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VARIABLE BAND-PASS WAVE RECORDER AND ITS USE AT USNEL OCEANOGRA--ETC(U)
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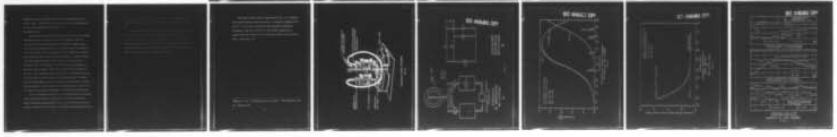

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⑨ Technical memo., ⑭ NEL-TM-668

~~TECHNICAL MEMORANDUM~~ ~~TM-668~~

⑥ VARIABLE BAND-PASS WAVE RECORDER AND ITS USE AT USNEL OCEANOGRAPHIC TOWER.

⑪ 26 Feb~~ruary~~ 1964 ⑫ 20p.

SR 004 03 01 (0580)
NEL L4-4

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⑯ SR00403

⑰ SR0040301

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Variable Band-Pass Wave Recorder and its Use at USNEL Oceanographic Tower

Robert R. Smith

Introduction

A pneumatically filtered wave recorder was built, using a Wiancko type P2-1306 differential pressure transducer as the sensing device. The pneumatic filters are analogous to electrical RC-circuits, passing waves only in a desired pass band. With the proper choice of filters, the tide or swell or both can be attenuated to a great extent. Hence the record obtained is free from "swell noise" so that longer period waves can be seen.

The wave recorder is used on the USNEL Oceanographic Tower, and filters are chosen to attenuate swell by a factor of 100, and the semidiurnal tides by a factor of 1.2. With the equipment set up in this way, waves with periods from 3 minutes to 3 hours are detectable. The minimum detectable wave height is a function of frequency, but over most of the pass-band range, waves with 0.30 ft peak-to-peak amplitude can be detected.

This type of pre-filtering wave recorder has the advantages of making data quite easy to reduce and allowing data on wave phenomena in certain pass bands to be taken by direct methods. If swell is not attenuated, some sort of electronic or digital filtering is necessary and data cannot be taken on a strip chart recorder for long periods of time.

[redacted]

Apparatus

An inner tube is used as a pressure sensor. It is connected to two air chambers by tubes containing resistive materials. The air chambers are then connected across the differential pressure transducer. (See figures 1 and 2a). The chambers are identical solid-wall volumes which, in the electrical analogue, serve as capacitors. The resistive material was a Millipore® filter, which is similar to filter paper but of very small porosity. By choosing various pore sizes and exposing various surface areas to the air pressure from the inner tube, the flow rate through these filters can be adjusted. The filters are glued to aluminum discs with holes through the middle of them. These discs, with the filters on them, are analogous to electrical resistors. Many such discs were made with various flow rates in order to have a choice of resistances.

Mechanically, a resistive disc in series with a chamber is analogous to an electrical RC-filter. Since there are two such systems in parallel with each other, the total effect is that of a band pass filter as shown in figure 2. Each RC-filter must be calibrated to find $\tau = RC$, which determines the response of the wave recorder for any two filters.

The two chambers are connected by copper tubes to the third chamber, which contains the pressure transducer. A solenoid valve inside the latter chamber connects both tubes when power to the solenoid is off. This safety device protects the pressure transducer from overload while the equipment is being lowered. In connecting this tubing, Swagelok® fittings, which proved superior to the conventional flange fittings, are used.

Electrical connections are supplied by a 4-conductor cable which is passed through a stuffing gland and extends to the platform at the surface. Twenty-eight volt DC across two conductors supplies both the solenoid valve and the pressure transducer. The other two conductors are connected to the pressure transducer output.

Because the wave recorder is somewhat temperature sensitive, a thermistor is included in the apparatus within six inches of the air chambers to get a simultaneous temperature record with the pressure record. A bridge* made at NEL for the particular thermistor used is employed to obtain a linear voltage response from 9° to 19°C. Both the temperature and pressure are recorded on a two-channel recorder.

Theory

Assume that a filter is subjected to a pressure variation $p(t) = p_s + p_0 \sin \omega t$. As seen in figure 2, the filters are equivalent to RC-filters, where

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*Olson, J. R., and D. F. Brumley, "Optimum Parameters for Linearizing Thermistor Temperature Bridges," NEL Technical Memorandum 460.

$$C = \frac{n_o}{p_s} = \text{capacitance},$$

$$r = \frac{\Delta p}{\left(\frac{dV}{dt}\right)} = \frac{\Delta p}{\left(\frac{dn}{dt}\right)\frac{RT}{p_s}} = \text{resistance, assuming } p_o \ll p_s{}^{*},$$

where

n_o is the number of moles in the chamber at p_s,

T is the temperature, °Kelvin,

R is the universal gas constant,

$\frac{dn}{dt}$ is the rate of change of the number of moles of gas in the chamber if the pressure difference across the resistance is Δp.

The differential equation in steady state is

$$p_s + p_o \sin\omega t - r\frac{dV}{dt} - \frac{n}{C} = p_s + p_o \sin\omega t - r\frac{RT}{p_s}\frac{dn}{dt} - \frac{n}{C} = 0.$$

Assume a solution $n_o(t) = A\sin(\omega t - \phi) + K$.

Then

$$p_s + p_o \sin\omega t - r\frac{RT}{p_s}A\omega\cos(\omega t - \phi) - \frac{A}{C}\sin(\omega t - \phi) - \frac{K}{C} = 0.$$

Solving this equation and using the fact that $\sin\omega t$ and $\cos\omega t$ are orthogonal, we get

$$A = \frac{p_o}{\left[\omega r\frac{RT}{p_s}\tan\phi + \frac{1}{C}\right]\cos\phi}, \quad \phi = \tan^{-1}\left(\frac{rRT\omega C}{p_s}\right),$$

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[*] Snodgrass, F. E., "Operational Manual Shore Wave Recorder Mark IX, Model 5, "Univ. of Calif., Inst. of Eng. Research, Series 3, Issue 364, June, 1954, pp. 16-17.

and $K = p_s C$.

Hence $n_0(t) = \dfrac{C\, p_0}{\sqrt{1+\left(\frac{rT\omega CR}{p_s}\right)^2}} \sin(\omega t - \phi) + p_s C$, $\phi = \tan^{-1}\left(\dfrac{rRT\omega C}{p_s}\right)$.

The corresponding time dependent pressure in the chamber is

$$p_c(t) = \frac{n_0(t)}{C} = \frac{p_0}{\sqrt{1+\left(\frac{rT\omega CR}{p_s}\right)^2}} \sin(\omega t - \phi) + p_s .$$

But $C = \dfrac{n_0}{p_s} = \dfrac{V}{RT}$

so $$p_c(t) = p_s + \frac{p_0}{\sqrt{1+\left(\frac{r\omega V}{p_s}\right)^2}} \sin(\omega t - \phi).$$

This is the same as the expression for an electrical RC circuit, with time constant $\tau = \dfrac{rV}{p_s}$.

Thus $$p_c(t) = p_s + \frac{p_0}{\sqrt{1+(\tau\omega)^2}} \sin(\omega t - \phi), \quad \phi = \tan^{-1}(\tau\omega).$$

Considering the case of a band-pass RC-filter with time constant τ_1 for one section and τ_2 for the other, the signal

$$p(t) = p_s + p_0 \sin \omega t$$

applied to both filters gives the outputs:

$$E_{01} = p_s + \frac{p_0}{\sqrt{1+(\tau_1\omega)^2}} \sin(\omega t - \phi_1), \quad \phi_1 = \tan^{-1}(\tau_1\omega),$$

$$E_{02} = p_s + \frac{p_0}{\sqrt{1+(\tau_2\omega)^2}} \sin(\omega t - \phi_2), \quad \phi_2 = \tan^{-1}(\tau_2\omega),$$

which are simultaneous inputs to the differential pressure transducer.

The output is $E_0 = E_{01} - E_{02}$

$$= \frac{p_0}{\sqrt{1+(\tau_1\omega)^2}} \sin(\omega t - \phi_1) - \frac{p_0}{\sqrt{1+(\tau_2\omega)^2}} \sin(\omega t - \phi_2).$$

Call $A_1 = \frac{p_0}{\sqrt{1+(\tau_1\omega)^2}}$, $A_2 = \frac{p_0}{\sqrt{1+(\tau_2\omega)^2}}$, and note that

$\cos\phi_1 = \frac{A_1}{p_0}$, $\cos\phi_2 = \frac{A_2}{p_0}$.

$$\begin{aligned} E_0 &= p_0[\cos\phi_1[\sin(\omega t - \phi_1)] - \cos\phi_2[\sin(\omega t - \phi_2)]] \\ &= p_0[\cos\phi_1(\sin\omega t\cos\phi_1 - \cos\omega t\sin\phi_1) \\ &\qquad - \cos\phi_2(\sin\omega t\cos\phi_2 - \cos\omega t\sin\phi_2)] \\ &= p_0[\sin\omega t(\cos^2\phi_1 - \cos^2\phi_2) + \cos\omega t(\sin\phi_2\cos\phi_2 - \sin\phi_1\cos\phi_1)]. \end{aligned}$$

Since $\sin \omega t$ and $\cos \omega t$ are orthogonal

$$\begin{aligned} E_{0\,\max} &= p_0\sqrt{(\cos^2\phi_1 - \cos^2\phi_2)^2 + (\sin\phi_2\cos\phi_2 - \sin\phi_1\cos\phi_1)^2} \\ &= p_0\sqrt{\cos^2\phi_1 + \cos^2\phi_2 - 2\cos\phi_1\cos\phi_2\cos(\phi_1 - \phi_2)}. \end{aligned}$$

This is response of the filter for any ω and any τ_1 and τ_2.

Observations at the NEL Oceanographic Tower are made using filters with time constants of $\tau_1 = 3.2$ minutes and $\tau_2 = 2.5$ hours. The net response for these two filters is plotted in figure 3.

Calibration

In the filters for which the time constant is less than one minute, a sinusoidally varying pressure head could be used to determine τ. However, where it is longer, a step function is applied to the chamber and τ determined from the response.

For sinusoidal pressure fluctuations, the response R is given by $R = \frac{1}{\sqrt{1+(\tau\omega)^2}}$. Several wave frequencies are applied to the system and plotted against response. From this graph the ω_0 for $R = 0.707$ is determined and τ is given by $\tau = \frac{1}{\omega_0}$

For step functions, τ is the time necessary for the chamber to change $(1 - \frac{1}{e})$ of the total step change in pressure. This is measured by recording the pressure in the chamber as a function of time.

From the theory, $\tau = \frac{rV}{p_s}$, where p_s is the static pressure. Hence the τ determined in these tests had to be converted to the τ associated with a head of 50 ft of water, which is the head used at the tower.

Observations

The wave recorder was lowered into about 50 ft of water at the USNEL Oceanographic Tower. The filtering was set up so that $\tau_1 = 3.2$ min and $\tau_2 = 2.5$ hrs at this depth. The response curve for these filters is given in figure 3. The wave height was recorded on a strip chart recorder with a full scale of ± 5 ft or ± 2.5 ft, depending on the magnitude of the tides. Temperature and pressure were recorded on a dual channel recorder. Because the wave recorder was temperature sensitive, if the temperature of the water changed 1°C, the pressure could change up to 3.2" of water. This temperature dependence is explained by Charles' law applied to the gas volume within the air chambers on the wave recorder. Because the two chambers were connected to the inner tube through different resistances, this pressure change did not leak from the chambers at the same rate and hence caused a pressure differential for certain frequencies of temperature changes. With the equipment set up in this way, data were taken continuously from 1300 on 21 Oct to 0900 on 25 Oct 1963, and from 0900 on 15 Nov to 1230 on 19 Nov 1963. These original data were then reduced further to optimize detection of any waves which may have been recorded on the original chart.

Reduction of Data

The data were reduced by playing the chart paper back through the recorder at a much higher tape speed and a voltage generated manually to reproduce the ordinate of the original data. This output was recorded on an FM tape recorder and then played back at a higher speed. The end result was a signal on tape that was the same as the original, but with a frequency multiplication of 192. A portion of this time-compressed record is shown in figure 5(b). All waves with period less than 3 minutes were filtered out by eye when the original data were traced. The data in this form were much more compact and easier to reduce.

The signal was filtered with successive band-pass filters using a Krohn-Hite band-pass filter to search for waves of various frequencies.

The time and date, period, amplitude, and number of oscillations of all waves with amplitude greater than 0.10 ft on the filtered record were measured. Hence any wave which appeared on the original record with amplitude greater than 0.20 ft was noted, since the gain of the filter was greater than 0.5 in all bands from 0.3 cycles/min to 0.3 cycles/hr. Since the response of the pneumatic filters was not unity for all frequencies and since the water depth attenuated the wave height for higher frequencies, the actual minimum wave height noted was a function of the period of the wave. (See figure 4). Any temperature changes which occurred at the time of the noted wave were taken from the original record.

Results

Every wave greater than 0.20 ft on the original was noted. The amplitude of any temperature change that occurred simultaneously with these waves was noted. The greatest possible effect on the pressure record which these temperature fluctuations may have caused was computed by Charles' law. In every case, the wave height predicted by Charles' law was within 25% of the actual wave height. Two possibilities are evident; (1) that the temperature fluctuations cause the pressure changes and no real waves are present, or (2) low frequency surface waves are present, implying that, in general, surface waves of these frequencies have internal waves (which cause the temperature fluctuations noted) associated with them. This problem was resolved when more data were taken from 15 Nov to 19 Nov. During this time, the temperature changed abruptly on three occasions, but remained constant both before and after each change. The pressure changed in a fashion similar to an RC-response, the amplitude change being within 10% of that predicted by Charles' law in all three cases. Figure 5(a) shows such a step change in temperature and the associated pressure response. The difference between the actual and predicted pressure changes is less than the accuracy of the strip chart recorder.

Assuming that there are no real waves with a waveform like that in figure 5(a), any temperature change of the right frequency (period of about ten minutes to one hour) will produce a corresponding pressure change in the gas. Thus, any pressure wave indicated by this system must be discounted as a possible surface wave if accompanied by a temperature change of appropriate magnitude.

As noted above, all pressure changes greater than 0.20 ft had temperature changes associated with them, the difference in actual pressure change and that predicted by Charles' law being always less than 25%. Figure 5(b) shows such a wave as it appeared on the time-compressed pressure record. By referring back to the original (shown in figure 5(c)), we see that these waves were accompanied by temperature fluctuations with magnitude of about 1.0°C. By Charles' law, the pressure fluctuations should be about 3.2" = 0.27 ft. The actual pressure change is about 0.30 ft. The difference between the actual and predicted pressure changes is less than the accuracy of the strip chart recorder. Hence temperature alone caused the pressure fluctuation. Without exception, the reduced pressure fluctuations and their associated temperature fluctuations were of appropriate magnitude to be explained by Charles' law. Also, there were a few cases where the temperature was constant for several hours and there were no visible pressure fluctuations during these hours of constant temperature. Since all waves greater than 0.20 ft. were reduced, there were no real waves greater than 0.20 ft on the original chart. Therefore, there were no real waves above the minimum detectable wave height during 21-25 Oct and 15-19 Nov.

The minimum detectable wave height is the minimum observed wave height on the original (in this case, 0.20 ft) divided by the response of the wave recorder and divided by the attenuation of wave height due to the depth of the recorder.* The minimum detectable wave height is a function of frequency and is plotted in figure 4. Since no waves were detected during the weeks noted, the maximum possible surface wave height is given by figure 4. For example, from the figure we see that there were no surface waves greater than 0.30 ft with periods between 18 min and 3 hrs. The response of the recorder is still high above 3 hrs, but

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*Snodgrass, F. E., "Ocean Wave Measurements," Univ. of Calif., Inst. of Eng. Research, Series 3, Issue 342, Aug 1952, Figure 22 (Pressure response factor for any submergence in any depth of water).

interference from the tides prevented detection of waves above this period. Also, no waves with period less than 3 min. could be detected because of interference from the swells.

Recommendations

The wave recorder has been used sufficiently to ascertain its high reliability over several weeks of continuous recording. The wave recorder is convenient for measuring wave height for long periods of time if the loss of data with periods near swell or tide is not important. Since the mechanical filter has a gradual cut-off, swell noise prevents observing waves with period less than three minutes. A better method to measure higher frequency waves would be to record all waves, including swells, on a magnetic F. M. Tape Recorder and bring these data back to the laboratory, where sharp cut-off electrical filters are available. This would permit attenuating swell to a sufficient extent and still retaining waves with frequency near swell frequency. The disadvantage of this method, which is not a problem with the wave recorder, is that large amounts of data would have to be taken and waves could not be recorded too long without a forbidding amount of data having been taken.

In this memorandum, the wave recorder was used only in the ocean, where swell and tide noise are appreciable. For other applications, where undesirable background noise may occur at different frequencies, the time constants of the system can be changed to measure any wave from

0.5 cps to one cycle per week or even greater. This versatility could make the instrument useful for measurements in lakes, bays, rivers, etc.

The readability of this instrument was only 0.20 ft because of swell noise. However, the pressure transducer has 0.1% linearity over a ± 2.0 p.s.i.d. range, so that the readability could be as low as .005 ft if the background noise were low enough. In small signal measurements, it might be necessary to temperature compensate the system or insulate the air chambers from any temperature variations.

The author wishes to express appreciation to Dr. A. A. Hudimac for the initial design, which was similar to a design Dr. Hudimac used in 1953,[*] of the wave recorder and many subsequent suggestions. Jay Burritt, Code 4343, also offered many helpful suggestions in construction of the recorder and coordinated the efforts of the machine shop, welding shop, etc.

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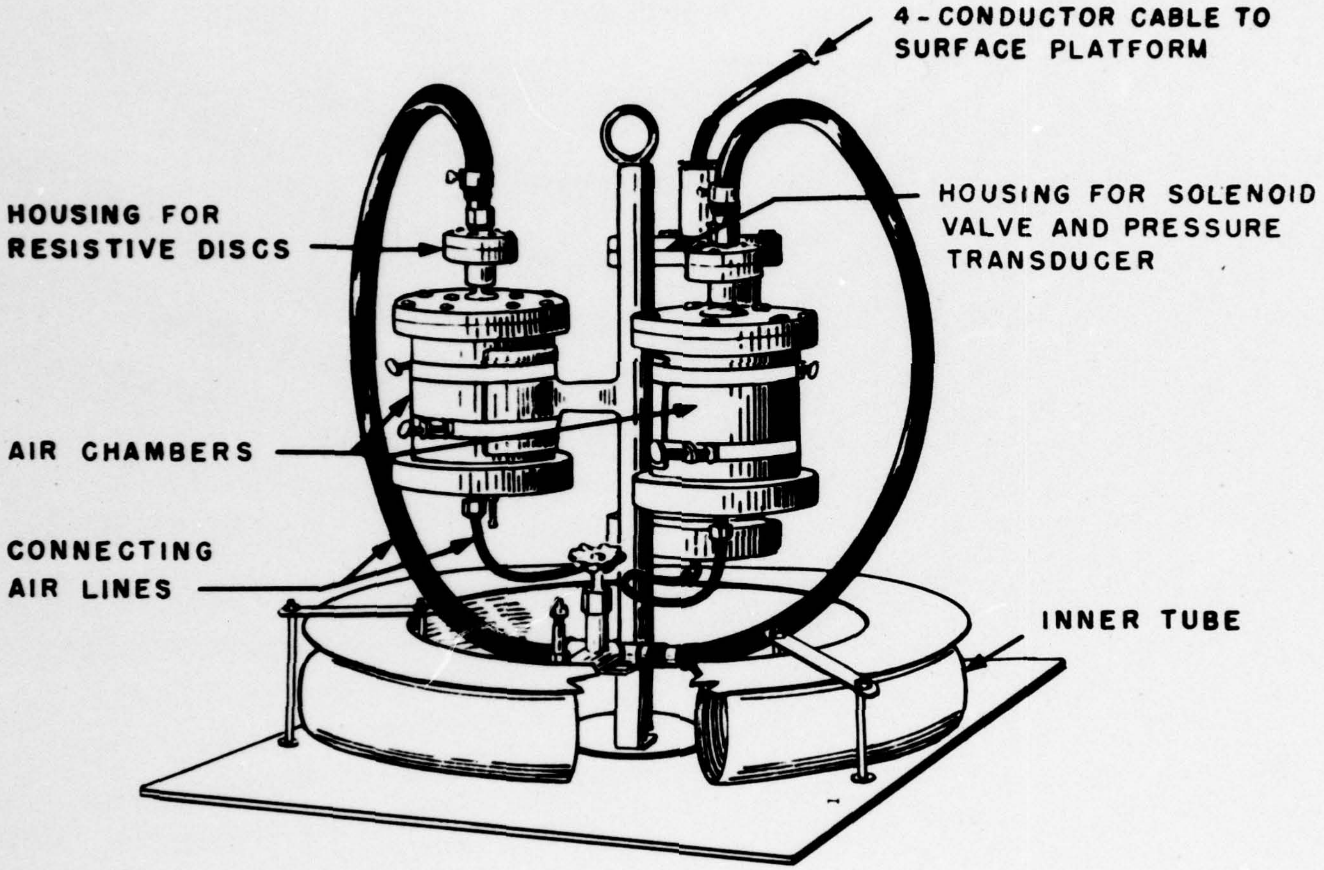
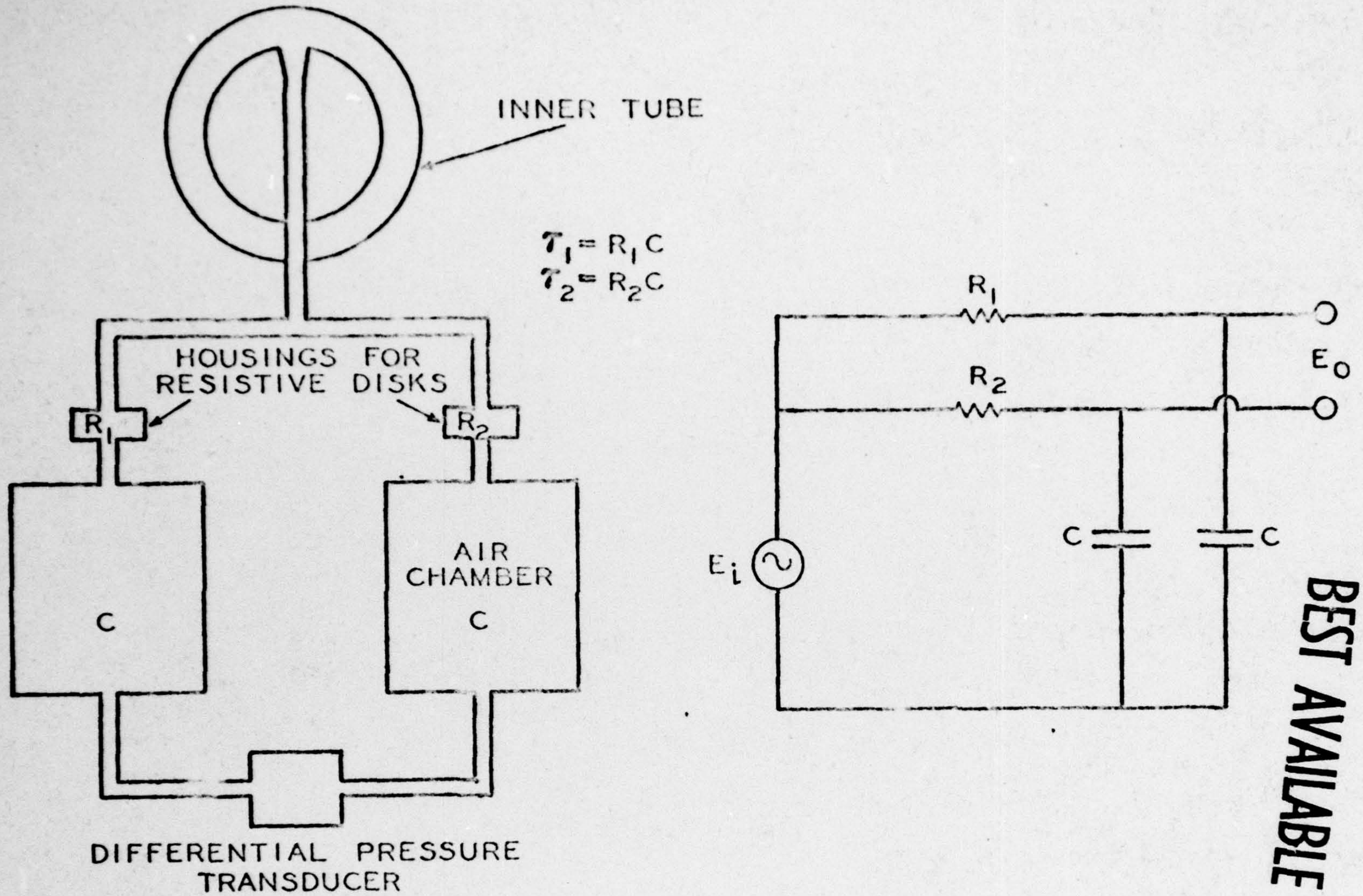
[*] Hudimac, A. A., "A Momentum Wave Recorder," NEL Report No. 359 (C), 18 March 1953.



DRAWING OF WAVE RECORDER

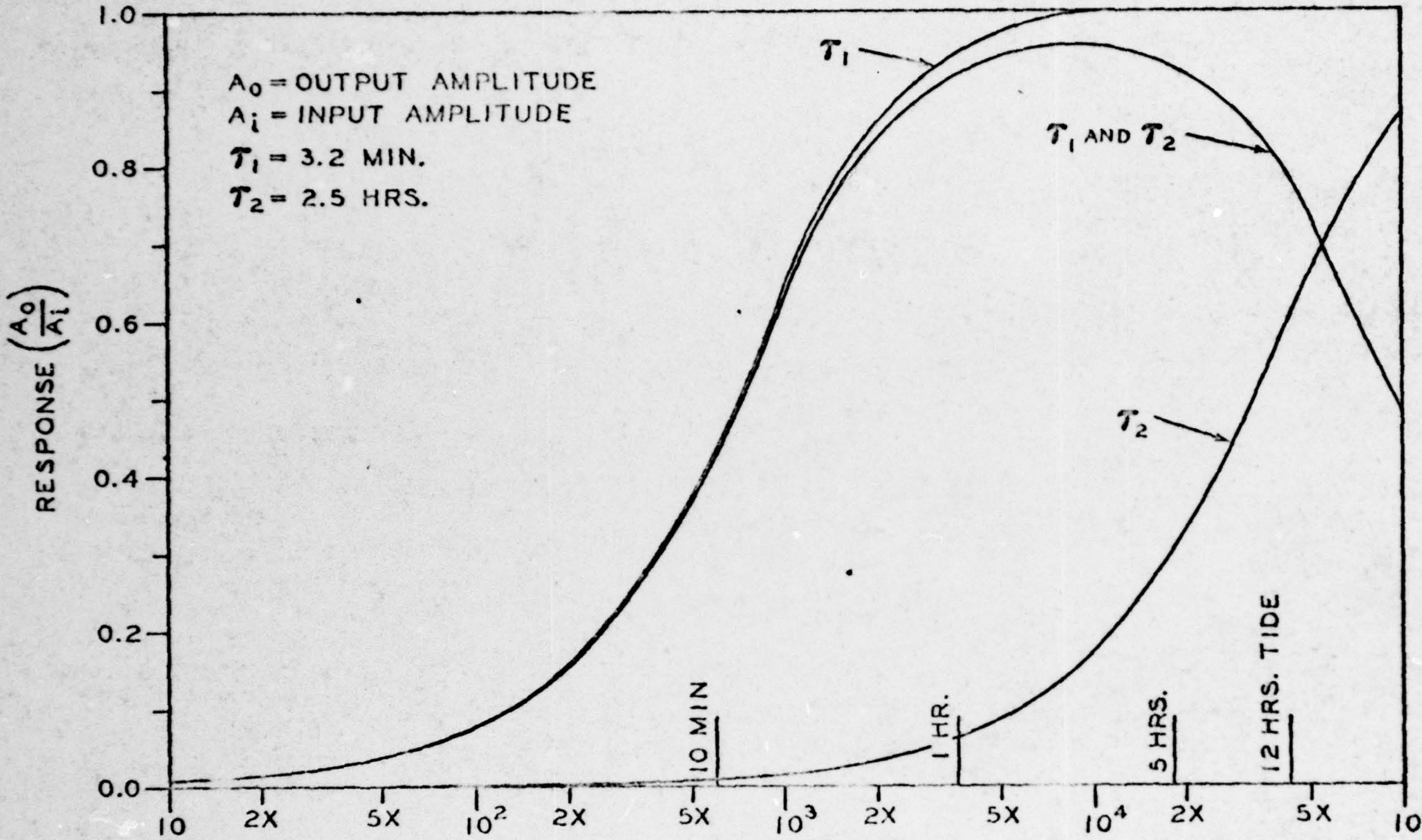
FIG. I



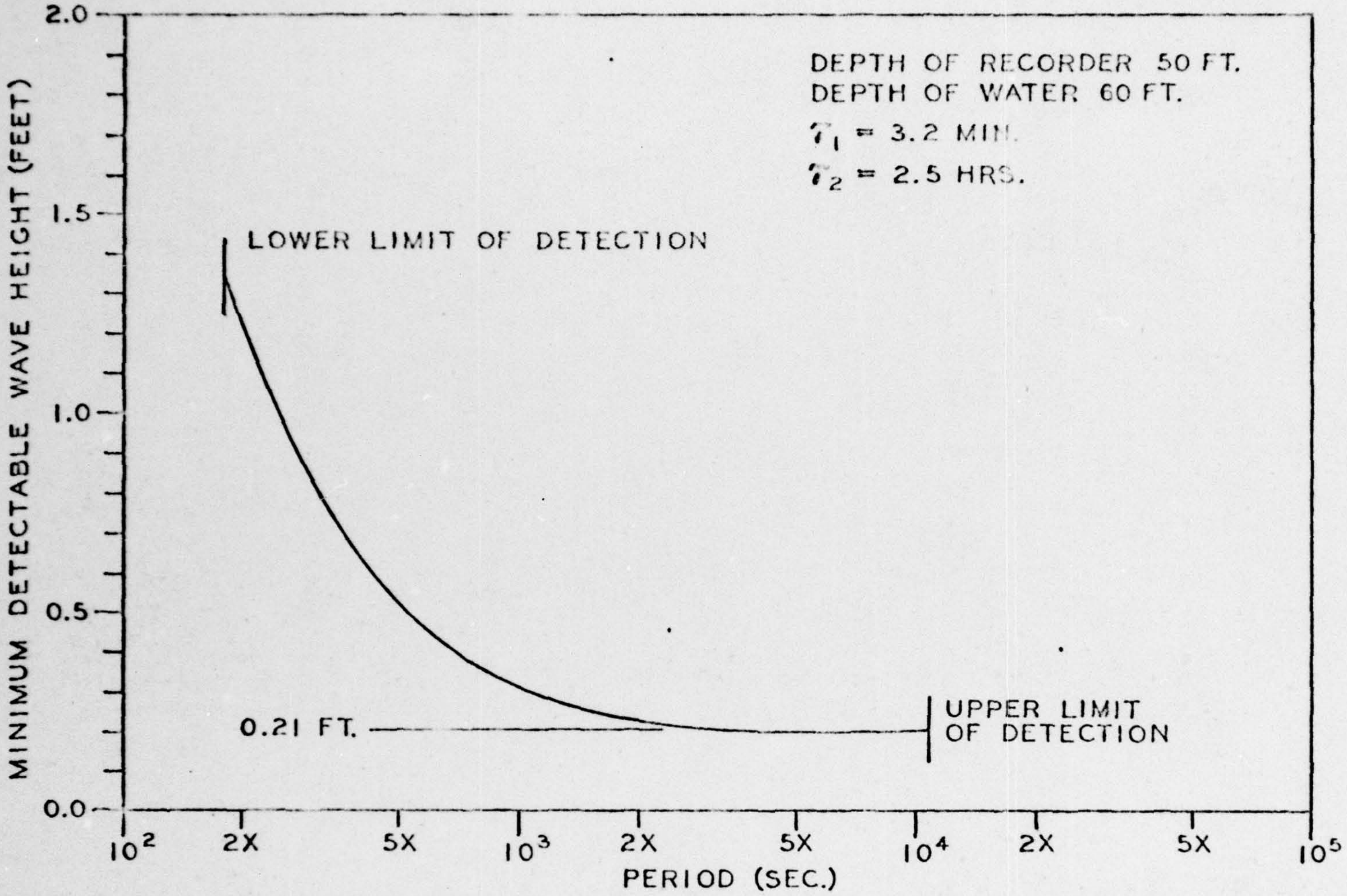
SCHEMATIC
OF MECHANICAL
RC-FILTERS
(a)

EQUIVALENT
ELECTRICAL
RC-FILTERS
(b)

FIG. 2

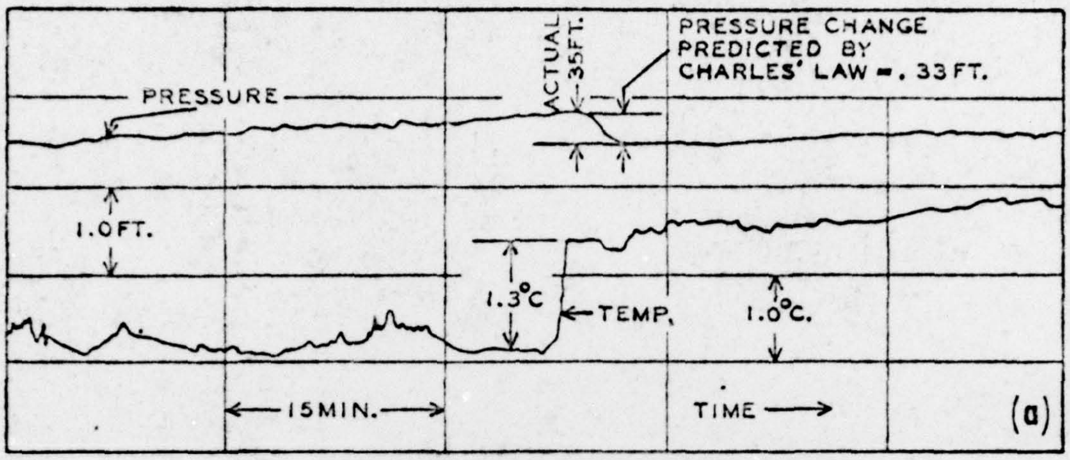


RESPONSE OF WAVE RECORDER
AS USED AT NEL TOWER
FIG. 3

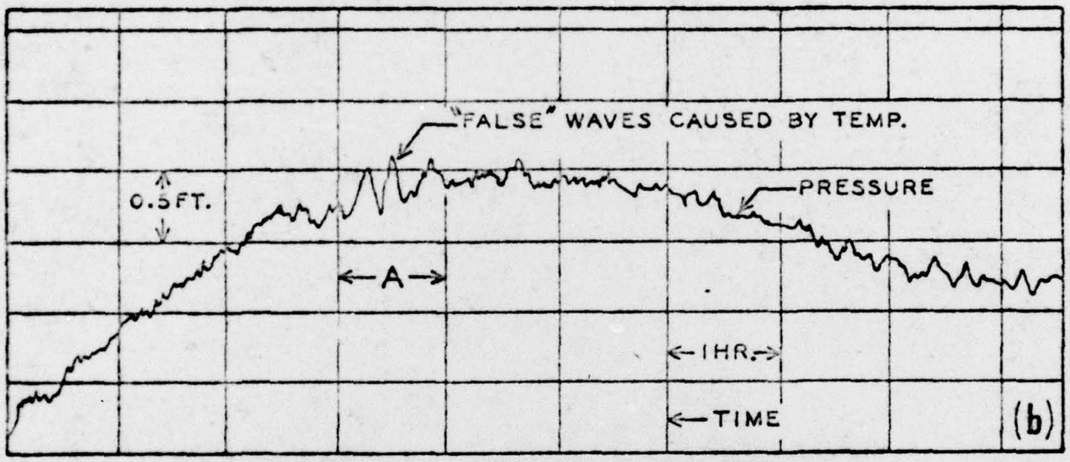


MINIMUM DETECTABLE
WAVE HEIGHT
VS.
PERIOD OF WAVE

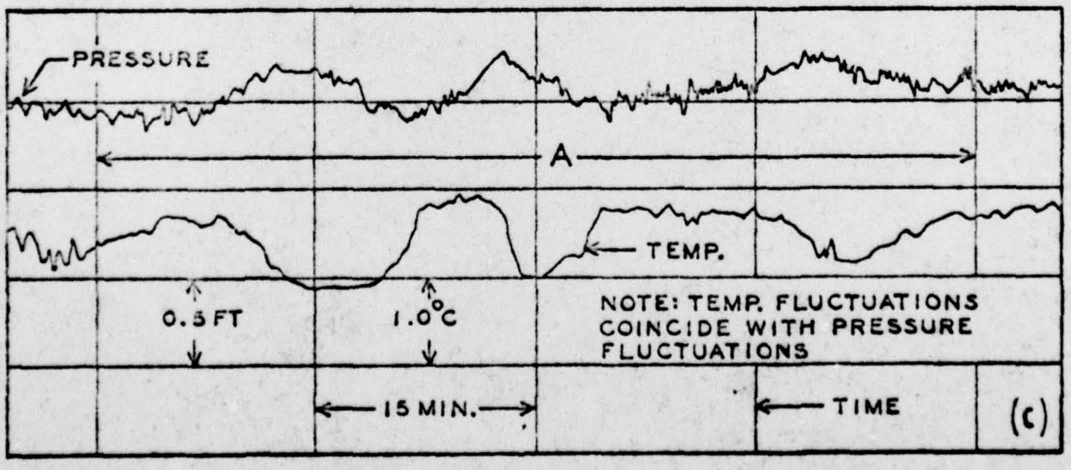
FIG. 4



ORIGINAL DATA RECORD SHOWING STEP CHANGE IN TEMPERATURE



TIME COMPRESSED PRESSURE RECORD (FROM TAPE RECORDER)



EXPLODED VIEW OF "A" IN (b) ABOVE (ORIGINAL)

SAMPLES OF DATA RECORD

FIG. 5