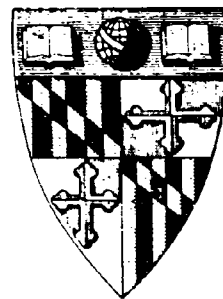


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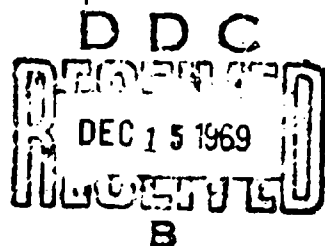
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THE CHESAPEAKE BAY INSTITUTE
WAVE FOLLOWER

Mart Peep
and Ronald J. Flower

Technical Report 58



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TECHNICAL REPORT 56

THE CHESAPEAKE BAY INSTITUTE WAVE FOLLOWER

by

Mart Peep and Ronald J. Flower

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D.W. Pritchard
Director

ABSTRACT

In studies of wave generation an exploration of the wind field close to the water surface is critical. Such an exploration can be made with a hot-wire or film anemometer mounted on a device driven by a servomechanism which will maintain the anemometer at a fixed distance from the fluctuating water surface. This report describes the CBI Wave Follower which has been designed to hold anemometers at fixed distances from 60 cm to 1 cm from the water surface. It may be used with waves up to 30 cm in height. It allows adjustment for tidal changes in mean water elevation up to 60 cm and for slow vertical scanning.

ACKNOWLEDGEMENTS

To bring the wave follower into existence has required knowledge and know-how of many different kinds. Over the two years that it has been building the authors have sought help when and where they could find it. For this reason, it has become impossible to properly acknowledge and, in some cases, even identify individual contributions. The authors are no less grateful to those who have helped and whose names do not appear here than they are to those specifically mentioned. General guidance during the development of the wave follower and assistance in preparing this report were given by Dr. B. Kinsman. The machining of parts which were often complex and subject to irritating modifications was cheerfully and skillfully done by Messrs. S. Krausman, M. Fischer, B. Baker, and R. Faulkner. Mr. E. Schiemer designed the mounting pedestal. We have drawn heavily on the skill and knowledge about hot-wire anemometry of Messrs. F. Merceret, Jr. and M. Banner. The typing of this report was done by Mrs. Arlene Sullivan and by Mrs. Kathy Shinn while the graphic work was done by Mr. W. Wilson, Mrs. Dean Loose, and Mr. R. Linfield.

To all these and to the many others not named who gave unstintingly of their help when it was needed, we are deeply grateful. Without their assistance there would be no wave follower.

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I. INTRODUCTION

Previous work in the field of air-sea interactions has often been limited by the problem of measuring the velocity field of the air in the layer immediately above the water surface since the surface is continually in motion. Most measurements have been taken with anemometers at fixed positions above the mean water surface. These measurements yield little information about the velocity field inside the wave troughs. In addition, most estimates of the curvature of the wind profile have been deduced from data provided by vertical arrays of fixed anemometers. These measurements seldom have enough spatial resolution to define the shape of the wind profile accurately very near the water surface. Measurements from an instrument which holds a sensor very close to the water surface while following this surface may be expected to yield new insight into the problem of momentum and energy transfers from air to sea. To be practical such an instrument must be suited to field operations, and it should disturb the velocity field of the air as little as possible. An electrical servomechanism used as a laboratory wave follower for small-amplitude waves with frequencies up to 1 Hz is described in Shemdin and Hsu (1966). It did not have a frequency response high enough for air-sea interaction studies contemplated at the Chesapeake Bay Institute. See Kinsman (1968).

II. SPECIFICATIONS

The specifications for the CBI Wave Follower are set implicitly by the concepts used in the current wave-generation theories (Phillips, 1957; Miles, 1957) and explicitly by the conditions to be expected in the field and the state of the engineering art. The *initial* requirements selected by the scientists were:

(a) *Field specifications:* (1) The wave follower is to be required to track a random wind sea with maximum wave heights no greater than 30 cm. (2) The water surface is to have no accelerations greater than 1 g.

(b) *Instrument specifications:* (1) The wave follower is to hold an anemometer at selected fixed distances above the water surface from 2 m to 1 cm. (2) The maximum departure from the fixed distance shall be no more than ± 2 mm at a height of 1 cm. (3) The instrument shall be adjustable for mean water level changes of ± 100 cm without instrument case mounting changes. (4) The wave sensor shall record waves up to 20 Hz in frequency.

(c) *Auxiliary mode specification:* (1) The wave follower shall be capable of moving the probe slowly and continuously in the vertical without following the wave motion. (2) The wave follower shall be operable as a fixed mount.

(d) *Calibration specification:* The wave follower shall be equipped with such auxiliary circuits as will permit field testing of its behavior. Specifications (a2) and (b2) imply a high-frequency response on the order of 10 Hz¹ and specifications (a1) and (a2), coupled with

¹ For the wave follower one must use the frequency response concept

observed wave spectra, imply a maximum vertical velocity on the order of 150 cm/sec.

Instrument specifications by scientists must usually be supplemented by engineering specifications to insure that the operation of the instrument will be convenient and safe for both the instrument and the scientist. They are:

(a) *Acceleration limit:* The acceleration limit is provided to reduce transients in the hydraulic system. Such transients may occur naturally, as, for example, when water beads on the wave probe or they may occur when the mode of operation is changed, for example, when changing from following to stationary.

(b) *Velocity limit:* The velocity limit is a safety feature. If the wave follower is switched on it is unlikely that the zero of the wave probe and the water will coincide. If nothing were done the wave follower would see a jump discontinuity and respond with a deleterious attempt at an infinite velocity. The velocity limit permits the wave follower to correct the initial misalignment at safe speeds. This mode of response we call the "search-and-follow" mode.

(c) *Automatic range limit:* End stops are needed since the hydraulic piston can not be allowed to slam into them at high speed. This device slows the actuator just as it approaches the stops.

III. EVOLUTION OF THE CBI WAVE FOLLOWER

The demand for an instrument to follow the sea surface having specifications (a) through (d) (page 2) was made by Dr. Kinsman of CBI in

in an unusual way. See Appendix A.

November 1966. In response, the authors decided it was conceivable that a servo-system could be designed to meet the requirements.

The first system considered was similar to that of Shemdin and Hsu (1966), viz., an electric motor in a servo loop. A DC motor was preferred over an AC motor of comparable size since the DC motor has greater torque over a wider range of speeds and a smaller time constant. Since the desired motion for the wave follower is linear, the rotary motion of the motor must be converted in some way. A pulley system or a rack-and-gear system were possibilities. Such a conversion is not necessarily a disadvantage since it may be used to amplify either speed or torque mechanically.

The idea is attractive but the authors found after some analysis and experiment that the torque to inertia ratio of electric motors was too low. The difficulty is that while they may be made to meet either the frequency response specification or the velocity specification, they can not be made to meet both simultaneously.

The next system investigated by the authors was a hydraulic servomechanism. Pneumatic systems were also considered but were rejected since the power medium--air usually--is compressible, resulting in springiness in the actuator. This would decrease the cut-off of the frequency response as well as introducing distortions in the amplitude ratios and phase shifts.

Hydraulic systems have many advantages for our purposes. One is the possibility of achieving a very high force to inertia ratio--a result of the very high hydraulic pressures that are currently available. (In the case of rotary motion, torque replaces force.) Force

is directly proportional to the piston area and pistons with areas from 3 cm^2 (0.5 in^2) to 10^3 cm^2 (a few hundred square inches) may commonly be had. Systems with pressures up to $2 \times 10^8 \text{ dynes/cm}^2$ (3000 psi) and more are common.

Another advantage is high frequency response. A typical servo valve, for example, the Moog type 73-103, which we finally used, has the 3-db down-point of its frequency response at about 100 Hz at no load and $1.3 \times 10^8 \text{ dynes/cm}^2$ (2000 psi) supply pressure.

Control power to a servo valve can also be very low. For the Moog 73-103 a current of 15 ma will pass a flow of $6.3 \times 10^{-1} \text{ l/sec}$ (10 gpm) at the rated pressure.

Hydraulic control systems can achieve a very high force to system weight ratio, a quantity which is important for an instrument sufficiently portable to be used easily in the field. If the hydraulic power supply is placed in a remote location connected with the actuator only by hydraulic cables, only the cylinder need be present at the actuator location. For better response it is advisable to place the servo valve nearby as well.

Not the least important advantage for our purpose is that the hydraulic system provides linear motion directly. Motors have rotary motion, and require some sort of system to translate this into linear motion. Such rotary systems provide simple adjustment of the mechanical gain. However, such systems are seldom satisfactory to oceanographers. The classical oceanographic definition of a satisfactory electronic system is "one with less than one vacuum tube." To the oceanographer complexity is suspect and cumbersomeness is anathema.

Further, in his opinion, the problem of sealing rotary devices against the sea has not been solved--salesmen to the contrary notwithstanding. Hydraulic cylinders, on the other hand, provide linear motion directly, and gain can be adjusted by the choice of a cylinder diameter.

There are a number of additional considerations peculiar to piston devices. If, in an effort to reduce the volume flow of the hydraulic fluid, a cylinder of small diameter is chosen, then the cylinder must also be reasonably short. If it is too long, then the cylinder, and particularly the piston rod, will bend. The CBI Wave Follower uses a 90 cm (3 ft) cylinder with an I.D. of 2.54 cm (1 in) and a piston rod 1.6 cm (5/8 in) in diameter. The authors feel that from a design point of view this cylinder is undesirably long but no difficulties have yet arisen from bending.

Hydraulic systems also have disadvantages. One is the need for a power supply that is usually large, heavy, and noisy. A reservoir, hydraulic pump with electric motor, and a filter characteristically constitute the power supply. The unit presently being used weighs about 100 kg and occupies about 0.5 m³. These undesirable features could be eliminated to a considerable extent but for our purposes it is simpler to remove the offense to a tolerable distance. If the supply is removed to a distance of some hundreds of meters from the actuator and connected to it by hydraulic cables the bulk, weight, and noise can be ignored.

The servo valve itself presents difficulties: it is inherently nonlinear, exhibits hysteresis, and is very sensitive to any contamination of the hydraulic fluid. The first two can be overcome satis-

factorily by proper design of the electronic feedback circuit, and filtration of the hydraulic fluid will reduce the third to an acceptable level. The impression gleaned by the authors from the literature is that hydraulic fluid contamination is particularly hard to prevent and that extreme precautions must be taken. In almost a year of laboratory operation, during which only reasonable filtration has been practised, no difficulty has arisen from wear in the valve.

There are other inherent difficulties with hydraulic systems which for us are minor. One is that components must be connected by hydraulic lines which are either rigid tubes or clumsy semi-flexible hoses. Another arises from the use of a fluid as a power transmitter. This means that power losses in the forms of heat, turbulence, acoustic noise, hydraulic shock, and leaks in the system, to name only a few, can all occur. Power losses from these sources can be minimized by a scrupulous attention to the choice of components which is no more onerous than the necessary attention to cleanliness.

An enumeration of the difficulties to be anticipated if a hydraulic system were attempted might well lead to the abandonment of the idea. However, one must not lose sight of the overwhelming advantages promised by the very favorable force-to-inertia and force-to-weight ratios. To secure those advantages it was decided to attempt to overcome the difficulties and to design a wave follower based on a hydraulic system. The next step had to be a decision about the actual configurations to be tried.

We found the following references to hydraulic-system characteristics and design useful: Lewis and Stern (1962), Merritt (1967),

and Blackburn, Reethof, and Shearer (1960). These are texts on hydraulic-system theory and design which cover the subject from the elements through examples of hardware to design equations for feedback-control systems. Lewis and Stern is a good introductory text; the others are somewhat more advanced.

IV. THE SEARCH FOR A CONFIGURATION

The design for a hydraulic wave follower can be conceived in two ways. It may be either a direct-acting system or a mechanically amplified system. In the first, the cylinder rod attaches directly to the probe and simplicity and compactness are secured while springiness, backlash, and inertia are reduced. In the second, mechanical amplification, e.g., racks, gears, levers, or pulleys, intervene between the cylinder and the probe². A shorter cylinder can be used to produce the same travel distance with a desirable reduction in the volume-rate of fluid flow for the same probe velocity.

In order to gain experience with hydraulic systems without, at first, complicating our study with the problems of mechanical amplification, we began our experiments with a direct-acting system. Our calculations, in which we later found an arithmetic error, had indicated that the desired maximum velocity of 150 cm/sec could be obtained with a fluid volume flow-rate of 9×10^{-2} l/sec (1.5 gpm) with a cylinder bore of 2.54 cm. Since this flow rate appeared, then, to be satisfactorily low, no mechanical amplification seemed

² Note that such intervening mechanisms are necessary with rotary driving motion; with linear motion, they are optional.

necessary. The problem of achieving the desired stroke length was reserved for later consideration and the first system tried consisted of the following components:

- (a) *Cylinder*: The cylinder was a type-3L made by the Parker-Hannifin Corporation with the dimensions: bore 2.54 cm (1 in), stroke 30 cm (12 in), and oversize piston rod 1.6 cm (5/8 in).
- (b) *Servo valve*: The servo valve was the Mark 3.3 from Delta Hydraulics, Inc. having an advertised maximum flow rating of 0.2 l/sec (3 gpm) at a pressure of 7×10^7 dynes/cm² (1000 psi) using MIL-5606 hydraulic fluid.
- (c) *Hydraulic power supply*: The power supply was a Continental Hydraulics POLYPAC R-10 power unit with a 3/4 hp electric motor driving a variable-volume vane pump.³ It was set at 1.7×10^7 dynes/cm² (250 psi) providing a flow of about 0.25 l/sec (4 gpm). A 10-micron filter was placed in the fluid return line. The fluid reservoir held 3.8×10^4 cm³ (10 gallons). For this initial experiment the signal and feedback from the nulling wave probe were replaced by a dummy signal and a voltage proportional to position from a potentiometer.

Our first difficulty came from the servo valve. The unit with which we worked had a very low, erratic gain (rate of fluid flow per unit electrical current to the control coil), a shifting null, and a

³ A variable-volume pump was preferred to a fixed-volume pump since heat build-up would be less with the former. A constant-volume pump must be set for the maximum expected fluid flow. Unused fluid must be bypassed which generates heat. Since a variable-volume pump delivers only as much fluid flow as is required, and since in our system the average fluid flow is much less than the peak flow, unnecessary heat generation is avoided.

poor frequency response. Although the manufacturer was most cooperative, repeatedly reworking the valve at our request, the valve as it then existed never came up to our expectations. However, the experience gained while working with it confirmed our feeling that the system was correct in concept and would work if the right valve could be found.

The search for a satisfactory servo valve was briefly interrupted at this point when the arithmetical error came to light. It would have been of no use to build and laboratory test a device which showed no promise of meeting the minimum specifications for a field instrument. The correct arithmetic suggested that mechanical amplification would be necessary if there were to be any hope of achieving the required travel and velocity without major redesign. The arrangement shown in Fig. 1 using a right-angle lever was incorporated.

The amplified system was first tried with the original Delta servo valve in the hope that it would be adequate. No improvement in the response resulted and it was necessary to replace the valve. A Moog Industrial Flow Control Servo Valve of Type 73-103 which has a rated flow capacity of 0.6 l/sec (10 gpm) at 1.3×10^8 dynes/cm² (2000 psi) was substituted and has functioned to our complete satisfaction. After the valve was replaced, the hydraulic pressure was doubled to 3.4×10^7 dynes/cm² (500 psi) to improve the frequency response, the oil was replaced with MIL-5606 hydraulic fluid, and the pump motor by a 1.5 hp repulsion-induction electric motor. Further, a new filter rated at 0.9 microns replaced the old one and was inserted in the supply line instead of in the return line. With all these

changes maximum oil delivery was still about 0.25 l/sec (4 gpm), less than we would like, but an accumulator in the line could supply transient peak demands.

The results with the lever system were discouraging. There was too much inertia and springiness in the lever arms. Elasticity in the structure remained the main problem throughout our experiments. Springiness contributes a time lag in the response which tends to instability and lower frequency response in the system. To achieve stability, gain had to be lowered which reduced tracking accuracy. The tracking error ran as high as 30% of the input signal at low frequencies. At frequencies near resonance (~ 9 Hz) the error often went over 100%. Thus, the useful frequency response of this system was limited to a band from 0 to 5 Hz.

Another difficulty inherent in all lever systems--one probably known to Archimedes--arises from the immutable tendency levers have to move in arcs. A point on a lever will not track the water surface in a vertical line. If the amplitudes of the waves are small compared with the lever arm, the error introduced by departures from the vertical may be negligibly small but for larger waves the position distortion rapidly becomes unacceptable. A longer lever is no answer since difficulties with bending, elasticity, and inertia rapidly become insuperable. The search for a mechanically amplified system compatible with linear vertical tracking as well as with all the other demands had to begin again.

Before continuing with that story let us digress to the design

of the nulling wave probe which was going forward at the same time.

The wave follower is required to follow water level motions up to 10 Hz. It is also desired to preserve a record of motions up to 20 Hz. The first number tells how fast the follower must move and the second defines the size of the nulling wave probe. In its field form the signal from the nulling probe will be preserved as an addition to the gross motion of the water reported by the follower. It was decided, following McGoldrick (1965), to try a 0.5 to 1.0 mm capacitance wave probe. The probe must be linear in its response. A length of 10 cm was needed. Further, the probe had to be reasonably rigid since it was to be supported at one end only.

After some exploration we first chose mercury-filled glass capillary tubes which we drew and filled ourselves. The conductors are the mercury and the seawater while the glass is the dielectric. Capacitance secured ranged from 4 to 6 picofarads/cm, and linearity was 1 to 2 per cent depending on the particular probe. The probes proved fragile and easy to bend but could have been used in the field with reasonable care. Unfortunately, the final design of the wave follower requires a probe much longer than 10 cm. Good, long glass capillaries are difficult to draw and the danger of breakage (and mercury poisoning) is greatly increased. Fortunately, the basic idea of the associated electronic system can still be used with little modification.

The electronic system for the nulling wave probe, Fig. 2, provided two signals, one a frequency signal suitable for transmission over long cables with minimum degradation, and the other a DC voltage

for the nulling signal. The system consisted of a unijunction transistor relaxation oscillator driving a ramp generator whose signal was integrated by an RC filter. The oscillator covered the range from 2 to 10 kHz when used with probe capacitances from 0 to 50 pf, physically, from minimum to maximum probe immersion. The ramp generator produced a ramp of the same constant slope each time it was triggered by a pulse from the oscillator. The RC filter converts the ramps to a DC output inversely proportional to pulse frequency and thus directly proportional to probe immersion depth. The entire system together with a battery sufficient to operate it for one day was housed in a watertight cylinder having a 2.5 cm OD and 7.5 cm long.

Let us resume our account of the development of the design for the mechanical part of the wave follower. So far our promising ideas had found no practical realization for a simultaneous solution of the problems associated with inertia, springiness, stroke length (with or without amplification), and vertical tracking.

Our next attempt used a cogwheel and chain arrangement. See Fig. 3. A mechanical gain of three secured by the choice of cogwheel diameters, a rectilinear motion, and a travel of 2 m were achieved. Satisfactory frequency response was limited to the band from 0 to about 7 Hz since the system had a resonance at approximately 8.6 Hz. This is an improvement over the 0 to 5 Hz band of the earlier design but still not enough to meet the field requirement. The tracking error was reduced to roughly 10% for 30 cm of travel at 0.8 Hz,

also an improvement but again not enough to give us a field instrument.

With the cog system, the dummy nulling signal was replaced for the first time with the nulling wave probe. It was tested in two ways. In the first the nulling probe was immersed in a beaker of water and the beaker moved up and down. In the second, the beaker was held fixed and an external signal moved the follower while the signal from the nulling probe was also recorded for comparison. In both kinds of test the nulling probe behaved well. As might be expected some trouble arose from water beads clinging to the probe and from the meniscus. Water beads are not expected to cause difficulty in the field since the wind will act to clear them. Keeping the probe clean helped somewhat. However, when the probe was rapidly withdrawn from the water menisci as long as 2 cm were sometimes observed.

Although there was an improvement in performance with the cog system, the basic problems of springiness, inertia, and field compatibility still remained. To overcome these, it was decided to go to a direct-acting system using a cylinder having a stroke capability of 90 cm (3 ft). Even though this meant a reduction in the maximum vertical velocity that could be achieved, it was felt that the reduced springiness and inertia made the sacrifices worthwhile. Further, a waterproof enclosure for the more compact direct-acting system is easier to design.

This decision meant that some of the original wave follower specifications had to be modified. The stroke specifications had to be reduced from 2 m to 90 cm, thus reducing the ability to adjust for large changes in the mean water elevation, and decreasing the length

of the vertical scans. The maximum vertical velocity specification had to be reduced from 150 cm/sec to 120 cm/sec since the pump could not deliver, nor could the servo valve pass, the required 0.44 l/sec (7 gpm) oil flow at the low pressures used. The other specifications remain unchanged.

These changes in specification mean only a slight reduction in the range of conditions over which the wave follower will be useful. For the first studies planned for the Chesapeake Bay, where the tidal range is small, gross vertical adjustments will not be needed and the reduction in stroke length only reduces the vertical scans. If longer scans prove necessary, an auxiliary scanning instrument could readily be designed. Further, if it becomes necessary to achieve the original maximum vertical velocity, the servo valve could be replaced with one having the required flow rate.

V. THE DESIGN OF THE WAVE FOLLOWER FOR FIELD USE

A. Introduction

The design of the chassis and case was dictated mainly by the largest component of the wave follower, the hydraulic cylinder, which requires some 180 cm of space. The smaller items, the servo valve, the accumulator, the electronic system, and the plumbing, must also be housed in the same case and the case must be of a manageable size. It was decided to use an aluminum pipe having a nominal diameter of 27 cm (10 inch standard pipe) and a length of 215 cm as the outside case. Since it was also desirable to mount to entire machine underwater,

a way had to be found to seal the moving member--the piston rod--against sea water. A collapsible boot covering the rod solved that problem. The anemometer and nulling wave probe are mounted on the end of the piston rod which extends vertically out of the case when the instrument is in use.

The chassis of the wave follower is assembled around the hydraulic cylinder, and the electric and hydraulic components are mounted on the chassis. See Fig. 4. The chassis breaks into two sections, one containing the hydraulic components and the other containing the electronic equipment. This was done to allow easy disassembly in the event that field repairs become necessary.

The upper or hydraulic section of the chassis contains the servo valve, bypass valve, accumulator, water catching bottle, check valves, plumbing, and the body of the hydraulic cylinder. One end of the piston rod extends out of the case, and the other end extends down into the lower or electronic section which contains the feedback and control circuitry, feedback and position potentiometers, piston rotator, power system, and cables for the transmission of signals and power. See Fig. 5.

The hydraulic section of the wave follower is assembled on three aluminum rods, 3.17 cm in diameter, held together by two aluminum end plates. The top end plate is welded across the end of a short piece of 27 cm dia. aluminum pipe and also forms the top end (the "top hat") of the watertight case. The hydraulic cylinder is bolted between these two end plates, and the rod extends through holes in each. On the outer side of the top end plate there is an

assembly which seals the boot to the case. This assembly is threaded, and a protective cap fits over the end of the rod and boot when the rod is completely withdrawn. This cap also serves as a handle by which the case can be lifted and manipulated.

The electronic section of the wave follower is arranged similarly except that there are six rods, three of aluminum, and three of 1.9 cm dia. stainless steel which serve as bearing surfaces for the ball bushings of the three-armed "spider." See Fig. 6. Most of the electronic system is mounted on an aluminum plate which is secured to one of the aluminum rods. The rods are held together by two end plates and an additional end plate on the bottom of the section protects gears. All other parts are mounted either on the spider or on the aluminum rods. Most of the aluminum parts are Martin Hardcoated and dichromate sealed.

B. The hydraulic section

The components of the hydraulic section are 1. the hydraulic cylinder, 2. the bypass valve, 3. the servo valve, 4. the water collecting bottle, 5. the plumbing, 6. the accumulator, and 7. the check valve. See Fig. 7. For a schematic of the entire hydraulic circuit, see Fig. 8.

1. *The hydraulic cylinder*

The hydraulic cylinder is a Hydro-Line type R2-J modified to our order. It is double-acting, double-ended, has a 90 cm (3 ft) stroke, a 1.6 cm (5/8 in) stainless steel oversized piston rod, and a 2.54 cm (1 in)

bore. A hole 0.51 cm in diameter has been drilled axially through the piston rod to accomodate cables from the wave probe and anemometer.

The oil volume of this cylinder is 3 cm^3 per cm of rod travel (0.47 cubic inch per inch). The area of the piston on which the oil exerts useful pressure is 3 cm^2 (0.47 square inch), and the maximum force in the absence of pressure drops is 1100 newtons (240 pounds). To achieve the velocity of 150 cm/sec specified for the design would require an oil flow of 0.46 l/sec (7.3 gpm). Our pump and motor can deliver, at best, only 0.24 l/sec (4 gpm) corresponding to a velocity of 82 cm/sec. Since the design specification was derived for waves on the verge of breaking, and these waves are infrequent, velocities much less than 150 cm/sec will be "normal." Some extra flow to meet transient peak demands is, however, provided by the accumulator. See § V.B.6.

2. *The bypass valve*

The remote control bypass valve is a rotary hydraulic valve modified to be driven by an electric gear motor. A magnetic reed switch was added to sense the full open and full closed positions. A motor driven valve provides surgeless opening and closing and allows the bypass flow to be set at any value--characteristics not easily attained with the usual solenoid valve. The bypass valve allows hydraulic power to be cut off briefly from the system when adjustments are necessary, the application of reduced power to the system while testing, circulation of oil to the filter without cycling the system, and the starting of the pump under no load.

3. The servo valve

The servo valve is a Moog 10 gpm model 73-103 flow control valve. It is four-way acting and has two stages of hydraulic amplification. The valve directs flow, metered by the spool which adjusts the inlet and exhausts ports, in two directions while controlling the flow rate. Within the valve itself there is a cascade of valves the weakest of which is actuated by the small electric signal from the nulling probe. These amplify the hydraulic force to the point where it is capable of moving the main spool.

4. The water collecting bottle

One of the most critical problems to be solved in building a wave follower for field use is to provide for the watertight integrity of the case. If nothing were to be brought out through the case but electric connections, then the traditional O-ring seals would make the job trivial. A projecting oscillating rod is another matter. It would be nice to be able to claim that the boot mentioned on page 16 is the ultimate solution. The fact is that it is not; the truth being that it is the weakest point of the entire case. In use the boot is constantly being flexed and it must be relieved of air pressure. This has been done by drilling a hole in the top of the case through which the boot vents air into the case. The prospect of losing an expensive instrument and aborting an even more costly field expedition because the boot developed a pinhole leak is not tolerable. The water collecting bottle was provided as a first line of defense. Should the

boot develop a leak, the water reaching the interior of the case through the pressure vent drips into the collecting bottle. A sensor in the collecting bottle when wetted actuates an alarm on the control panel. The sensor also reports the rate of water accumulation the alarm goes off, the operator can retract the rod. This comp the boot and helps to retard the entry of more water. The field crew can then cap the follower and retrieve it for repair before major damage occurs. The hot-wire probes carried by the follower are relatively inexpensive and would be expendable in an emergency.

5. *The plumbing*

The plumbing consists of 1.27 cm ID copper tubing connected by Swagelok flareless tubing fittings. Copper tubing having 0.95 cm ID was used in a few places where unusually tight bends were necessary. The sizes were chosen to minimize pressure drops.

6. *The accumulator*

The accumulator is a Von Mfg. Co. Model 121-60 with a volume of 1000 cm³. The accumulator acts to reduce transients imposed on the hydraulic lines by the servo valve and to store fluid which can be used to meet peak flow demands. It also prevents damage to hose and tubing from "water hammer" effects.

7. *The check valves*

The check valves are of standard type and simply prevent reverse flow in the event that the line pressure becomes less than the pressure in the accumulator. They are also useful in preventing oil loss while the hydraulic cables are being disconnected.

C. The electronic section

The major electronic component systems of the wave follower are:

1. the feedback amplifier, 2. the acceleration limit, 3. the velocity limit and search-and-follow mode, 4. the end stops, 5. the drift mode, 6. the anemometer circuit board, 7. the nulling probe electronic circuitry, and 8. the remote-control mode change. All of these systems, except for a part of 7 at the top of the piston rod, are located on an aluminum plate in the electronic section. See Fig. 9. For a block diagram of 1 through 5, see Fig. 10.

1. *The feedback amplifier*

The wave follower is a servomechanism and as such demands a closed-loop gain to provide a proper balance between stability and response in each mode if the specified accuracy is to be attained. In particular, when the follower is in the tracking mode the gain of the amplifier adjusts the error signal from the wave probe for proper operation of the feedback loop. Again, when it is in the external signal mode the error signal is the difference between the external

signal and a follower position signal (§ V.D.2) and the feedback amplifier also acts as a differential amplifier.

The amplification that closes the loop between the servo valve and the error sensing device is provided by two Fairchild $\mu A741$ integrated-circuit operational amplifiers. The first stage, A2, is a differential amplifier described by $e_{out}/e_{in} \sim (R_{feedback}/R_{input})(e_1 - e_2)$. In the tracking mode the non-inverting input is grounded: $e_1 \equiv 0$ and e_2 is the error signal emanating from the wave probe. In the external signal mode e_1 is the external signal and e_2 is the follower position signal. The second stage, A8, provides a gain of $e_{out}/e_{in} = -R_{22}/(R_{20} + R_{21})$. This stage drives the servo valve and has provision for trimming the closed-loop gain of the system by varying R_{21} ⁴. See Fig. 11.

2. Acceleration limit

Two $\mu A741$ operational amplifiers, A3 and A4, and their associated components, form an acceleration limiting system. See Fig. 11. The circuit is a modified version of that shown in Burr-Brown (1963). It limits the rate of change of an input signal to some value prescribed by setting C_1 and R_{17} : $(\text{volt/sec})|_{\max} \sim V_b/C_1 R_{17}$. So long as the rate of change is slower than the limit, the circuit does not affect the signal. When the limit is not exceeded the gain is $e_{out}/e_{in} = -R_{18}/(R_{13} + R_{14})$.

⁴ The general reader unfamiliar with the practical aspects of circuits employing operational amplifiers would be well advised to consult Philbrick/Nexus Research (1968). A brief discussion of the stability of feedback systems may be found in Blackburn, Reethof, and Shearer (1960), pp. 468-497.

The output e controls the servo valve which in turn controls the volume flow to the hydraulic cylinder. The *velocity* of the piston is thus proportional to the error signal.⁵ Effectively, the *acceleration*, the rate of change of the piston velocity, is limited by limiting the rate of change of the error signal.

Since gravity waves have accelerations not exceeding g , a setting of $1.5 g$ allows the follower to operate without interference under normal conditions. In the event of emergencies such as failure of the wave probe or in the presence of transients while switching modes, the acceleration limit protects the follower against destructive thrashing about.

3. *The velocity limit and search-and-follow mode*

Closely associated with the first stage of the feedback amplifier (A2) and the acceleration limit circuit (A3 and A4) is a system of voltage sensors and switches which change the gain of the feedback amplifier. This system, composed of a Fairchild $\mu A711$ dual comparator, LS1, and a Fairchild SH3002 analog switch, AS6, provides a maximum velocity sensor and limiter for the wave follower. See Fig. 12.

The amplified error signal present at the output of the first stage of the feedback amplifier, A2, is proportional to the velocity of the piston⁶, or, equivalently, to the departure of the wave probe from the null position. The first forms the basis of the velocity

⁵ Except, of course, for the inevitable phase lag.

⁶ Except, again, for the inevitable phase lag.

limit, and the second forms the basis of the search-and-follow mode.

If the magnitude of the error signal at the output of A2 reaches the limit set by R_{40} and R_{42} , the Fairchild $\mu A711$ dual comparator, here wired as a double-ended limit detector (Giles, 1957), senses this and opens the analog switch, AS6. This switch adds resistor R_{13} in series with R_{14} , which decreases the gain of the acceleration limit circuit. In turn, this decreases the closed-loop gain by an order of magnitude. The resulting transient is smoothed by the acceleration limit. Thus, if the velocity of the piston should become too high, or if the wave probe should break, the circuit senses the condition and slows the piston to a lower velocity. In the case of a broken wave probe, the piston continues to move slowly until it reaches the end of its travel. In all other emergencies the piston remains under servo control.

In the field an operator may switch into the tracking mode when the wave probe null is well away from the water surface. Without a velocity limit the follower would seek the null, possibly with considerable violence. The velocity limit prevents this any time the null is more than 2 cm from the water surface. The follower moves sluggishly until the surface is found when AS7 restores the follower to normal action in the tracking mode.

It should be mentioned that the velocity limit is protected from noise in the electric lines by the low-pass RC-filter, C_3 and R_{44} , across the input to the analog switch, AS6.

4. The end stops

Without some means of slowing it down the piston of the wave follower could hit the ends of its travel with destructive force. This undesirable event is precluded by incorporating an extra $\mu A711$ dual comparator wired as a double-ended limit detector, LS2, and using the analog switch, AS6, already present in the velocity limit system, to create an end stop. See Fig. 12.

The limit detector, LS2, senses the voltage from the position potentiometer. When the piston closely approaches either end of its travel, the voltage sensed reaches a threshold of the limit sensor which opens analog switch AS6, decreasing the gain of the system. As with the velocity limit, the velocity of the piston is decreased, and if it hits its extreme position it does so gently. The transient created by the switching is again smoothed by the acceleration limit. Servo control is maintained so that as soon as the condition which activated the end stop is removed (e.g., the arrival of an inordinately high wave) the wave follower comes out of the end stop control automatically and resumes tracking. To prevent the introduction of noise into the limit detector from the potentiometer in accordance with the manufacturer's recommendation, a voltage follower, A7, has been incorporated as a high input impedance buffer.

It will have inevitably occurred to the reader that there are less elaborate ways to create an end stop. A simple break in the connection between servo valve and amplifier would gain the desired end. However, such a solution would lose servo control and the system would be unable to recover without intervention. Many hydraulic

cylinders incorporate mechanical cushions. These, as simpler, might be preferable to our system but we were unable to find a commercially available internally cushioned hydraulic cylinder of sufficiently small bore. External cushioning would have been unacceptably cumbersome.

5. The drift mode

A slow vertical scan may be secured by using a ramp as input to the wave follower. The ramp may either be externally or internally generated. While the slope of an external ramp can be easily controlled by the operator, and this method is relatively simple, it is unacceptably sensitive to any noise in the cable connecting the follower and the control system. For this reason an internal ramp was chosen even though field adjustment of the slope of an internal ramp is more difficult.

The ramp generator system consists of A5, A7 (Fairchild μ A741 operational amplifiers), and AS5 and AS7 (Fairchild SH3002 analog switches). See Fig. 13. Wired as an integrator, A5 is the ramp generator in accordance with
$$e_{out}(t) = - \frac{1}{RC} \int_0^t e_{in}(\tau) d\tau$$
 where $1/RC$ is a scale factor depending on C_2 , R_{25} , and the settings of potentiometers R_{24} and R_{30} or R_{31} . If $e_{in}(t)$ is a constant, k , $0 \leq t \leq T$, where T is the time required to saturate the amplifier, then $e_{out}(t) = - (k/RC)t$ is linear in t and $- k/RC$ is the slope of the ramp. The value of T depends on the operational amplifier used and is given by $T = RC|K/k|$ where K is the voltage at which the operational amplifier saturates. In our case, $K \approx \pm 10$ V. Analog switch AS5 is used to

reset the integrator, A5, to zero after the completion of a ramp.

Since in the drift mode the piston is to travel slowly between its extreme positions it is necessary to add a bias, i.e., an additive constant voltage, to the output of integrator A5, which starts the ramp at either end. For this purpose a summing amplifier, A9, has been included, and analog switch AS7 is used to select the polarity of this bias. This same bias voltage is also used as the input, k , to the integrator A5 where the symbol k is to be taken as positive. When analog switch AS7 selects a voltage $+k$, the magnitude of which is adjusted by R_{31} and R_{24} , the output of the summing amplifier, A9, is an ascending ramp of slope $+k/RC$ starting at the voltage $-k$. When a negative voltage, $-k$, is selected whose magnitude is set by R_{30} and R_{24} , a descending ramp of slope $-k/RC$ starting at $+k$ results. The sign inversions are caused by A9. In either case, the starting point of the ramp can be changed by adjusting potentiometer R_{30} or R_{31} . Note that R_{24} can adjust only the slope of the ramp, while R_{30} or R_{31} adjust both the slope and starting point.

The output of the ramp generator system can be switched into the input of the feedback amplifier as an "external" signal, i.e., with feedback provided by the position potentiometer instead of the wave probe, by analog switches AS4, AS3, and AS2. This causes the piston rod to move up or down at a slow and constant velocity in the vertical drift mode. This system can provide drifts having a nominal velocity of ± 1 cm/sec.

6. Anemometer circuit board

The external electronic systems of the wave follower are separated from it by 60 m of cable. Such a separation between a hot-wire anemometer probe and its electronics is intolerable. The probe is a variable resistor whose minute fluctuations are crucial to the measurement. If it is connected to the rest of its circuit by very long leads the error from the impedance swamps the useful signal. For this reason it was decided to mount the anemometer circuit inside the wave follower, close to the probe, and to transmit the output of the complete anemometer system through the cable. The circuit board for the anemometer is mounted next to the wave follower electronic system in the electronic section of the case. See Fig. 14.

While this solution circumvents long leads it places the anemometer electronics where they are hard to get at when calibration becomes necessary. For a field instrument where fouling and breakage with the ensuing need for new calibrations are to be expected this is not trivial. Each time a calibration becomes necessary the wave follower will have to be retrieved, and opened up. With the probable short life of a hot-wire probe some relief might be had by precalibrating a battery of standby probes. Some sense of the magnitude of the calibration problem may be gained from Merceret, (1968, 1969). Unfortunately, at this time, lacking field experience with the wave follower, we can say little that would be useful.

The anemometer electronic system is a DISA type 102 Industrial Constant Temperature Anemometer (CTA) circuit board. This is a compact, solid-state circuit which is suitable for most hot-wire probes.

As it comes from the manufacturer, it requires the addition of a time-delay switch, null meter and two trimming potentiometers. To prevent a transient from destroying a probe, the time-delay switch (see Fig. 15) is required to apply power to the probe after the CTA circuit has had a chance to warm up. The null meter and potentiometers are required to calibrate the CTA circuit each time a new probe is used. Once the adjustments are made, the system needs no further attention.

The output of the CTA goes to a VCO (see §V.D.4.) so that the signal (which has not yet been linearized) can be transmitted to the control station with minimum degradation.

7. The nulling probe electronic circuitry

On pages 12 and 13, a laboratory nulling wave probe was described. For field tests, a 60 cm probe is necessary since the hot-wire anemometer height adjustment depends on the ability to change the null position on the wave probe itself (see §V.D.5.) over a range of 60 cm. Thus a long nulling probe having the same *absolute* resolution as the short laboratory probe had to be devised. Further, the authors found that the meniscus problem became very severe with the 60 cm long, 0.049 cm diameter, Kynar-covered computer wire that was chosen as the sensor. At an excitation frequency of 20 kHz, the wave probe would "remember" an immersion for several minutes after being withdrawn.

To meet the absolute resolution requirement it was necessary to develop a more stable electronic circuit. Serendipity solved the meniscus problem. The authors found that the wave probe, when operated at high frequencies--on the order of several megahertz--would "ignore"

meniscus effects. Thus the "more stable electronic circuit" became a high-frequency circuit as well.

At first, high-frequency relaxation oscillators were tried since they had the desired $f \sim 1/C$ relationship. All the circuits failed because of excessive drift in the frequency. Other kinds of oscillators were far more stable, but they didn't have the desired f - C relation. The key to the conflict proved to be the linearizer, already described on page 13. By changing the linear ramps to exponentials, i.e., "de-linearizing" the linearizer, functions other than $f \sim 1/C$ could be linearized, opening the way to other oscillators. The exponentials are simply generated by putting a resistor across the charging capacitor of a standard ramp generator (see §V.B.5.). This creates a ramp of the form $1 - e^{-kt}$ where k is selected by choosing the values of the resistor and capacitor.

The oscillator chosen is the Colpitts (see Fig. 16) described in Cleary (1964). With a proper choice of components it has a stability better than one part in ten thousand over the frequency range of interest. Its f - C relation is $f \sim [(CC'), (C + C')]^{-1/2}$ where C is the probe capacitance and C' is a fixed capacitance chosen to set the center frequency and the deviation about the center. The new delinearized linearizer (see Fig. 17) makes $V_{out} = a + bC$ (a, b constants) to within one percent. The oscillator operates over the range from 1.923 to 1.962 MHz with probe capacitances from 0 to 300 pf. The output of the Colpitts oscillator is mixed with a crystal-controlled local oscillator, having a frequency of 1.92 MHz, which produces intermediate frequencies (IF's) covering the range 3 to 42 kHz. The IF's are

divided by four by a Fairchild CμL9989 and the resulting frequencies are used in two ways. They trigger the exponential "ramps" of the linearizer and the exponentials thus generated are then integrated to produce the linear voltage output which ranges from 3 to 6 volts. In addition, the IF's divided by 4 are sent down the electric cable to be recorded.

The oscillator-mixer-linearizer system operating with a fixed capacitor as the "nulling probe" has a stability better than 0.05% over several hours, but the overall stability of the nulling probe system including the physical wave probe is on the order of 0.1% of full scale. Thus, the main source of drift is the wave probe itself. The probe is temperature-sensitive and can vary in capacitance 0.085 pf per degree C per cm of immersion. However, since water temperature changes slowly, these effects are long-term, and it was decided to go ahead for the time being with the Kynar-insulated wire probe while seeking either a better probe material or temperature-compensation. The circuit, in any case, is not very sensitive to salinity changes as long as the salinity is above 5%.

The Colpitts oscillator is housed in the nulling probe bracket (see §V.E.1.) on the end of the piston rod (see Fig. 18), while the linearizer circuit is on the aluminum plate in the electronic section of the wave follower. Power to the oscillator, as well as the oscillator signal, are both transmitted along a single coaxial cable through a hole in the center of the piston rod. From the end of the rod to the electronic circuitry, the signal is routed through a retractable

cable. A filter at each end of the line separates the oscillator signal and the DC power.

8. The remote control mode changing system

The wave follower has been designed to operate in five different modes--following the sea surface, following an external signal, drifting up, drifting down, and drifting while following the sea surface. Additional modes of operation can easily be added. To select among the modes a remote control has been provided. Since the number of conductors in the electric cable is limited, a coded command system was adopted. See Fig. 19.

The mode changing system consists of a Fairchild CuL9960 binary-to-decimal decoder which drives combinations of analog switches through a diode-transistor signal routing network. The input to the 9960 is a four-line binary-coded-decimal (BCD) number and the output is a voltage level change on one of ten lines, each corresponding to a number in BCD at the input. With five modes of operation only five of the ten lines are presently needed. Each of the five lines goes to a diode-transistor network which activates the proper combination of SH3002 analog switches to effect the change of mode.

Analog switches are used instead of relays because here, as elsewhere in the wave follower, they give superior noise immunity. If one could operate at high voltages, relays might be advantageous but, despite the 0.4 V sensitivity of the 9960, analog switches which are free of contact bounce and insensitive to vibration are the better choice. Analog switches and the binary-to-decimal decoder isolate

the electronic system of the wave follower from nearly all noise in the electric cable.

D. Auxiliary systems

In addition to the basic mechanical and electronic systems required for sea surface tracking, the wave follower contains several auxiliary systems. They are: 1. the power supply, 2. the position potentiometer, 3. the piston rotator, 4. the voltage controlled oscillators (VCO's), 5. the system for adjustment of the wave probe nulling position.

1. The power supply

The wave follower requires ten different voltages: $\pm 5V$, $-6V$, $+10V$, $-12V$, $\pm 15V$, $-20V$, $\pm 28V$. The power required by the electric systems of the wave follower varies from 6 to 20 watts depending on which systems are operating. Battery operation is clearly feasible--and desirable, from the standpoint of noise immunity. However, the limited space in the wave follower case rules out batteries. Instead, a Zener diode regulated power supply inside the wave follower derives all necessary voltages from two power lines at ± 28 volts, thus economizing on transmission cable. This method provides good regulation and noise reduction, and a great saving in space, although some power is wasted. A more efficient power supply could be made from integrated circuit regulators, e.g., the Fairchild SH3200 or SH3201, but the prospective gain in efficiency would be more than offset by the increased cost.

2. *The position potentiometer*

Attached to the spider and driven by a rack fixed to one of the bearing rods of the electronic section is a dual-section, ten-turn, infinite-resolution potentiometer, R_A and R_B . See Figs. 6 and 10. It serves two functions: (a) it provides a voltage proportional to the position of the piston (and hence, the gross sea surface elevation), and (b) it provides the feedback signal when the wave follower is operated by an external signal.

The potentiometer is a 10 k Ω unit, number 7810, from the Computer Instruments Corporation. The voltage across it is 10, setting the voltage-position analog at 0.11 V/cm.

The sea surface elevation is given by the sum of the nulling probe and the position potentiometer signals. From one point of view the nulling probe record is an error signal. It is the record of the component of the sea surface elevation that the wave follower is unable to track; hence, it provides the high-frequency part of the wave record. The position potentiometer supplies the record of the piston position, i.e., the component of the sea surface elevation that the wave follower *can* track; hence, it contains the low-frequency part of the wave record. The crossover occurs at 10 Hz. Thus it is possible to record the gross motion of the sea surface while at the same time resolving the details of the fine structure which rides on it--a capability only poorly provided by a single fixed wave probe.

3. *The piston rotator*

In the laboratory, the wind direction can be kept constant over the duration of an experiment. In the field, wind shifts of $\pm 180^\circ$ are entirely possible. However, in the Trades extreme shifts are almost unheard of (see Kinsman, 1968). In any case, useful wave generation records can hardly be made during periods when the wind is changing direction rapidly through wide angles. From record to record the situation is quite different. In the Chesapeake Bay a number of usable 5-minute records may be possible during the course of a day when the wind backs from NW to SW. To allow the wave follower to be adjusted between records, a rotation mechanism has been incorporated which allows the operator to rotate the piston rod and the anemometer through an angle of $\pm 90^\circ$ about its zero position by remote control.

Attached to the spider is a 2 rpm, 28 VDC gear motor. The piston rod is free to rotate in a bearing on the spider and the gear motor drives the rod through a reduction gear. See Fig. 9. The direction of rotation is determined by the polarity of the power applied to the motor. When not energized, the gear motor brakes the piston rod enough to prevent further rotation. The angular position of the piston rod is given to the operator by a potentiometer mounted on the spider and driven by the same gear that turns the piston rod.

4. *The voltage controlled oscillators (VCO's)*

Direct transmission of signals over the 60 meters of electric cable linking the follower with the controls may degrade the data too much.

To insure the quality of the three critical signals, those from the nulling probe, the follower position potentiometer, and the hot-wire anemometer, frequency modulation (FM) has been adopted. The wave probe output is intrinsically FM while the other two are converted to FM by Solid State Electronics Corporation Model V-510 voltage controlled oscillators. The VCO's have a center frequency of 30 kHz deviated by $\pm 30\%$. This deviation results in a data frequency response on the order of 2 kHz.⁷ The VCO's are mounted on the same aluminum plate with the follower electronic systems. See Fig. 14.

5. The system for adjustment of the nulling probe null position

Present design specifications require that the anemometer be adjustable to any fixed height above the water surface from 1 cm to 60 cm. This is achieved by changing the position of the null point on the nulling probe. This is accomplished by subtracting a constant voltage from the voltage version of the nulling probe signal. The constant voltage comes from a potentiometer driven by a gear motor, and is subtracted by a 741 differential operational amplifier, A1. The motor drives the potentiometer through a reciprocating linkage, thus preventing potentiometer jamming on the end stops as well as voltage jumps during transits of the resistive gap. An internally generated constant voltage which is remotely controlled is preferable to one transmitted from the control station since this lessens the chance of noise entering the system.

⁷ The precision required for all three signals is provided by the unusually large deviation used. However, the resulting frequency response is necessary only for the hot-wire.

E. External assemblies

In addition to the internal systems and components already described, five external assemblies are required to operate the wave follower:

1. the hot-wire and nulling probe bracket, 2. the hydraulic power supply, 3. the hydraulic cables, 4. the electric cable, and 5. the mounting pedestal.

1. The hot-wire and nulling probe bracket

The hot-wire probe and the nulling probe are held in a separate bracket which is designed to be easily detachable from the wave follower piston rod. See Fig. 4. The bracket itself contains the nulling probe oscillator and mixer (see §V.C.7.) in a watertight housing near its base. Electric contact with the wires in the piston rod is made by a four-connector underwater coupling. The bracket is attached mechanically to the rod by two machine bolts. The hot-wire probe plugs into a connector near the top of the bracket. It extends to the nulling probe and is mounted about 2 mm to one side to provide readings as closely above the nulling point as possible.

Since both the nulling probe and the anemometer probe are fragile, breakage during handling and operation in the field is expected. For this reason the mounts for both probes are designed to facilitate probe replacement in the field. The nulling probe is attached by machine bolts and is sealed to the bracket by O-rings. See Fig. 20. Tension is adjusted by shifting the bottom connector in the bracket until the wire is taut, and tightening a setscrew. The

hot-wire probe has a straight coaxial connector which plugs into a mating connector in the bracket. The connection is sealed against water splashes by a piece of plastic tubing and silicone grease.

2. *The hydraulic power supply*

The basic hydraulic power supply consists of a Continental Hydraulics POLYPAC R-10 unit with a 1.5 hp repulsion-induction motor as the power source for the $2 \times 10^7 - 4 \times 10^7$ dynes/cm² (300-600 psi), 0 - 0.25 l/sec (4 gpm) variable-volume vane pump, Model PVR1-6B. The reservoir holds 3.0×10^4 cm³ (10 gallons) of MIL-5606 hydraulic fluid, and filtration is provided by a large-capacity oil filter rated at 0.9 micron.

In addition to these components, which are found in any hydraulic power supply, a system has been provided for filling and purging the hydraulic cables connecting the wave follower with the power supply. Since they hold a substantial amount of fluid, 2.5×10^4 cm³ (7 gallons) weighing some 2.1×10^4 g (57 lb), some method of filling and emptying the cables without draining or overflowing the reservoir was necessary. Filling is accomplished by a small auxiliary pump mounted on the power supply. While the main pump fills the hydraulic cables, the auxiliary pump is used to fill the reservoir from the oil drum. Emptying is achieved by pressurized nitrogen which, when valved into the cable (with the wave follower in bypass), pushes most of the oil in the cables back into the reservoir. The auxiliary pump in this case is reversed, draining the fluid in the reservoir back into the oil drum.

3. *The hydraulic cables*

In the field, the wave follower must be mounted a considerable distance from the control station to minimize disturbance of the wind and waves by the station and its support. For the preliminary trials in the Chesapeake Bay, the control station will be in a trailer mounted on a 20 m by 5.5 m anchored barge. A separation of 40 m was judged sufficient for testing which requires two 60 m lengths of cable. The cable should be flexible to contribute to ease of handling in the field and it should be large in diameter to minimize pressure drop. For these reasons Synflex #3300-12 hydraulic pressure hose with an ID of 1.9 cm was chosen.⁸

Ease of assembly in the field being a paramount consideration, self-sealing quick-disconnect couplings polarized to prevent misassembly were used throughout. The 60 m cables connect with the wave follower by 3 m jumper cables so that the cables may always be disconnected above the water even when the follower is submerged.

4. *The electric cable*

All the power and electric signals from the sensors of the wave follower are transmitted by a Belden Type 8286 TV camera cable. It contains three coaxial cables used for the hot-wire, nulling probe,

⁸ Although Synflex #3300-12 has a minimum bend radius on the order of 25 cm, and much was hoped for its flexibility, it has proved a veritable beast to handle even on a *geared* cable drum having a nominal radius of 25 cm. The authors, beginners at the game of field work, didn't fully appreciate this fact until the cable arrived and had to be stored on the drum for the first time. It took an hour for three of us and the laboratory wasn't rolling and pitching.

and position potentiometer signals, and groups of single conductors, each separately shielded, which are used for power, control, and minor sensors. The cable has an overall shield which is grounded at both ends as are all the other shields.

The cable is connected to the wave follower with Vector Type MS-2 22-conductor watertight connectors. The connections have to be made above water which requires the use of 3 meter jumpers.

The hydraulic and electric cables are held together by large rubber bands. This should facilitate handling in the field. Ship-side hydraulic and electric connectors are mounted on the side of the reel. See Fig. 21.

5. *The mounting pedestal*

For the first field trials a tripod mount, resting on three tower bases, was designed. See Fig. 22. The bases are 92 cm in diameter, spaced with their centers on the vertices of an equilateral triangle 175 cm on a side. They are free to swivel and the mount can be adjusted vertically at each corner, allowing the pedestal to be leveled on sloping, uneven bottom. About 0.5 m of vertical adjustment is should the mount sink in a soft bottom or should the tides be excessive.

The first field experiments will be made in water depths as nearly 4.7 m as we can find. Should we be satisfied with the results, another mount which will permit operation in depths up to 15 m will be designed and built.

VI. LABORATORY TESTS

A. The control station

At the control station are located the hydraulic power supply, cable reel, electronic control panel, and electronic test instruments. In the field, there will also be a tape recorder.

The hydraulic power supply was described in §V.E.2. The cable reel is geared and has a 90 cm drum 40 cm in diameter. The diameter of the flanges is 80 cm. The base was lengthened and quick-disconnect couplings were mounted on one flange. On the electronic control panel (see Fig. 23) are all of the inputs, outputs, and mode changing switches necessary for the operation of the wave follower. The inputs and outputs are as follows:

Inputs:	External signal	(§V.C.1.)
	Power	(§V.D.1.)
	<i>and the adjustments</i>	
	Anemometer height	(§V.D.5.)
	Piston rotation	(§V.D.3.)
	By-pass valve actuation	(§V.B.2.)
Outputs:	Anemometer	(§V.C.6.)
	Nulling probe	(§V.C.7.)
	Piston position, vertical	(§V.D.2.)
	Piston position, rotational	(§V.D.3.)
	Water collecting bottle	(§V.B.4.)

Monitors are available for all output signals and the first three may be inspected in either voltage or FM forms while the piston rotational

position is in voltage form only and the water collecting bottle is a resistance. The electronic test instruments are those ordinarily found in any well-equipped electronics laboratory.

A tape recorder will preserve FM signals from the anemometer, nulling probe, and piston position. A 31 kHz reference frequency will be recorded for tape speed error compensation. Demodulation for final data processing of the anemometer and piston position signals will be provided by Sonex S-35 FM discriminators, while the nulling probe signal will be demodulated by the linearizer described on page 30.

Quick-lock demodulation for the FM signals is provided by simple pulse-averaging discriminators (see Fig. 24) and the nulling probe linearizer. The pulse-averaging discriminator clips the incoming frequency signal and sends it to a Fairchild DTpL 9951 one-shot multivibrator. This generates a pulse of constant width, T , less than the minimum value of $1/2 f$, for each cycle of the input frequency. These pulses are then RC integrated to give a DC level proportional to frequency. This system was chosen, instead of the usual tuned circuit and diode discriminator, because of the large deviation of the FM signal.

B. The test procedure and results

The frequency response, tracking error, acceleration, and maximum velocity of the wave follower were measured with external signals as the input. If the nulling probe were ideal, and the dynamic effects of the nulling probe bracket moving in water were negligible, the frequency response of the wave follower would then be known exactly.

To the extent that the frequency response of the nulling probe is much higher than that of the rest of the wave follower system the overall response will be nearly the same as the response to an external signal. The effects of the bracket, if any, will become evident in the field. This scheme of evaluation was adopted because the generation of precisely known wave forms on a water surface is a matter of very great delicacy and difficulty.

The results of the external signal tests are:

1. Frequency response

The reader should bear in mind that the term "frequency response" as applied to the wave follower has a somewhat unorthodox meaning. For the sense appropriate here he can consult Appendix A. The follower was tested with sine waves with frequencies from 0 to 30 Hz. The response of the wave follower extends from DC to 10 Hz as required by the design specification. At 10 Hz, with a wave 7 mm in height⁹ the phase shift is on the order of 90 degrees, and the maximum tracking error is 6 mm. Both errors decrease as the amplitude of the external signal decreases.

2. Tracking error

The tracking error, the absolute value of the discrepancy between the external signal and the piston position, varies with the amplitude and

⁹ The external test signals were fluctuating voltages. The wave follower is to be used for displacements whose dimension is length. To make the test conditions more directly intelligible, equivalent heights are given rather than the double voltage amplitudes. Since 10 volts corresponds to 90 cm of piston travel, 0.11 volts = 1 cm.

frequency of the external signal; more precisely, it is directly proportional to the derivative (velocity) of the input signal¹⁰. (See page 23.) In the field, there is a rough physical limit to the amplitude of the wave which may be associated with any particular frequency. The higher the frequency the smaller the amplitude. (See Appendix A.) Since the wave follower is intended for generation studies it was decided not to use it when the wave heights were greater than 30 cm. Figure 25 shows the extreme wave heights as a function of frequency. Between 0 and 0.86 Hz the 30 cm decision controls. From 0.86 to 10 Hz the physical limit is in force. The tracking error is also shown in Fig. 25. The worst error is 2.4 cm for 30 cm waves of frequency 0.86 Hz, for which the maximum vertical velocity is 82 cm/sec. In the field, during the initial stages of generation, it is not anticipated that waves of all frequencies will be present with their maximum possible amplitudes, and the actual tracking errors will probably be smaller than the extremes shown.

The components most responsible for the tracking error are the servo valve and pump. When the velocity is great the valve is nearly wide open and the pump can not quite maintain the necessary flow. Should our hope for less than extreme conditions in the field be disappointed, the tracking error can always be reduced by incorporating a larger servo valve and more powerful pump.

¹⁰ This is strictly true only at lower frequencies; near 10 Hz, the nonlinearities of the wave follower, as well as its inertia, cause the error to be larger than the velocity would indicate. Nevertheless, the maximum error for the wave follower across its entire specified range is 2.4 cm, and is usually much less.

3. Square-wave response

The wave follower was tested with square waves for two reasons. One was to choose the best balance between stability and response (tracking error), the best for us being a slight overshoot with a rapidly decaying oscillation. The other was to check the wave follower's acceleration and velocity. The response shows an overshoot which varies with the amplitude and frequency of the input square wave but characteristically is some 25% followed by four cycles of a 14 Hz damped oscillation--a frequency corresponding to the natural frequency of the follower. The observed maximum velocity for square waves is about 100 cm/sec.

In order to form some idea of the maximum acceleration possible to the follower all safeguards were deactivated and the follower subjected to a square wave. From the curvature of the resulting oscilloscope photograph of the response the maximum acceleration was *estimated* to be about 4 g.

The velocity limit is set at present at about 45 cm/sec. If the vertical velocity of the piston exceeds this value, it is automatically reduced to about 20 cm/sec.

4. Durability tests

The wave follower has been run continuously for 24 hours in air and 12 hours submerged. Under these laboratory conditions the follower passed the sub aerial test with no performance changes. At the end of the submerged test it was found that the housing had several small

leaks at the welds, at the junction between the top hat and the boot, and at the threads of the quick-disconnect couplings. These leaks were eliminated by redesigning and refabricating the "top-hat" section of the case and by the application of a bit of paint to a pinhole leak in the lowest weld.

Although the boot was thought to be the weak point in the design of the wave follower, it performed magnificently, remaining airtight (and watertight) under considerable abuse from both excessive pressure (it is rated at 0.5 atmosphere, but withstood 1.4 atmospheres) and mechanical abuse.

5. *Tracking test*

Just before the wave follower was to go to sea, it was tested in the flume, at CBI. For lack of sufficient space, the wave follower was laid in the flume at an angle, and it did manage to track the surface, even though tap water was used and the angle of the probe effectively multiplied the closed loop gain of the feedback system.

VII. CONSTRUCTION COSTS

The authors estimate the cost of the mechanical parts for the wave follower at two thousand dollars. To this should be added the cost of machining, which may be considerable since nearly all of the parts of the case and chassis are special. The cost of the hydraulic power supply is about \$500 while the cables and reel add another \$1000. The electronic components cost about \$1100, but some items, such as the

analog switches and 711's, have since dropped in price. The construction time for the electronic circuits is considerably less than that for the mechanical components.

In sum, the authors estimate total cost for *duplication* in 1969 to be about \$5000 to \$8000. For *modification*, the extra design time would increase the price.

VIII. FURTHER WORK

The wave follower will ultimately be used for an air-sea interaction study off the island of Aruba, N.A. (See Kinsman, 1968.) For this application, several changes in the present instrument will have to be made. Among them are: A. Mounting systems for depths to 15 m, B. Longer vertical drifts, C. Location at greater distances from the control station, D. Accommodation for two- or three-axis hot-wire probes.

A. Use in depths to 15 m

The initial field tests of the wave follower will be made in water depths of 4.7 m--a depth selected so that the wave follower can comfortably reach the surface while sitting on its pedestal on the bottom. Since the design specifications envisage using the follower in water depths up to 15 m without restriction, it will be mounted on an adjustable, guyed tower for depths between 2.5 m and 15 m. If it proves necessary to work in depths shallower than 2.5 m the configuration and dimensions of the follower itself will have to be redesigned. One way

to make a shallow water follower would be to use a piston having a shorter stroke, on the order of 15 to 30 cm, which would reduce the overall length to approximately 60 to 90 cm and allow its use in water 90 to 120 cm in depth. The shorter stroke would be no handicap for generation studies since the waves in shallower water in the lee of a shore will be smaller. For even shallower water, the advantages from submerging the wave follower could be sacrificed and precautions taken to minimize interference with the wind.

B. Longer vertical drifts

At the present, vertical scanning is achieved by adding a ramp to the wave probe signal. (See §V.C.5.) This requires a wave probe as long as the scan itself. However, if a separate scanning mechanism were attached to the piston rod, a wave probe only 10 cm long would suffice. This would relax the full-scale accuracy requirement on the wave probe, and would permit longer vertical scans. This mechanism would also serve to adjust the tracking height of the hot-wire probe. Alternately, a completely separate drifting mechanism could be designed.

C. Location at greater distances

The wave follower is designed to be located no farther than 40 m from the control station. This distance is insufficient for the experiment planned for Aruba where one or more wave followers may have to be separated by as much as 800 m from the control station. Pressure drop and handling make it clearly impractical to run hydraulic cables

to such distances, and even electric cables present problems. At such distances a self-contained hydraulic power supply, mounted either in or under the wave follower, will be necessary. The two long hydraulic cables thus reduce to a single electric cable to control the hydraulic pump. The electric signals to and from the wave follower may have to be telemetered if the 800 m of electric cable proves too noisy at such distances.

D. Two- or three-axis hot-wire probes

Again, for the purposes of testing the feasibility of using hot-wire probes near the water surface, the wave follower carries only a single-channel anemometer. If hot-wire contamination can be overcome, the next step is to use a two- or three-axis anemometer. This requires the addition of one or two extra circuit boards and the installation of more cables through the piston rod. The latter is the harder of the two since the piston rod is rather fully stuffed, and the two retractable cords connecting the moving spider and the stationary electronic systems are already rather bulky. See Fig. 26. Nevertheless, this does not seem to be an insuperable difficulty. In addition, of course, more conductors (or multiplexing) in the electric cable would be required to send back the extra signals.

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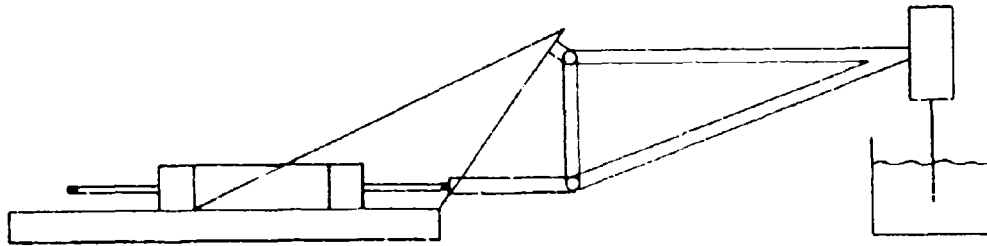


Fig. 1. Schematic of right-angle lever wave follower.

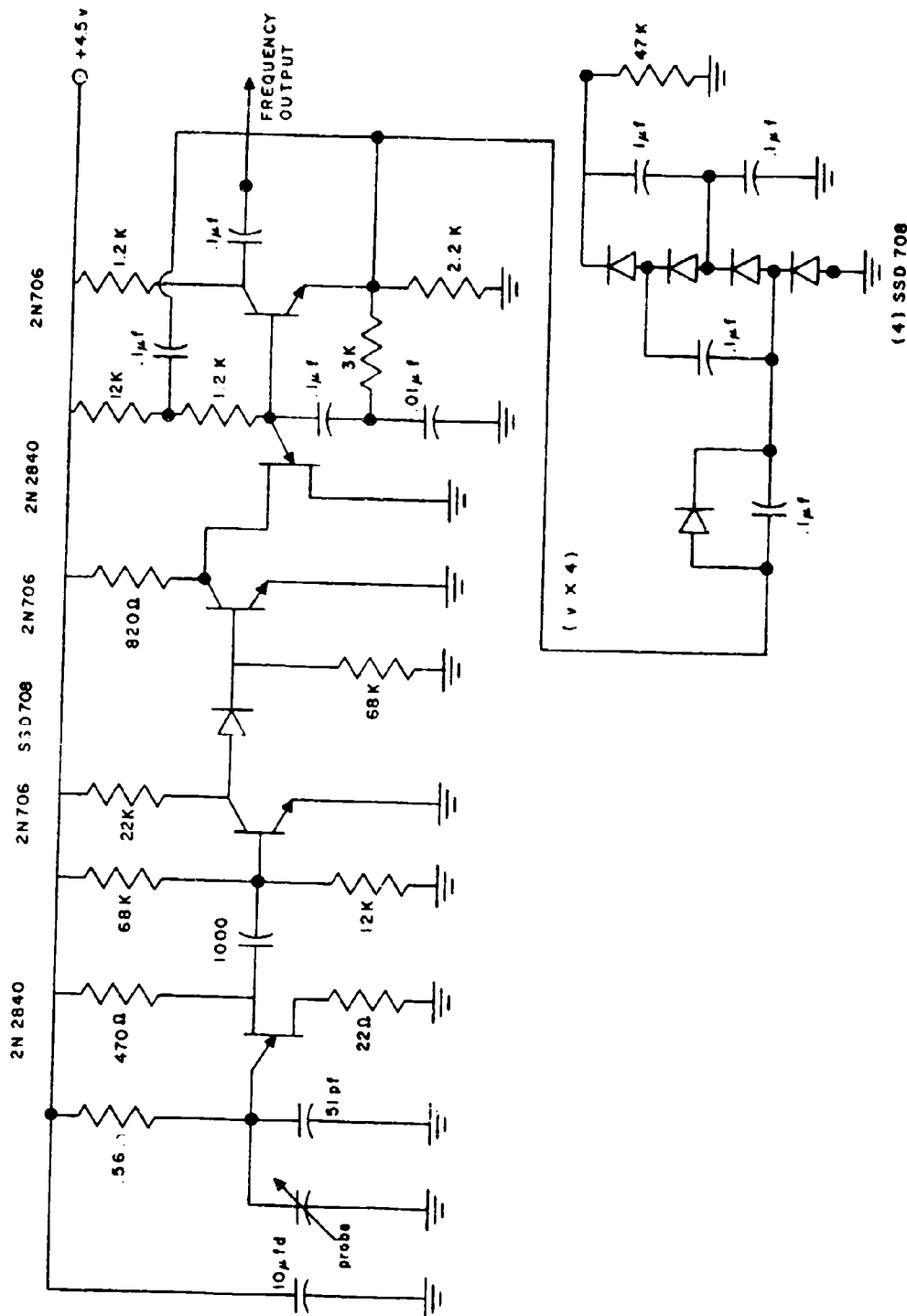


Fig. 2. Wave probe circuit using a relaxation oscillator.

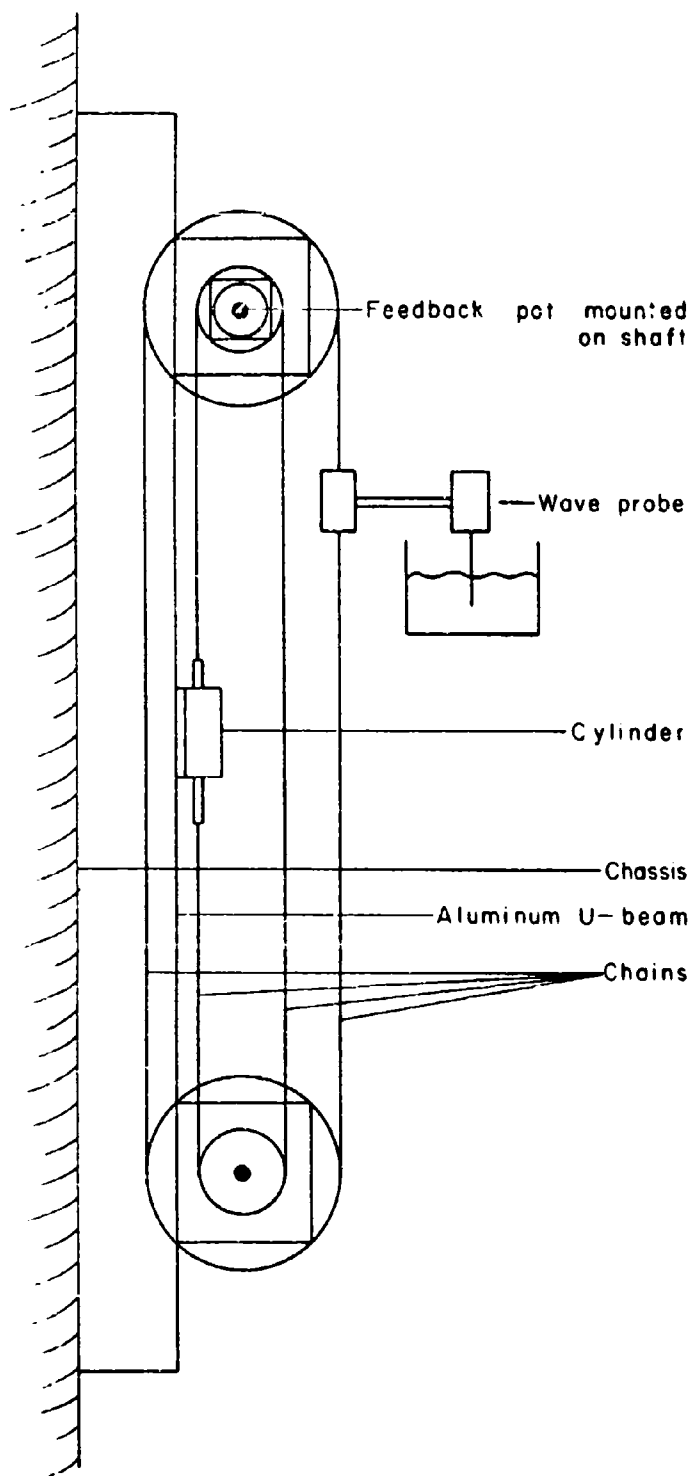


Fig. 3. Schematic of cog wave follower.

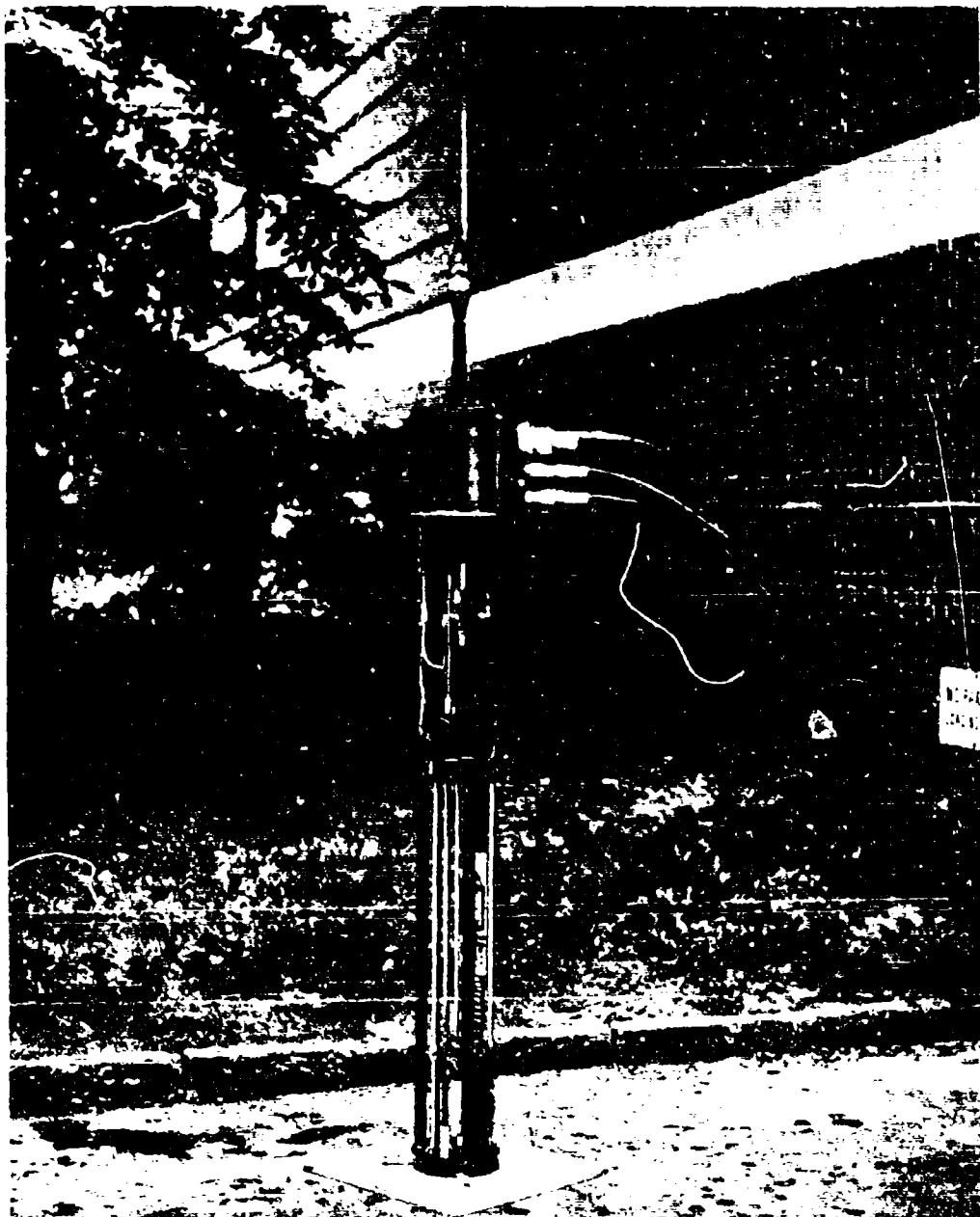


Fig. 2. Chassis of wave follower, with cover removed.

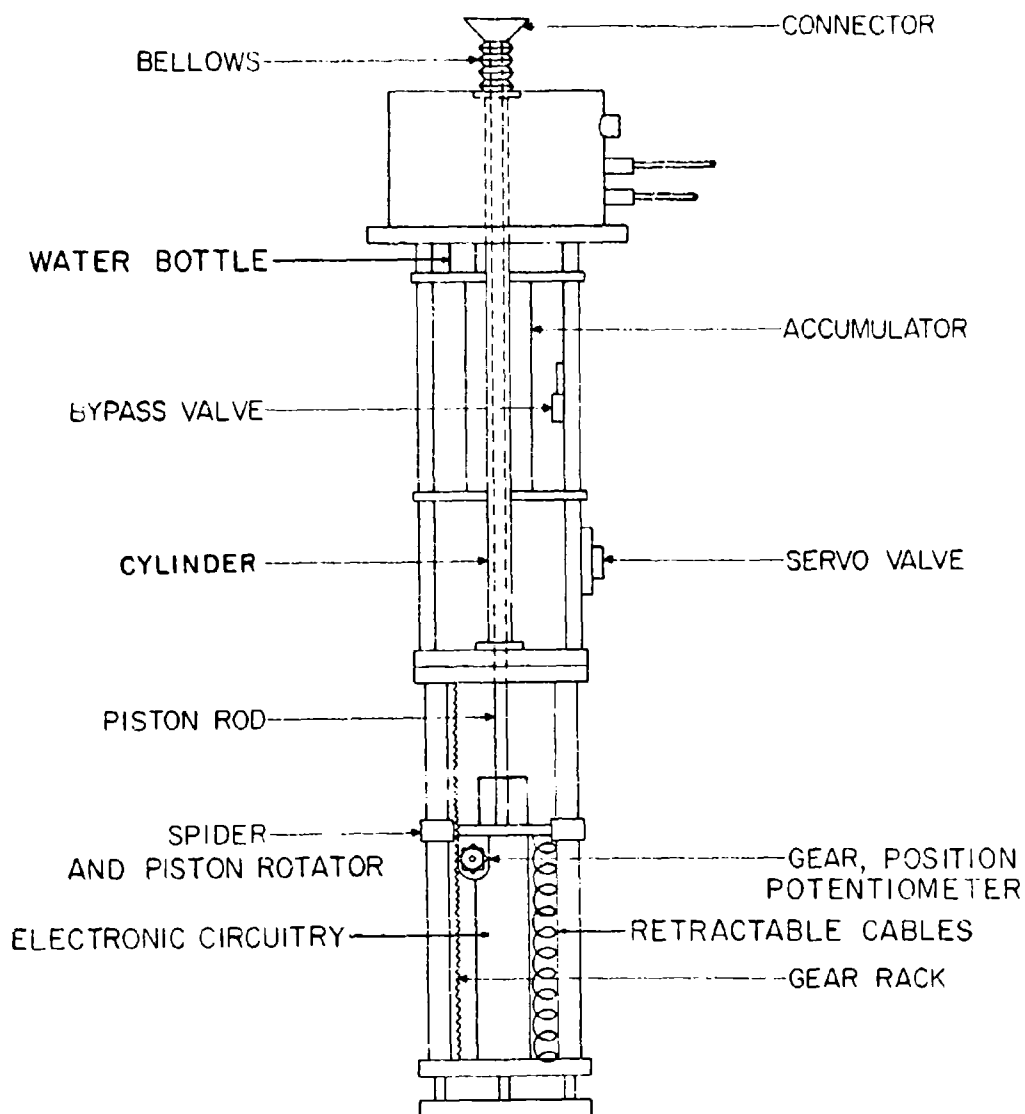


Fig. 5. Schematic of wave follower, with locations of major components.

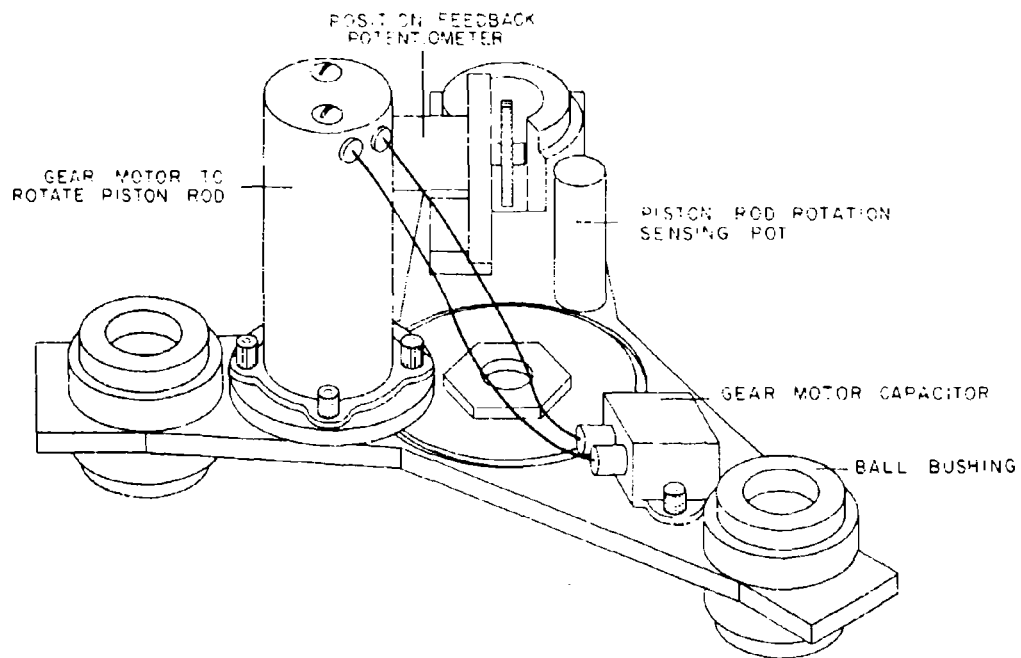
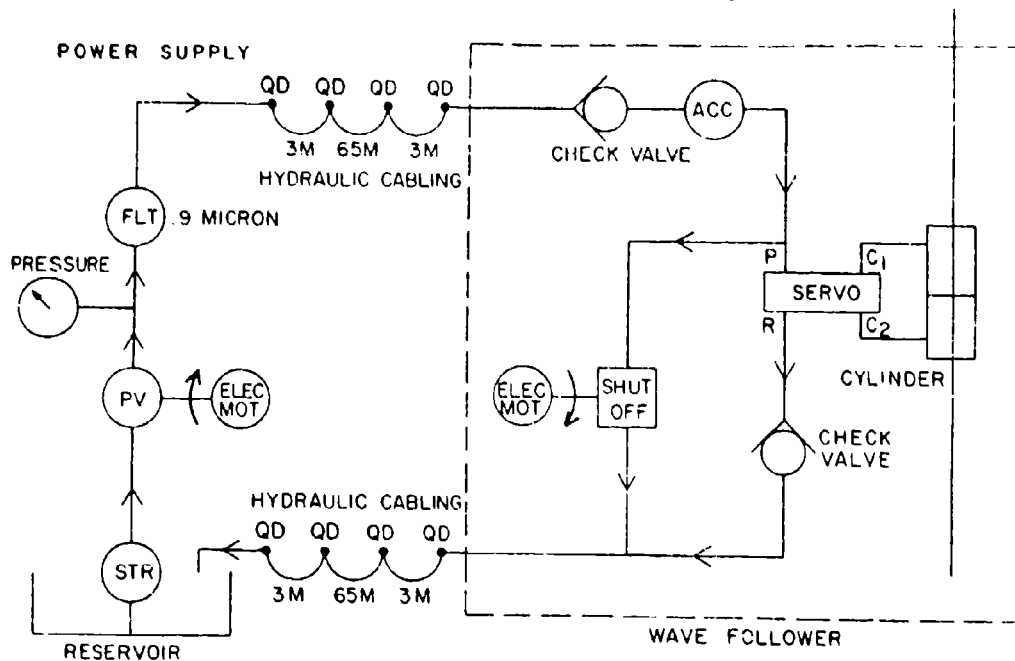


Fig. 6. Schematic of the "spider."



Fig. 7. The hydraulic section of the wave follower.

WAVE FOLLOWER HYDRAULIC SCHEMATIC



NOTE QUICK-DISCONNECT FITTINGS INDICATED BY "QD"
ELECTRICAL SIGNAL PATHS NOT SHOWN.

Fig. 8. Hydraulic schematic of wave follower, connectors, and hydraulic power supply. Filling and purging system (See Section V.E.2.) not shown.

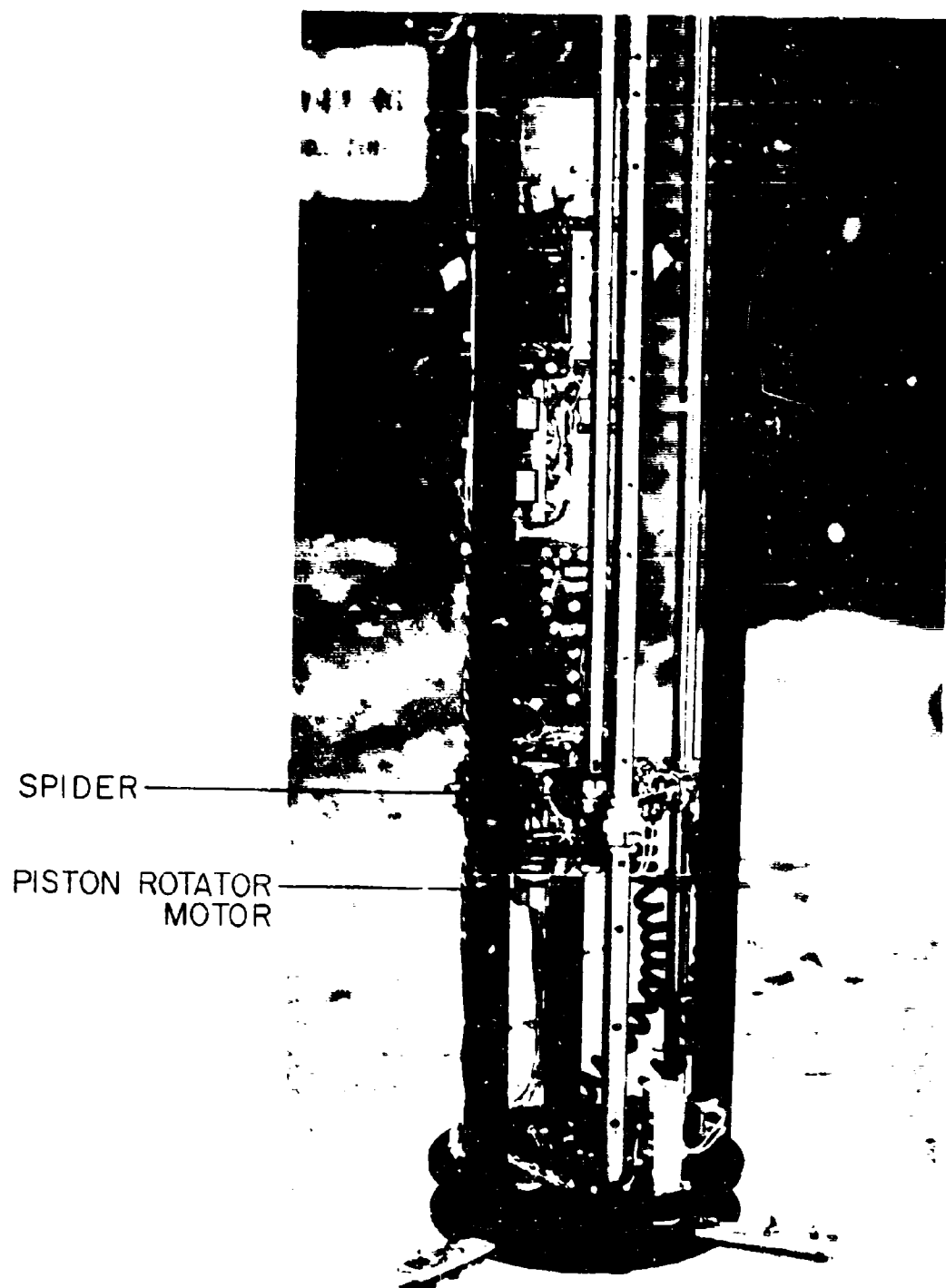


Fig. 9. Electronic portion of wave mill.

Fig. 10. Block diagram of wave follower control system, with limit detectors, acceleration limit, and ramp generator.

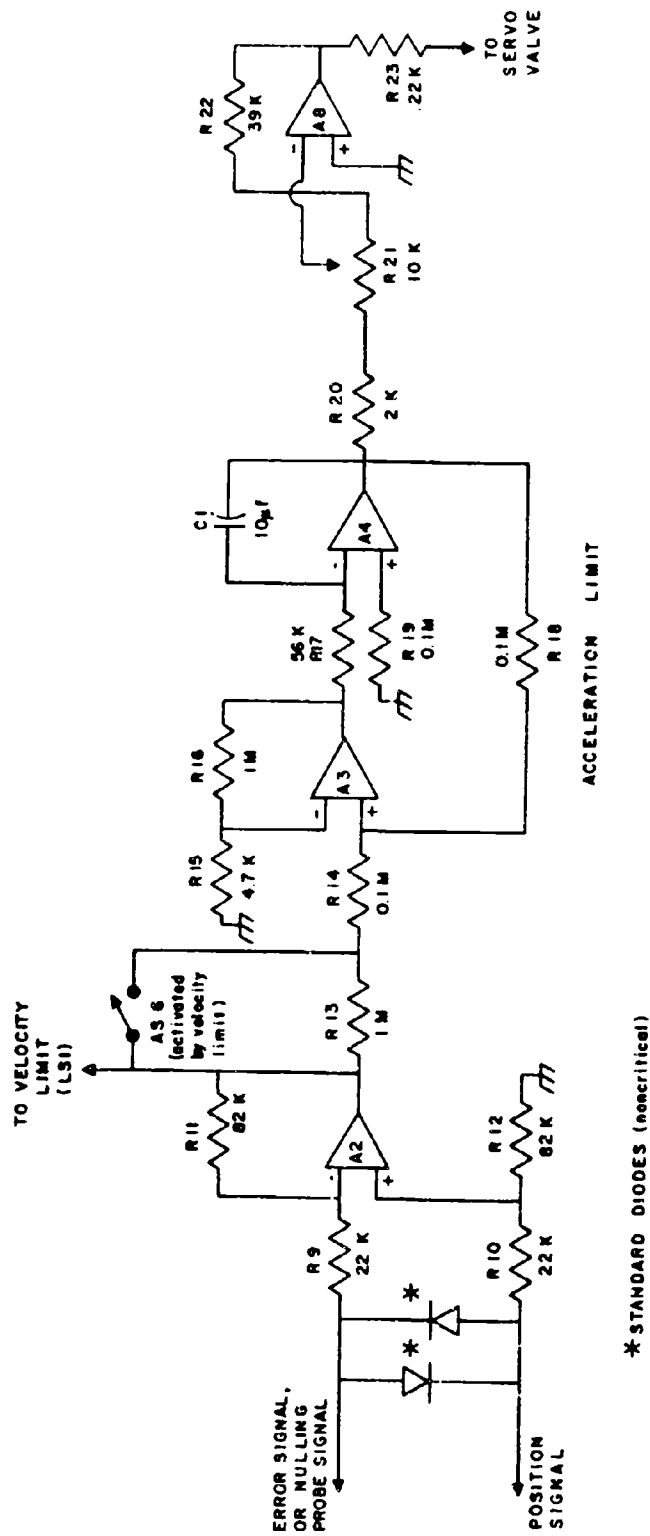


Fig. 11. Feedback amplifier, acceleration limit, and velocity limit showing change of gain circuit.

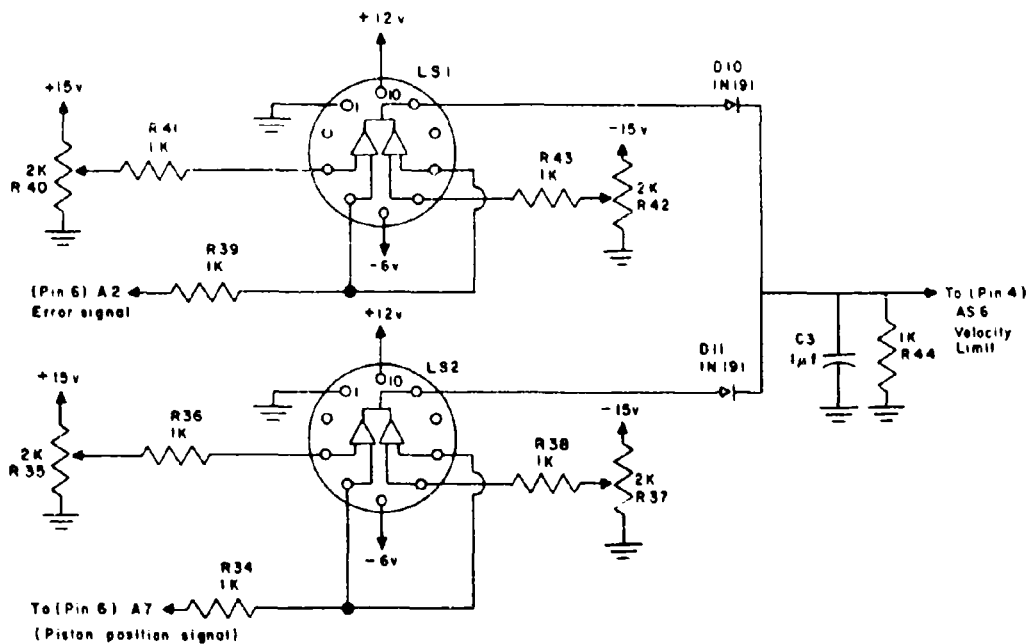


Fig. 12. Velocity limit and end stop sensors.

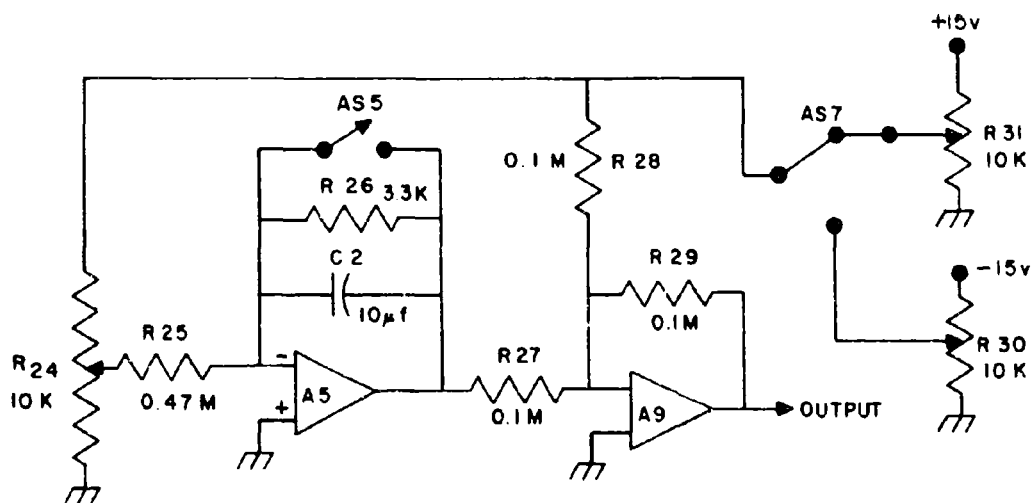


Fig. 13. Ramp generator for drift mode.

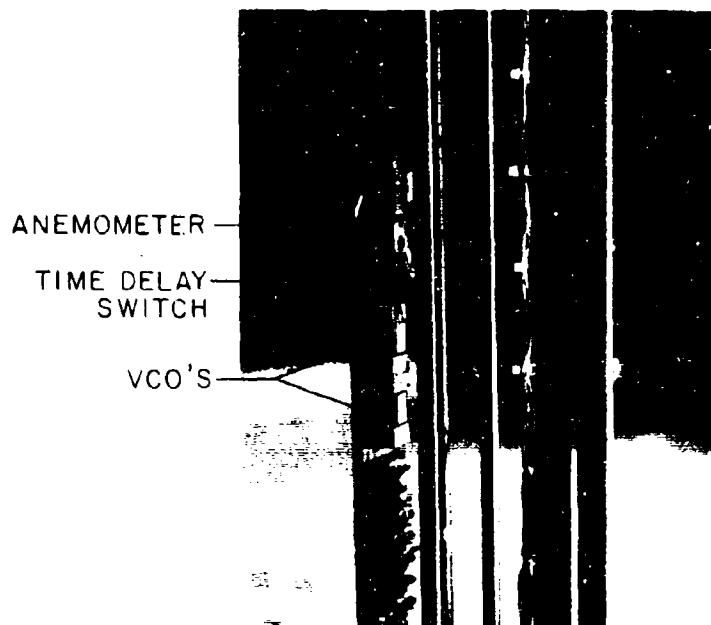


Fig. 14. Location of VCO's, hot-wire anemometer circuit, and time-delay switch on plate in electronic section of wave follower.

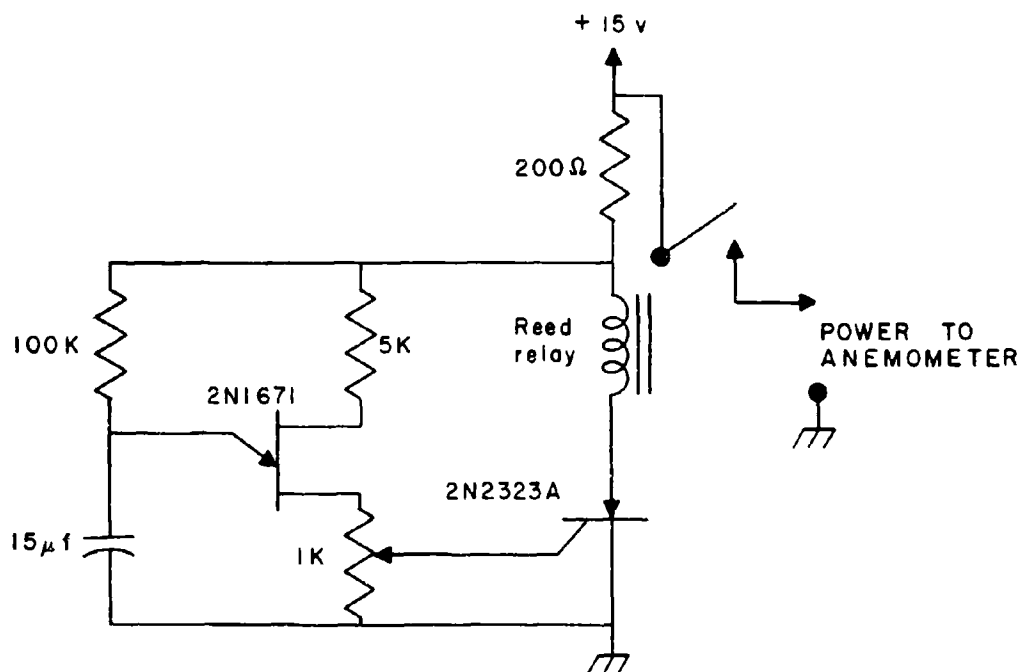


Fig. 15. Time-delay switch for anemometer.

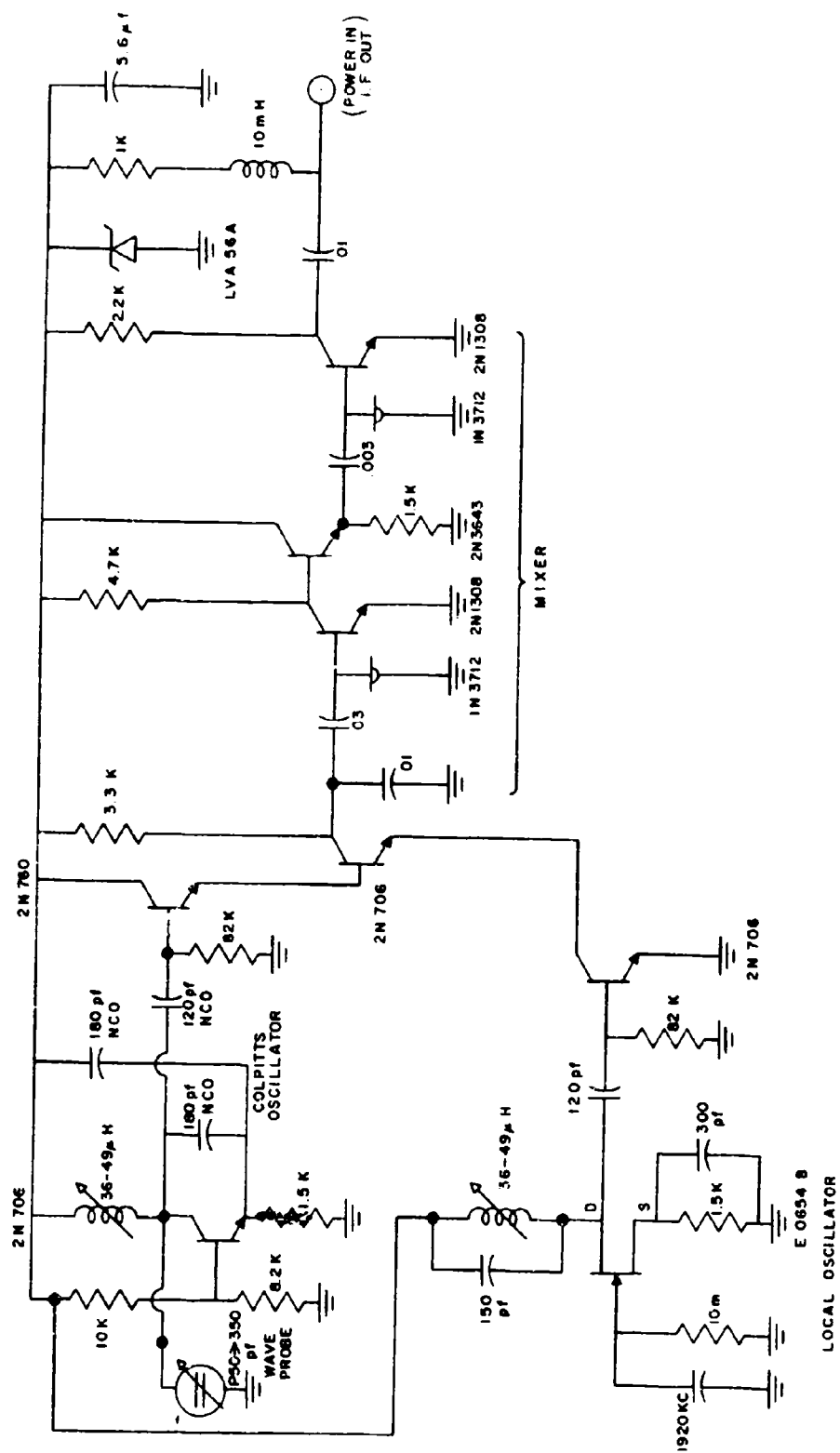


Fig. 16. Nulling probe electronics contained in the nulling probe bracket-Colpitts oscillator, local oscillator, and mixer.

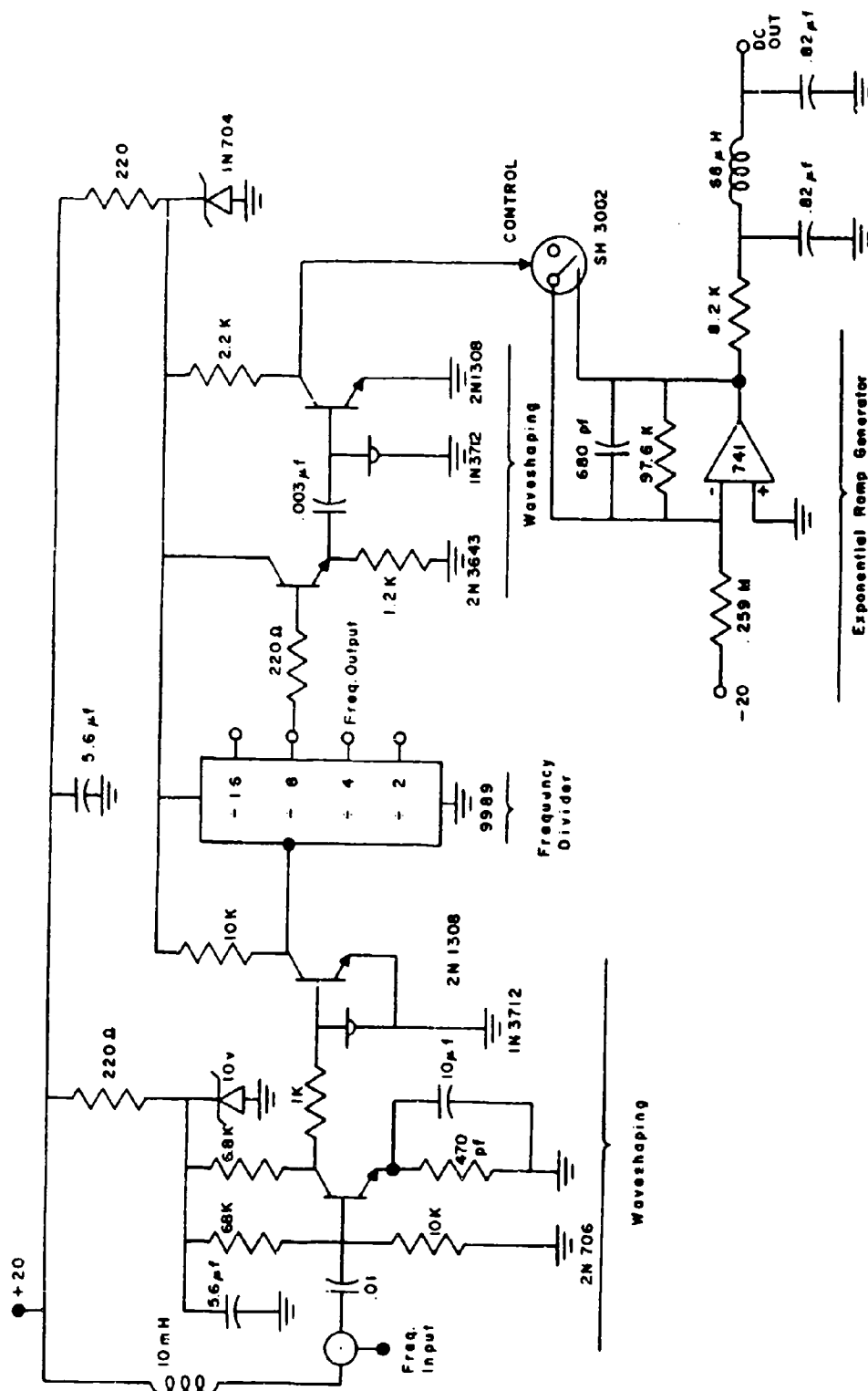


Fig. 17. Nulling probe linearizer.

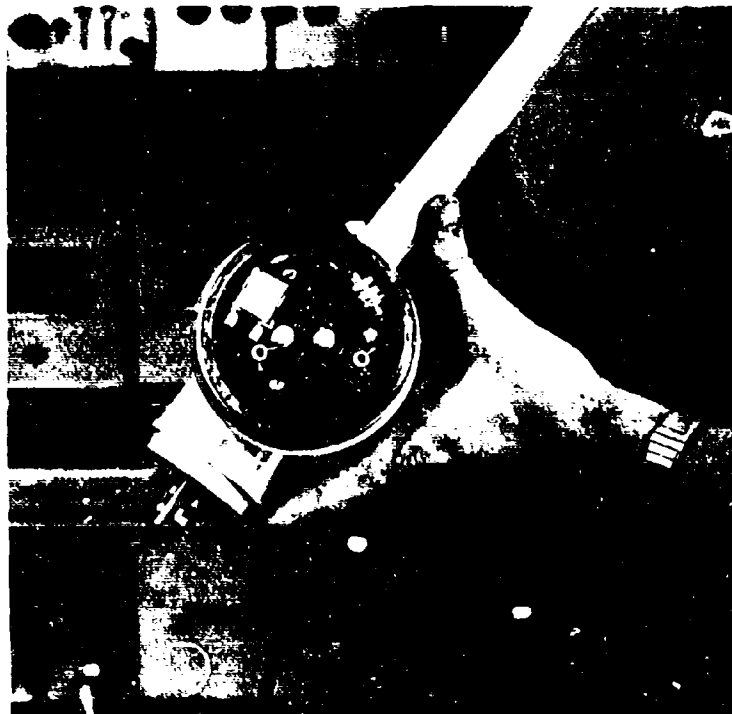


Fig. 18. Location of nulling probe electronics in the nulling probe bracket.

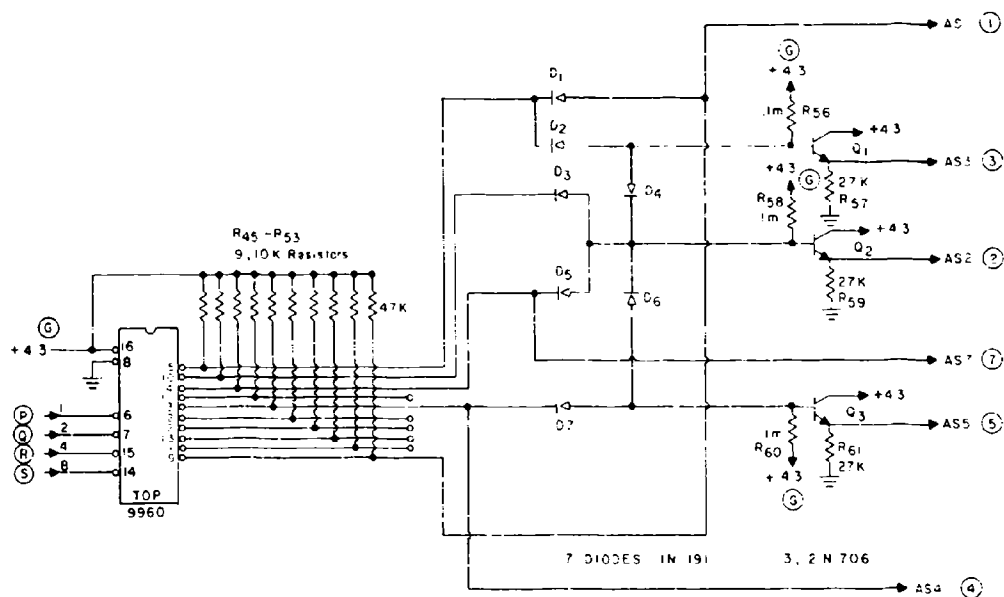


Fig. 19. Logic for the remote control audio changing system.

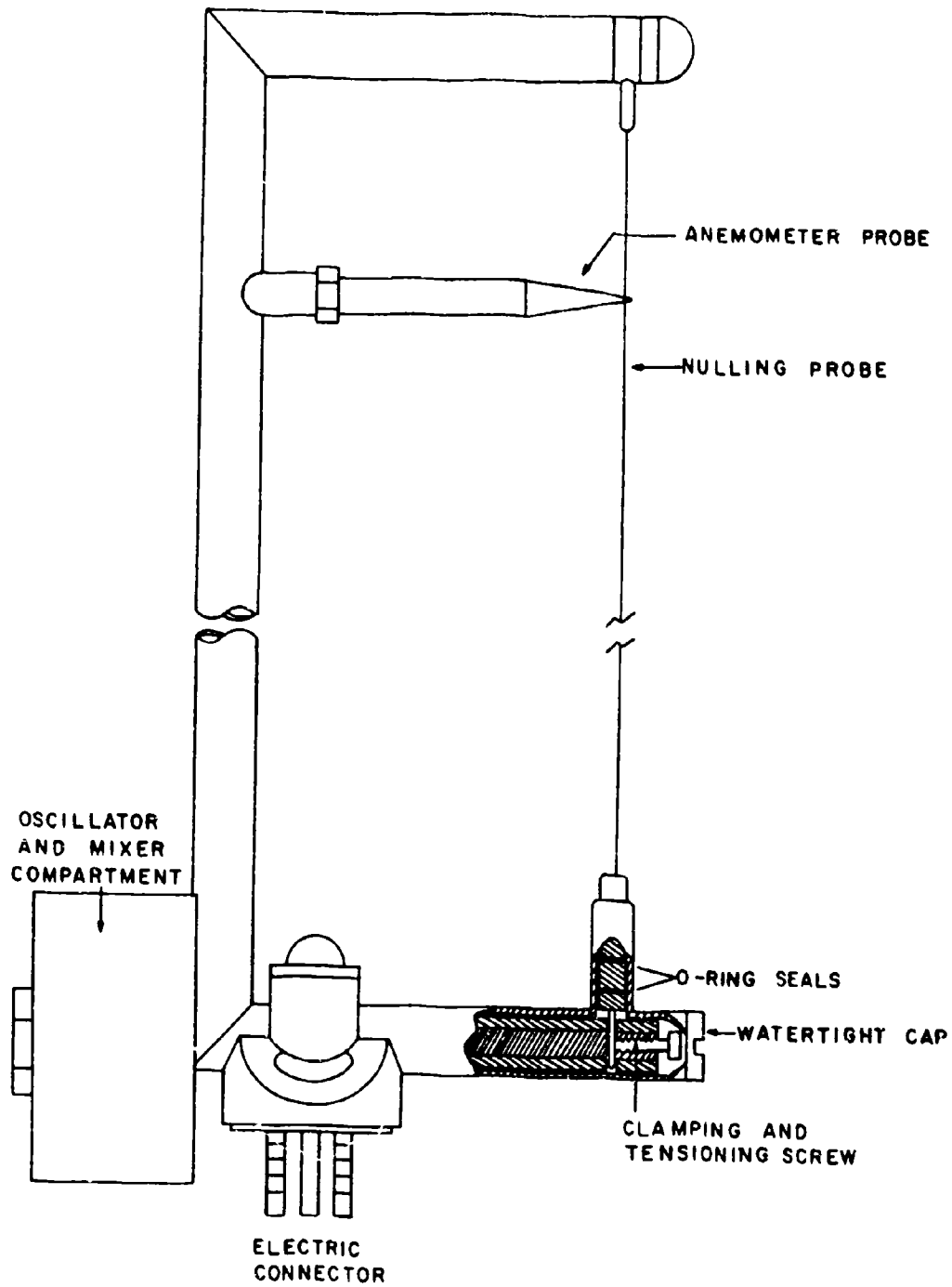


Fig. 20. Nulling probe and hot-wire probe bracket.

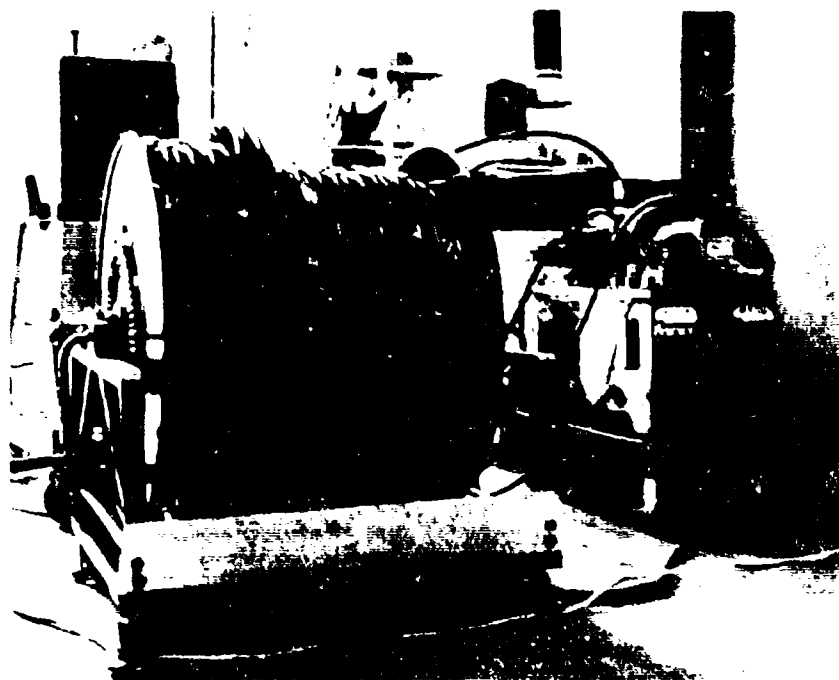


Fig. 21. Cable reel and hydraulic power supply.

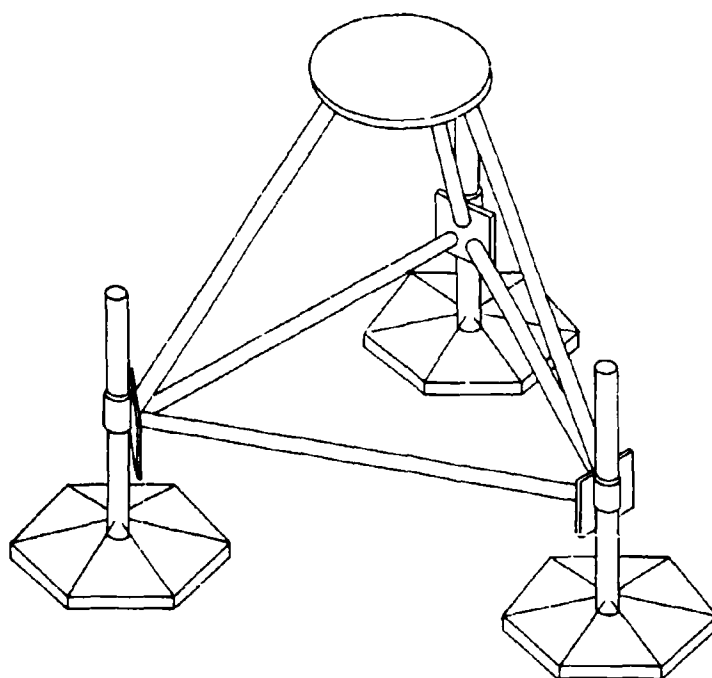


Fig. 22. Mounting pedestal.

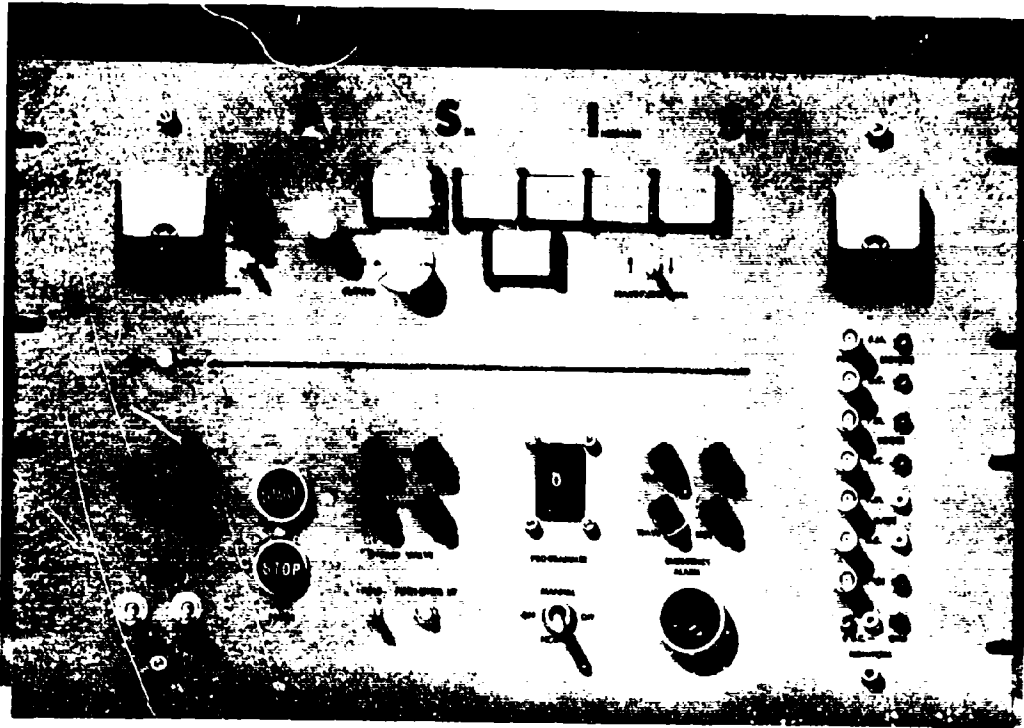
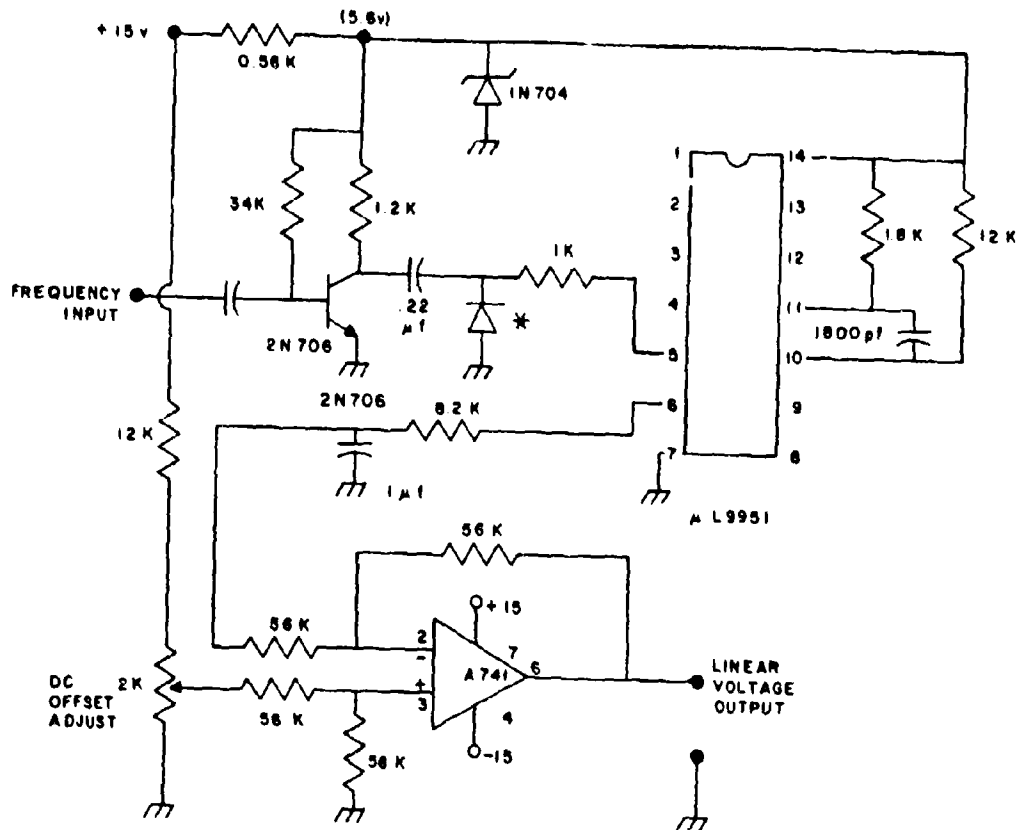


Fig. 33. Control panel.



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Fig. 24. Quick-look pulse-averaging discriminator.

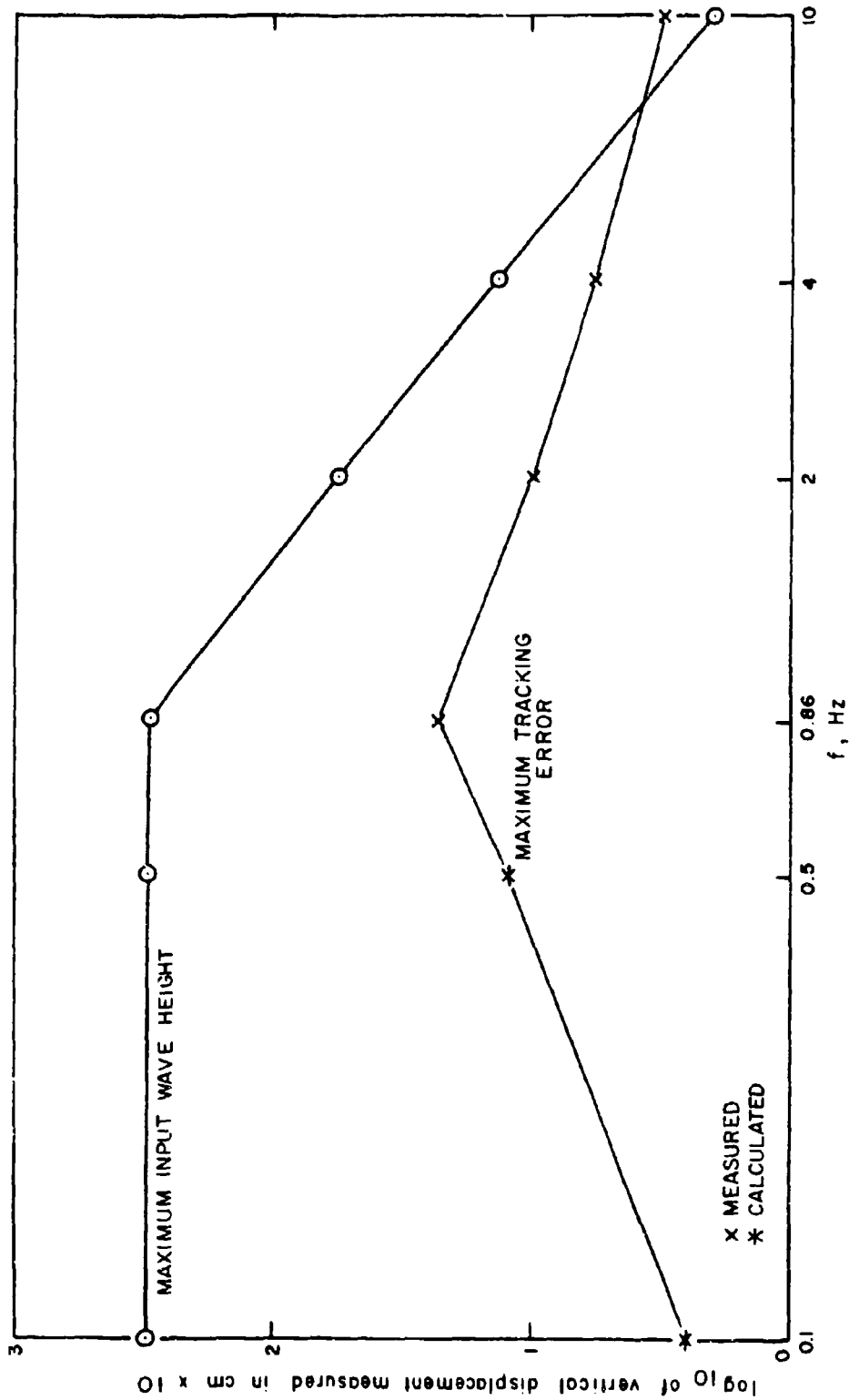


Fig. 25. Sine wave response curves of the wave follower: maximum error and maximum amplitude vs. frequency.

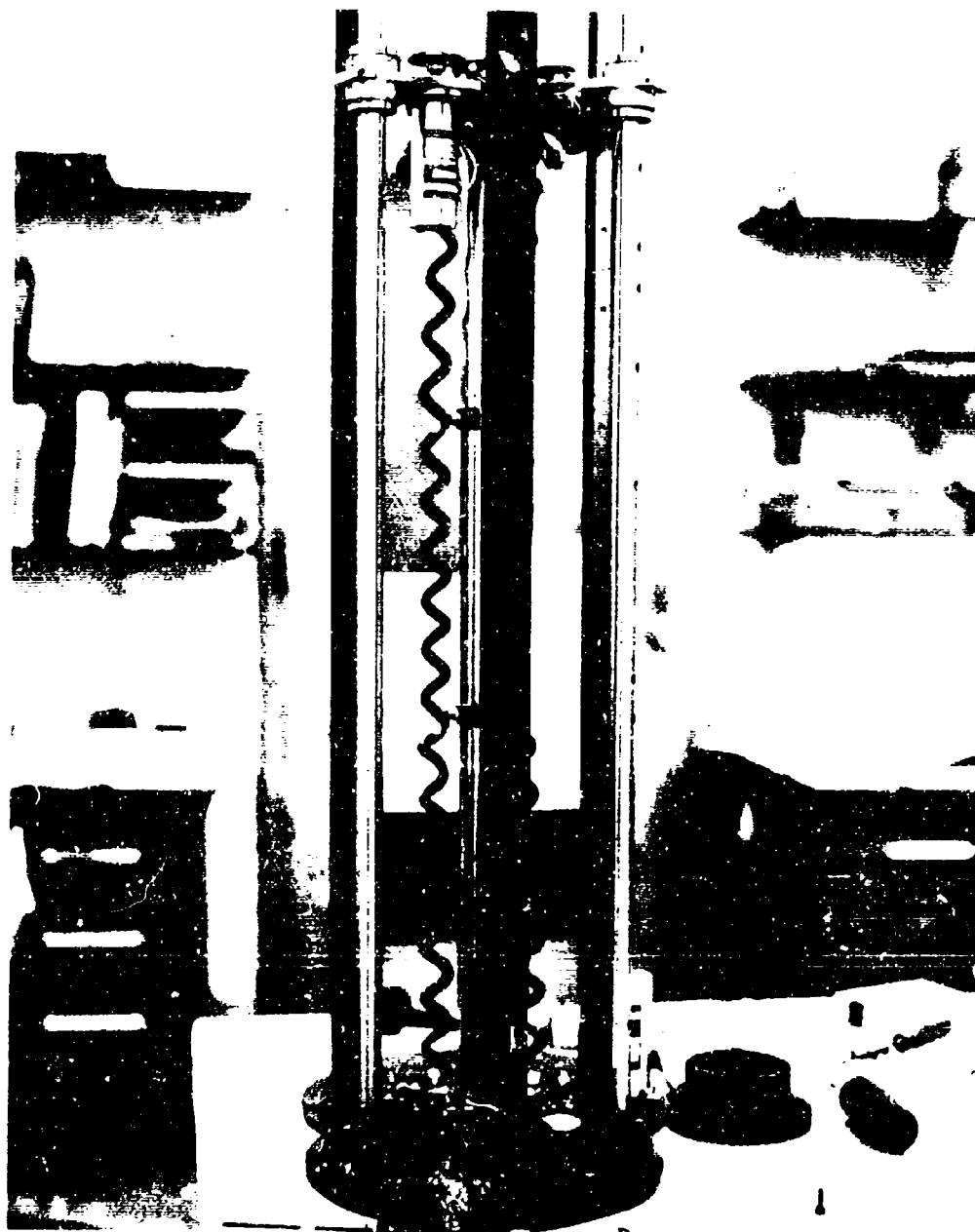


Fig. 26. Spider and retractable coris.

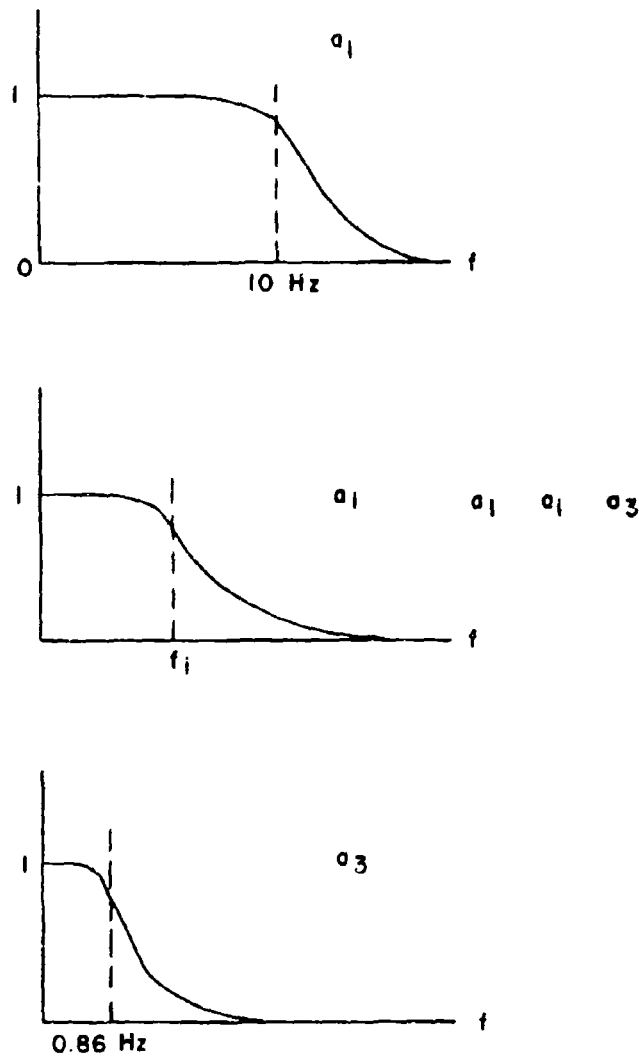


Fig. 27. Family of frequency response functions for a system when the amplitude of the input signal is included as a parameter.

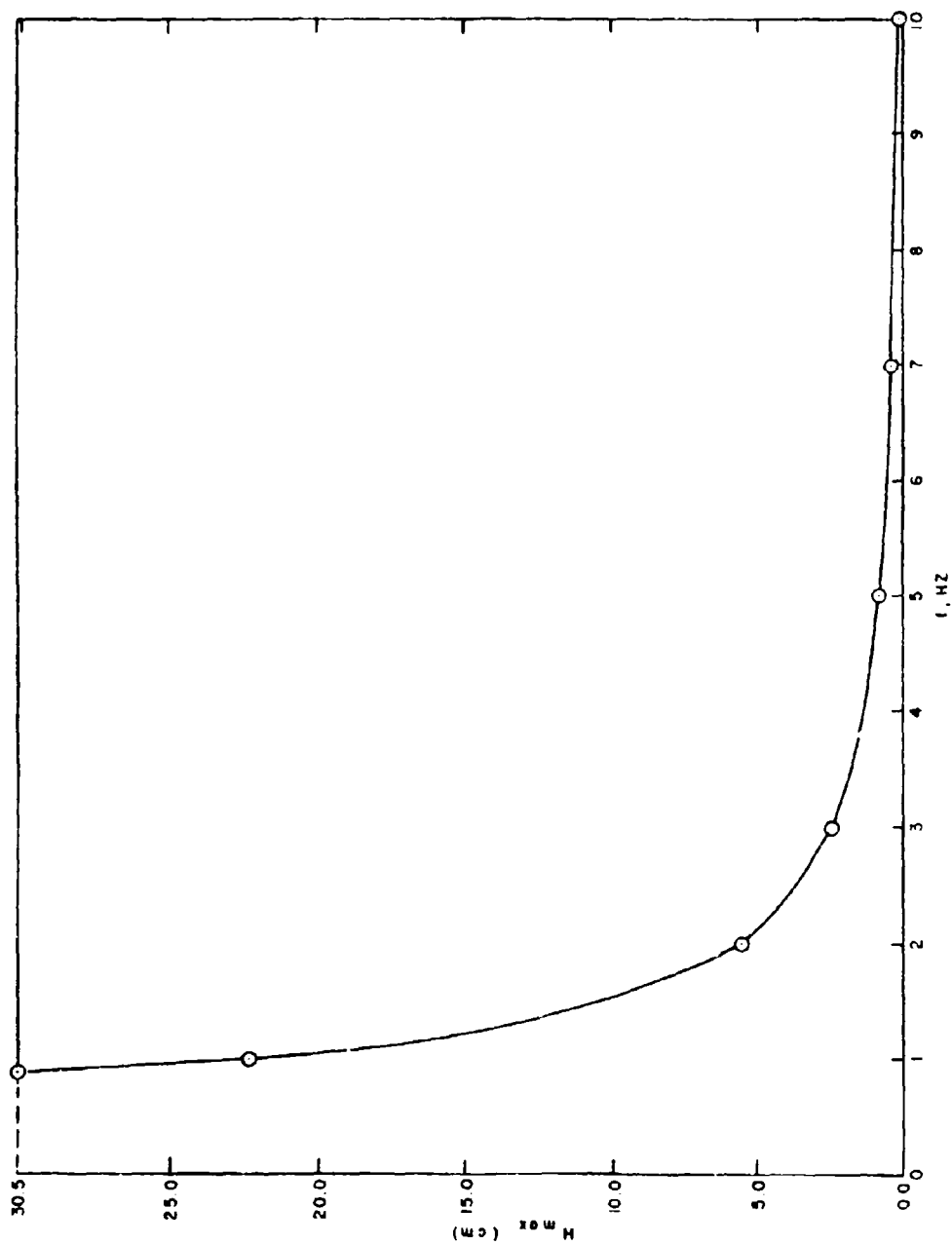


Fig. 28. Maximum wave height as a function of frequency.

APPENDIX A

It is customary to ignore the amplitude dependence of frequency response functions. If the response of an instrument is said to be flat to 10 Hz the tacit understanding is that it remains flat when the instrument is subjected to an input signal of any amplitude. This, of course, is never strictly true except for conceptual systems. Figure 27 illustrates the real state of affairs. If the frequency response function is interpreted in the usual way, the engineer is required to design a system for which the frequency response function is flat for the greatest possible amplitude combined with the highest possible frequency. This combination poses a design problem which is often unnecessarily difficult and overly stringent for the use for which the instrument is intended. This is certainly the case with the wave follower.

Both observation and theory abundantly confirm the fact that ocean wave heights and ocean wave frequencies are not free to occur in every combination. For any given frequency there is a height beyond which the wave can not grow without becoming unstable and breaking. An estimate of the maximum height to be expected as a function of frequency can be very simply derived from the theory of the Stokes wave. (See Kinsman, 1965, pp. 248-258 and 271-274.) The maximum height that a wave can attain in relation to its length is $H_{max}/L \sim 1/7$. Observation shows that the extreme value is seldom encountered at sea. For deep water waves the length and the frequency are related by $2\pi f^2 \sim g/L$ where g is the acceleration of gravity.

Thus the maximum height as a function of frequency is

$$H_{\max} \sim \frac{g}{14\pi f^2} = \frac{22.3}{f^2} \text{ cm} \quad . \quad (\text{See Figure 28.})$$

Our wave follower is intended for generation studies during the initial period of formation and will be used only under conditions where the longer waves (lower frequencies) are small. There is therefore no difficulty in getting a satisfactory response at frequencies less than 1 Hz. Above 1 Hz each frequency f_i identifies a maximum height $H_{\max_i}$ which in turn selects a value of the parameter a_i and an appropriate response curve. If for each f_i in the range from 1 to 10 Hz the response curve selected is still flat at f_i then the instrument will be satisfactory. To insist that it be flat at $f_j > f_i$ for amplitudes corresponding to $H_{\max_i}$ is a waste since $H_{\max_i} > H_{\max_j}$. (See Fig. 27.)

It is our opinion that situations of this sort occur with sufficient frequency to make it worthwhile for design engineers to keep the amplitude dependence of the frequency response function well in mind.

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13. ABSTRACT In studies of wave generation an exploration of the wind field close to the water surface is critical. Such an exploration can be made with a hot-wire or film anemometer mounted on a device driven by a servomechanism which will maintain the anemometer at a fixed distance from the fluctuating water surface. This report describes the CBI Wave Follower which has been designed to hold anemometers at fixed distances from 60 cm to 1 cm from the water surface. It may be used with waves up to 30 cm in height. It allows adjustment for tidal changes in mean water elevation up to 60 cm and for slow vertical scanning.		

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Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Feedback control system						
field instrument						
Hot-wire anemometer						
Hydraulics						
Wave follower						
Wave probe						
Wind wave generation						

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