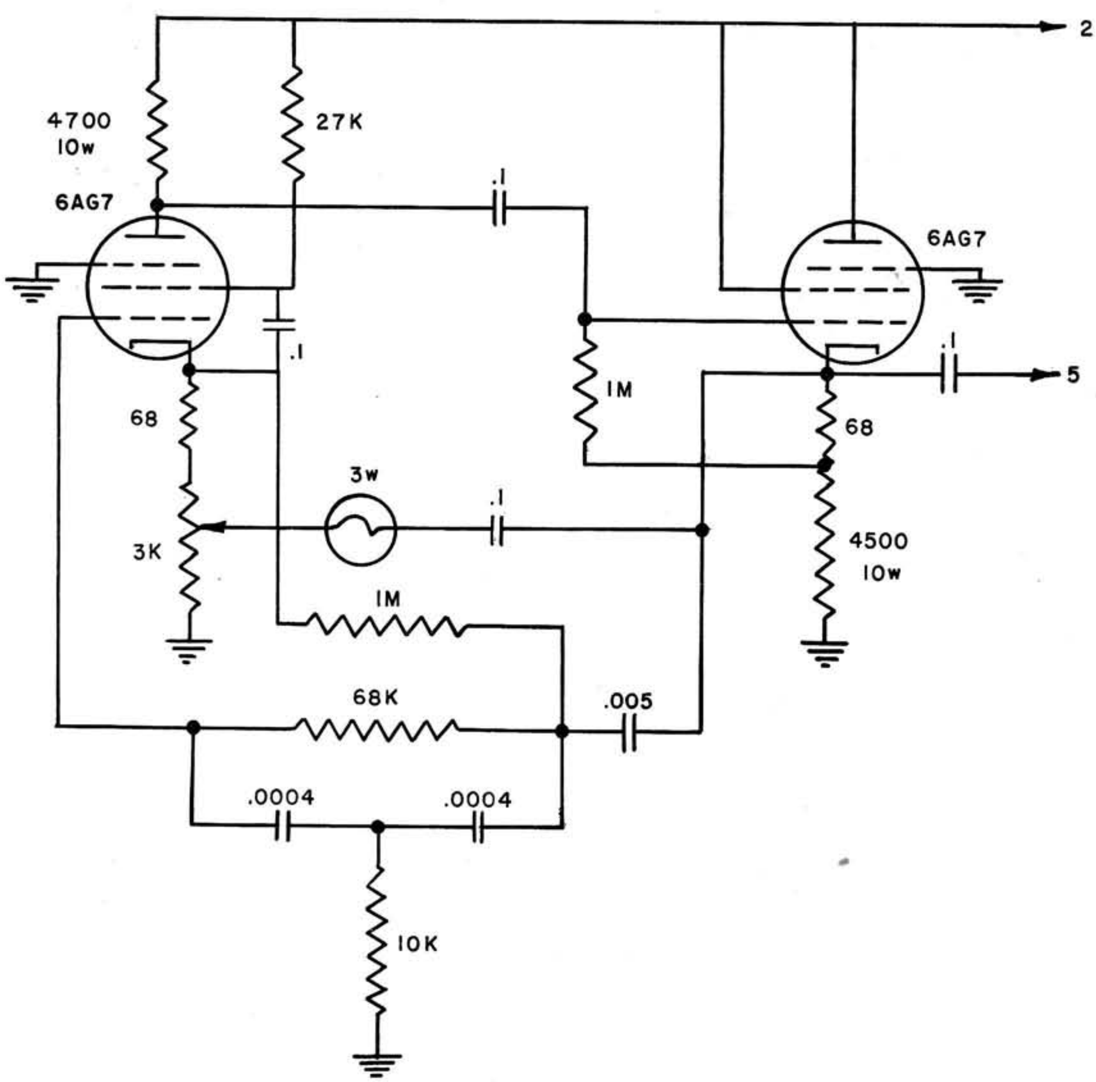


Fig.5 - Wave Profile Recorder
Oscillator

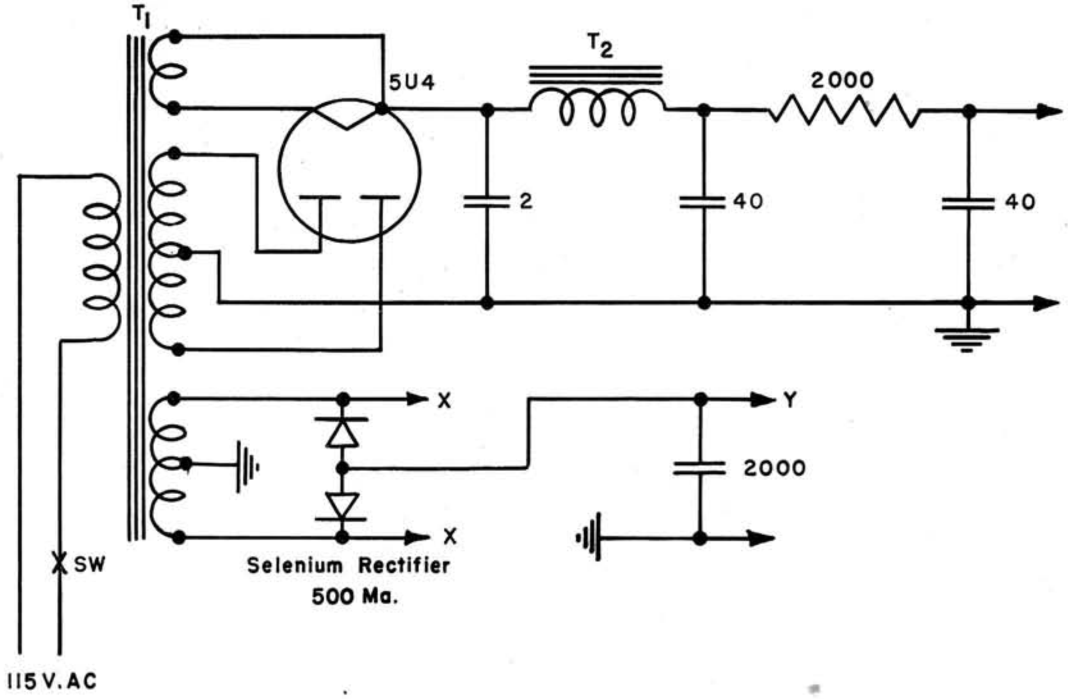


Fig. 6 - **Wave Profile** Recorder
Power supply

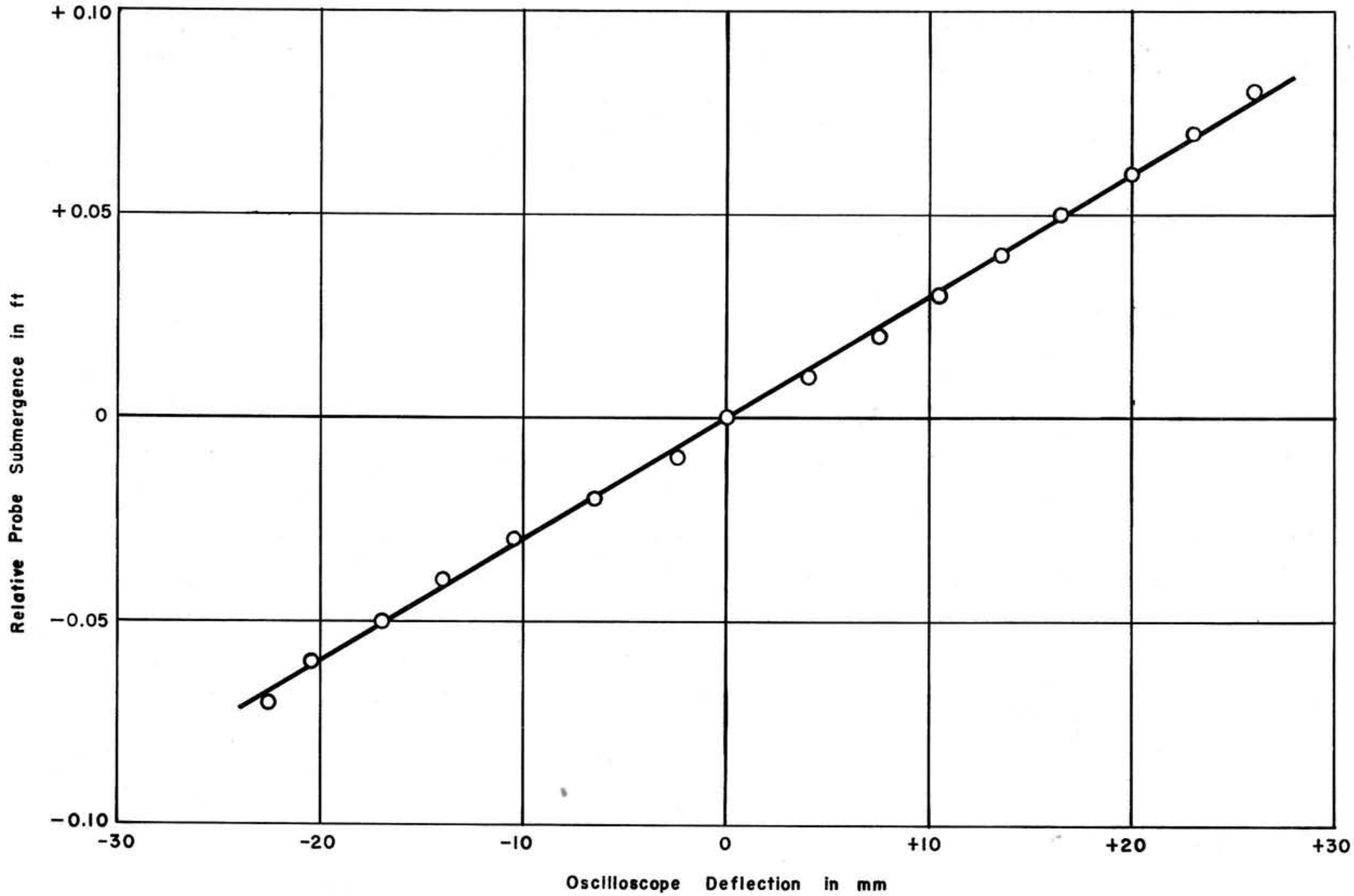


Fig.7 - Sample Calibration Curve for Wave Profile Recorder

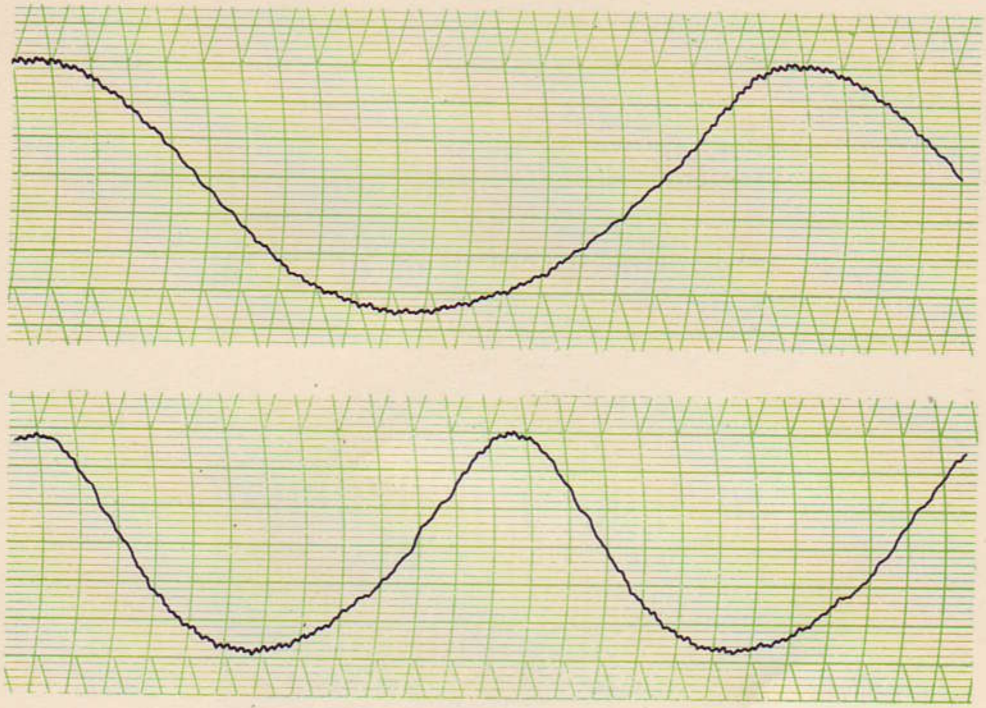


Fig. 8 — Sample Records Showing Capillary Waves Reflected from Bow Support and Superimposed on Primary Wave

The Reflections have a Maximum Amplitude at the Crest and Trough of the Primary Wave.

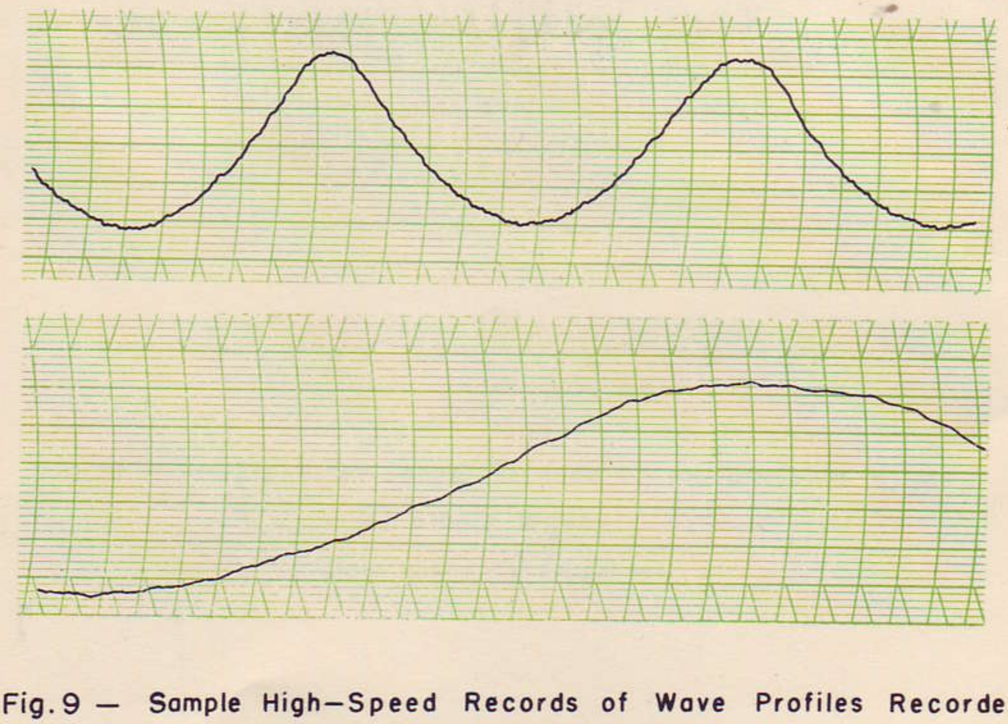
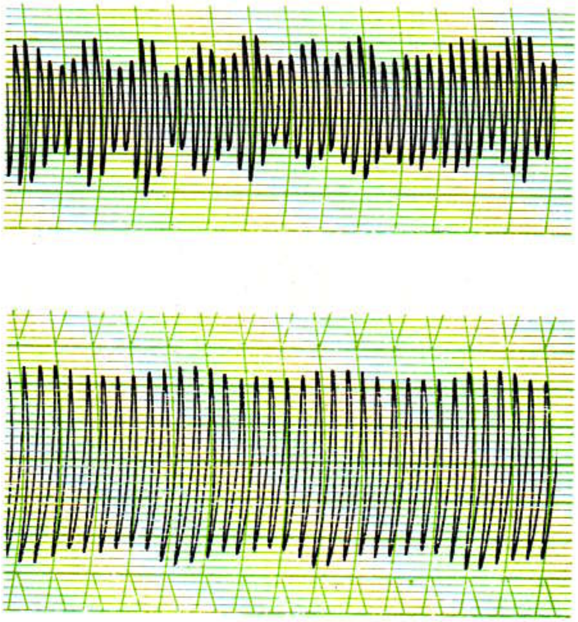
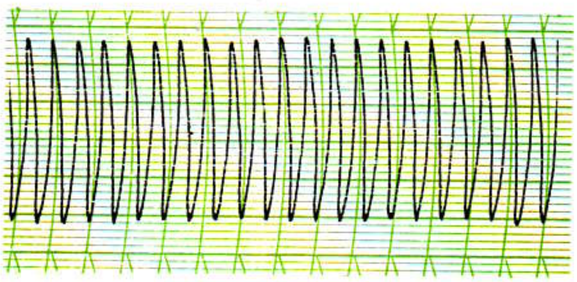


Fig. 9 — Sample High-Speed Records of Wave Profiles Recorded with Spring-Mounted Wire



(a)



(b)

Fig. 10 — Sample Slow-Speed Records of (a) Unstable Waves
(b) Stable Waves
Chart Speed - $\frac{1}{2}$ cm. per sec.