CER54EFS10

March 1954

DEVELOPMENT OF A FACILITY FOR TESTING THE PERFORMANCE OF SHIP HULLS IN OBLIQUE SEAS

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Prepared for
The David Taylor Model Basin
Bureau of Ships
Navy Department
under Contract No. N9onr 82403
through the
Colorado A & M Research Foundation

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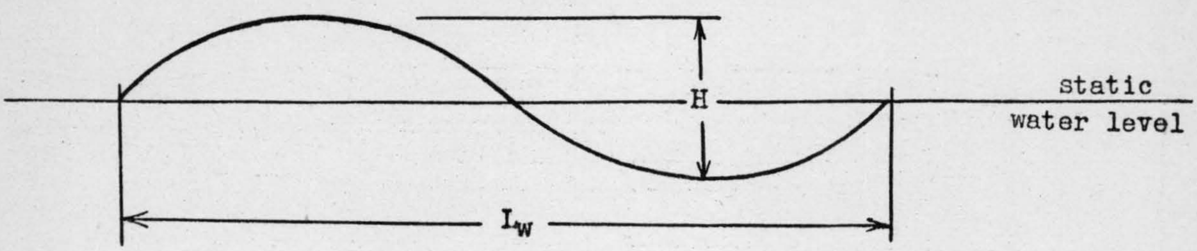
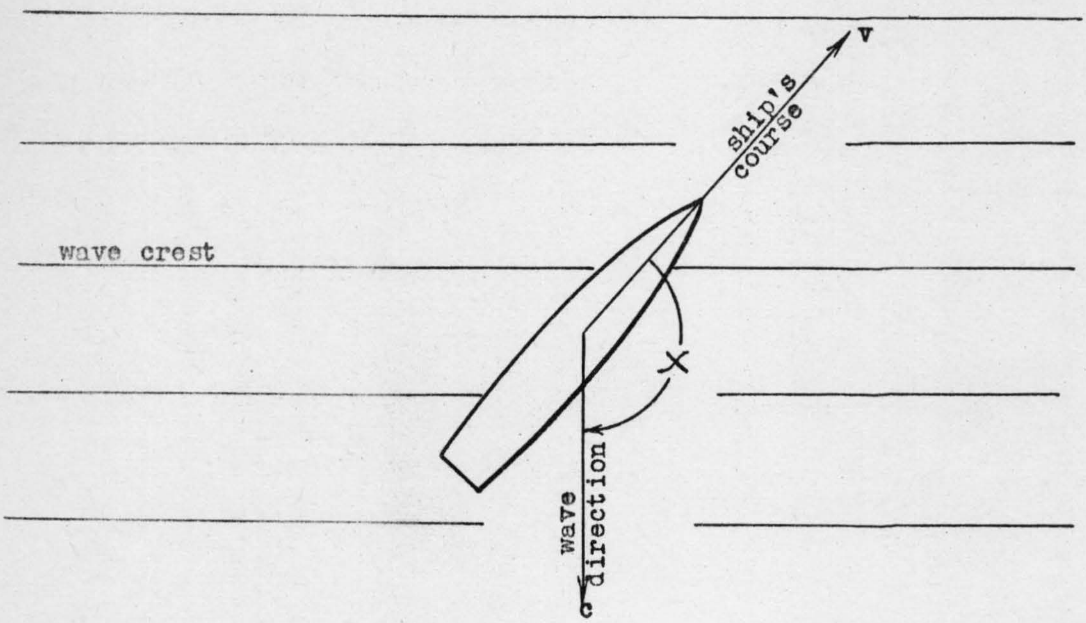
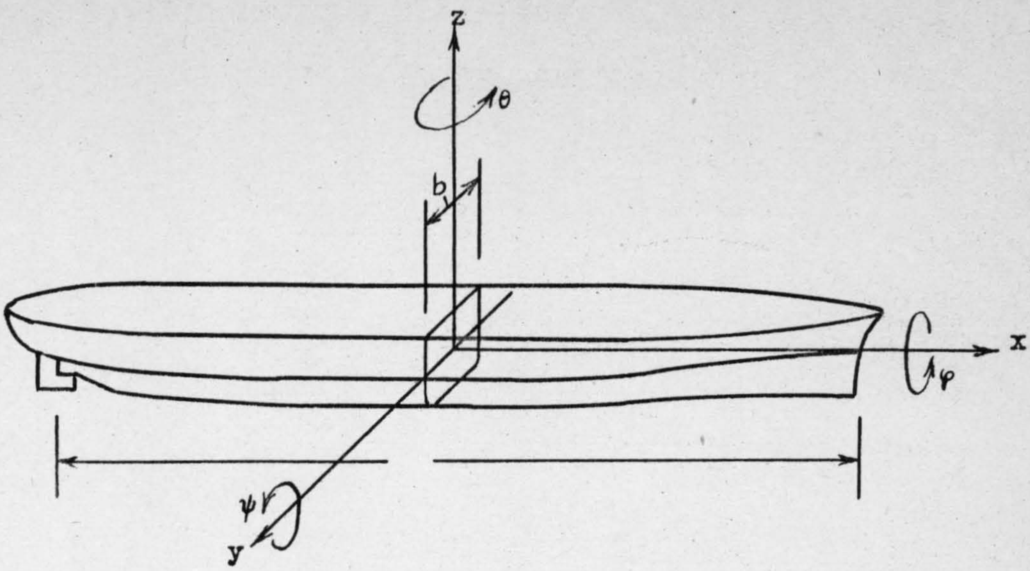


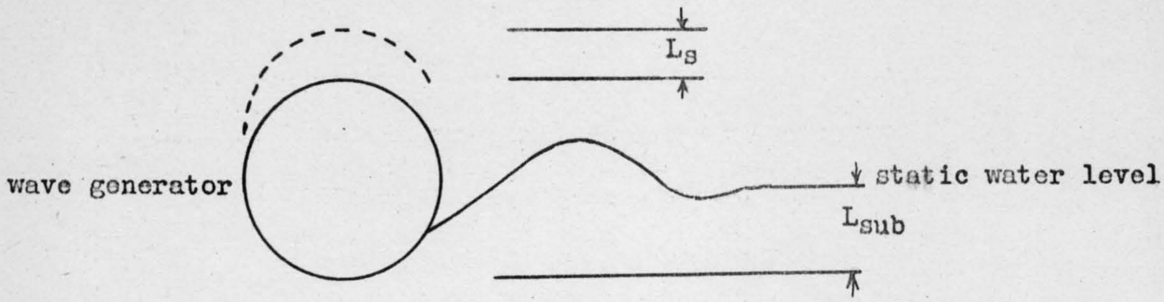
Symbol	Dimensions	Definition
L_w	feet	Wave length
H	feet	Wave height
ω	cps	Wave frequency
T	seconds	Wave period $1/\omega$
c	fps	Wave celerity



χ	degrees	Angle between the heading of the ship and the direction of wave travel



Symbol	Dimensions	Definition
v	fps	Average speed of the hull
h	feet	Heave of hull or translation of center of gravity along z-axis
ψ_u	degrees	Maximum angle of trim (bow up)
ψ_d	degrees	Maximum angle of trim (bow down)
$\Delta\psi$	degrees	Maximum change in angle of trim
φ_r	degrees	Maximum angle of roll to the right
φ_l	degrees	Maximum angle of roll to the left
$\Delta\varphi$	degrees	Maximum change of angle of roll
θ_r	degrees	Maximum angle of yaw to the right
θ_l	degrees	Maximum angle of yaw to the left
$\Delta\theta$	degrees	Maximum change in angle of yaw
L	feet	Length of hull at waterline
M	slugs	Mass of the hull



Symbol	Dimensions	Definition
L_{sub}	feet	Relative plunger submergence
L_s	feet	Lenghh of plunger stroke
e	inches	Eccentricity of crank pin
D	cu ft/ft	Net plunger displacement per unit of plunger length
D_t	cu ft/ft	Plunger displacement at top dead center
D_b	cu ft/ft	Plunger displacement at bottom dead center

The construction of this wave basin was first suggested by Mr. F. W. S. Locke, Jr., of the Bureau of Aeronautics, Navy Department. Many suggestions and helpful comments were obtained from different people all over the country. These have been very useful. The writer wishes specifically to mention the following people: Dr. M. L. Albertson and Mr. A. D. Farmanfarma, colleagues at Colorado A & M College, both of whom are on leave at the present time for further advanced study; Mr. M. St. Denis and many members of the staff at the David Taylor Model Basin; Dr. K. S. M. Davidson and members of the staff at the Experimental Towing Tank at the Stevens Institute of Technology.

Professors John E. Dean and C. C. Britton of the Department of Electrical Engineering at the College contributed much to the electrical instrumentation.

Dr. D. F. Peterson, head of the Department of Civil Engineering at the College, gave valuable suggestions and assistance in the preparation of this report and the conduct of the work.

Without the enthusiastic support of Mr. Ralph Asmus and his staff at the Hydraulics Laboratory Shops the equipment could hardly have been built and installed.

Prof. T. H. Evans is Dean of the School of Engineering wherein all this work was done.

ABSTRACT

The conversion of a round 85-ft diameter outdoor pond to a facility for testing model seaplanes and ships in oblique seas is described. Waves are created in the 40 by 65 ft seaway by oscillating a 14-inch dia. cylinder in a vertical plane. A sloping gravel beach absorbs the waves after they have traversed the seaway. Diffraction of the wave train is prevented through the use of wave guides. Wave lengths of 2.4, 4.6, and 9.4 ft have been produced. Waves as steep as 1:11.5 have been produced. Some experimentation with model seaplane hulls has been completed. The variations of the model motions in heave, pitch and roll were measured from 16 mm motion picture film. The models were photographed simultaneously from the front and side during the tests. Improvements in the various structural components and the instrumentation used for measuring the model motions were discussed. It was concluded that a 5-ft model could be tested effectively at any heading to the seaway and at speeds up to 10 fps. Calibration curves for the wave generator, wave profile recorder and convectron tube are included.

Introduction

The facility described by this report has been developed under the sponsorship of the Navy Department through the David Taylor Model Basin and the Bureau of Aeronautics. Since the towing basin is situated out-of-doors, testing is limited to the period from March through October when the weather is calm. In the local climate this imposes no serious limitation to the testing program because the winter months can be used to construct modifications and to analyze data. During the summer of 1953 the facility was established, the wave generator constructed, wave guides installed, wave absorbers installed, wave profile recorder built, towing mechanism built, carriage wires suspended across the pond and a light weight aluminum carriage built. Some preliminary tests were completed for the purpose of calibrating the wave generator. In addition, preliminary experiments were conducted on two model seaplane hulls for the Bureau of Aeronautics and a number of runs were conducted with a 5-ft model tanker supplied by the David Taylor Model Basin. Further testing of the tanker was suspended pending completion of additional construction on the wave generator, wave absorbers, aluminum carriage and other instrumentation and establishment of the specifications for testing the tanker. The work will be continued as soon as all improvements in the equipment have been completed and the weather permits.

This report gives a summary of the performance of wave generator, wave guides and wave absorbers.

Towing Basin

The towing basin was developed from an outdoor tank 85 ft in diameter and approximately 6-1/2 ft deep. The sides slope inward and the bottom diameter is 72 ft. The sides and bottom of the tank are made from wire-reinforced concrete with a sheet copper lining cemented to the concrete with an asphaltic cement. These elaborate steps were taken when the tank was constructed in 1915 in order to make the tank absolutely water tight because the pond was originally built for use in evaporation studies where seepage losses had to be eliminated. The reservoir holds 31,678 cu ft or 236,950 gallons.

Water can be supplied to the tank from two sources. (1) The tank can be filled using a 4-in. line from the Fort Collins City water supply. (2) Water can also be pumped from the sumps in the Hydraulics Laboratory through a 12-in. line.

The basin can be drained into the Hydraulics Laboratory sump system or into the city sewer through a 12-in. drain. The outlet valve has been repaired so that the water surface can be maintained at a constant level. Installation of the wave generator necessitated drilling a number of holes into the bottom of the tank for the installation of anchor bolts. Evidently, this has caused a small leak in the tank. This loss of water from the tank causes a drop in the static water level of approximately 0.005 ft per hour.

The position of the static water surface is an important factor in the performance of the wave generator. A water stage indicator was installed so that the static water level could be carefully adjusted and the water level maintained at a fixed point during testing. The indicator is actuated by a float mounted in a stilling well. Flow into the stilling well is through an inlet approximately 1/2 in. in diameter located about 3 ft below the static water surface so that the float is unaffected by any surface waves.

Fig. 1 is a photograph of the pond taken in June 1952 before the pond was reconverted to a wave basin. Fig. 2 was taken in October 1953 after modification to a wave basin was completed. Fig. 3 is a photograph of the stilling well and float gage used to measure the water surface elevation. Fig. 4 is a drawing showing the arrangement of the towing basin and other components.

Towing Mechanism

The power for the towing mechanism is supplied by a 1 1/2-Hp, 3-phase, 440-volt induction motor. The motor is equipped with an 18 to 1 worm gear reduction unit and a magnetic brake which stops the motor as soon as the power is cut off.

Speed variation is accomplished through a pair of seven-step cone pulleys and a pair of adjustable V-pulleys. V-belts are used throughout the final speed reduction system. The adjustable pulleys permit fine adjustments of the speed. Large changes in speed are made by shifting the V-belt on the step cone pulleys.

The towing line consists of 108 pound fishing line. The towing line is an endless line driven by a plastic pulley 8-1/4 in. in diameter. The towing line rides in a V notch in the pulley thus increasing the coefficient of friction between the pulley and the line. The towing line passes over the basin around an idler pulley and is returned to the towing

Fig. 1 View of Pond Before
Conversion to Wave Basin

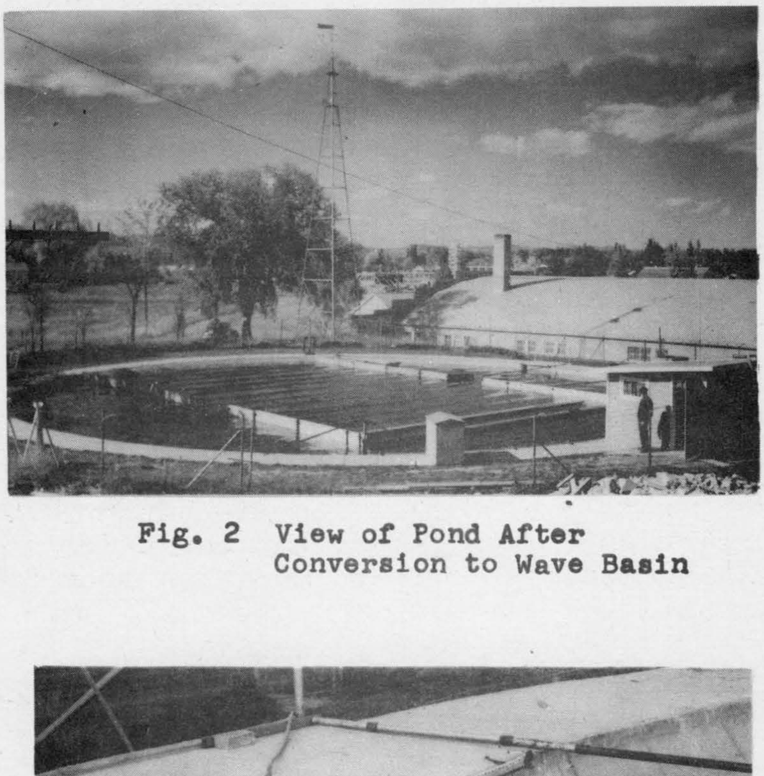
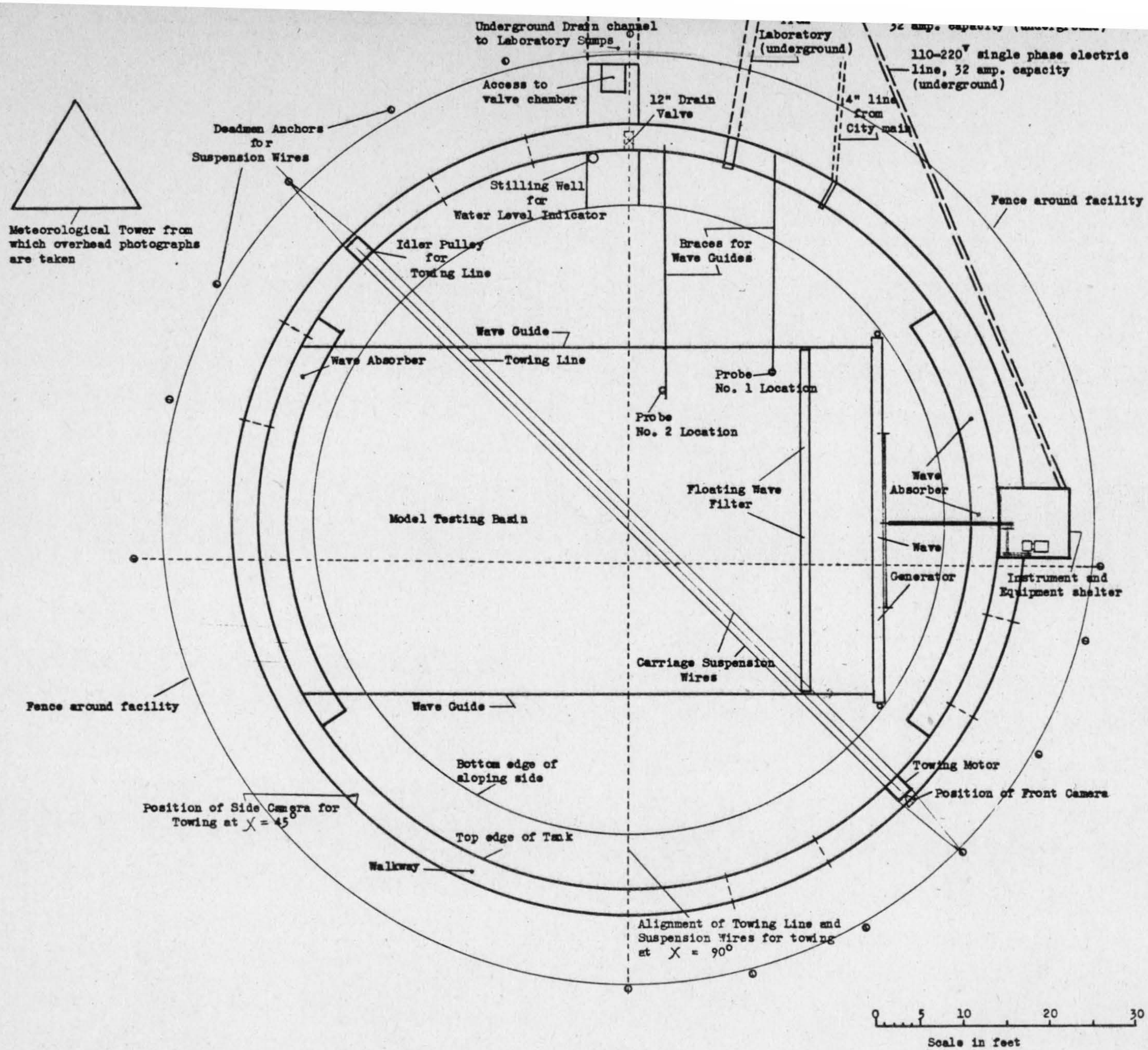


Fig. 2 View of Pond After
Conversion to Wave Basin

Fig. 3 Water Stage Indicator
and Stilling Well



ARRANGEMENT OF WAVE BASIN AND COMPONENTS

Fig. 4

mechanism. The towing mechanism and idler pulley are portable and can be moved to any location around the pond.

Tension of about sixty pounds is applied to the towing line through a counter weight on the idler pulley. Some slippage occurs at the starting and stopping of runs at speeds in excess of 10 fps. For model speeds of 5 fps or less, slippage is not an important factor. The maximum speed attained while towing a 9-pound model was 19.5 fps. Several failures of the towing line occurred either at the start or end of high speed runs (greater than 10 fps). These failures resulted from small accidental abrasion damage to the towing line.

The average speed of the hull is determined by measuring the speed of the towing line. The towing line passes over a 8-1/4 in. plastic idler pulley mounted on a ball bearing on the towing mechanism. A small permanent magnet is cemented to the idler pulley. When this magnet passes near a coil, a small current is induced in the coil. This current is used as a signal on the oscillograph record. Since the inertia and friction on the bearings of the idler pulley is small, it is assumed that the peripheral speed of the idler pulley is equivalent to the speed of the towing line. To assist in making fine speed adjustments, the final counter shaft of the towing mechanism is equipped with a direct reading tachometer calibrated to read the towing line speed.

Fig. 5 is a photograph showing the towing mechanism and speed recording idler pulley. The tachometer was not installed when this photograph was made. Fig. 6 shows the idler pulley and the counter weight used to apply tension to the towing line.

Wave Generator

Waves are produced by oscillating a cylinder in a vertical plane. The waves thus produced travel away from the generator on either side. The cylinder is 14 in. in diameter and made from standard 10-gauge steel pipe (wall thickness 0.134 inches). The cylinder is forty-two ft long (the seaway is forty ft wide) and is supported at the quarter points. The ends of the pipe have been capped by welding a 1/2 in. plate to each end. A vertical guide is attached to each end of the cylinder. The guide consists of a sleeve with six adjustable rollers which bear on a 2-1/2 in. vertical pipe. The vertical guide pipe is securely anchored to the floor of the tank on one end and with two pipe braces to the edge of the tank at the other. This vertical guide restrains the motion of the wave generator to a vertical direction.

The wave generator was located as near to the edge of the tank as the curvature of the tank and the sloping sides would permit. It was decided to set all major components of the wave generator on the bottom of the tank because of uncertainity regarding the thickness of the concrete on the side slopes and competence of the supporting soil. Because of this location, the wave generator is actually from 10 to 20 ft from the edge of the pond at the top of the pond. The waves created in the area behind the generator are a problem and a detriment to the performance of the remaining useable part of the testing basin. Fig. 7 is a photograph showing the wave generator with the tank empty.

The power required to drive the wave generator is supplied by a 10-Hp, 3-phase, 440-volt induction motor operating through a worm gear reduction drive, a pair of double roller-chain sprockets, an adjustable crank pin, a long connecting rod, a camshaft and two short support links to the cylinder itself. The different components are listed in the order in which they are mounted. The motor is somewhat oversized from the point of view of power requirements; however, the speed variations are small for an ordinary induction motor operating at a fraction of full load. The motor and worm gear reduction drive are mounted together as an integral unit. The worm gear drive reduces the motor speed to 63 rpm. When the wave generator is at bottom dead center, the buoyant force on the pipe tends to speed up the motor; however, the characteristics of a worm gear are such that a relatively large torque is required to accelerate the motor. The oversize motor and the worm gear reduction drive thus work together to produce uniform motion throughout the cycle provided all lost motion is eliminated.

The wave length produced can be varied by changing the speed of rotation of the crank pin. Since the motor is essentially fixed speed, the speed of rotation of the drive is changed by the introduction of a double roller chain and sprocket system in the final drive. The sprockets are interchangeable and produce wave lengths of 2.4, 4.6, and 9.4 ft. Sprockets are being ordered which will produce wave lengths of 3.8, 6.3, and 7.5 ft. The driving motor, worm gear, roller chain drive and adjustable crank pin are shown in Fig. 8.

Wave height can be varied by changing the eccentricity of the crank pin and to some extent by changing the water level in the pond. At the present time four holes have been drilled and tapped into a 3/4 in. by 14-1/2 in. diameter crank plate. These holes are at radii of 1-1/4, 2-1/4, 2-3/4, and 3-1/2 in. The crank plate is being modified so that a continuously adjustable crank pin can be employed.

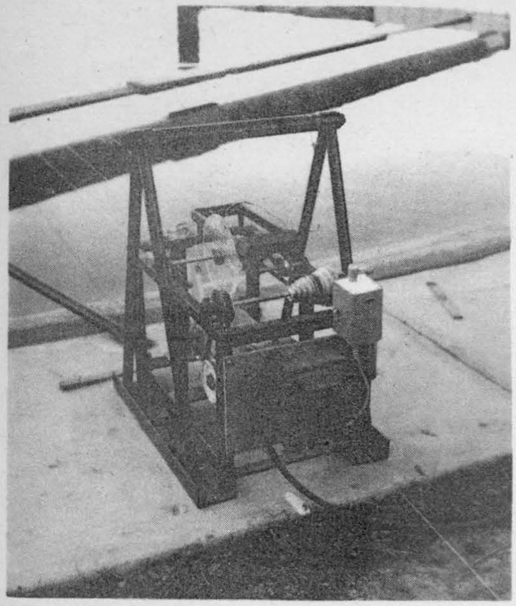


Fig. 5 Photograph of Portable Towing Mechanism

Fig. 6 Photograph of Idler Pulley and Counterweight

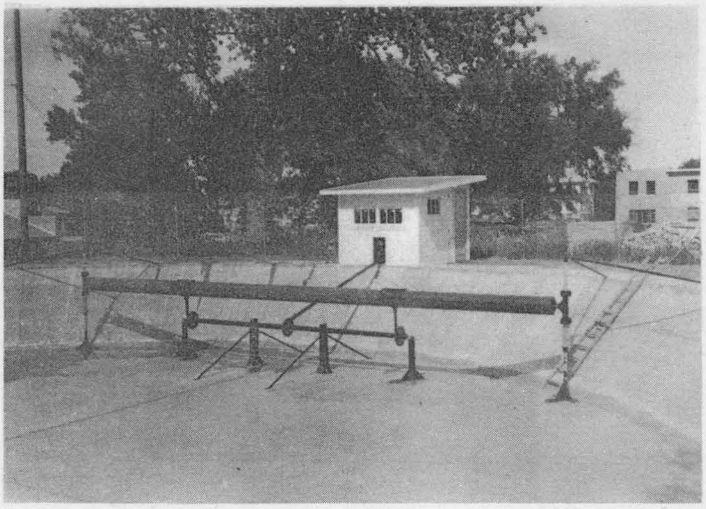


Fig. 7 View of Underwater Structure of Wave Generator

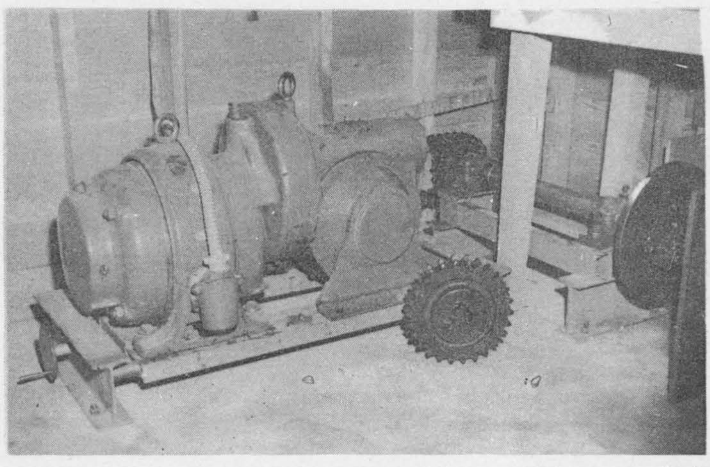


Fig. 8 Detail of Wave Generator Drive Motor, Roller Chain Drive and Adjustable Eccentric

This will make it possible to set the wave height precisely for a particular water surface elevation.

Experience has shown that uniformity of the wave profile varies somewhat with a change in the static water surface elevation. Fig. 9 shows portions of the wave profile records taken at different static water surface elevations. Fig. 9 also shows the wave profile measured at two locations 12 and 24-1/2 ft away from the wave generator and 5 ft from the right wave guide. After comparison of these records it was decided to test the models when the water surface is 12.30 ft (relative to an arbitrary datum) and with the probe mounted at the #2 location (24-1/2 ft from the wave generator).

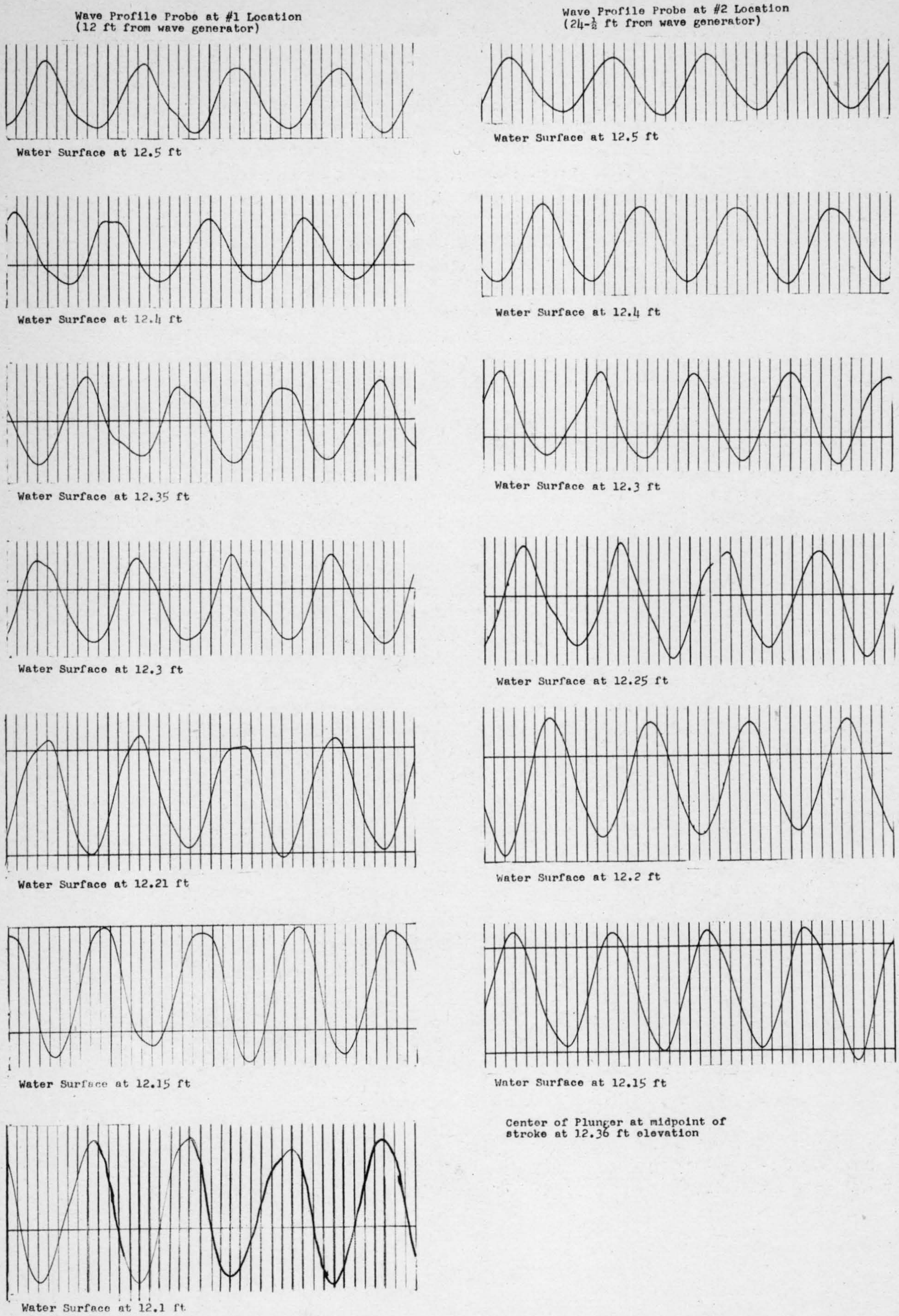
A series of runs to calibrate the wave generator were conducted to determine (1) the affect of changing the static water surface level on the wave height, (2) relate the wave height with the length of plunger stroke (vertical travel of wave cylinder), and (3) determine the overall adequacy of the various structural components. The wave generator was set for a particular period and stroke length and the static water surface was adjusted to a given level and a series of readings taken. The wave height was measured visually using a hook gage. The point of the gage was first set to probe the water surface in the trough of the wave and then the water surface of the crest. The difference of these two readings was a mean value of the wave height.

The plunger stroke was determined by visually reading the maximum and minimum readings indicated on a fixed scale by a pointer which was attached to the vertical guide bearing at the right end of the wave generator. These readings were taken during the operation of the wave generator and therefore include all deflections of the plunger and any lost motion in the linkage.

The wave celerity was determined by timing the wave front over a 41-1/2 ft length of the seaway at a uniform depth to the bottom. Each value of the celerity used is the average of five different measurements.

The wave period is equal to the plunger period, and was determined by timing 50 plunger strokes. Each value of the period represent the average of five different measurements. These average measurements of the period agree quite well with periods determined from previous data taken from the oscillograph records of the wave height.

These tests were repeated for each value of plunger period and each value of plunger stroke for a water surface elevation at 12.15 ft, 12.30 ft and 12.50 ft. Three



COMPARISON OF WAVE PROFILES AT VARIOUS STATIC WATER LEVELS

Fig. 9

different values of plunger period were used -- 0.66 seconds, 0.95 seconds and 1.39 seconds. Four different values of plunger stroke were used -- 0.083 ft, 0.313 ft, 0.375 ft and 0.51 ft. Data for the shortest plunger periods were limited to the stroke of 0.083 ft because of the alarming strain experienced at a longer stroke. This is understandable since the wave height to length ratio encountered (at 0.313 ft stroke) was approximately 1:8. The wave crests were very pointed in shape and the wave crests "broke" at the slightest disturbance. This is in agreement with references (2), (3) and (7).

The calibration data and the dimensionless parameters derived from these data are tabulated in Table 1. The plunger period, plunger stroke, average wave height and wave celerity were used to compute these variables (see standard notation).

$$H \; , \; L_w \; , \; c \; , \; T \; , \; L_{sub} \; , \text{ and } D \; .$$

From these variables the following dimensionless parameters were derived:

$c/\sqrt{gH}$ - Froude number-ratio of unit inertial force to the unit gravitational force,

H/L_w - ratio of wave height to wave length,

$\dfrac{H\,L_w}{8D}$ - ratio of wave crest volume to net plunger displacement volume.

The wave length was computed from the relationship $L_w = cT$. The wave length was also computed from the theoretical equation (see reference (2) and (7):

$$L_w = \frac{g\,T^2}{2\pi} \qquad (1)$$

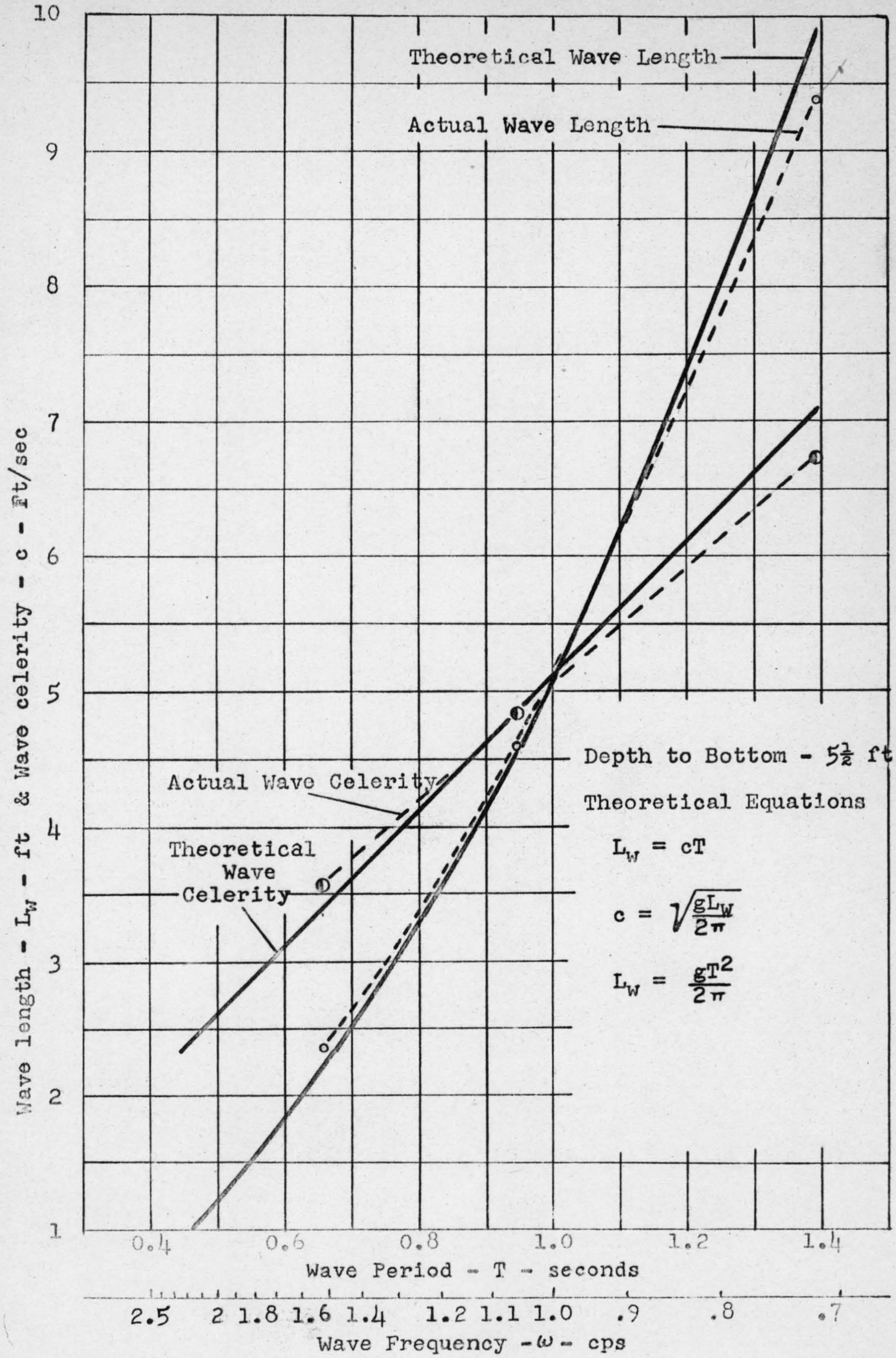
Fig. 10 shows the comparison of the wave length and wave celerity derived from Eq. 1 with the observed wave characteristics. The deviation from the theoretical equation is greatest at $L_w = 9.3$ ft where the waves may have started to "feel" the bottom of the pond (depth = 5.5 ft).

The Froude number is plotted as a function of the wave height to length ratio. Each point on this graph is identified with its value of the wave volume ratio. Two equations giving the empirical relationships between wave

Table 1

Calibration Data for Wave Generator

H (ft)	W.S. Elev. (ft)	Net Plunger Displacement D (cu ft/ft)	Relative Plunger Submergence L_{sub} (ft)	H/L_W	$\frac{HL_W}{8D}$	$\frac{c}{\sqrt{gH}}$
L_W = 2.36 ft	c = 3.58 fps	e = 1.25 in.	L_s = .083 ft			
.198	12.53	.092	.795	.084	.635	1.42
.205	12.31	.097	.575	.087	.624	1.40
.174	12.155	.117	.420	.074	.438	1.51
L_W = 4.60 ft	c = 4.85 fps	e = 1.25 in.	L_s = .083 ft			
.103	12.52	.094	.785	.022	.630	2.66
.129	12.30	.096	.565	.028	.773	2.38
.147	12.162	.090	.427	.032	.940	2.22
.121	12.40	.096	.665	.026	.725	2.45
.124	12.307	.095	.572	.028	.751	2.42
.139	12.15	.089	.415	.030	.900	2.29
L_W = 4.60 ft	c = 4.85 fps	e = 2.5 in.	L_s = .3125 ft			
.272	12.50	.350	.879	.059	.446	1.64
.332	12.306	.361	.785	.072	.529	1.48
.299	12.15	.336	.529	.065	.512	1.56
L_W = 4.60 ft	c = 4.85 fps	e = 2.75 in.	L_s = .375 ft			
.333	12.52	.412	.930	.073	.465	1.48
.344	12.30	.428	.710	.075	.462	1.46
.307	12.15	.404	.560	.067	.437	1.54
L_W = 4.60 ft	c = 4.85 fps	e = 3.5 in.	L_s = .51 ft			
.353	12.16	.539	.638	.077	.376	1.39
L_W = 9.39 ft	c = 6.73 fps	e = 1.25 in.	L_s = .083 ft			
.052	12.54	.092	.805	.006	.664	5.21
.075	12.30	.094	.565	.008	.937	4.31
.096	12.149	.089	.414	.010	1.27	3.82
L_W = 9.39 ft	c = 6.73 fps	e = 2.5 in.	L_s = .3125 ft			
.115	12.41	.361	.789	.012	.374	3.49
.178	12.293	.359	.672	.019	.581	2.80
.172	12.148	.334	.527	.018	.604	2.85
L_W = 9.39 ft	c = 6.73 fps	e = 2.75 in.	L_s = .375			
.148	12.53	.410	.940	.016	.423	3.07
.205	12.305	.427	.715	.022	.563	2.61
.221	12.151	.399	.561	.024	.650	2.51
L_W = 9.39 ft	c = 6.73 fps	e = 3.5 in.	L_s = .51 ft			
.251	12.53	.547	1.008	.027	.539	2.36
.288	12.30	.570	.778	.030	.593	2.21
.232	12.164	.540	.642	.025	.505	2.46



WAVE CHARACTERISTICS

Fig. 10

height and Froude number have been derived from this graph. This relationship is shown on Fig. 11. Examination of Fig. 11 disclosed that the wave volume ratio is virtually independent of the height to length ratio.

In order to further examine the interdependence between the parameters, the Froude number was plotted as a function of the wave volume ratio in terms of the wave height to length ratio on Fig. 12. This graph shows that the wave volume ratio is nearly independent of wave height to length ratio except at very high values of wave height to length ratio or at very low wave volume ratios. This occurs when the waves are very steep (steeper than specified for testing model ship hulls by the American Towing Tank Conference). This is also the range where the wave generator seems to be laboring greatly.

The basic purpose of these calibration tests was to develop relationships between wave height, wave length and plunger displacement. Consideration of the dimensionless graphs serves to establish the fundamental relationships and to determine mistakes or unexplained deviations of individual measurements. The wave height is plotted as a function of the net plunger displacement in terms of the wave height to length ratio on Fig. 13. The graph represents the general performance curve for the wave generator as installed in this particular wave basin.

Recommendations for improvements:- Several suggestions for improving the wave generator can be made. The pipe plunger deflects under certain conditions. This is particularly true at the ends of the plunger which are essentially cantilevers restrained to motion in the vertical direction. This deflection is apparently the result of a number of factors:

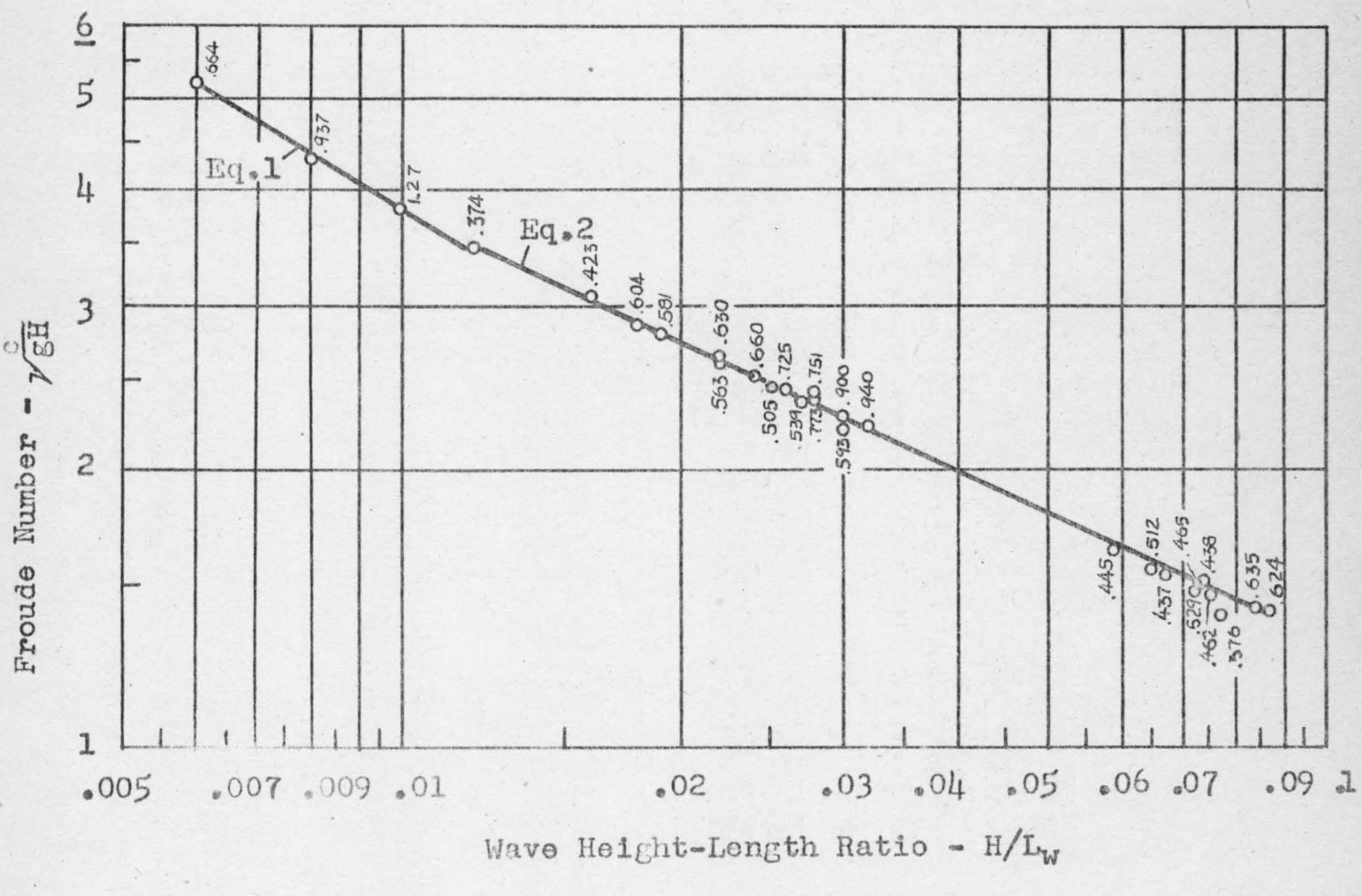
1. Slight elastic flexibility of the pipe plunger in the vertical direction.

2. Some binding in the vertical guide bearing at the ends of the plunger.

3. Slight misalignment in the main vertical support links caused by slipping or rotation of the attachment sleeve about the longitudinal axis of the plunger.

These steps have been taken to improve the facility:

1. The stiffness of the plunger is being increased by increasing the moment of inertia of the cross

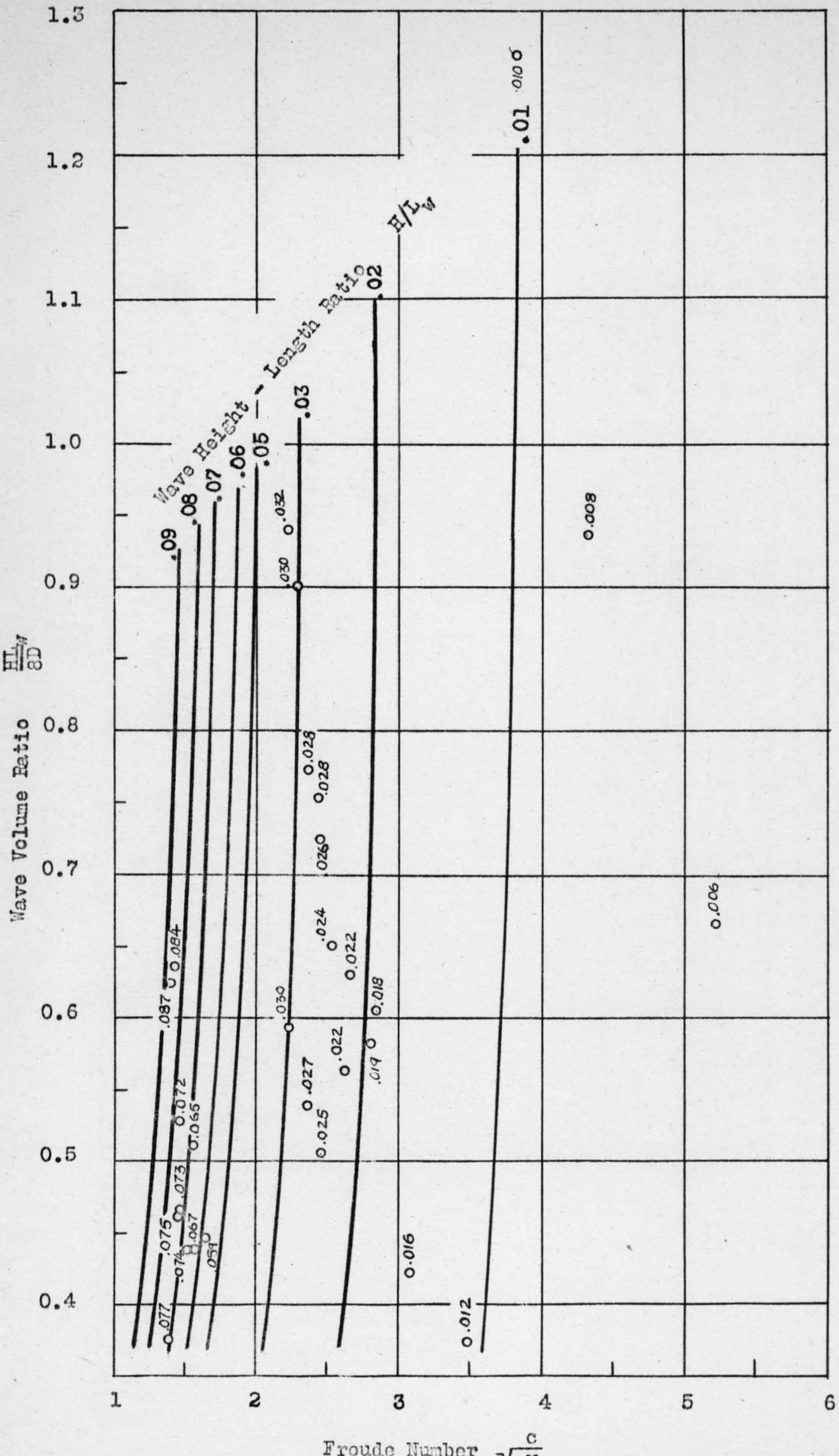


$$\text{Eq.1} \quad \frac{c}{\sqrt{gH}} = 0.23(H/L_W)^{-0.60} \quad \text{for } H/L_W < .01$$

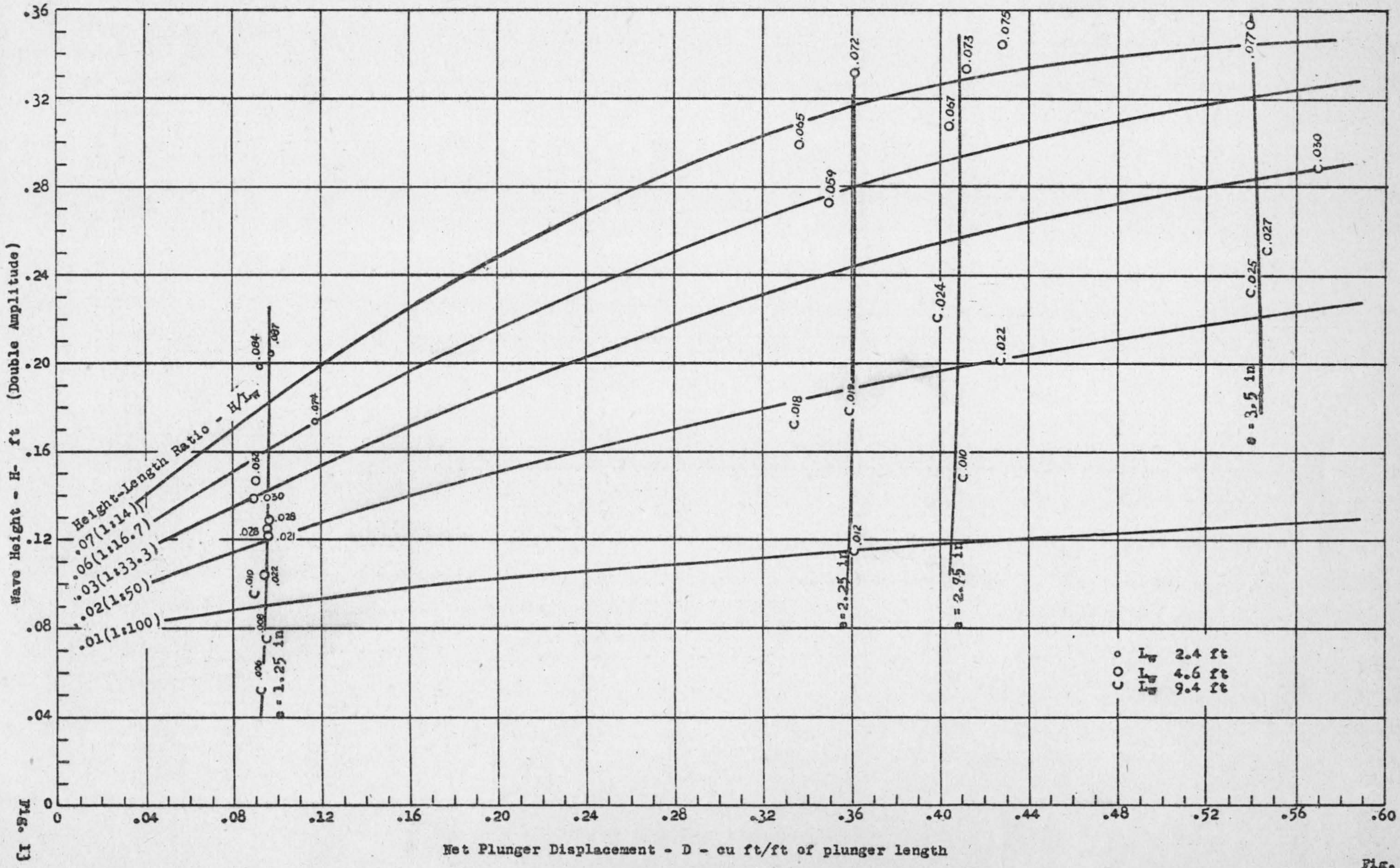
$$\text{Eq.2} \quad \frac{c}{\sqrt{gH}} = 0.45(H/L_W)^{-0.46} \quad \text{for } H/L_W > .01$$

RELATIONSHIP BETWEEN WAVE FROUDE NUMBER AND HEIGHT-LENGTH RATIO

Fig. 11



RELATIONSHIP BETWEEN WAVE VOLUME RATIO AND FROUDE NUMBER Fig. 12



WAVE GENERATOR PERFORMANCE CHARACTERISTICS

Fig. 13

section in the vertical direction (about the horizontal axis of the cross section) by welding a 1/4-in. by 12-in. hot-rolled steel plate longitudinally along the entire bottom edge of the plunger. The plate is being welded to the pipe so that the 12 in side will extend down into the water. It will thus form an excellent foundation for a potential wedge cross section which may be added at some future date to the lower side of the plunger.

2. The binding of the vertical guide sleeve was evidently caused by slight misalignment of the vertical support links resulting from slight bending of the end-axle supports of the pipe plunger. This is being corrected and larger axles are being installed.

3. The vertical support links are attached to the plunger through an attachment sleeve. The attachment sleeve was fabricated from two thicknesses of 10-gauge 14-in. pipe each 36 in. long. These were cut longitudinally along the top so that they could be bent open slightly and slipped over the plunger. Provision was made to clamp the attachment sleeve securely to the plunger; however, this clamp is evidently not positive. To remedy this situation, holes are being drilled and tapped through the sleeve and into the plunger. A cap screw will be inserted making a positive connection.

These modifications are under construction (winter 1953-54) and will be completed before the testing begins this spring (1954).

Wave Absorbers

To maintain a simple and uniform seaway for experimental purposes the wave at the end of the seaway must be absorbed and any reflections prevented. In most towing basins the wave generator is situated at one end of the tank and no seaway is created "behind" the wave generator. Because of the configuration of the Colorado A & M wave basin, it was necessary to construct the wave generator at some distance from the edge of the basin. Hence when the waves are formed, they travel in both directions from the wave generator. Both of these wave trains must be abosrbed. A sloping gravel beach was used to absorb the waves and prevent reflections. A shelf was constructed from wire fastened to a wood frame. This supported the gravel which consisted of 1-1/2 in. crushed rock. Fig. 14 is a drawing showing the cross section of the gravel beach wave absorber. The gravel is completely surrounded with 1/4-in. galvanized wire mesh. This prevents movement or erosion of the gravel. The 1/4-in. wire mesh is supported by 2 x 4-in. wire reinforcing fabric made from No. 10 wire.

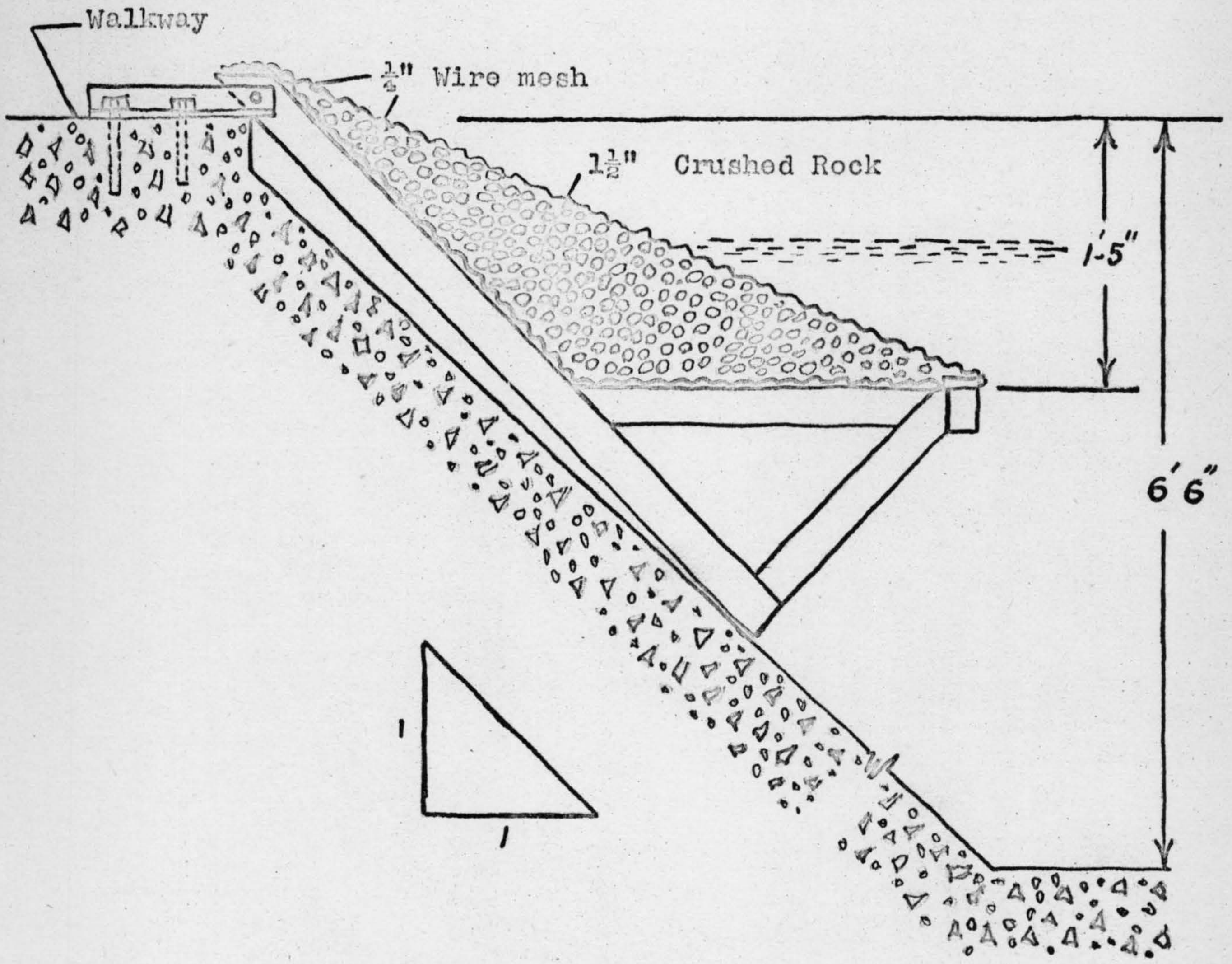
Effectiveness:- These absorbers are quite effective in absorbing the waves. There is evidence that extension to a greater depth into the pond may increase their effectiveness. This is especially true for the absorber located "behind" the wave generator (see Fig. 15). After the wave generator has been in operation for a period of from 4 to 8 seconds a small wave of approximately twice the celerity of the primary wave train can be observed traveling down the seaway. This could be reflections from the side of the tank beneath the absorber. Because the wave absorbers are so shallow (approximately 0.75 ft below the water surface), it is possible that the top of the wave is effectively absorbed but the lower part of the wave, as evidenced by pressure, could be reflected from the side of the pond beneath the absorber.

This reflection was not detected from the absorbers at the other end of the seaway. Possibly the normal forces producing wave attenuation combined with the wave absorbers have effectively absorbed the entire wave energy at this end.

It is believed that by welding the plate to the bottom of the plunger, the reflected wave will be considerably reduced. If the reflections still exist, a pressure cut-off wall to the bottom of the tank will be installed.

Wave Guides

To prevent diffraction of the wave front after leaving the wave generator, wave guides were installed. In plan view the testing basin is rectangular in form -- 40 ft wide and approximately 65 ft long. The testing basin or seaway is bounded at one end by the wave generator, on the other end by a wave absorber, which is actually curved (in plan view) to conform to the edge of the pond, and on the two sides by wave guides. Fig. 16 is a photograph showing the wave testing basin. These wave guides were constructed from 4 ft x 8 ft sheets of oiled plywood 1/2 in. thick. They are supported by 1-1/4 in. pipe standards anchored to the bottom of the tank. The plywood panels are mounted so that there is



CROSSECTION OF GRAVEL BEACH WAVE ABSORBER

Fig. 14

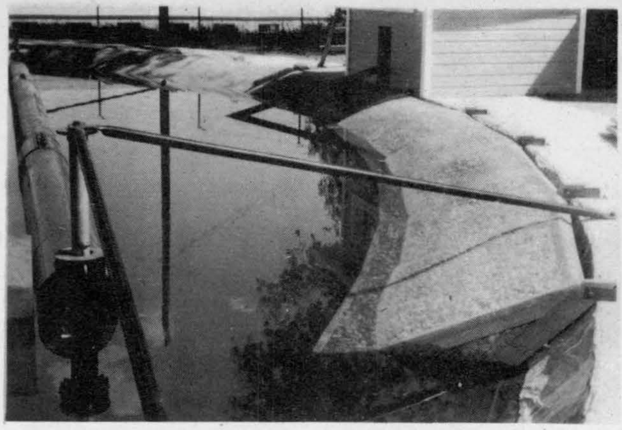


Fig. 15 Wave Absorber Located
Behind the Wave Generator

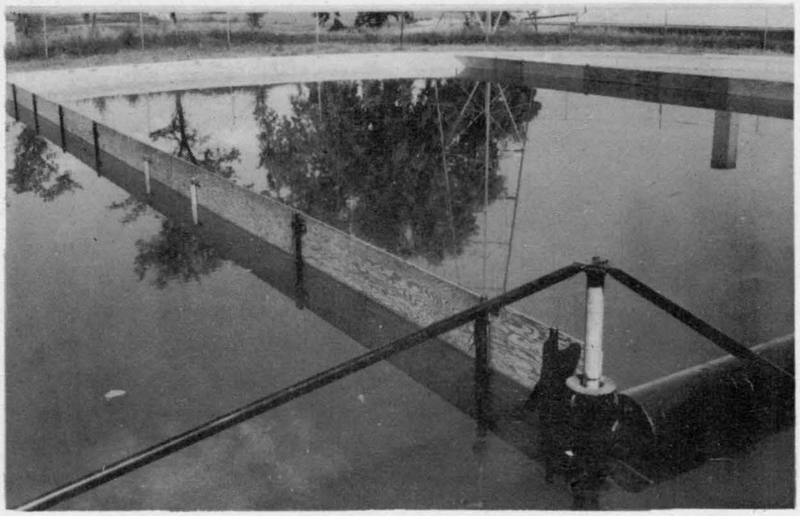


Fig. 16 Wave Testing Basin

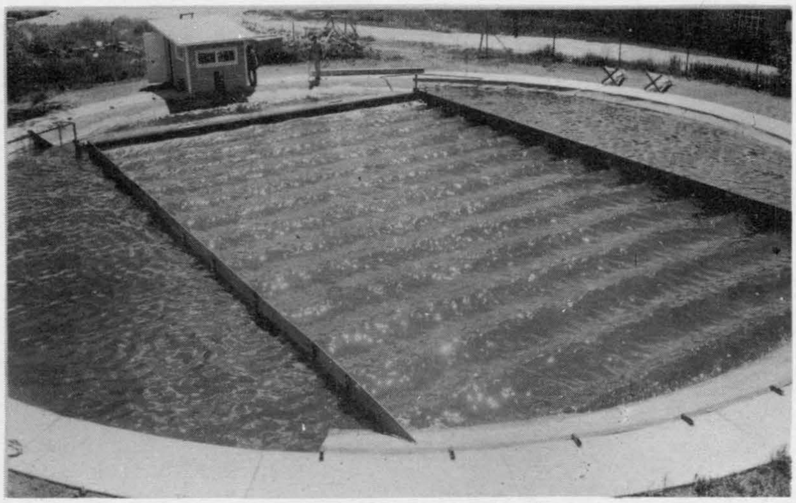


Fig. 17 Wave Basin After About
10 Minute's Operation

approximately 1 ft of freeboard and 3 ft submerged.

There is considerable deflection of the wave guides as the wave front passes through the seaway. Part of the deflection results from the deflection of the pipe support which is essentially a 6-1/2 ft cantilever. This bending can be prevented by bracing the top of the pipe from the edge of the pond or by a diagonal support to the bottom of the pond. Deflection of the plywood panel can be reduced by bolting a 2 x 4 or 2 x 6 stiffener horizontally to the wave guide at the static water level and outside the seaway.

The problem of reflections from the wave guide has been unimportant; however, reflections from the sides may become bothersome if the wave guides are made too rigid. The movement of the wave guides causes a secondary wave system in the area outside the seaway. If the wave generator is allowed to operate for a period longer than two or three minutes, the secondary wave system is quite noticeable in the seaway also. This secondary wave system takes the form of a wave train traveling across the seaway at 90° to the primary wave train. This interference is illustrated in Fig. 17. This photograph was made from a meteorological tower about 30 ft above the pond. In this photograph the wave generator had been in operation approximately 10 minutes. This interference can be avoided by operating the wave generator as little as possible. The procedure being to turn on the wave generator, conduct the run as soon as two or three fully developed waves have reached the end of the seaway and turn off the wave generator as soon as possible. The next run is not started until the pond has become calm again.

At the present time no modifications of the wave guides are planned. If it is demonstrated that more rigidity of the wave guides is desirable, steps will be taken to reinforce and brace the wave guides.

One of the purposes of the wave basin is to test model seaplane hulls at model speeds up to 15 fps. To successfully test the models at these speeds, it is necessary to have about ten feet of space at the beginning and at the end of the test run for acceleration and deceleration. In order to have sufficient length of run in the seaway, a number of panels in the wave guides were constructed so that they could be made to slide down until the top edge is about 0.7 ft below the water surface. This forms a slot in the wave guides through which the model can be towed. In this manner the model can be accelerated to speed before entering the seaway. A metal guide was attached to the edge of the slot to help guide the model through the opening. This guide is important if a wide model such as a seaplane equipped with tip floats is being tested in an unrestrained manner using a towing bridle. If a model is being tested so that swaying is restrained, these metal guides are unnecessary.

When a wave guide panel is in a lowered position, diffraction of the wave front occurs as the wave passes the slot. This diffraction causes some modification of the wave as it passes by the opening. The principal change is apparent in a reduced wave height for approximately one wave length along the crest caused by "stretching" of the wave front as it passes through the opening. Photographs of the wave basin with the guides lowered for testing at angles of wave travel relative to the model course of 45°, 60° and 90° are shown in Figs. 18, 19 and 20 respectively. Examination of these photographs discloses that the effect of the slot in the wave guide on the general wave pattern is of minor importance. The waves may be compared with those of Fig. 17 for uniformity.

Wave Filter

Bending of the wave plunger, reflections from the wave absorber behind the wave generator or structural vibrations induced by the roller chain drive caused waves of small amplitude and short wave length to be superimposed on the primary wave front. A wooden plank 2 in. x 12 in. x 39 ft long was moored in the seaway about 7 ft from the wave generator. This very effectively filtered out all of the small-amplitude high-frequency disturbances. The plank lost its effectiveness as soon as it became waterlogged. The plank evidently requires about 1 in. free board in order to be effective. This filter cannot be used when the primary wave length is less than about 4 ft because as the ratio of plank width to wave length approaches 0.25 the filter begins to modify the primary wave front. For the short wave lengths, a plank width of 6 in. will be used.

Measuring Wave Profile

A continuous record of the wave profile is essential. Since continuous records of some of the model movements was also essential, it was decided that a multichannel recording oscillograph should be purchased. This decision was made after the sponsor informed the contractor that no oscillograph could be loaned. A Heiland Model 708B Recording Oscillograph was purchased. This oscillograph was chosen because of superior construction and performance of the galvanometers and greater latitude in choice of writing speeds. Up to 24 galvanometers can be used. The galvanometers vary

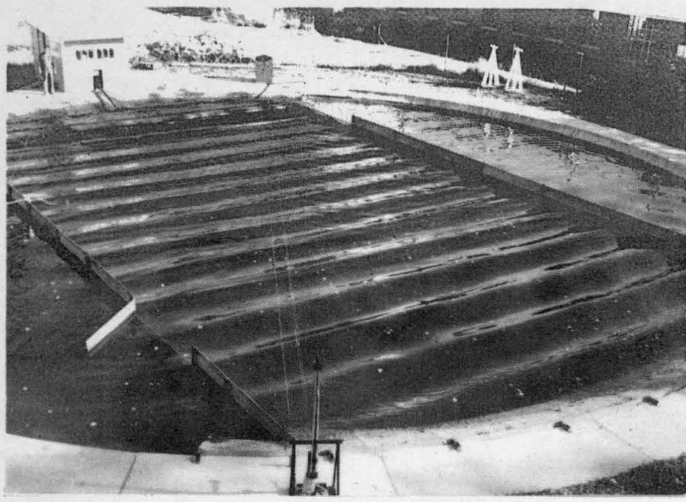


Fig. 18 Wave Guides lowered for Towing at $\chi = 45^{\circ}$

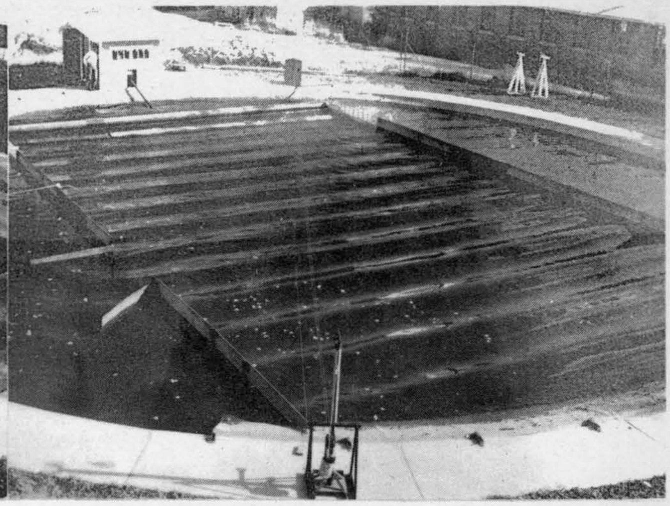


Fig. 19 Wave Guides lowered for Towing at $\chi = 60^{\circ}$

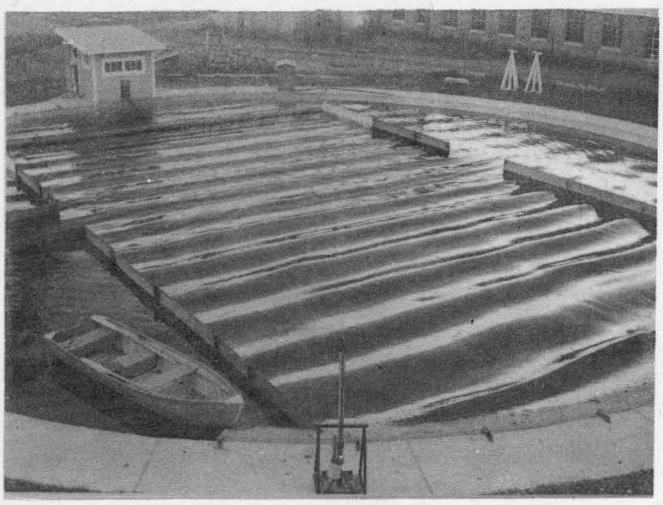


Fig. 20 Wave Guides lowered for Towing at $\chi = 90^{\circ}$

Fig. 21 Wave Profile Probe

in sensitivity from 12.5 μa/in. to 212 ma/in. and the flat frequency range varies from 0-24 cps to 0-1980 cps.

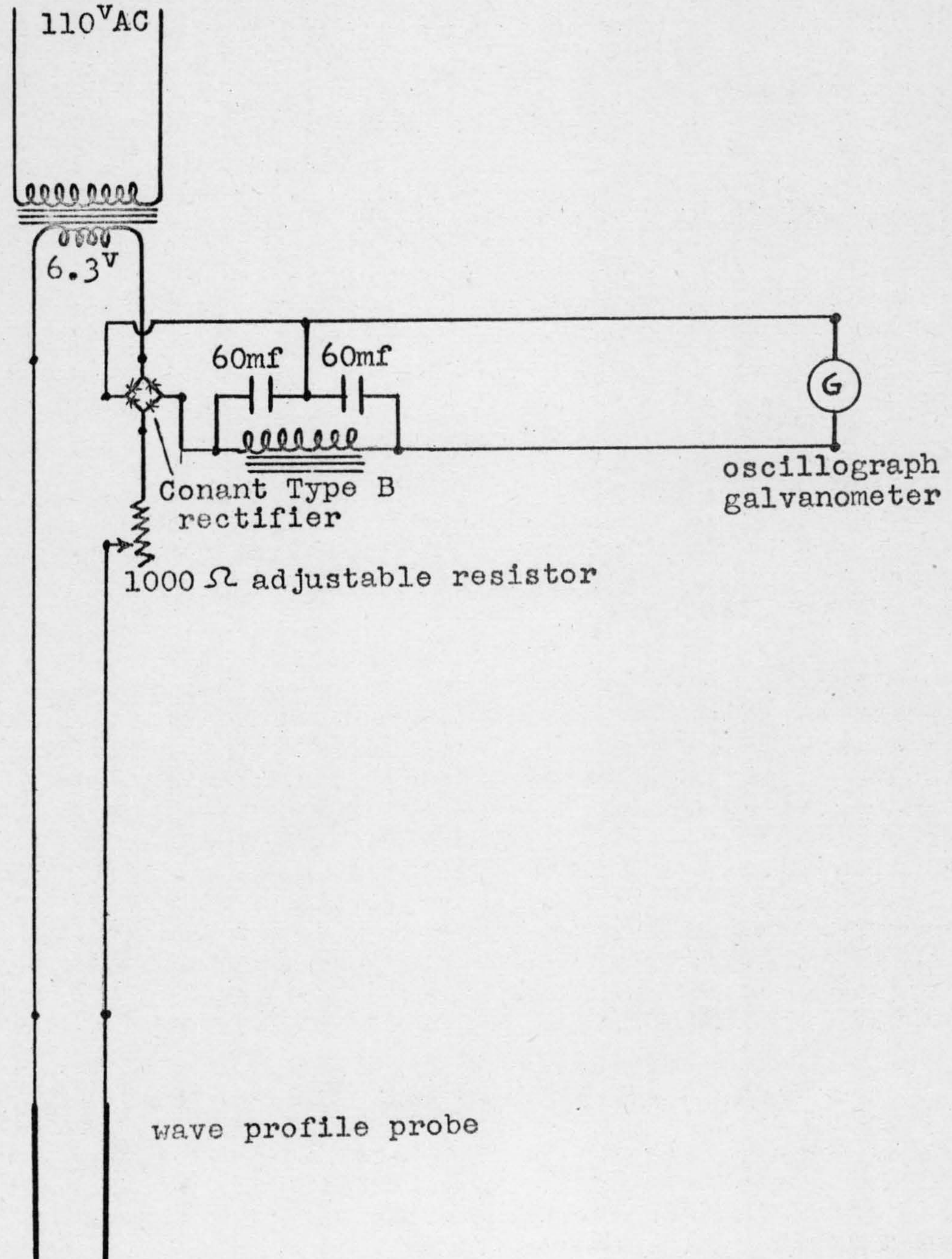
Having this wide range of galvanometer sensitivity permitted a considerable latitude in the design of the wave profile probe. A resistance type probe was used employing a pair of chrome-nickel wires 0.016 in diameter and having 0.23 ohms resistance per inch. These two wires were about 15 in. long and were suspended vertically on a frame. The ends were fastened to Lucite at the top and bottom. Two leads were taken from the top to the oscillograph. The wave profile was recorded by measuring the change in resistance of these two wires as the rising and falling water surface changed the total length of wire submerged. The Lucite plates at the top and bottom were fastened to a frame made from brass. The frame was graduated to facilitate calibration of the probe. Normally the probe was fastened to a support approximately 3 ft from the right wave guide. The end of the probe was immersed about 7 in. Fig. 21 is a photograph of the probe showing the details of construction and Fig. 24 shows the probe mounted on its support in the wave basin.

The probe was calibrated by immersing it at different levels in the pond while the water surface was quiet. The calibration was always made in its actual environment to properly take account of the effects of nearby pipes and other submerged metal objects.

It was necessary to use alternating current in the probe circuit to avoid the hydrolysis phenomenon of the water around the probe wires. A small instrument rectifier was used to convert the current in the probe circuit to D-C for measurement by the oscillograph. A twin-π low pass filter was employed to eliminate the A-C pick-up which appeared in the circuit. Fig. 22 is a wiring diagram of the probe circuit. Fig. 23 is a calibration curve of the wave profile recorder. Unfortunately there is a non-linear relationship between galvanometer reading and water surface position. This makes it necessary to always know exactly the water surface position in order to properly use the calibration curve.

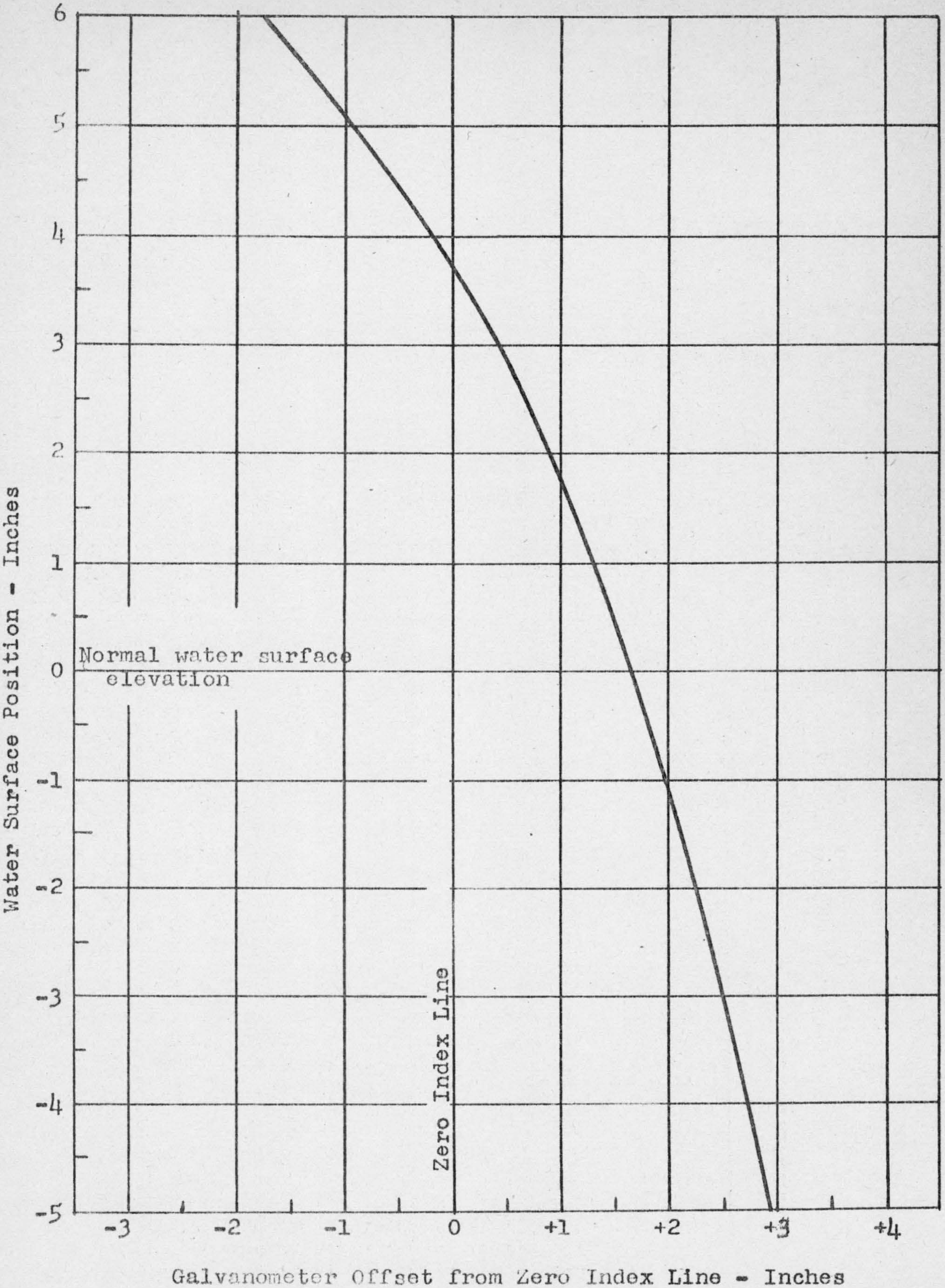
The probe makes an excellent micro water-level indicator. The index reading of the galvanometer when the water is calm can be used to measure the static water level. A D-C micro-ammeter was connected in parallel with the oscillograph. This meter is used for visually monitoring the record being taken by the galvanometer.

The probe is being modified in an attempt to achieve a linear relationship between galvanometer reading and water



WIRING DIAGRAM FOR PROBE CIRCUIT

Fig. 22



WAVE PROFILE PROBE CALIBRATION

Fig. 23

surface position. Lucite is being substituted for all metal parts in the probe support except the wires and their binding posts. The spacing of the wires has been 0.375 in. Possibly this spacing may be changed to obtain a linear calibration.

To improve the ease and accuracy of adjusting the probe to the static water level, the probe was mounted on an adjustable boom. The probe was at a distance of 5 ft from the right wave guide and 24-1/2 ft from the wave generator. The vertical position of the probe can be adjusted from a boat outside the test basin by turning an adjusting nut. A hook has been added to the probe so that it can be used as a hook gage. Fig. 25 is a photograph of the modified probe mount.

Model Motions

If completely unrestrained, the motion of the model could be defined as translation of the center of gravity along three orthogonal axes fixed in space and by rotation of the model about axes parallel to these orthogonal axes. The linear displacements have been termed surge, heave, and sway for motions along the longitudinal, vertical and lateral axes respectively. The rotation about these axes has been called roll, yaw and pitch. If the model is to yield exact information on the motion of its prototype, then the model must be restrained only to the extent that the prototype is restrained. Any corrective measures supplied by steering or control in the prototype must also be supplied in correct scale and at the correct time scale to the model. Because of the scale ratios usually encountered, it becomes very difficult to simulate these corrective measures on the model. Furthermore, the surface of the sea which is encountered by the prototype is very complex. The sea virtually never repeats itself. In order to obtain data or information on the seaworthiness or the seakindliness of prototype from model studies, the conditions of the model testing must be somewhat simplified. This can be done by:

1. Simplifying the state of the sea by producing a simple wave train of a single length and height. The waves are made regular, long crested, the crests rectilinear with each other, and of sinusoidal profile.

2. Restricting the model to only a single degree of freedom, such as pitch only. Then conduct a separate series of experiments permitting only roll and so on. This gives information about the specific degree of freedom; however, the practical problem is one of intercoupled motions.

It is a single mass which can move in six different ways. The net acceleration experienced is the result of the six possible motions.

3. Permit freedom of motion in a number of degrees of freedom and restricting the others. This technique will yield information regarding the relationships between the coupled motions.

St. Denis and Pierson (5) point out that of the six possible motions, heave, pitch and roll are the most important oscillations to which a ship is subjected because the restoring forces for these three motions are mobilized by virtue of changes in the distribution of buoyancy of the vessel. On the other hand, the restoring forces for the motions of surge, sway, and yaw develop hydrodynamically. The serious accelerations experienced by a vessel are a result of heave, pitch or roll.

Instrumentation for Measuring Model Motions

The purpose of the foregoing discussion, which is incomplete and elementary (see (4), (5) and (8)) is to develop background for simplification of the experimental testing program. Initially all model testing in oblique seas will be conducted in a simple seaway -- that is a seaway which is composed of uniform waves having a single height and wave length and be as nearly sinusoidal as possible. Actually, the waves are very nearly trochoidal if the height to length ratio is less than 1:10 (2)(6)(7). As the wave height becomes small compared to the length the trochoidal profile approaches the sine curve (2) and certain generalizations are permissible (4). If the profile of the seaway can be assumed to be sinusoidal, then analysis of the data is simpler.

From the foregoing discussion of model motions, it can be concluded that the pitch, roll and heave motions are most important and if any simplification is to take place, then the motions of surge, sway, and yaw can either be eliminated by restraining them or ignored by not attempting to measure them. Surging accelerations can be eliminated by maintaining a taut towing line at all times and by towing at a uniform speed. Sway can be eliminated by attaching the model to a carriage which permits freedom in pitch, roll and heave but resists movement in the lateral direction resulting from the model's tendency to sway. Yaw can be eliminated by resisting turning on the vertical axis resulting from the model's tendency to yaw. Instrumentation, therefore, then must be developed for measuring heave, pitch and roll.

Another method of testing would be to tow the model with a simple bridle at a uniform speed. The motions of surge, sway, and yaw are not entirely restrained although the restoring forces for these motions are entirely different than in a free self-propelled model or in the prototype.

A third method of testing would be to use a free self-propelled model. The difficulty here is to properly produce the corrective measures in the model which would be present in the prototype. This method would involve a complex control system in addition to the problem of measuring heave, pitch and roll.

Probably the simplest and easiest type of instrumentation to measure the motions of the model is the motion picture camera. It is amenable to either of the three methods of towing previously discussed. If the motions are slow enough so that one exposure represents an instantaneous picture, then motion picture photography is an adequate technique. Fortunately for most models of ships and seaplane models in the displacement range, a standard 16 mm motion picture camera operating at 24 frames/sec is quite adequate. If more detail is required, the speed can be increased to 32 or 64 frames/sec. Unfortunately, analyzing the data is only approximate, laborious and time-consuming. A displacement, such as heave can be obtained by measuring the position of the center of gravity of the model relative to some reference. Both the model and the reference must be photographed simultaneously. Rotation of the model is determined by measuring the angle between a reference line on the model and some fixed base line. If all six modes of motion are to be studied, then three cameras should be mounted such that the line of sight of each camera represents one of the orthogonal axes. All cameras can be synchronized by flashing a timing light on or near the model. If only heave, pitch and roll are to be studied, then two cameras are needed -- one along the longitudinal axis and one on the transverse or lateral axis. The cameras can be mounted either at some distance from the model or they can be mounted in the model itself and photograph simultaneously a fixed non-moving datum and a reference attached to the model. The 16 mm gun cameras are excellent for this purpose because they have a reference grid etched in the lens which conveniently serves as the model reference.

Summary of Testing Experiences

During the summer of 1953, a number of experiments were conducted on model seaplane hulls. Weight considerations were such that the gun cameras could not be mounted in the model. Since the models were to be tested at several different headings with respect to the wave front, it was imperative that the towing mechanism and any structure which must be moved when the heading is changed be kept at a minimum. At the start of the tests it was not known if the models could be successfully towed at different angles to the seaway or if the seaway would be large enough to establish a stabilized condition between model and sea. Because of these uncertainities, the photographic method employing two 16-mm movie cameras was used during the first experiments. Since mounting the two cameras near the model and on the exact longitudinal and lateral axes was impractical, the cameras were mounted on sturdy tripods on the edge of the pond. Telephoto lenses were used to obtain an image of the model large enough to fill the frame. One camera was mounted approximately three feet above the ground and behind the towing mechanism sighting down along the towing line. The other camera was mounted on a tripod approximately 4-1/2 ft above the ground and at a point normal to the towing line and opposite the center of the run. Under these circumstances the angles and distances measured from the movie film were distorted because the measurements were not made in a plane parallel to the vertical axis nor along an extension of the longitudinal or lateral axis of the model. However, the measurements were actually small (less than 15° of rotation in either direction or 0.5 ft displacement) and the distance from the model relatively great (in excess of 45 ft); therefore, the distortion could reasonably be ignored. A simple bridle was used to tow the model. The towing line was located about 2-1/2 ft above the static water level and the total length of bridle was about 10 ft. The thrust line was slightly inclined; however, in the case of the seaplane the prototype thrust line would be also inclined. A short persistence type of flash bulb was mounted near the starting point of the run. This flash bulb was fired at the start of the run. This identified one exposure (sometimes two exposures at 24 frames/sec) on each film and also produced an identifying point on the oscillograph record. Thus all of the records could be synchronized. The entire run was photographed. The length of time required to establish stabilized conditions was determined, by inspection, from the film. Measurements of heave and pitch were obtained from frames exposed when the model was opposite the side camera (when the line of sight was nearest normal to the course of the model). Angles of roll were obtained from the front view of the model. A reference baseline and a scale was painted on the side of the model. A steel cable painted a contrasting yellow, was stretched tightly across the pond about 1 ft above the static water level. The two ends of cable were at the same elevation. This cable was used as the reference datum.

The number of waves encountered before the model reached a stabilized condition was determined for each loading, speed and heading. These data are tabulated in Table 2. Examination of the data shows that the model

Table 2

Length of Run Required for Stabilization of Model

Speed coefficient $v/\sqrt{gb}$	Angle of Heading 0: Number of waves encountered before stabilized	0: Total number of waves encountered during run	30: Number of waves encountered before stabilized	30: Total number of waves encountered during run	45*: Number of waves encountered before stabilized	45*: Total number of waves encountered during run	60*: Number of waves encountered before stabilized	60*: Total number of waves encountered during run	90**: Number of waves encountered before stabilized	90**: Total number of waves encountered during run
Light gross weight $C_\Delta = \Delta/wb^3 = 1.0$ $L_w = 4.6$ ft $L_w/L = 1.15$										
0.56	2	36	2	32	3	27	3	14+	2	10+
1.47	2	20	2	16	3	16	4	11+	3	7
3.67	3	13	4	15	5	10	4	7+	2	4
Heavy gross weight $C_\Delta = 1.5$ $L_w = 4.6$ ft $L_w/L = 1.15$										
0.56	2	15+	2	17+	3	19+	3	14+	2	12+
1.47	2	20	3	20	4	14+	4	11+	3	8
3.67	3	11	6	14	7	11	5	8+	2	5

14+ indicates that 14 encounters occurred when run was stopped; however, the end of the seaway had not been reached.

* Model accelerated before entering seaway.

** Model accelerated before entering and decelerated after leaving seaway.

encounters an insufficient number of waves while traveling at the highest speed (model speed 15 fps) and heading at 90° to the wave front. At this heading the useable seaway is 40 ft wide. There is some evidence that a shorter run is required to reach stability for the lighter gross weights. At speed coefficients (Froude number) of 0.5 or less the model is subjected to a large number of wave encounters before reaching the end of the run. In general the basin is adequate for testing of small models.

Methods of Data Reduction

The data must be reduced using a Recordak projector or some other type of viewer. There are several shortcomings in the type of photographic method of obtaining the data used during 1953.

1. Care must be taken not to "burn" the film.

2. Several exposures must be examined near the maximum and minimum points in order to find the precise maximum or minimum.

3. The method of measuring the angles and displacements may be subject to considerable error because of the geometric distortion.

4. There is only one location in the entire run where the model is directly opposite the side camera. This limits the measurements of the motion of the model to the wave encountered nearest this point.

5. It is difficult to obtain simultaneous measurements of pitch and roll because the synchronizing exposure is usually located about six ft ahead of the exposures being used in the roll of film. This could be made more practical by mounting the flash bulb on the model and firing the bulb near the center of the run or by using more synchronizing exposures per run.

Probably a more precise and easier method of reduction could be devised to obtain the necessary data. The photographs are an excellent history of the test; however, the reduction of data from photographs is a manual operation and not easily checked to eliminate possible errors. A method whereby the data is reduced mechanically or electrically is desirable. It would be highly desirable to have the pitch, roll, and heave reduced to electrical signals which could be recorded on the oscillograph along with the records of wave height and length and model speed. Investigators at several towing tanks were contacted to study their methods of measuring and recording these motions. The many suggestions which they offered are summarized as follows:

1. Use a D-C Wheatstone bridge circuit and micro-potentiometers for measuring heave, pitch and roll.

2. Use an A-C circuit and Schaevitz linear variable transformers for measuring heave, pitch and roll.

3. Use a D-C Wheatstone bridge circuit and Bendix Convectron tubes for measuring pitch and roll only.

4. Mount a metal sphere or hemisphere on the model near the center of gravity and mount a second plate preferably a segment of a sphere on a carriage above the model. Heave can be obtained by the change in capacitance between the two plates. This requires an A-C circuit.

Towing Carriage

Nearly all of the more elaborate systems require the presence of a stationary geometric reference from which the measurements are made. The reference must be reliable, relatively rigid, and in some cases capable of supporting a carriage which in turn may be called upon to restrain some of the less essential model motions. For the Colorado A & M tank this reference must be readily portable so that the heading of the model can be easily changed. A relatively rigid bridge could be constructed across the pond. The clear span must be 86 ft. The maximum deflection at any point should be less than 0.01 ft (about 1/8 in.). The carriage and necessary equipment to be carried by the bridge may weigh as much as 50 to 100 pounds. The bridge would probably be mounted on a circular track for ease of movement, maintenance of a horizontal plane and effective distribution of the weight to the supporting walkway.

Eventually this bridge will probably be constructed; however, at the present time a less elaborate and less expensive reference datum will be used. Three parallel 1/8-in. diameter high strength steel wires have been suspended across the pond. The two ends of each wire are at the same elevation. The three wires have been arranged to have the greatest resistance to twisting reaction of the carriage resulting from restraining the model in sway and yaw. Approximately 1300 pounds tension will be applied to each wire. A light weight aluminum carriage has been constructed to travel on these wires. The carriage is now being modified so that the model can be restrained in surge, sway and yaw. The carriage will also tow the necessary leads for any instrumentation so that the model will be uninhibited by virtue of any electrical connections with the edge of the pond.

Electrical Transducers

All electronic devices have been avoided in the circuitry to make the instrumentation simpler, less expensive, and more reliable. The galvanometers of the oscillograph are sufficiently sensitive to measure the output from most of the D-C transducers previously suggested. The Bendix convectron tubes have been chosen as the transducers to measure the angles of pitch and roll. A micropotentiometer will be used in conjunction with a bow string and pulley to measure the heave. The fundamental principle of measurement for all of these circuits is the Wheatstone bridge.

The convectron tube consists of an "L-shaped" sealed glass bulb with a standard grid cap mounted at each end of the legs and one mounted at the point of juncture of the two legs called the base. A fine nickel filament runs centrally through each arm to the base cap. The glass tube is filled with an inert gas (argon). The two filaments are heated to approximately 400°F. They form two arms of a Wheatstone bridge. When the tube is tilted in the gravity field, differential convection causes a temperature difference surrounding the two filaments and therefore a difference in the resistance of the two filaments. This unbalances the bridge and may be used as a signal for measuring angle of tilt. Fig. 26 shows the two convectron tubes and their support structure before assembly. Fig. 27 shows the two convectron tubes after assembly and ready for mounting in the model. Fig. 28 is the wiring diagram for one convectron tube.

The disadvantage of the convectron tube is that its reference datum is the earth's gravity field; therefore, it is sensitive to accelerations. As the convectron tubes are mounted in the model, they will be subjected to linear accelerations along the longitudinal and lateral axes. Another disadvantage of the convectron is that the environmental air temperature can be a critical factor in changing the calibration. The sun's radiation is also important if one leg of the convectron should happen to be in the shade

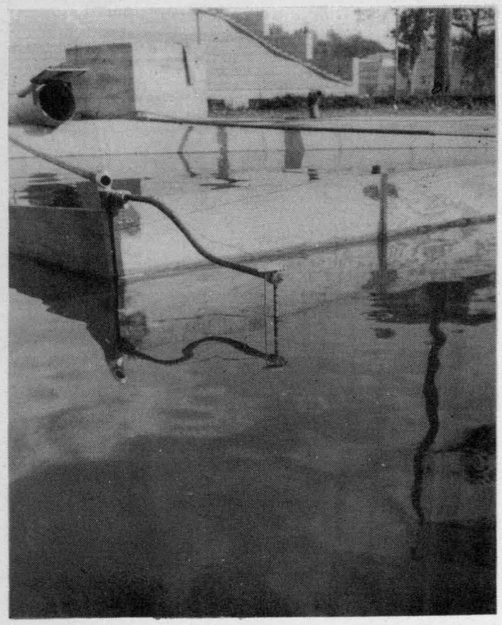


Fig. 24 Wave Profile Probe

Fig. 25 Revised Boom and Probe at #2 Location

Fig. 26 Convectron Tubes Unassembled View

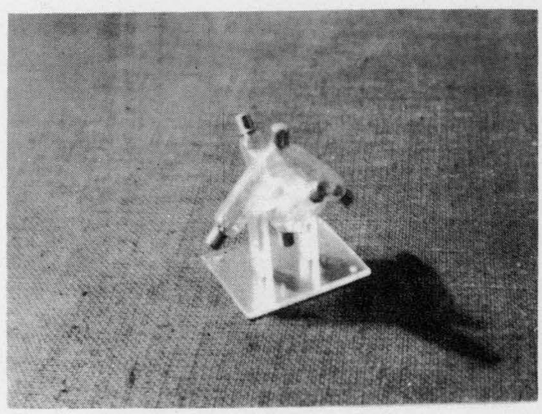
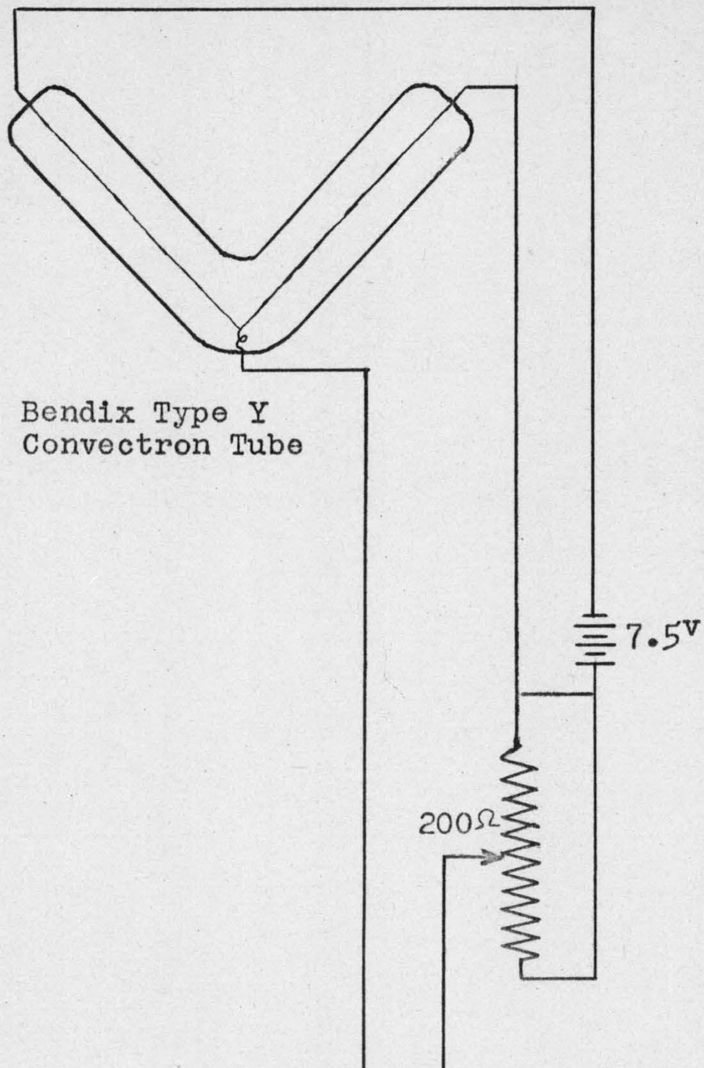
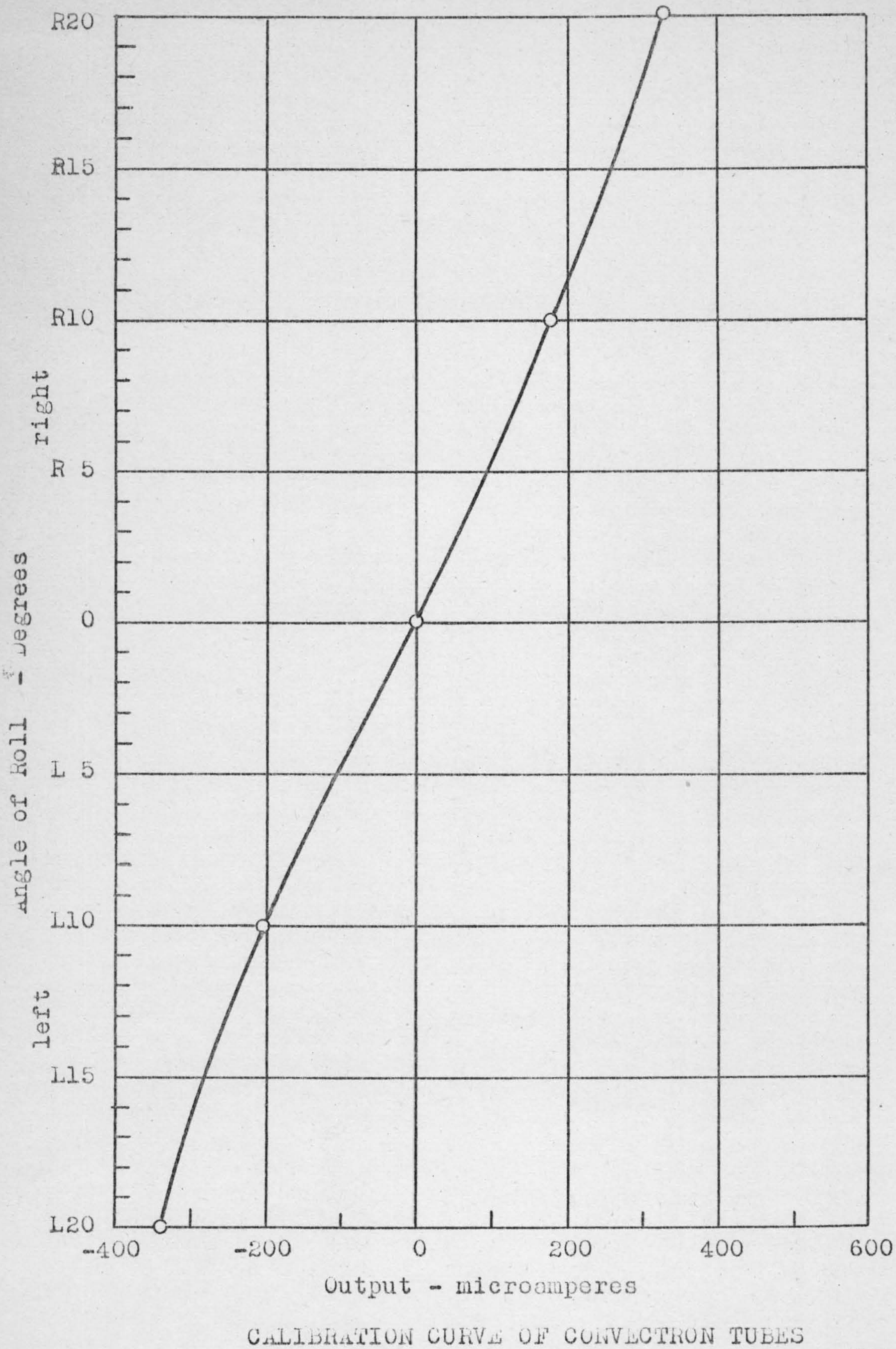


Fig. 27 Convectron Tubes Assembled View



CIRCUIT FOR A SINGLE CONVECTRON TUBE Fig. 28



CALIBRATION CURVE OF CONVECTRON TUBES

Fig. 29

and the other in the sun. The convectron tube itself is a source of heat; therefore, the temperature sensitive features of the tube can be disposed of by shielding the tube. The shield material itself will be aluminum foil. The interior of the shield will be coated with a black plastic tape or sprayed with flat black paint. Thus the inside of the shield will act as a heat sink which will absorb the heat from the tube and the outside will be a good reflector should the sun shine on the shield.

Because of their low relative magnitude, it is believed that the linear-acceleration sensitivity of the tubes can be ignored because the model will be restrained in the longitudinal and lateral directions. Doubtless some accelerations along these axes will occur; however, they are expected to be small if the actual nonuniform translation along these axes is reasonably small. Of course the model will have to be accelerated at the beginning and ending of the runs; however, starting and stopping will not be considered part of the run. Furthermore, the model will also be photographed from two directions with movie cameras; therefore, two sets of independent data will be available. In this way the validity of these assumptions can be checked and a "dynamic" calibration of the tubes obtained.

The great advantage of using the convectron tube is its light weight, high sensitivity, and the absence of necessity for any structural member to support the carriage. The only connection with any non-model component is three lead wires. These wires could be attached to the towing line should it be desired to tow the model using a simple bridle only.

Conclusions

It can be concluded that a 5-ft model can be tested effectively at model speeds of less than 10 fps on any heading. In fact longer models could be accommodated at model speeds of less than 5 fps. Some modifications of the wave generator and the wave absorber behind the wave generator as originally constructed were found desirable and are being made. The other wave absorber and the wave guides perform in a satisfactory manner. Two movie cameras photographing the model simultaneously from the bow (or stern) and from broadside can be used to obtain measurements of heave, pitch and roll. Reducing the data from the movie film is laborious and a method of recording these motions using a convectron transducer and oscillograph is explored. The performance of the resistance type wave profile probe was non-linear and it is being redesigned in an attempt to develop better performance. This basin can be employed to obtain a considerable amount of data at a relatively low cost.

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