A NEW TYPE OF WAVE GENERATOR

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R. E. Glover

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The David Taylor Model Basin

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Technical Report No. 7

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Abstract

In a previous report it is shown that an observed storm sea can be reproduced to model scale in a wave basin if the storm sea undulations are reproduced around the entire perimeter of the wave basin. A new type of wave generator is essential if these possibilities are to be realized because the interference of incoming reflected waves would lead to insurmountable programming difficulties with presently available types. The new type of wave generator will automatically compensate for the effects of incoming waves. Estimates are made of the closeness of realization of the programmed levels.

Introduction

Reproduction of an observed storm sea, to model scale, in a wave basin would provide a design tool of unusual value because it would permit model tests to be made under conditions truly representative of the seas to be encountered on the open ocean. Previous studies have indicated that such a reproduction can be made if the storm sea undulations are imposed, to model scale, around the entire perimeter of the wave basin. The older types of wave generators would not be adaptable for these uses because of the programming difficulties presented by reflected waves. The new type of wave generator described here will automatically compensate for the effects of reflected waves while maintaining the programmed surface levels at its location. The studies described in the following paragraphs relate to stability and to the closeness of attainment of the programmed levels.

Wavemaker Arrangement

The general arrangement of the wavemaker is shown schematically in Fig. 1. Alternative spool valve arrangements are shown in Fig. 2. A plunger type of wavemaker is illustrated in Fig. 1 and the spool valve suitable for this case would be as shown in Fig. 2a. A pneumatic type of wavemaker would need a spool valve similar to the one shown in Fig. 2b. The program input is represented by a cam but an electrical signal would probably be used if a true storm sea representation was to be made.

Preliminary Considerations

Even though an analysis may indicate certain capabilities, actual realization may still be an impossibility because of the limitations of the types of mechanism which may have to be used. It is considered to be justified, therefore, to investigate an actual design to see whether such impossibilities may be encountered. Such computations would also serve as a guide for future use in preparing designs for this type of wavemaker. Since the expense of equipping a wave basin with wave generators for production of a replica sea would be large, the design construction and testing of an experimental wave maker would be desirable. This design will relate to an experimental plunger type of wave maker 2 feet in length, driven by an oil operated servo-cylinder to produce waves of a 5 foot wave length and 0.25 foot amplitude. The design will incorporate commercially available parts when they are obtainable.

For effective operation it would be necessary to have the natural period of the plunger short compared to the period of any wave to be produced. A ratio of 1 to 4 would be desirable. The period of a deep water wave of 5 foot wave length is given by a relation of the type.

$$T = \sqrt{\frac{2\pi\lambda}{g}} \qquad (1)$$

In this case the period comes out to be 0.938 seconds. For our present purposes this may be rounded out to 1 second. If 5 feet is the shortest wave length to be produced then a natural period of 1/4 second would be satisfactory. It is unlikely that a plunger type wave generator with a hydraulic drive would have too long a period but a pneumatic type might give trouble. For purposes of illustration we may digress long enough to estimate the period of such a wave generator having a capacity suitable for the conditions of our example. We must first select some dimensions. The volume displacement of the water particles from an initial position of rest, due to the passage of a wave is (Lamb)

$$X = -ae^{ky} \operatorname{Sin} kx \operatorname{Sin} (\sigma t + \epsilon) \qquad (2)$$

where

$$\sigma^2 = gk \qquad k = \frac{2\pi}{\lambda}$$

and λ represents the wave length. The horizontal and vertical coordinates are x and y. The coordinate x is measured in the direction of wave travel. The wave travels with the velocity σ. The symbol t represents time and ϵ is a constant which specifies a phase position. The volume displacement which the wave generator must produce to create the wave amplitude a and length λ is

$$V = \pm a \int_{-\infty}^{0} e^{ky}\, dy = \pm \frac{a\lambda}{2\pi} \qquad (3)$$

This volume V is the displacement required per unit length of wave generator. Both V and a are reckoned as departures from a mean value.

In the present case

$$V = \pm \frac{a\lambda}{2\pi} = \pm \frac{(0.25)(5)}{2\pi} = 0.2 \text{ cubic feet per foot (nearly)} \tag{4}$$

This could be provided by a wave generator 0.5 feet wide, in the direction of wave travel, and immersed to a depth of 0.75 foot. It will be assumed that the top of the wave generator is 1.5 feet above the equilibrium level. For each unit of length of the generator the spring constant, for small oscillations, is provided by an air cushion 1.5 feet deep and the mass is represented by the 0.75 depth of water in the wave generator plus an addition due to the hydrodynamic effect of the water which must be set into motion outside the wave generator. The equivalent mass of the water outside the wave generator may be visualized as a half cylinder of water which moves with the water in the wave generator. The arrangement is illustrated in Fig. 3.

If a weight W departs from a position of rest by the amount y and this departure is resisted by some sort of a restoring force proportional to y the differential equation of motion is

$$\frac{W}{g}\frac{d^2y}{dt^2} + Ky = 0 \tag{5}$$

where g represents the acceleration of gravity and K is the spring constant. The product Ky is the force tending to restore the weight W to the position of rest.

For our case the spring constant K for small oscillations, can be obtained from the isothermal pressure law

$$pv = p_0 v_0 \tag{6}$$

where p and V are the absolute pressure and volume respectively and the subscripts o indicate the conditions at the position of rest. Then

$$p = \frac{p_o V_o}{V} \tag{7}$$

and

$$\frac{dp}{dV} = -\frac{p_o V_o}{V^2} \tag{8}$$

If the area is A the restoring force is Adp and the increment of volume is $dV = -Ady$, we may, for small displacements y take $V = V_o$ so that

$$Adp = \frac{p_o A^2 \, dy}{V_o} \tag{9}$$

The spring constant is then

$$K = \frac{Adp}{dy} = \frac{p_o A^2}{V_o} \tag{10}$$

At an altitude where the atmospheric pressure is about 12.2 lb/in^2 or 1750 lb/ft^2 we would have, for a unit length of wave generator

$$K = \frac{p_o A^2}{V_o} = \frac{(1750)(0.5)^2(1)^2}{(0.5)(1)(1.5)} = 585 \text{ lb/ft} \tag{11}$$

The weight, based upon 62.4 lb/ft^3 as the density of water is

$$W = (62.4)(0.5)(1)(0.75 + \frac{\pi}{8} 0.5)$$
$$= 29.5 \text{ lbs}$$

A solution of the differential equation is

$$y = A \sin \sqrt{\frac{Kg}{W}}\, t + B \cos \sqrt{\frac{Kg}{W}}\, t \tag{12}$$

A complete cycle will occur in the period T when

$$\sqrt{\frac{Kg}{W}}\, T = 2\pi \qquad (13)$$

the period is then

$$T = 2\pi\sqrt{\frac{W}{Kg}} \qquad (14)$$

In our case the period will be

$$T = 2\pi\sqrt{\frac{29.5}{(585)(32.2)}}$$

$$= \frac{\pi\, 2}{25.25} = 0.249 \text{ seconds}$$

This would do for wave lengths longer than 5 feet but would be too slow for wave lengths shorter than this.

An alternative form of wave generator is shown in Fig. 1. This is in the form of a wedge which is moved vertically by means of a hydraulic cylinder. If the wedge is 2 feet high, 1 foot wide at the top and the plunger is 2 feet long, the cross-sectional area at mid height will be 1 sq foot. The previously estimated displacement required to produce the wave of amplitude 0.25 feet and wave length 5 feet is 0.20 cu foot per foot of length of wave generator. The total displacement required for the 2 foot length of plunger is then (2) (0.2) = 0.4 cu feet. This can be obtained with a vertical movement of approximately 0.4 feet in either direction. The natural period of a plunger of this type would be determined by its own mass, plus the equivalent mass of water, and the spring constant provided by the rigidity of the hydraulic drive. These rigidities would provide a very large value for the restoring force K and it seems quite certain that its period would be short compared to that of any wave it would be desired to produce.

A similar problem is present with the float system because good performance of the wave generator could not be obtained if the float responded sluggishly to level changes. Suppose we try a float made of a foam plastic block 18 in. long, 4 in. wide and 2 in. high, to float with the 2 in. dimension vertical. If the density of the plastic is 12 lbs per cu foot the weight of this float will be 1 lb. The equivalent mass of water will be nearly that contained in one half of a cylinder of water 4 in. in diameter and 18 in. long. The volume of the float is 1/12 cu ft and the volume of the equivalent mass is

$$\frac{1}{12} \frac{\pi}{4} = 0.0655 \ ft^3$$

The density of water is 62.4 lb/ft^3 and the weight of the equivalent mass is therefore

$$(62.4)(.0655) = 4.08 \ lbs$$

If the attachments weigh an additional pound the total weight would be

$$1 + 4.08 + 1 = 6.8 \ lbs$$

The restoring force would be produced by floatation in this case. The horizontal cross-section of the float is 0.5 sq ft. Then the K value is

$$K = (62.4)(0.5) = 31.2 \ lb/ft$$

The natural period is then

$$T = 2\pi \sqrt{\frac{W}{Kg}}$$

$$= 6.2832 \sqrt{\frac{6.08}{(31.2)(32.2)}} = 0.489 \text{ seconds.}$$

This is too slow to follow satisfactorily a wave of even 1 sec period since about a 4 to 1 ratio is needed for close following. A cylinder with its axis vertical does somewhat better because the equivalent mass of water is 1/2 of that contained in a hemisphere having the same diameter as the float but the improvement is not sufficient to make it a satisfactory device. We can overcome these difficulties by increasing the restoring force. A cantilever spring mounting as shown in Fig. 4 could be made to accomplish this. To complete the design we chose to operate the float with a 1-1/2 in. diameter double acting hydraulic cylinder with 6 in. stroke, connected to the float by a lever having a 5 to 1 ratio. At 500 lbs per sq in. oil pressure this will exert 176 lbs of thrust at the float. This is ample to completely submerge the float.

For a displacement of the plunger of 0.4 ft and a frequency of 1.0 cycle per second required to produce the wave of wave length 5 ft and amplitude 0.25 ft the displacement would be

$$\gamma = 0.40 \operatorname{Sin} \frac{2\pi}{T} t \qquad (15)$$

The velocity would be

$$\frac{d\gamma}{dt} = 0.40 \left(\frac{2\pi}{T}\right) \cos \frac{2\pi}{T} t \qquad (16)$$

The maximum rate will occur when $\cos \frac{2\pi}{T} t = 1.$

Then with T = 1 second

$$\left(\frac{d\delta}{dt}\right)_{max} = 0.40 \left(\frac{2\pi}{T}\right) = \frac{(0.40)(6.2832)}{1} = 2.51 \frac{ft}{sec} \quad (17)$$

After taking the lever ratio into account the cylinder rate would be $\frac{30.12}{5}$ = 6.02 in./sec. With a 1-1/2 in. diameter drive cylinder of area 1.78 sq in., the maximum oil supply rate will be

$$(6.02)(1.78) = 10.63 \text{ cu in./sec}$$

This is equivalent to

$$\frac{(10.63)(60)}{231} = 2.76 \text{ gallons per minute}$$

Solenoid operated hydraulic servo-valves are commercially available. One such valve[a] which would be suitable for our purposes has the following characteristics:

Capacity (1000 lb/in²) 5.0 gpm

Operating pressure 200 to 1000 lb/in²

Differential current 40 milliamperes

Coil resistance 1200 ohms

Coil inductance 2 Henries

This valve will follow 20 cycles per second with less than 10 degrees phase lag.

Two pair of resistance type strain gage elements are shown mounted on the float restoring spring of Fig. 4. These can be arranged in a temperature compensated bridge which will produce an electrical signal indicative

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[a] Pegasus Model 120-F Electro Hydraulic Servo Valve. Pegasus Laboratories Inc., 3690 Eleven Mile Road, Berkeley, Michigan. The price quotation for one of these valves is $462.00.

of the float position. A similar signal would be obtained from an electrically recorded program. These two signals would be compared by a vacuum tube circuit comprising a power supply and an amplifier. The amplifier would be connected to the solenoid of the electro-hydraulic servo-valve and would cause it to act if the wave height, as indicated by the float, disagreed with the program wave height. If the maximum flow rate for the valve is 3.5 gallons per minute at 500 pounds per square inch pressure it would be within the capacity of the wave generator and its controls to make the servo-piston travel at its maximum rate if the actual wave height departed from the program wave height by 0.1 ft. An analyses of the performance of such a system will be carried through as an example.

Let

α represent the ratio of the spool valve displacement to the port width-positive if it produces a positive motion of the plunger.

β The ratio of the sleeve valve displacement to the port width - positive if it produces a negative motion of the plunger.

γ The displacement of the plunger from the neutral position - positive down.

ζ Departure from normal level in the wave basin - positive up.

m_1, m_2, m_3 etc. positive constants.

t time

The equations of motion are:

$$\frac{d\delta}{dt} = n_1 (\alpha - \beta) - n_2 \delta$$

$$\zeta = n_3 \frac{d\delta}{dt} \qquad (18)$$

$$\beta = n_4 \zeta$$

In these expressions the constant n_1 relates to the relation between the rate of plunger movement and the departure from the closed position of the valve. In our case with $(\alpha - \beta) = 1$, which would indicate a wide open valve, there would be a flow of oil to the servo-cylinder at the rate of 3.5 gallons per minute. This will give a float travel of 3.18 ft/sec which, it will be noted, is not greatly in excess of the 2.51 ft/sec previously computed as being required for the production of a wave of amplitude 0.25 ft and wave length 5 ft. Then with $(\alpha - \beta) = 1$, for a wide open valve and $d\delta/dt = 3.18$, $n_1 = 3.18/1 = 3.18$ ft/sec. The constant n_2 relates to a leakage which is provided so that the plunger may be restored to its neutral position. If this were not provided a slight maladjustment would cause the machine to run until the plunger were either submerged or out of the water, thereby rendering the wave generator inoperative. We will return to a consideration of the value of this constant later. The value of n_3 can be obtained from previous computations which indicate that a wave of amplitude 0.25 ft can be generated by a plunger motion of 2.51 per second. Then

$$n_3 = \frac{0.25}{2.51} = 0.10 \text{ seconds.}$$

The constant m_4 can be evaluated from a choice such that a rise of 0.1 ft in the water surface should, in the absence of other changes, open the valve ports wide then

$$1 = m_4\, 0.1$$

and

$$m_4 = 10 \quad 1/ft$$

Then we have, as a set of trial values

$m_1 = 3.18$ ft/sec

$m_2 =$ (to be determined later) 1/sec

$m_3 = 0.10$ seconds

$m_4 = 10.0$ 1/ft

Elimination of the variable γ from the equations 18 yields the ordinary differential equation

$$\frac{d\zeta}{dt} + a\zeta = b\frac{d\alpha}{dt} \qquad (19)$$

where

$$a = \left(\frac{m_3}{1 + m_1 m_3 m_4}\right) \qquad b = \left(\frac{m_2 m_3}{1 + m_1 m_2 m_4}\right) \qquad (20)$$

If the program demands that

$$\alpha = \alpha_o \operatorname{Sin}\frac{2\pi}{T}t \qquad (21)$$

then

$$\frac{d\alpha}{dt} = \frac{\alpha_o 2\pi}{T}\cos\frac{2\pi}{T}t \qquad (22)$$

and a solution of equation 19 is

$$\zeta = \frac{b\alpha_o 2\pi}{T}\left(\frac{a\cos\frac{2\pi}{T}t + \frac{2\pi}{T}\sin\frac{2\pi}{T}t}{\left(a^2 + \frac{4\pi^2}{T^2}\right)}\right) + c_1 e^{-at} \qquad (23)$$

We may now return to a consideration of the constant m_2 . We note that it occurs in the numerator of the quantity a and that this is related to the rate at which the plunger will return to its neutral position. Suppose, for example, we adjust the leak so that the plunger will return through 0.1 of an initial displacement in one period. Then we could write

$$0.9 = e^{-aT}$$

In our case, with $T = 1.0$ and, from tables of the exponential function, $aT = 0.1$ approximately, we can conclude that $a = 0.1/1.0 = 0.1$. Then

$$a = \left(\frac{m_2}{1 + m_1 m_3 m_4}\right) = 0.1$$

$$m_2 = 0.1(1 + (3.18)(0.10)(10) = 0.418$$

We may now evaluate the performance of the wave generator.

$$a^2 = 0.01$$

$$\frac{4\pi^2}{T^2} = \frac{(4)(9.8696)}{1.00} = 39.5$$

$$\left(a^2 + \frac{4\pi^2}{T^2}\right) = 39.51$$

$$b = \left(\frac{m_1 m_3}{1 + m_1 m_3 m_4}\right) = \frac{(-3.18)\ (0.10)}{1.318} = 0.242$$

$$\frac{a\,\frac{2\pi}{T}}{\left(a^2 + \frac{4\pi^2}{T^2}\right)} = \frac{(0.1)(6.2832)}{39.51} = 0.0159$$

$$\frac{\left(\frac{2\pi}{T}\right)^2}{\left(a^2 + \frac{4\pi^2}{T^2}\right)} = \frac{39.5}{39.51} = 1.00$$

We notice several things.

The program demands an amplitude

$$\alpha = \alpha_0 \sin \frac{2\pi}{T}t \tag{24}$$

After the transient, as represented by the exponential term has died away, the machine yields a wave having both a sine and a cosine term. We may consider the cosine term as a distortion since we seek a sine wave. If we measure the distortion by the ratio of the amplitudes of the cosine and sine terms we obtain a distortion of approximately

$$\frac{aT}{2\pi} \qquad \text{if} \quad a \ll \frac{2\pi}{T} \tag{25}$$

In the present case the distortion is only about 0.0159/1.00. This would be an acceptable ratio. The distortion is due to the leak since the expression for a has the quantity m_2 in the numerator. The response we get is

$$\zeta = b\alpha(0.0159 \cos \frac{2\pi}{T}t + 1.00 \sin \frac{2\pi}{T}t) \tag{26}$$

If b were nearly 1.00 instead of 0.242, the performance would be satisfactory. It would not be satisfactory with the constants chosen. We must change the adjustments to improve the operation of the wavemaker. We need, approximately,

$$b = \left(\frac{m_1 m_3}{1 + m_1 m_3 m_4}\right) = 1.0$$

We cannot change m_3 but we can change m_1 and m_4. We solve this equation for the product $m_1 m_3$ to obtain

$$m_1m_3 = 1 + m_1m_3m_4$$

$$m_1m_3(1 - m_4) = 1$$

$$m_1m_3 = \left(\frac{1}{1 - m_4}\right)$$

It is apparent that m_4 must be less than 1. If we make $m_4 = 0.5$, then $m_1 = 20$. Then $m_1m_3 = (20)(0.1) = 2$ $m_1m_3m_4 = 1$.

$$a = 0.1 \qquad b = \frac{2}{1 + 1} = 1.00$$

This would be a satisfactory performance. The high amplifier gain implied by $m_1 = 20$ would not cause trouble unless the capacity of the servo-valve was exceeded. This will not occur in the present case. The distortion is less than 2 percent.

It remains to investigate the performance of the machine as a wave absorber. Suppose an incoming wave makes

$$\beta = m_4\left(\zeta + 2\zeta_0 \sin \frac{2\pi}{T}t\right) \quad \text{while } \alpha = 0 \tag{27}$$

The factor 2 takes care of the doubling of the amplitude by reflection. The differential equation now takes the form

$$\frac{d\zeta}{dt} + a\zeta = b_1 2\,\zeta_0 \frac{2\pi}{T} \cos \frac{2\pi}{T}t \tag{28}$$

where

$$b_1 = -\left(\frac{m_1m_3m_4}{1 + m_1m_3m_4}\right)$$

A solution is

$$\zeta = -b_1 2 \zeta_0 \frac{2\pi}{T} \frac{\left(a \cos \frac{2\pi}{T} t + \frac{2\pi}{T} \sin \frac{2\pi}{T} t \right)}{\left(a^2 + \frac{4\pi^2}{T^2} \right)} + c_2 e^{-at} \qquad (29)$$

with the new constants

$m_1 = 20$

$m_3 = 0.10$

$m_4 = 0.50$

$m_1 m_3 = 20$ $\qquad$ $m_1 m_3 m_4 = 1.0$ $\qquad$ $b_1 = -0.5$ then $2b_1 = 1.0$

We then have an acceptable wave absorption, but the absorption is not complete. The amplitude of the outgoing wave is about $aT/2\pi$ times that of the incoming wave. In this case the ratio of amplitudes $aT/2\pi = 0.1/6.2832 = 0.0159$.

<u>Arrangement of Wave Generators</u>

The arrangement of wave generators around a wave basin for producing a replica of an observed storm sea must be such that the program wave height at each generator can be continually compared with the wave height existing at its location. If there is a difference the wave generator must move in a direction and at a speed which will bring the wave height to that called for by the program. The total number of wave generators must be enough to reproduce the storm sea in sufficient detail for testing purposes.

As an example of the considerations which would be involved in the planning of a wave generator installation of this kind the requirements for an installation on the Colorado State University wave basin will be outlined. This basin is circular and is 80 ft in diameter. The factors involved when a wave moves at an angle with the wall may be presented more clearly with a basin of this shape than with a rectangular basin. To fix ideas we may suppose that the direction north to south represents the downwind direction with reference to the storm sea to be reproduced.

There is evidence that a storm sea is composed of elementary wave profiles which are, to a degree, random in amplitude, phase, wave length and direction of propagation. We may consider one of these wave elements which runs toward the south. The generators on the north and south portions of the rim will have only the task of generating and absorbing the wave. Those on the east and west sides will have nothing to do because the wave runs transverse to them but those on the northwest and northeast portions of the rim must contribute to the generation of the wave. Those on the southwest and southeast portions must similarly contribute to its absorption. For these generators the wave profile will appear along the wall and there must be enough generators in the wave length to define the wave. We may assume that models of approximately 5 ft length are to be used in this basin and that it will be important to generate waves of a wave length equal to the model length and that some shorter components should be included. Along the northwest portion of the rim a 5 ft wave length, of a wave being propagated toward the south, would cover about 7 ft. A one foot length for an individual wave generator would place 7 generators in this length. This should prove adequate since the wave profile should be well reproduced by a control at 7 evenly spaced points in the profile. All resolution would be lost, however, for waves less than 2 ft length along the wall or 1.4 ft wave length as measured in the direction of propagation toward the south. We may conclude that this resolution will be satisfactory but we will realize at the same time that some of the sharp-crestedness present in the actual storm sea will be absent from the model reproduction because of the limitations imposed by the individual wave generator lengths. We could only improve the resolution by using shorter wave generators and more of them. We may decide to use 60 wave generators in each quadrant or 240 for the entire perimeter.

An effective arrangement could be built around an electrically recorded program. The programmer, which reads this record, could be placed near the rim of the basin and the program wave height could be transmitted to each individual wave generator by a pair of wires. At each generator there would be a power supply and a vacuum tube amplifier. Each generator would have a float just on the wave basin side of it to sense the wave height and convert it to an electrical signal, and a solenoid operated hydraulic servo valve. The program and wave height signals could be compared by a Wheatstone bridge arrangement whose output would be fed to the grids of the amplifier. The amplifier output would be connected to the solenoid of the hydraulic servo valve which would control the oil supply to the hydraulic servo cylinder attached to the wave generator plunger. A small leak in a bypass connecting the two ends of the hydraulic drive cylinder would permit the wave generator plunger to creep back toward its neutral position to prevent the wave generator from exhausting itself as a result of small errors in adjustment to the wave basin level. A cable tray would carry a power line, to supply the vacuum-tube power supplies, and the pairs running from the programmer to the individual wave generators. This power line should have a capacity of about 10 kilowatts. An oil pressure lever and an oil return line would encircle the wave basin to supply oil to the drive cylinders under the control of the hydraulic servo valves and to convey the used oil back to the pump. This oil pressure line would need to be fitted with air tank, at intervals to prevent sluggishness of oil flow due to the inertia of long supply lines. We will assume one of these to be located in the middle of each quadrant. Oil under pressure could be supplied by a pump adjacent to the programmer. This pump would probably consume about 10 kilowatts also.

Some inquiries were sent out to firms who manufacture computing equipment to learn whether some of their devices would be adaptable for use as a programmer. The desired characteristics were outlined as follows:

1. To have up to 240 channels
2. To run for 2 minutes
3. To repeat at the end of the program, if possible
4. To permit an easy substitution of one program for another
5. To be readily reset to the starting position
6. To permit the program to be made up from data plotted in the form of curves
7. To have the program records in a form which is easily stored and not easily damaged.
8. To have the records remain essentially unchanged over a period of several years

The replies received indicate that there is no device presently available which is exactly suited to these needs. This is not surprising since they were made for other purposes. One gets the impression that they either run too fast or do not have enough channels or both. The capacity of these devices is expressed in "bits" of information. To obtain a rough idea of the capacity which would be required for our purposes we may suppose that the program will run 2 minutes and that the 5 ft wave length, mentioned previously, would be adequately defined by 10 bits of information per second. The period of this wave is about one second. This decision is somewhat arbitrary but we can get some idea of the limitations of such a choice by noting that the limit of resolution is reached when a wave is defined by two "bits". The period of such a wave would be 0.2 second. The wave length would be given by

$$\lambda = \frac{T^2 g}{2\pi} = \frac{(.04)(32.2)}{6.2832} = 0.20 \text{ feet}$$

Although the resolution for a wave of 0.2 second period would be poor, we can accept this quality of resolution as adequate for the wave lengths of primary interest. The total of these "bits" for 240 generators operating for 120 seconds (2 minutes) at 10 bits per second is

$$(240)(120)(10) = 288{,}000 \text{ bits}$$

At least one of the devices described in manufacturers literature had a capacity of 20,000,000 bits. It would appear therefore that presently available devices are potentially capable of storing the amount of data which we would need for our program.

While no device was found which was immediately applicable for our purposes it would be surprising if presently available parts could not be assembled into a suitable programming device. Consider for example, the possibilities of a magnetic tape looped over a series of 20 pulleys equipped with reading heads. Each loop would be long enough to run the full 2 minutes. A magnetic tape 1 inch wide will accommodate up to 14 channels and can be run at as low speeds as 1-7/8 inches per second. A 2 minute program would require

$$(2)(60)(1.875) = 225 \text{ inches or } 18.75 \text{ feet of tape}$$

We could use 20 reading heads with 12 channels each. If we allow 20 ft of tape between reading heads to provide for some adjustment we would need

$$(20)(20) = 400 \text{ feet of tape to contain the entire program}$$

At this tape speed a response from 0 to 312 cycles per second can be obtained, so it is obvious that there is ample resolution for our purposes. A standard 10-1/2 inch reel will hold 2400 ft of this tape and since we would need only about 400 feet for our program, we could store 6 programs on a single reel of this size. It therefore seems certain that available devices and parts can be assembled into a programming device suitable for our purposes. A 14 track recorder-reproducer consumes about 1600 to 2100 watts. An evaluation of the power requirements for a programmer with 240 reading heads would probably require the making of a detailed design.

Summary

The results of these studies can be summarized in the following way.

1. It is possible to reproduce an observed storm sea to model scale in a model basin.

2. The replica sea will appear in the model basin if the observed wave heights are reproduced, to model scale, around the entire perimeter of the model basin.

3. Because of the level changes produced by incoming waves a type of wave generator is needed which will sense the wave height, compare it with a programmed height, and act to bring the wave height at its location, to the programmed height.

4. The length of individual wave generators will set a lower limit to the wave length which may be reproduced. In this sense all resolution is lost when the wave length is less than two wave generator lengths.

5. It has been shown how a suitable wave generator may be built and controlled and an application to an 80 ft diameter wave basin has been outlined.

6. Devices now available could be adapted to the construction of a programmer suitable for the production of a "replica sea".

7. It is probable that pneumatic type wave generators will have too low natural frequencies for wave generators of the type.

8. It may be necessary to provide spring restoring forces for the floats to give them a sufficiently high natural frequency for these purposes.

9. The large amount of information necessary for the production of a replica sea would probably require an electrically recorded program.

10. Suitable solenoid operated hydraulic servo-valves are available commercially.

11. Where an electrically recorded program is used the electric circuit may need close adjustment for satisfactory operation.

12. The mechanism described could be used to produce waves of many patterns and these would be reproducible.

13. The analysis indicates that effective wave absorbing characteristics are possible.

14. A reproducible short-crested irregular sea could be produced by three wave generators of this type.

15. Wind forces provided on the model basin would contribute to the faithful representation of storm sea conditions in a model basin.

Selected References

1. St. Denis, Manley, and Willard Pierson. "Analysis of Storm Seas into Random Components". Ships and Waves, page 176.

2. Marks, Wilbur. "On the Status of Complex Wave Generation in Model Tanks". Transactions of the Eleventh General Meeting of the American Towing Tank Conference. July, 1956. Report 1069, page 218, Report 1099, page 215.

3. Beisel, Francis. "Wave Machines". Ships and Waves. Published by the Council on Wave Research and the Society of Naval Architects and Marine Engineers, 1950, page 218.
(Extract from Beisel --"If a given state of the sea has to be reproduced in a given body of water it is theoretically necessary to surround the latter completely with wave generators or absorbers capable of reproducing the desirable boundary conditions"--page 289).

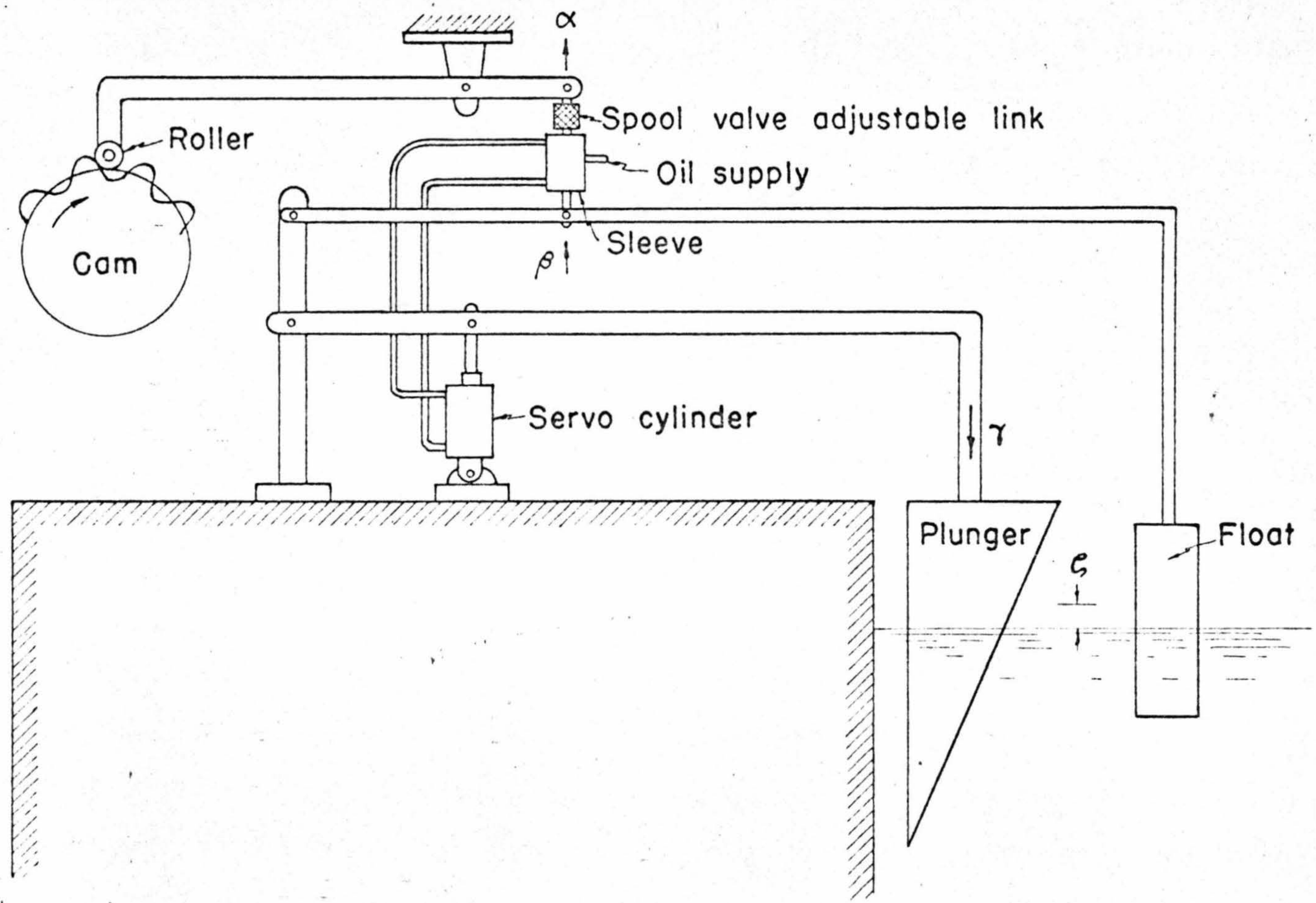

Fig. 1 Wave generator arrangement

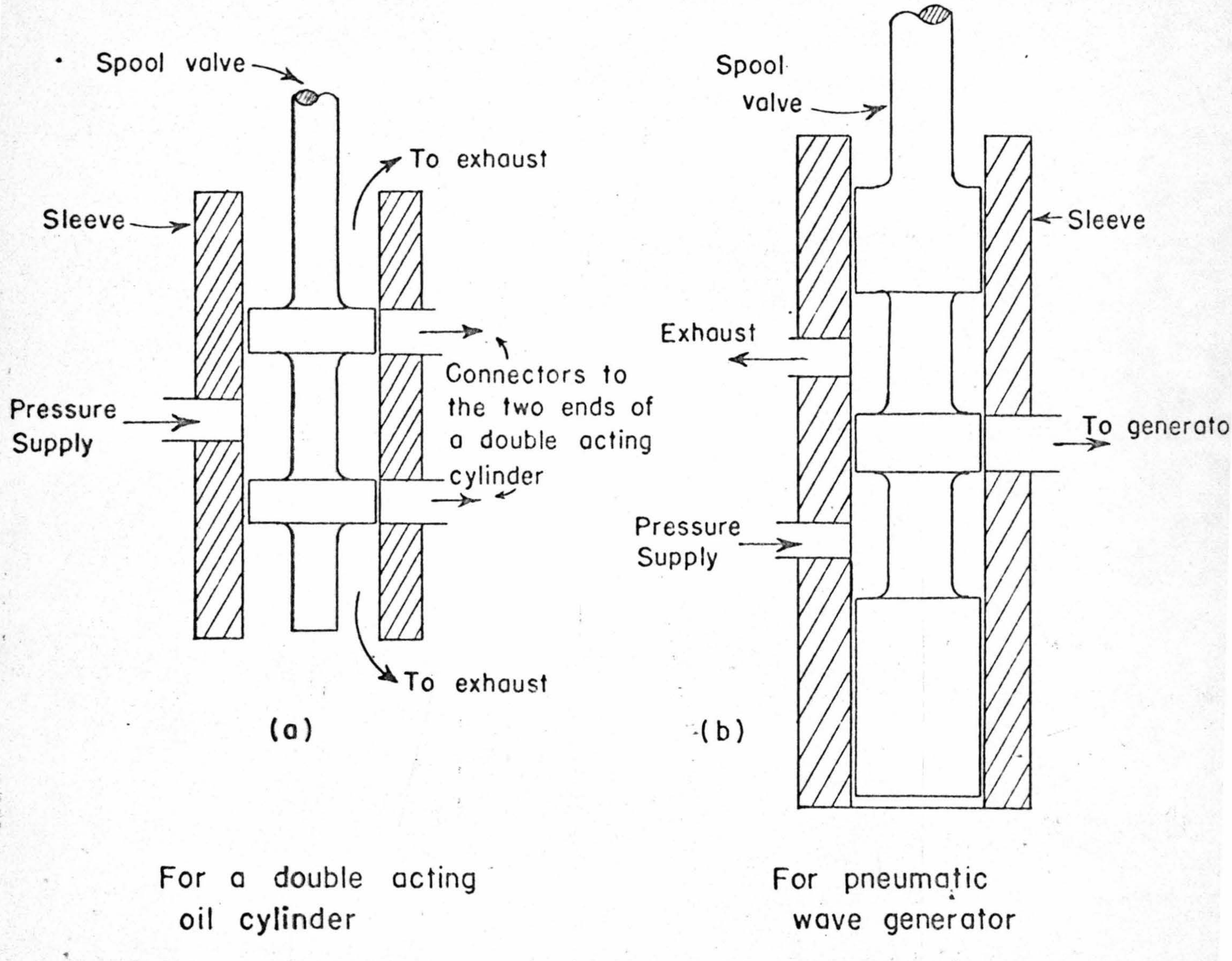

Fig. 2 Spool valve arrangement

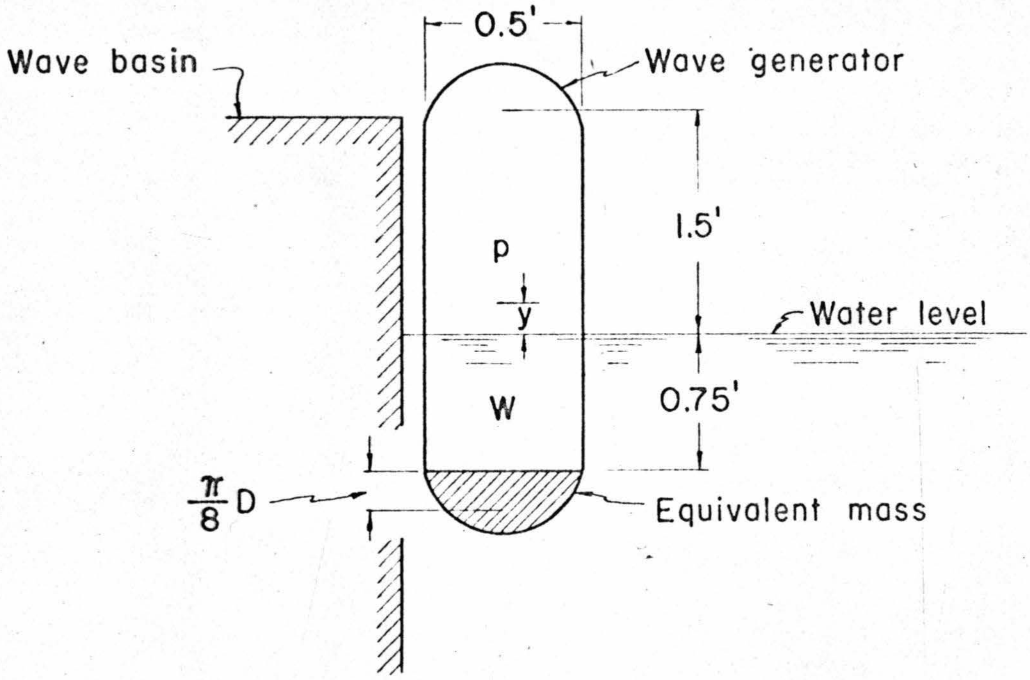

Fig. 3 Pneumatic wave generator

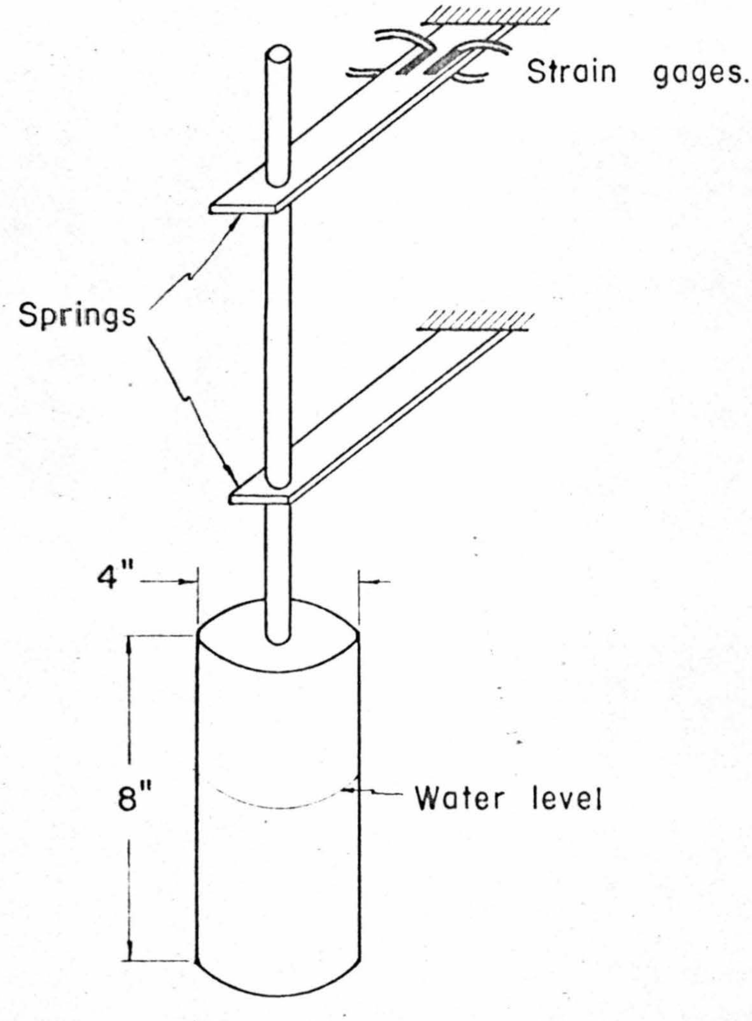

Fig. 4 Float with increased restoring force