A "SING-AROUND CIRCUIT" FOR THE MEASUREMENT OF SOUND VELOCITY

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George W. Ficken Jr.

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This is to certify that the

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A Sing-Around Circuit for the
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E. A. Hiedemann
Major professor

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A [illegible] CIRCUIT FOR THE MEASUREMENT OF SOUND VELOCITY

By

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George W. Ficken, Jr.

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INTRODUCTION

The measurement of the velocity of propagation of ultrasonic waves has become of considerable importance in the study of matter. Furthermore, there exist various technical devices based in some way or other on the measurement of ultrasonic velocity. Corresponding to these developments, the variety of methods for measuring ultrasonic velocities is rather great--in fact too great to allow a critical comparison of these methods in this paper.

However, two different types of objectives which have caused the development of so many methods may be pointed out. In basic research one usually wants to develop methods allowing a maximum in accuracy. For technical applications one might often be more interested in reliability and convenience. The method which has been studied in this report was first proposed by [illegible]. Hiedemann and H. Freund[1] (1940) for a technical application--namely, the detection of flaws in materials. The principle described by these authors consists of using a pulsed oscillator to drive a piezo-electric crystal which transduces the electrical energy into a sound pulse in the medium with which the crystal is in contact. This pulse travels through the material to a second crystal acting as a receiver which reconverts the sound into electrical energy. The pulse is amplified, detected, and instantaneously fed back to the oscillator via wire to trigger the next outgoing pulse. The frequency of the pulse sequence is dependent upon the ultrasonic velocity in that medium and the path length traversed. Knowing the path length, one can determine the velocity. Vice versa, the path length covered can be arrived at through a knowledge of the sound velocity. Since flaws in materials interfere with sound waves very strongly, their presence is indicated by incorrect velocity readings, and their approximate size and location can be determined by a series of measurements from the three perpendicular directions.

About the same time (1941), and quite independently, W. E. Kock[2] applied for a patent on a very similar method but for the propagation of electromagnetic wave-trains. Kock described a system in which two separate transmitter-receiver units can actuate each other in the following manner: oscillations are generated and interrupted to form a pulse which is sent out from one transmitter. A receiver tuned to this carrier frequency picks up the pulse which is used to start the associated transmitter; this transmitter behaves in a manner similar to the first one. The pulse sent out by this second source is picked up by the receiver working in conjunction with transmitter number one, making it send out its second pulse. The process continues back and forth, the time between pulses being determined by distance and velocity considerations.

[illegible] and [illegible][3] give an application of the principle in radar [illegible] its re-receiving [illegible]. For this application it is necessary to be sure that each receiver cannot be activated by its own transmitter, otherwise each transceiver [illegible] "sing-around" by itself.

R. D. Holbrook[4] reported on a device which is very similar to that [illegible] by [illegible]. Holbrook also used a system having one transmitter and receiver, and with it measured changes of sound velocity with temperature in solids. [illegible] Hansen[5] employed the same principle [illegible] with air as the medium. It is from his paper that the term, "sing-around circuit" has been adopted.

In principle, the method appeared to have possibilities for further development into a [illegible] sound velocity meter. Since the scarcity of literature on the method did not allow a conclusive judgement about the reliability and accuracy of the method, it appeared desirable to experimentally investigate its usefulness and associated problems.

II. PRELIMINARY CONSIDERATIONS

When the problem of making sound velocity measurements in liquids by means of the "Sing-Around Circuit" was first being considered, two difficulties immediately presented themselves. First of all, it was expected (this later proved true) that there might be a delay time in the electronic circuits, which, if large enough, would add to the time required for the sound to go through the medium, thereby causing errors. Secondly, it was seen that the distance between the crystals, which were partially enclosed in their special holders, would be difficult to obtain with the necessary accuracy. Therefore it was decided to make a *difference measurement*, that is, find the pulse rate with the transducers first in one position, and then again with them placed a *shorter* distance apart. By keeping one holder fixed, the distance the other moves could be determined as accurately as desired. By assuming the delay times to be equal in magnitude for both positions, it was possible to derive a formula for the sound velocity in which these equal delay times cancelled out; the velocity thus became a function solely of the two different pulse repetition rates and the change in distance.

Sound travel time for first position ≡ t_1

Sound travel time for second position ≡ t_2 ($t_1 - t_2$ = [illegible])

Change in travel time ≡ Δt

First (longer) path length in medium ≡ L_1

Second (shorter) path length in medium ≡ L_2 ($L_1 - L_2$ = [illegible])

Change in path length ≡ ΔL

Pulse repetition rate$_1$ ≡ frequency$_1$ ≡ f_1

Pulse repetition rate$_2$ ≡ frequency$_2$ ≡ f_2 ($f_2 > f_1$)

Velocity of sound in helium ≡ c

Constant delay time in circuits ≡ $\tau = \tau_1 = \tau_2$

$$t_1 = \frac{L_1}{c} \quad \text{and} \quad f_1 = \frac{1}{t_1 + \tau_1} \qquad f_1 = \frac{1}{\frac{L_1}{c} + \tau_1} \qquad \frac{1}{f_1} = \frac{L_1}{c} + \tau_1$$

$$t = \frac{L_2}{c} \quad \text{and} \quad f_2 = \frac{1}{t_1 - \Delta t + \tau_2} \qquad f_2 = \frac{1}{\frac{L_1 - \Delta L}{c} + \tau_2} \qquad \frac{1}{f_2} = \frac{L_1 - \Delta L}{c} + \tau_2$$

Using $\tau_1 = \tau_2$ since τ assumed constant, we obtain

$$\frac{1}{f_1} - \frac{L_1}{c} = \frac{1}{f_2} - \frac{L_1}{c} + \frac{\Delta L}{c} \qquad \frac{1}{f_1} - \frac{1}{f_2} = \frac{\Delta L}{c}$$

$$\frac{f_2 - f_1}{f_2 f_1} = \frac{\Delta L}{c} \qquad \boxed{c = \frac{f_2 f_1}{f_2 - f_1} \Delta L}$$

Another consideration necessary in the system under discussion was the geometry of the specimens through which the sound signal was to pass. In order to eliminate boundary effects and have plane waves striking the receiving crystal (an infinite medium situation), the wave length of the sound had to be made small compared to the dimensions of the medium. Since fairly small specimens are much easier to obtain for laboratory experiments, ten centimeters was a logical size for the path length, and a simple calculation showed that sound frequencies of between one and ten megacycles would be needed, depending upon the desired degree of accuracy.

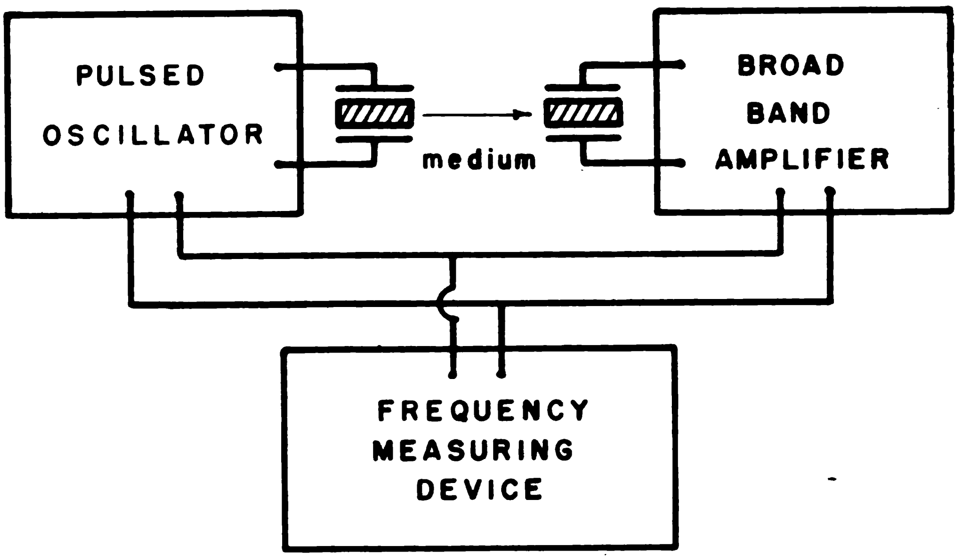


Fig. 1 – "SING-AROUND CIRCUIT"

It was decided to start out using the basic ideas incorporated in the "Sing-Around Circuit", a block outline of which is shown in Figure 1. As was briefly described in the section on "sing-around circuits" in the introduction, an oscillator which drives a sending crystal whose frequency is between the an [illegible], then is suddenly turned off in order to form a pulse of these high frequency oscillations. The sound pulse thus formed travels through the medium with the velocity of the compressional waves[9] and eventually hits the receiving crystal, forming a weak electronic pulse. Since what is essentially being done is the modulation of a carrier frequency by first switching off the oscillator and then triggering it into operation again by means of the returning pulse, the carrier has side bands which must be allowed to pass through the amplifier if the pulse is to retain its original shape. Therefore a broad band amplifier is used to build up the received pulse to a size sufficient to trigger the oscillator. At a convenient place in the amplifier (or if desired, in the oscillator itself) some sort of frequency measuring device is connected up so that the pulse rate can be determined.

A description of the apparatus which was finally used for the measurements follows in the next chapter.

III. THE APPARATUS ITSELF

The block outline of the previous chapter covers the principles of the final apparatus with the exception of the pulsed oscillator which has been replaced by a high voltage pulse making device. This pulser shocks the sending crystal into oscillations which take place because the crystal is electrically equivalent to the resonant circuit shown in Figure 2. L, C, and R are electrical equivalents of the

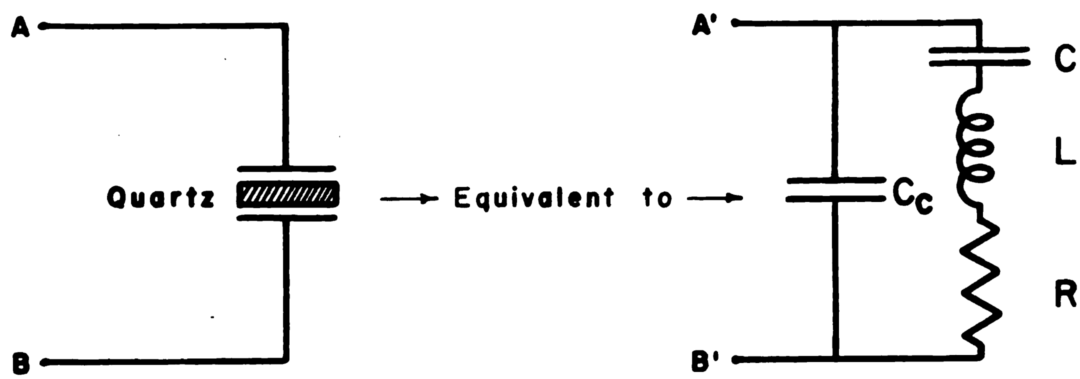


Fig. 2 - CRYSTAL EQUIVALENT CIRCUIT

mechanical properties of the crystal, or motional impedances; C_c is the capacitance of the electrodes with the crystal between them, or clamped capacitance. These oscillations are rapidly damped out due to energy losses within the crystal itself and energy lost by radiation into the liquid or solid medium with which it is in contact. The complete block diagram of the system is shown in Figure 3. The dotted lines

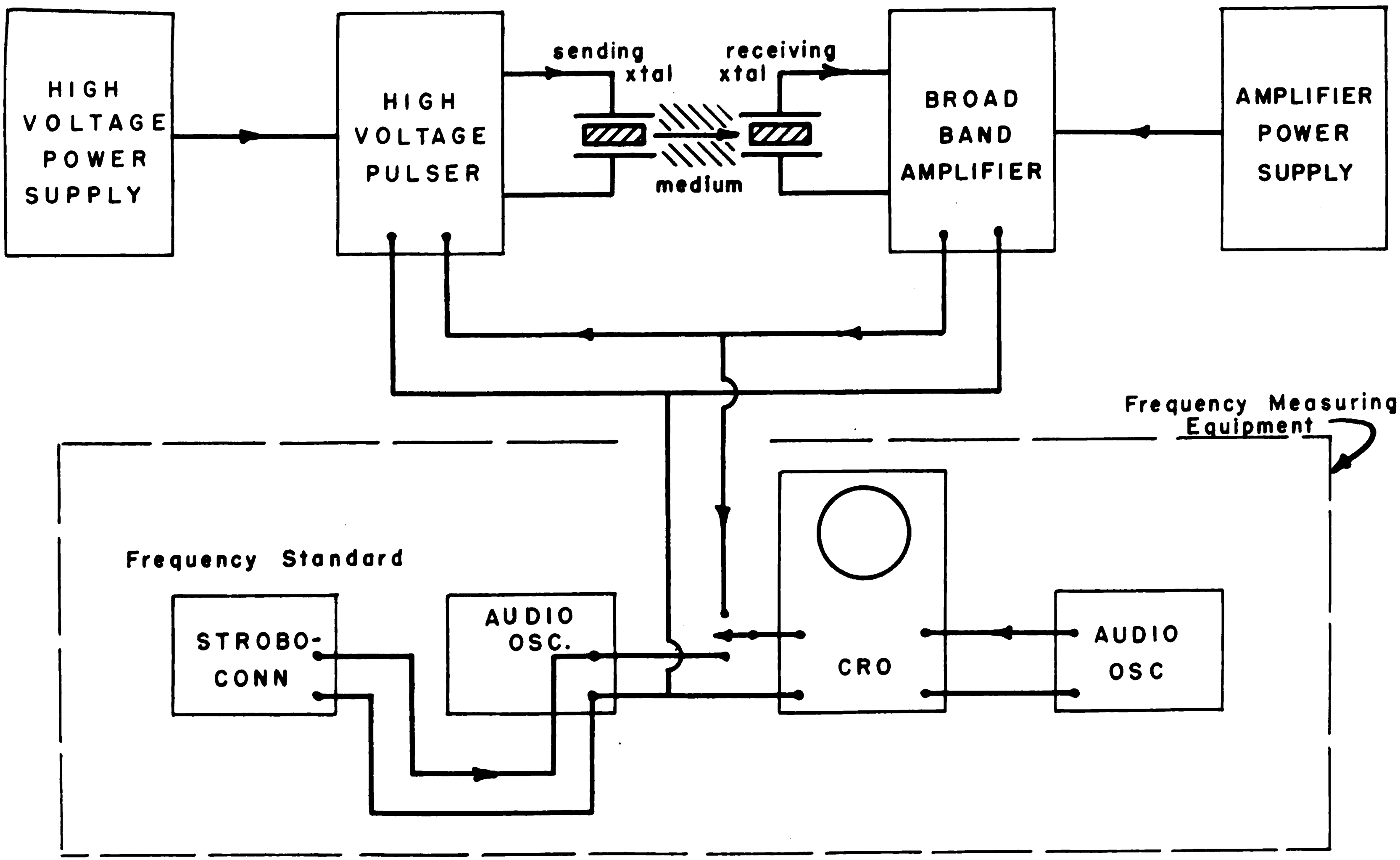


Fig. 3. CIRCUIT BLOCK DIAGRAM

enclose the equipment devoted solely to measuring frequencies accurately. The more detailed explanation of the operation of each component will start with the pulser and follow one pulse all the way around its path until it returns to trigger the next one.

A. Pulser

The high voltage pulse former consists of a 6SN7 tube used as a one-shot multivibrator which is operated with a B+ of about 800 volts D.C. Its circuit is shown in Figure 4, and the operation is as follows: a current of between 35 and 42 milliamperes flows through triode V_2 because its grid resistor is connected to the top of the cathode bias resistor common to both V_2 and V_1, thus keeping the grid and cathode of V_2 at about the same potential. V_1 however, is biased to cut-off by this current flow through R_K. Now if there arrives through C_1 a positive triggering pulse of sufficient amplitude and duration to raise the grid of V_1 above cut-off voltage, V_1 begins to conduct, and the voltage at its plate decreases. This decrease passes through C_2, and appears on the grid of V_2 as a negative-going voltage which decreases the plate current through V_2 by an amount greater than the initial increase in V_1, thereby causing a net drop in current flow through R_K. The voltage drop in R_K therefore decreases, allowing more current to flow in V_1. This makes the plate

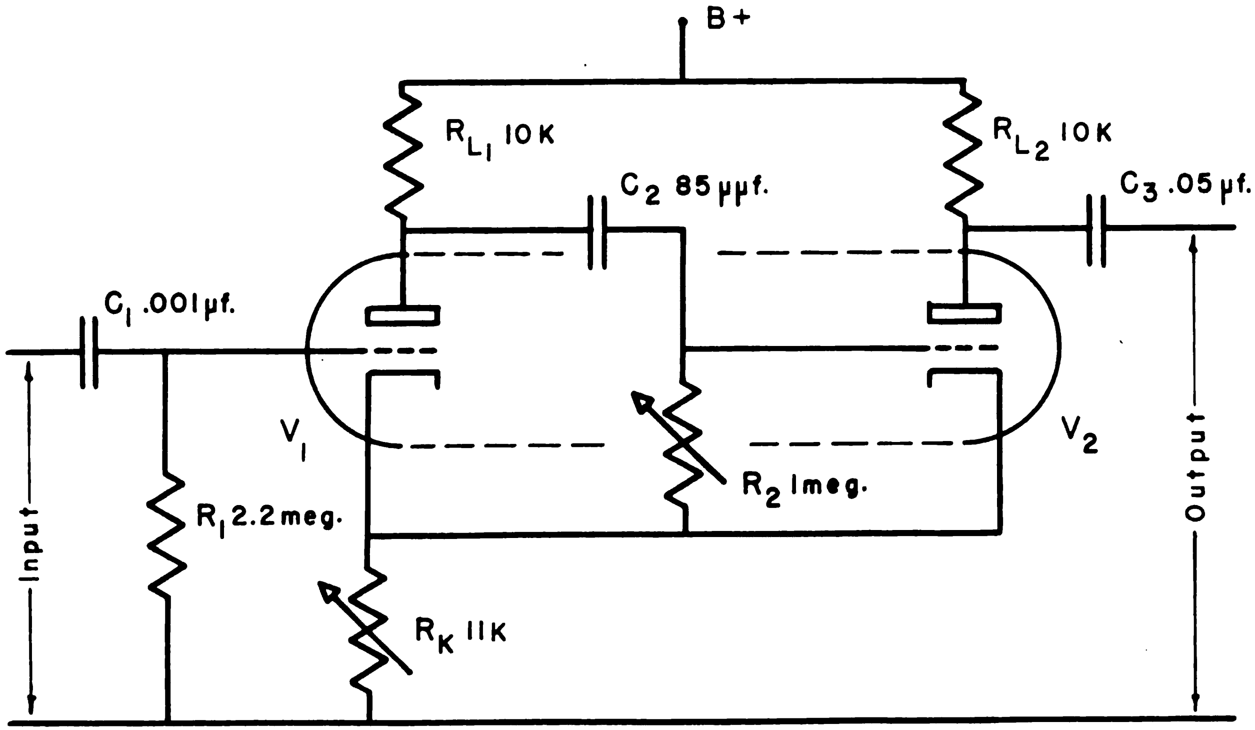


Fig. 4. ONE-SHOT MULTIVIBRATOR

voltage of V_1 decrease still further, and the grid of V_2 goes still more negative. This action is repeated until V_2 is cut off and V_1 is conducting, all of this happening practically instantaneously. The circuit remains with V_1 conducting and V_2 cut off while C_2 discharges sufficiently toward the lowered value of plate voltage of V_1 to allow the grid of V_2 to rise from its lowest value to cut-off voltage. Then V_2 begins to conduct, increasing the current flow through R_K and thereby raising the cathode voltage of V_1; this reduces V_1's plate current and allows its plate voltage to increase. This increase is coupled to the grid of V_2, increasing its plate current by an amount greater than the decrease in that of V_1, yielding a net increase in the flow through R_K. This reverse action keeps repeating until V_1 is cut off and V_2 is conducting heavily, as it was before the triggering pulse arrived; this whole process happens very quickly too. The result of all this is that the positive triggering pulse has caused a large positive-pulse output from the plate of the second tube. The length of this output pulse is controlled by the time constant of R_{g2} times C_2. However, since the sharpness of this output pulse is what determines how strongly the sending crystal will be shocked (high frequencies near that at which the quartz resonates must be present), it is advisable to have C_2 small and R_{g2} large.

3. Transducers

As was briefly mentioned before, the high voltage positive pulse from the one-shot multivibrator is sent out to shock the sending crystal, and this is done by merely coupling the plate of the second triode to one electrode of the quartz by means of a 500 microfarad, 1000 volt condenser and a 100 microfarad, 1000 volt condenser which follows it in series; the larger condenser just serves as a safety precaution against the high D.C. voltage in case the smaller should break down. The quartz's other electrode is connected directly to ground. This method of using the crystal itself as a resonating circuit was come upon after previously using oscillator circuits in which the output from a tank circuit attached either to the plate or cathode of a power tube drove the quartz. It gave a sharper sound pulse and eliminated all tuning of variable coils, thereby simplifying operations greatly. Of course, with this method only one specific frequency output can be obtained from the crystal, that being its fundamental mode of vibration. It is not possible to drive the quartz at frequencies slightly off the natural one or at higher harmonics as can be done with tank circuits.

For measurements in liquids, holders were designed which could be used in conducting liquids as well as non-electrolytes. They are shown in Figure 5. The shielded wire entering the back of the hollow, vertical mounting tube is the "hot" lead

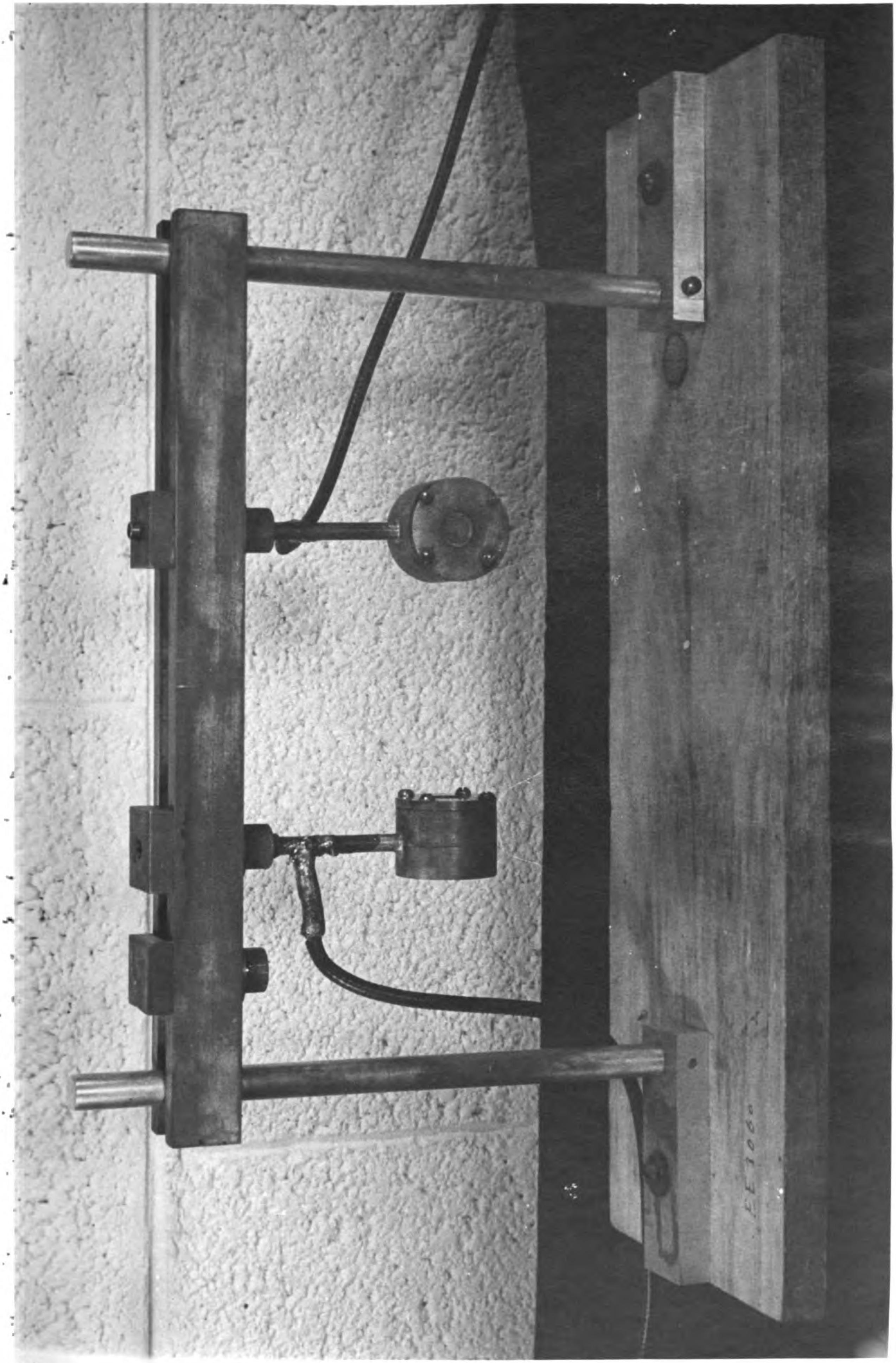


Fig. 5. TRANSDUCER HOLDERS AND TRAVERSING MECHANISM

from the multivibrator, and it goes down through the tube and into a horizontal, cylindrical chamber behind the crystal where it is connected to a spring which pushes against the electrode of the quartz. The wire, spring, and electrode are all kept insulated from the brass holder. The crystal has its front face glued onto the heavy brass washer, and the electrode on this face is in electrical contact with the brass. This washer is bolted to the rest of the holder, a gasket being used to keep the liquid from entering the chamber. The bolts also serve to electrically connect the washer with the rest of the holder which is grounded. The same set up is used for the receiving holder.

Both of the holders are mounted in T shaped blocks which slide back and forth in a groove in the horizontal supporting arm. The vertical part of the T fits into the groove and the horizontal part straddles it, each side resting upon one of the two rails. Each holder can be raised or lowered, rotated horizontally, and completely removed from its T. The grooved horizontal arm can also be raised and lowered. By clamping a third T behind the receiving holder's T and putting a fourth T between the sender and receiver, a method can be arranged whereby the receiver can be moved a limited distance which is known very accurately. The receiver T is backed tightly up against the T behind it, and then gauge blocks of the desired sizes are inserted between the front of the receiver T

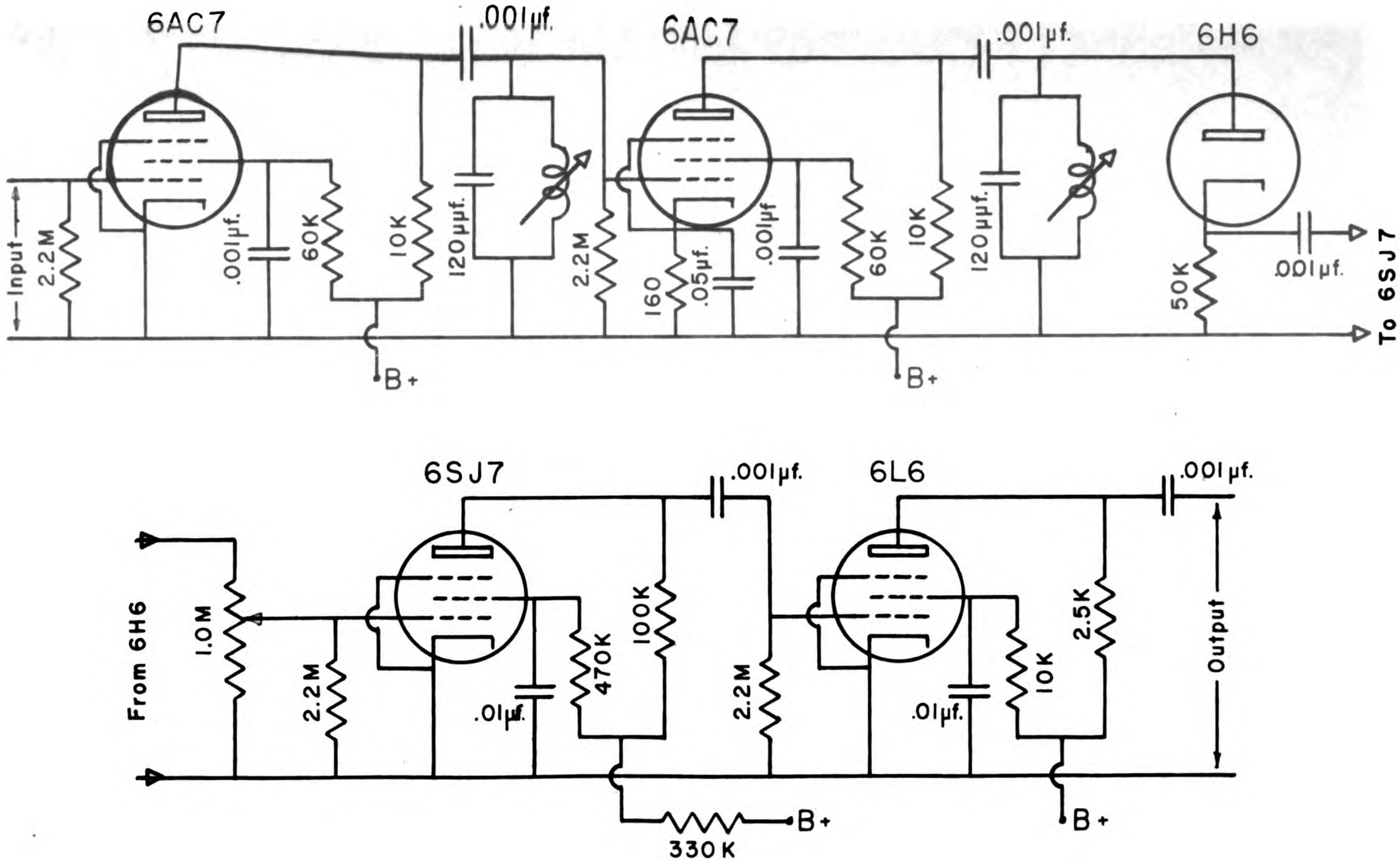


Fig. 6. WIDE BAND AMPLIFIER

and the one between the sender and receiver. This latter is then clamped, the gauge blocks removed, and the receiver now has room to slide back and forth in the vacated space. This enables the change in distance to be specified to .00025 centimeters, something which can not be done without a very expensive traveling vernier or gauge.

C. Amplifier

The weak pulse produced by the receiving quartz must be amplified, detected, and then further amplified before it is strong enough to key the multivibrator into operation. The circuit diagram for the wide band amplifier necessary to perform these functions is shown in Figure 8. The incoming pulses can be shown by a Fourier analysis to consist of the carrier frequency along with side bands of various frequencies. These sum and difference frequencies which determine the shape of the pulse must be allowed to pass through the amplifier, and so two stages of tuned, resistance-capacitance coupled, RF amplification are used in the following manner: between the output of the first stage and the input of the second a tank circuit containing a variable inductance is placed between the "high side" and ground. Since a parallel resonant circuit offers infinite impedance only to the frequency for which it is tuned (the impedance drops off rapidly on either side as the frequencies

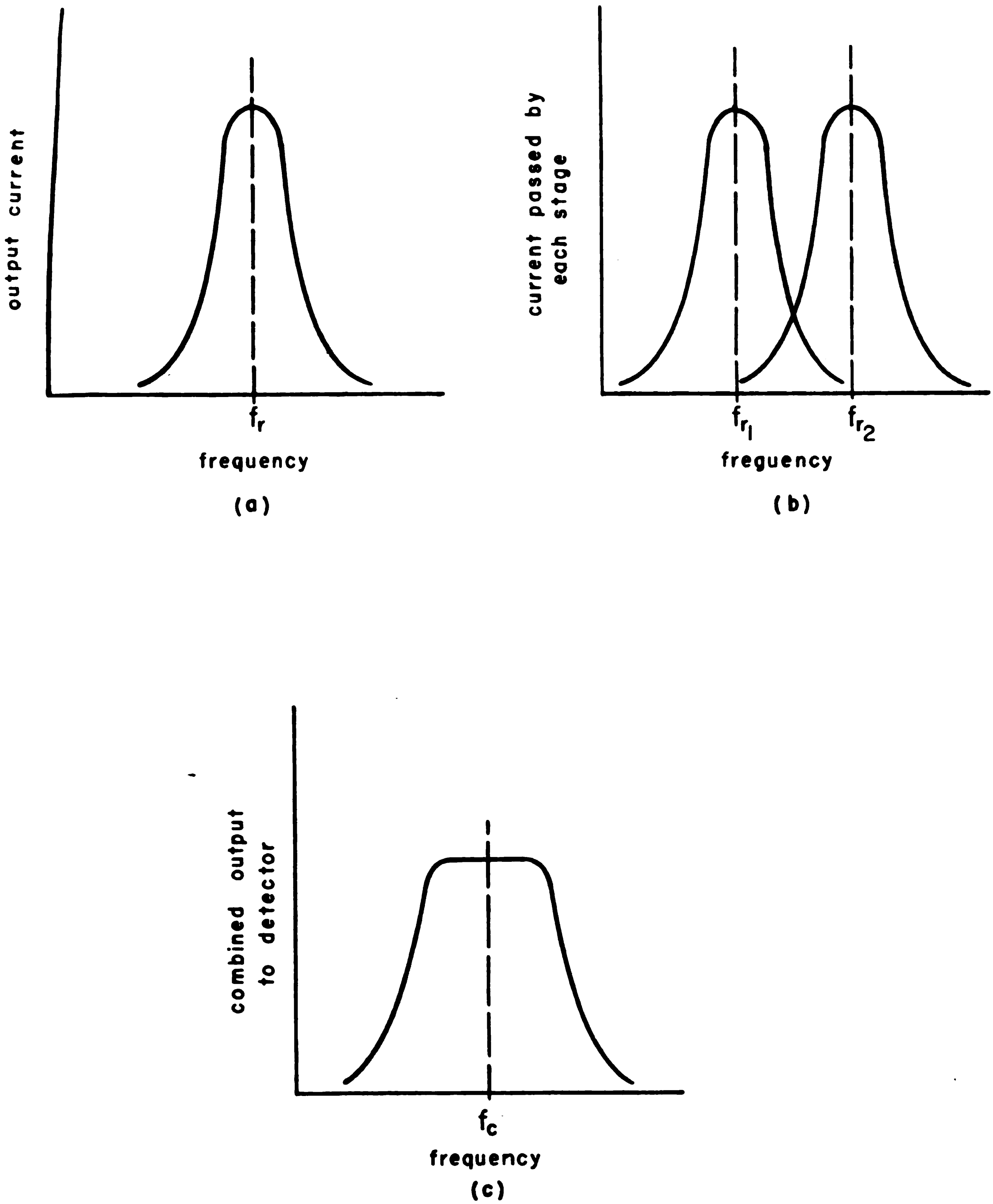
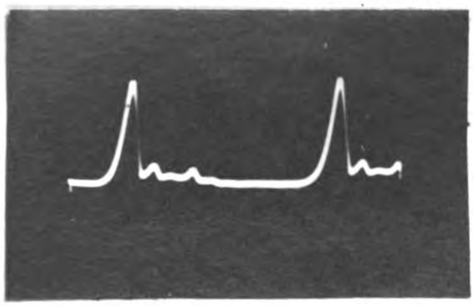


Fig. 7. AMPLIFIER RESPONSE CURVES

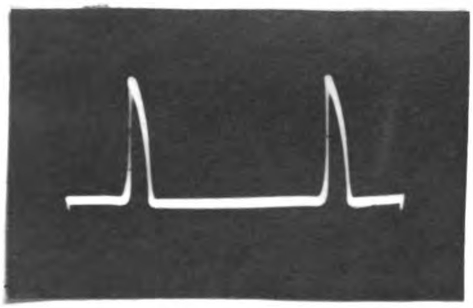
get farther from the resonant one), all other frequencies are shorted out to ground, and theoretically only the one reaches the second stage. However, due to resistance inherent in the coil and condenser, some adjacent frequencies are passed, the amplitude of which decreases the farther they are from the tuned frequency. A typical tuned resonance curve as shown in Figure 7a results. The same process takes place in between the second stage and the detector, where a similar tank circuit is located. By tuning the first tank to about 100 kilocycles above the carrier frequency and the second to about 100 kilocycles below, a frequency band is formed wherein the amplifier gives fairly uniform gain; this occurs because the tuning curves of the two tanks overlap somewhat as shown in Figure 7a, allowing a good percentage of the frequencies common to both curves to pass through both tanks and on to the detector. The curve in Figure 7c shows a typical band resulting from such overlapping.

Once detected, the signal is sent directly to the first audio stage in the amplifier where a potentiometer enables the input to be cut down as much as desired. The first audio stage is isolated from the second by a decoupling resistor and condenser combination which keeps fluctuations in the B^+ voltage caused by changes in current flow through the second, high power tube from affecting the first. It was found that these stages of resistance-capacitance coupled amplification did not give maximum gain when set up with components which followed standard charts. To get the best output, variable components had to be inserted and adjusted, the values thus obtained being used for the permanent ones. The reason for this discrepancy is that the signals from the detector and especially the first stage of audio are too large, and the tubes are being overdriven, yielding distortion. Some trial and error modifications which increased the gain were made in the RF section also. After these two stages of audio amplification the pulse is ready to be sent back to trigger the multivibrator. Figure 8a shows a photograph of two such

(a)



(b)



(c)

Fig. 8. PULSE SHAPES

pulses in succession, while [illegible] at appears at the detector and multivibrator outputs, respectively. In all cases the leading edges of the pulses are on the right hand side.

D. Power Supplies

The circuit for the high voltage power supply which runs the one-shot multivibrator is shown in Figure [illegible]; it consists of a full-wave bridge rectifier. Two extra filament transformers are necessary to isolate the cathodes of tubes 1 and 3. In this arrangement two rectifiers operate in series on each half of the cycle, one being connected to two successive filter chokes and thence to the positive end of the load resistor, the other to the negative end of the load, which is grounded. Over that portion of the cycle when the upper end of the transformer secondary is positive with respect to the other end, electrons flow through rectifier 1 to ground, up through the load, through the chokes, and finally through rectifier 2. During this period electrons cannot flow through rectifiers 3 or 4, because each of their plates is negative with respect to its cathode. Over the other half of the cycle, electrons flow through rectifier 3, the load, the chokes, and rectifier 4. The crossover connection keeps the current flowing in the same direction through the load. The filtering is accomplished by two choke input

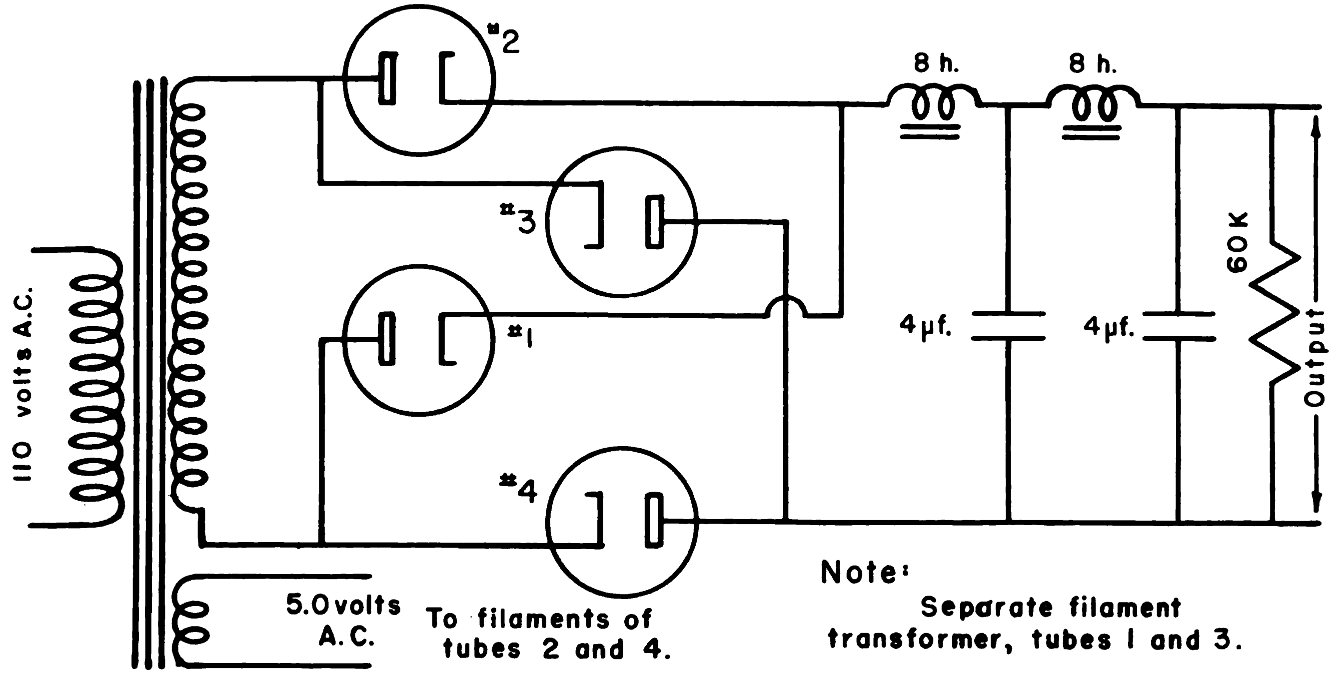


Fig. 9. HIGH VOLTAGE POWER SUPPLY

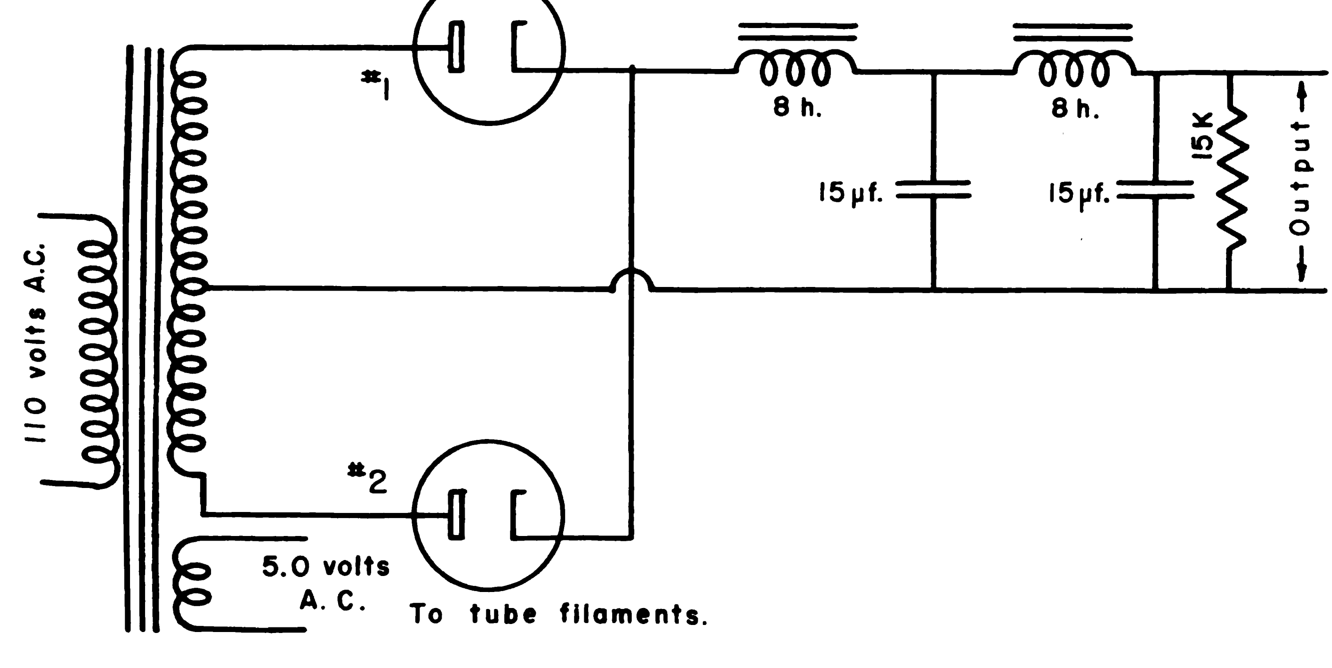


Fig. 10. AMPLIFIER POWER SUPPLY

filter sections. This circuit enables the entire voltage appearing across the transformer secondary to be used, rather than just half, as with the more common full-wave, center-tap rectifier. It puts out 618 volts D.C., with an A.C. ripple voltage of about .[illegible] volts. This power supply and the single-shot multivibrator are housed in the same chassis.

The circuit for the power supply which operates the wide band amplifier is shown in Figure 10. It is a full-wave, center-tap rectifier. The filtering is done by two choke input filter sections. The voltage output is 280 volts D.C., with a ripple of .008 volts A.C. The B^+ voltage can be increased to 350 volts by shorting out the first choke; this raises the A.C. ripple to .03 volts, but the amplifier gain goes up by a factor of roughly three. This power supply is located on the same chassis as the amplifier.

[illegible]. Artificial Pulse Maker

It was found necessary to construct a variable frequency auxiliary pulser which could be used to trigger the pulsed oscillator during its stages of development to the final form which consists of the one-shot multivibrator. This was necessary because until the high voltage pulser was properly running the crystal, no signal could be available in the amplifier output to do the triggering. This artificial pulse was obtained by using an audio oscillator set at maximum output to overdrive a 6SJ7 tube. All of the resistors attached to the 6SJ7 were made variable, and by properly adjusting them, a fairly sharp negative pulse of almost any desired amplitude could be gotten from the plate of the tube. This arrangement was put into a small separate chassis which could be connected to the amplifier's power supply by plug-in wires. This auxiliary pulser was also used for the trial and error adjustment needed to get maximum gain in the audio section of the amplifier by making a pulse of approximately the same shape and amplitude as that which would ordinarily appear on the particular grid in question when the circuit was in proper operation.

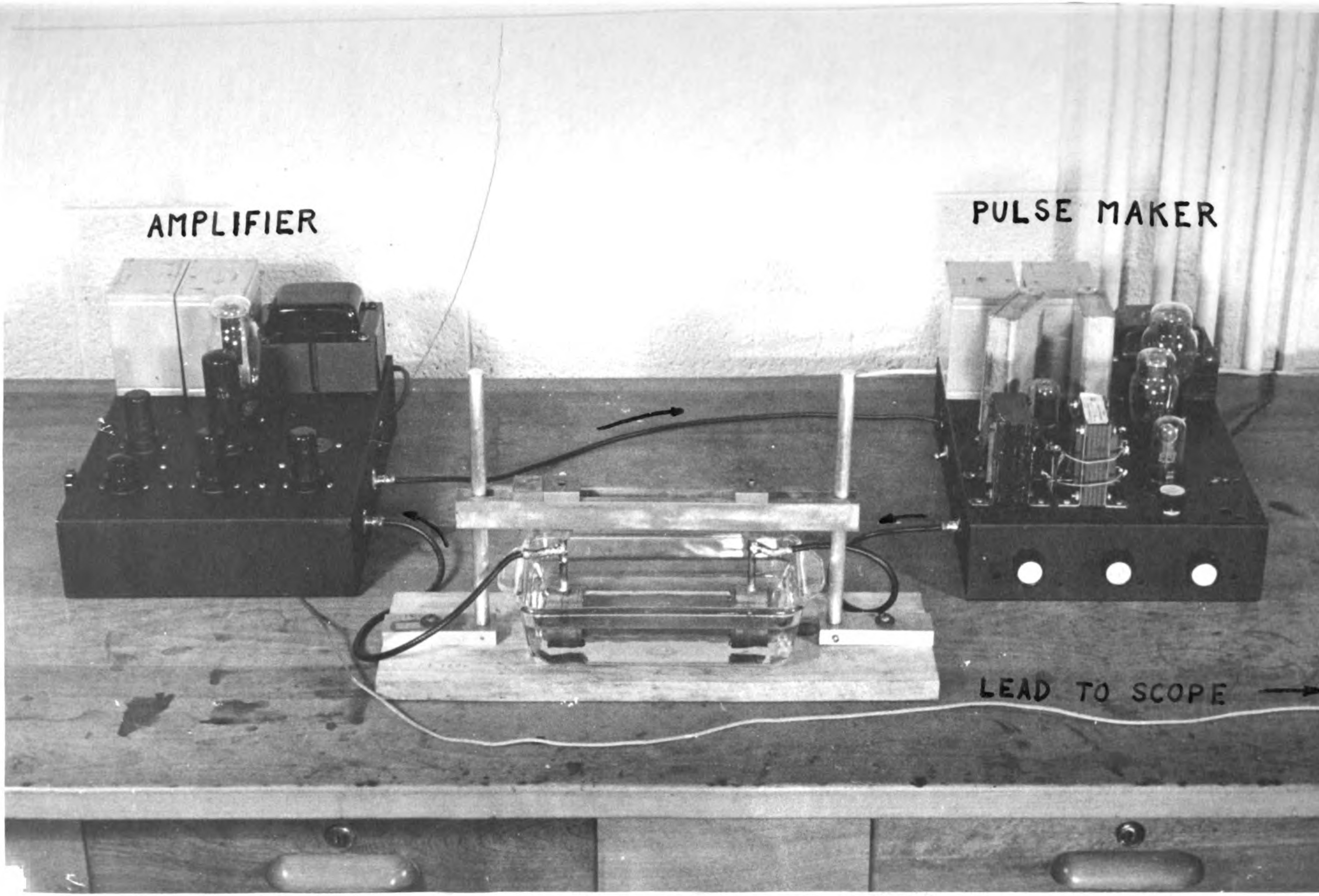


Fig. 11. "SING-AROUND CIRCUIT"

IV. OPERATION OF SYSTEM

A. Making Circuit "Sing Around" Properly

Since it is a rather tricky business to make the system continuously trigger itself at the proper interval, somewhat detailed information concerning this matter will be included. Figure 11 is a photograph of the "Sing-Around Circuit" without its associated frequency determining equipment. The four main controls used to adjust the cycling operation are as follows:

1. Trigger bias resistors
2. Pulse shaping resistors
3. Crystal alignment
4. Audio volume control

These four variable quantities leave room for a multitude of possible settings other than the proper one, which is quite critical, and so it was found that time could occasionally be saved in the balancing process by feeding an artificial triggering pulse from the auxiliary pulse maker into the last stage of the audio section of the amplifier. By using a pulse of the proper size and frequency (the audio oscillator is set at a frequency roughly equal to that expected for the liquid being measured), correct settings can be obtained on the variable resistors which control the triggering bias put on the one-shot multivibrator. This is done by observing the pulse output of the multivibrator on an oscilloscope. It can be seen on the oscilloscope that when there is little or no bias on the multivibrator, it triggers by itself at a "natural" frequency determined by its various components and the voltages on them. Slowly increasing the bias causes the output pulses to change shape and frequency, until finally a situation is reached wherein the pulses are of the "correct" shape and occurring at a rate of perhaps four times the frequency of the triggering pulses. Although these pulses appearing on the oscilloscope are spaced uniformly, usually this quadrupling can easily be recognized in that the extra pulses are less distinct and tend to waver somewhat. By carefully increasing the fine bias adjustment, the operator can cause these pulses to disappear one by one--that is, the quadrupling becomes first tripling, then doubling, and finally the one base frequency output pulse is all that remains. If the bias is raised very much beyond this point the pulses will cut off because of insufficient trigger pulse voltage. For reasons which will be given later, it is best to set the trigger bias dial midway between the cut-off position and the one for which the base frequency first appears. Then it is best to run the audio oscillator through the range of frequencies expected to be included in the measurement to make sure the multivibrator will "follow" correctly (trigger properly) over the whole range.

The second of the two main controls listed, the pulse sharpener, consists of a series combination of a large and a small variable resistor; this combination is placed in parallel with the grid resistor of the second triode of the OSMV. By decreasing either the large or small resistor (coarse or fine adjustment), the $R_{g_2}C_2$ time constant is decreased and the length of the one-shot multivibrator output pulse shortened, thereby increasing the sharpness of the pulse and the shocking effect on the crystal. Since small $R_{g_2}C_2$ values make the circuit quite unstable, they are used only for a liquid in which a large amount of damping occurs in order to step up the amount of signal reaching the receiving crystal. Therefore the coarse adjustment is set quite far toward the counter-clockwise position.

The next step is to determine whether any signal is getting through the liquid. This can be done by putting the oscilloscope lead on the output of the detector in the amplifier. The trick now is to try to get at least a little evidence of a signal at the detector, and then strive to improve its strength by making various slight adjustments. It is best to start with the crystals quite close to each other (one-half inch or so apart) and as nearly parallel as possible. This allows a maximum of energy to reach the receiving crystal. It usually happens that the crystals must be moved farther apart and misaligned somewhat for the steadiest and clearest signal (least st[illegible]). It is [illegible] this "[illegible]" occurs [illegible] reflections of [illegible] take place at the crystal faces [illegible] back and forth in the liquid path, becoming superimposed upon the main signal and causing distortion. (The first three reflections of the main signal, along with two secondaries, have been clearly observed on the oscilloscope). There is also the possibility that some sort of standing wave pattern is set up between the crystals by these reflections; this could serve to scatter the main pulse signal, give it a varying velocity, etc., and thus yield spurious signals of all sorts. Localized temperature gradients set up by the sound field might have a small effect also. This is doubtful, however, since a motor driven stirrer did not visibly improve the clarity of the picture on the oscilloscope. Thus, apparently much less power is being used in the system under discussion than in the one described by Pellam and Galt[illegible], because they very strongly emphasize the importance of stirring the liquid bath to disperse temperature gradients. It can be seen from geometrical considerations how the misalignment prevents reflections from reaching the receiver. The thought occurred that at least part of this [illegible] might be caused by an overdriving of the RF section of the amplifier when the signal grew quite large, and so a variable resistor was installed across the output from the multivibrator. By making this resistor smaller, any desired amount of the input pulse to the transmitting crystal could be [illegible], thus decreasing the size of the [illegible] signal. However, this will [illegible] effect on the relative amount of noise present, making a [illegible] case for the reflection theory. This extra control was left in the circuit just in case it might be necessary at some future time to lessen the shock applied to the sending transducer.

Once the parts of the circuit have been made to function properly, the attempt must be made to make the signal "sing around". After the audio volume control has been turned up for maximum gain, the audio oscillator supplying the energy for the artificial triggering pulses is shut off. Some sort of noisy pattern should appear on the oscilloscope. If not, the trigger bias may need to be decreased slightly. Provided the pattern is large enough to indicate that the liquid is not too great an absorber, it is usually best to move the crystals about six inches apart; a stable operating situation is easier to find for reasonably large path lengths. The amount of audio gain used plays an important role in getting the clear picture which indicates proper cycling of the pulses around the circle; the fine trigger bias control, the crystal alignment and perhaps the pulse shaper will all have to be adjusted again to secure a balanced condition. When this situation is finally reached, the receiving transducer should be slid back and forth along the sound path to make sure the triggering occurs properly over a range of frequencies which this time are brought about by the change in path length.

In addition to the four variable controls mentioned, there is also a starting button which is connected to the grid of the first audio stage through the automatic volume control. Pressing this button merely causes an electrical disturbance at this point; when amplified, this "noise" is usually sufficient to trigger the multivibrator and thereby start the circuit cycling around, provided that all the other controls are properly set. Since the circuit is very touchy and often stops singing around at the slightest provocation, this starter enables the operator to get it going again without changing any of the variable controls. The importance of this will be discussed shortly.

All the detailed information given in the first and third paragraphs of this chapter was included to explain what steps must be taken to put the circuit in a condition such that it is ready to "sing around". Fortunately, in practice these steps are never necessary once the system has been made to function properly for one liquid. It is only when some drastic change has been made which somehow prevents the signal from properly cycling around that these point by point checks along the line of progress of the signal must be made.

I. Measuring Sound Velocities by the Difference Method

1. Consideration of Sources of Error

a. <u>Nonconstancy of delay time</u>. In the chapter on "Preliminary Considerations", a formula was derived for the sound velocity in terms of frequencies and the change in path length. This was made possible by assuming a delay time in the electronic circuits which was <u>constant</u>. However, once a signal was finally made to "sing around", it was observed that changing the size of the triggering pulse sent to the multivibrator by means of the audio volume control caused a corresponding variation in the pulse repetition rate; increasing the gain brought about an increase in frequency. This meant that the delay time was <u>not</u> a constant, and the reason for the gain-versus-frequency relationship can be analyzed as follows:

Think of the first pulse of the multivibrator as being caused by some sort of disturbance at the head of the audio section of the amplifier. This can be precipitated by touching any one of the pins on the 6SJ7 with a conductor. The special starting button accomplishes this in a convenient manner. This disturbance is amplified into some sort of strangely shaped signal of sufficient size to touch off the first multivibrator cycle. The pulse sent out jars the sending crystal into producing a signal which is picked up by the receiver, amplified, and returned to the pulser. Because there naturally is some slope on the leading edge of the returning pulse, there is a "rise time" associated with the leading edge between its lowest starting voltage and its maximum or peak voltage. Let us assume for illustration that with the gain on the audio amplifier turned all the way up, only one-fourth peak pulse voltage is necessary to trigger the multivibrator. Assuming the slope of the leading edge to be uniform so as to simplify the explanation, it can be seen that only one-fourth of the "rise time" passes before the pulser fires. But this period of time (hereafter referred to as delay time) must be added to that required for the sound to pass through the liquid in the tank when determining how much time there is between the first and second firing of the pulse maker (it is assumed that everywhere else in the electronic circuits there is no such delay time to worry about, because all other tubes are conducting at all times; if there is somehow a small additional delay time, it is assumed that it will not change with signal size and therefore always cancel out).

The same procedure follows between the second and third firings, the third and fourth, etc. -- the delay time is always present. Since the size of the multivibrator output pulse is constant (as far as can be determined by observing it on an oscilloscope) for the range of trigger pulse amplitudes which occur when making a velocity measurement, the crystal is always shocked with the same intensity, and therefore changes

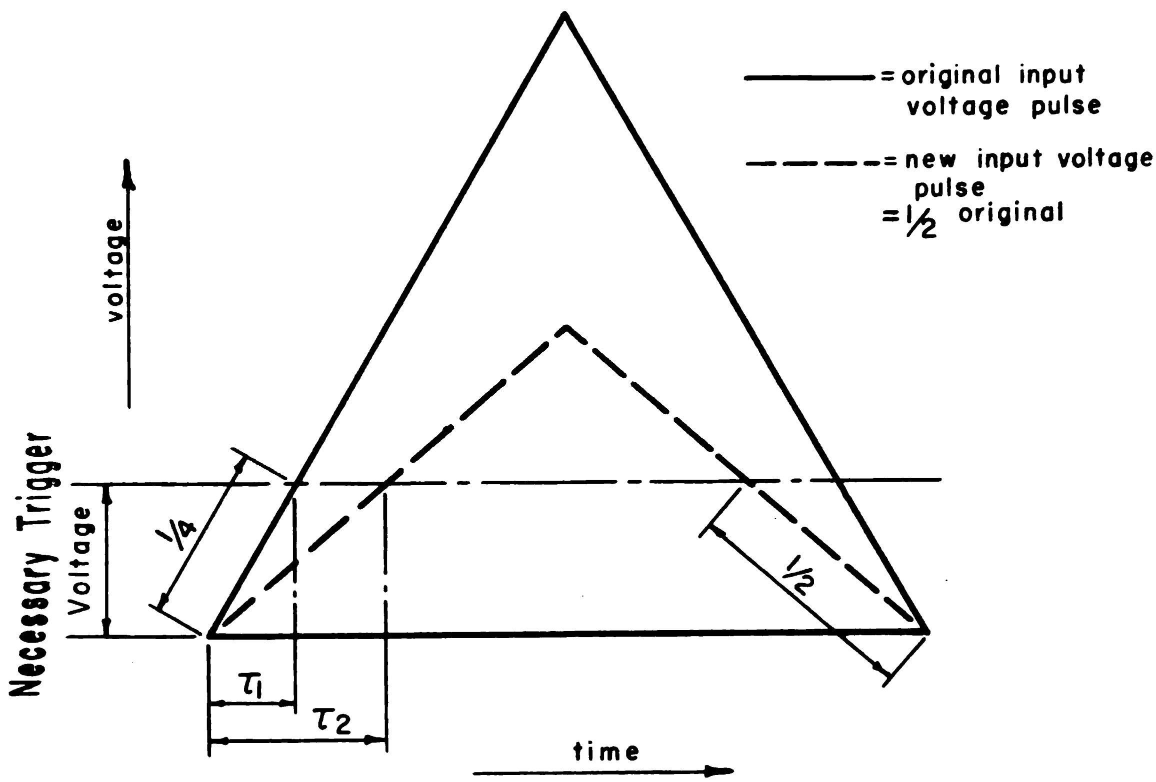


Figure 12

in audio gain can have no effect on the pulse's location on the time reference line nor on the pulse width at its base; however, the height of each point on the pulse voltage curve appearing on the oscilloscope is altered. Now suppose that the gain is turned down so that the input voltage is only one-half its previous value; every point on the trigger pulse is correspondingly lowered by a factor of two, and now <u>one-half</u> of the peak voltage of this new pulse is necessary to trigger the multivibrator. From Figure 12 we can see by simple geometry that the new delay time is twice the old. This increases the total time between pulses by an amount equal to one-fourth the rise time of the pulses. Suppose the rise time is ten percent of the distance between pulses. This changes the total time by about 1/4 times 1/10, which equals 2 1/2 percent.

It can likewise be seen that if the variable trigger bias resistor on the multivibrator is increased, a higher triggering voltage will be necessary, causing it to fire farther up on the leading edge of the pulse; this in turn causes a greater delay time and therefore a greater total time between pulses.

Now consider these facts in connection with the method used for obtaining the sound velocity. Because of greater absorption, diverging of the sound beam, and the possibility that the sending crystal is not pointed directly at the receiver (it can be seen that misalignment of the receiving crystal need not be considered), the farther apart the two crystals are, the smaller the signal that will enter the first section of the amplifier. Usually the circuit is made to "start around" first with the transducers at the greater of the two distances in order to insure that enough signal will get through to activate the multivibrator. When the receiver is moved closer to the sender and set at its new position, if the audio volume control is kept fixed, the input signal to the multivibrator will be larger, yielding a smaller delay time. The path time is naturally smaller also, and it can be seen that the change in total time is dependent on two factors instead of only the path length [illegible], giving a greater increase in frequency for the ΔL that would be compensated. The only way to keep the delay times equal in both cases is to decrease the signal until the output is the same size as for the first position of the receiving crystal. This can be done by viewing the output on the oscilloscope; observing the output from the RF section of the detector works equally well. However, often the circuit does not operate too well (becomes unstable) when this change is being made, necessitating some very careful adjusting by the operator. All this adjusting must be done solely with the volume control; the grid bias, the pulse shaper, and the crystal alignment cannot be changed, as can be seen from the preceding discussion (the starting button, of course, may be used). Once equal, the delay times cancel each other, and the time difference depends only upon the ΔL introduced.

To find the order of magnitude of the error which could be introduced by neglecting to keep the signal input voltage to the multivibrator constant, a series of measurements was made in which the increased signal size (caused by moving the crystals closer than during the second position) was gradually reduced until finally at the proper amplitude, readings being taken at reasonable intervals along the way. As was expected, the change in path length necessary to reach the second, predetermined position increased as the trigger amplitude [illegible] has [illegible] with [illegible]. Calculations showed that an error of [illegible] percent occurred when the [illegible] signal was not attenuated at all, whereas only .4 percent [illegible] from the accepted [illegible] for this liquid's velocity [illegible] the correct manner. This .4 percent falls within the limits of the instrument's accuracy.

b. Relative importance of accuracy of measured quantities. In the section on transducers, a method was described whereby the change in path length could be fixed at some value [illegible] to a high degree of precision. [illegible] to make measurements, it became evident that the accurate determination of audio frequencies, [illegible], was the real problem. Since no audio frequency meter was available, it was decided to use an audio oscillator to make Lissajous figures with the trigger pulse and thereby determine the frequency at which the pulses were travelling around the circuit. But the common audio oscillators with which the Lissajous figures were to be made are reliable only to about two percent or less because of their own internal errors coupled with the reading error always present. From the formula previously derived for the sound velocity, it can be seen that any error in frequency will be doubled when multiplying by the [illegible] and subtracti[illegible] [illegible], [illegible] for [illegible] the quotient, [illegible] a cumulative [illegible] the size of [illegible] L. Thus it can [illegible] [illegible] precise, [illegible] [illegible]. [illegible] ents are now available on the market which [illegible] measure frequencies [illegible] as [illegible] [illegible], [illegible]. [illegible] [illegible], [illegible] it [illegible] [illegible] -Around Circuit", at [illegible] state of development, would be good enough to permit such precision. Therefore it was decided to [illegible] between the first frequencies rather than the two first [illegible] which determined ΔL, [illegible] then measure ΔL the easiest way possible, with a vernier caliper. Although for the ΔL's used [illegible] distance determination [illegible] to only about one-third of a percent, no additive errors occur in the velocity formula as with frequencies. The [illegible] consists of [illegible] a stroboscope to [illegible] the frequency [illegible] out by an [illegible] oscillator. [illegible] cycles [illegible]-[illegible], [illegible] clearly [illegible] [illegible]-[illegible] [illegible] the [illegible]. [illegible], [illegible] of [illegible] on an oscil-loscope, [illegible] [illegible] frequency, [illegible] [illegible] liquid [illegible] [illegible]. The frequency [illegible] [illegible] [illegible] (Figure [illegible]) [illegible] (Figure 1c).

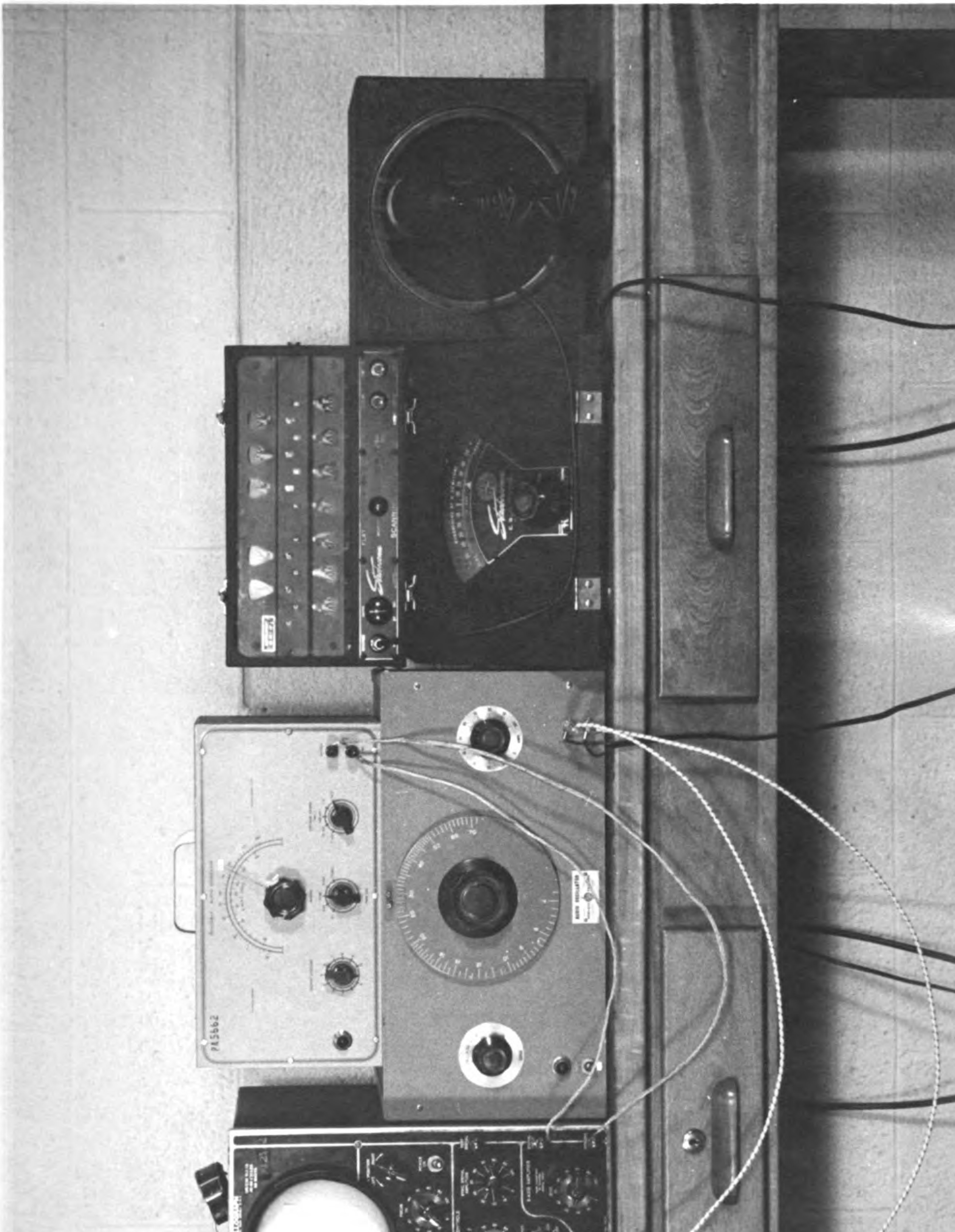


Fig. 13. FREQUENCY DETERMINING SET-UP

It [illegible] oscillators (as well as [illegible]) were stable [illegible], [illegible] they [illegible] frequency [illegible]. [illegible] the same, checks are periodically made with the Strobotac. The oscillator [illegible] is [illegible] of the [illegible] is used to obtain the one-to-one Lissajous pattern with the tri- [illegible], [illegible] of [illegible] os- cillator.

In [illegible] This distance is [illegible] result, [illegible]. It [illegible] greater accuracy, because this way the delay time is smaller compared with the path travel time; this also [illegible] the change in distance [illegible], [illegible] error in ΔL. [illegible] as large as possible is [illegible], [illegible]. Once the system is slightly [illegible], [illegible] oscillator is used to very roughly [illegible] of the frequency. After this has been done, the two oscillators are used in conjunction to make the [illegible] table one put, say, 500 or 1,000 cycles per second on the horizontal plates of the oscilloscope, whichever value corresponds more closely with the pulse repetition rate. Then the transducer holders are first adjusted (the one in the transducer's ... is backed tightly up against the block to its rear) until the signal appearing on the vertical plates forms a one-to-one pattern with that from the sine wave from the oscillator. Such a pattern is shown in Figure 14. Care must be taken to insure that a one-to-one ratio is what is being observed.

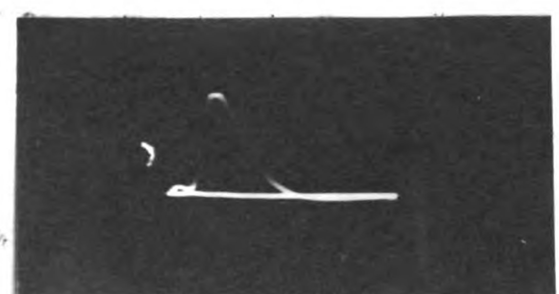


FIG. 13. LISSAJOUS PATTERN

Now, after the ... has been checked to make sure the first audio oscillator is still sending out 3000 cycles per second, the second one is set at the next (or second or third) multiple above the one used previously for the lower pulse frequency, and the receiving crystal is moved forward until the one-to-one pattern for the new frequency is observed (th[illegible] [illegible] also is naturally augmented by the proper amount). The receiver is charged, and the [illegible] with the [illegible]. [illegible] equation [illegible] substituted into the formula to calculate the velocity.

[illegible]. EXPERIMENTAL RESULTS

Using the method of [illegible], the velocities [illegible] a number of organic liquids were obtained. It was found that by taking about six readings for each one and averaging them, reproducible results could be obtained. As might be expected when recording any experimental data, occasionally a reading would appear which was quite far off from the rest, and it would naturally be discarded rather than included in the average. Since most available data concerning sound velocities give values which occur at 20°C, it was decided to take a note of the temperature of the liquid each time a measurement was taken and then, by knowing the velocity coefficient of temperature for that liquid[9], correct the reading to what it would have been at 20°C. This procedure eliminated the necessity for elaborate temperature controlling apparatus. It was observed that evaporation of the more volatile liquids caused them to cool several degrees below room temperature when they were placed in the tank, and so the temperature had to be checked rather closely until an equilibrium was reached. While working with less volatile liquids, it was found that no noticeable temperature increases occurred even when the sound was allowed to radiate into the medium for extended periods of time. This was taken as a further indication of the small power output of the system.

Since it is [illegible] that the [illegible] gradients [illegible] in a sound field [illegible] [illegible], it was decided to check this by stirring at different speeds in the region immediately adjacent to the sound beam and watching for corresponding changes in the sound velocity, something which Schreuer did observe and report. The circuit was made to "sing around" first with no stirring whatsoever, and care was taken to obtain a very steady Lissajous figure with the audio oscillator. Then the motor driving the stirrer was turned on, its speed being increased until the liquid was being very strongly agitated. Not the slightest drifting of the Lissajous pattern was observed, indicating that the frequency of the pulses and therefore the sound velocity had not changed in the least (it is believed that this method is capable of detecting variations in sound velocity as small as one part in 100,000, so long as the precaution is taken to keep varying the speed of the motor in a very irregular manner to insure that the associated electronic components are not drifting just enough to compensate for the possible change in pulse frequency which is being sought and keeping the Lissajous figure stationary). In Schreuer's extremely high precision work he obtained sound velocities in liquids which would exist at zero sound intensity, by extrapolation. These values have the best chance of being the most accurate ever recorded because of the decrease of sound velocities of all liquids except vary) with the increase in temperature in the sound beam itself, this increase being in direct proportion to the intensity. Since the instrument under discussion has thus been shown to be of negligible intensity, this would seem to be an important point in its favor.

Below is a data chart for some organic liquids along with their calculated sound velocities which have been temperature corrected to 20°C. The means and mean deviations have been computed, and the most widely accepted velocity[10, 11] for each liquid is shown for comparison. The percent difference between the mean and accepted value has in each case been determined. It will be noticed that the means for the liquids tried are all low, the amount varying from about .5 percent to 1.0 percent. The reason for this discrepancy is not obvious; further studies are necessary for its explanation.

<u>Carbon Tetrachloride (CCl_4)</u>

Trial	f_1	f_2	L	Temp.	Vel. Coeft. of Temp.	Vel. (corrected)
1	9000 cps	10,000	[illegible].12cm	[illegible].0°C	-3.1 m/s/°C	931 m/s
2	"	"	[illegible]	"	"	[illegible]
3	"	"	[illegible]	"	"	[illegible]
4	[illegible]	12,000	7.37	"	"	[illegible].5
5	"	"	[illegible]	"	"	931.5
6	"	"	7.[illegible]	"	"	[illegible]
7	"	"	7.[illegible]	"	"	[illegible].5
						7)6499.5
						928.5

Mean = 928.5 m/s Mean Deviation = 1.[illegible] m/s

Accepted Value = 938 m/s Percent Difference = 1.01

Methyl Alcohol (CH_3OH)

Trial	f_1	f_2	L	Temp.	Vel. Cfft. of Temp.	Vel. (corrected)
1	6000 cps	12,000	[illegible]	22.4°C	-3.3 m/s/°C	1130 m/s
2	"	"	5.10	21.	"	1115
3	7500	14,000	7.37	21.4	"	1110
4	"	"	7.3[illegible]	21.[illegible]	"	1111
5	"	"	7.30	20.7	"	1107
6	"	"	7.47	20.7	"	11[illegible]
						6)67[illegible]
						1117.3

Mean = 1117.3 m/s   Mean Deviation = 6.5 m/s

Accepted Value = 1103 m/s   Percent Difference = .43

Benzene (C_6H_6)

Trial	f_1	f_2	L	Temp.	Vel. Cfft. of Temp.	Vel.
1	6000 cps	12,000	4.82 cm	23.7°C	-5.2 m/s/°C	1311 m/s
2	"	"	4.79	"	"	1312
3	"	15,000	5.90	"	"	1313
4	"	"	5.9[illegible]	"	"	1310
5	"	"	5.90	"	"	1315
						5)6570
						1314

Mean = 1314 m/s   Mean Deviation = 1.0 m/s

Accepted Value = 1326 m/s   Percent Difference = .1

m-Xylene (C_8H_{10})

Trial	f_1	f_2	L	Temp.	Vel. Cfft. of Temp.	Vel.
1	6000 cps	12,000	7.36 cm	24.4°C	-4.1 m/s/°C	1326 m/s
2	"	"	7.34	24.5	"	1339.5
3	"	"	7.355	24.[illegible]	"	1331
4	"	"	7.33	22.9	"	1331
5	"	"	7.34	23.3	"	131[illegible]
						5)6635.5
						1327

Mean = 1327 m/s   Mean Deviation = 6.5 m/s

Accepted Value = 1340 m/s   Percent Difference = .97

Isopropyl Alcohol (C_3H_7OH)

Trial	f_1	f_2	L	Temp.	Vel. Cfft. of Temp.	Vel.
1	[illegible] cps	18,000	[illegible] cm	25.[illegible]°C	-4.[illegible] m/s/°C	116[illegible] m/s
2	"	18,000	[illegible]	"	"	1157
3	"	18,000	[illegible]	"	"	116[illegible]
4	"	18,500	[illegible]	"	"	1161
5	"	18,000	4.[illegible]	"	"	116[illegible]
6	"	18,000	[illegible]	"	"	1164
						6)6975
						1162.5

Mean = 1162.5 m/s Mean Deviation = 4.0 m/s

Accepted Value = 1170 m/s Percent Difference = 0.[illegible]

Cyclohexane (C_6H_{12})

Trial	f_1	f_2	L	Temp.	Vel. Cfft. of Temp.	Vel.
1	3000 cps	18,000	4.[illegible] cm.	25.0°C	-4.0 m/s/°C	1275 m/s
2	"	1[illegible],000	[illegible]	24.[illegible]	"	1261
3	"	"	[illegible].[illegible]4	"	"	1[illegible]7
4	"	"	[illegible]	"	"	12[illegible]
5	"	18,000	4.[illegible]	"	"	12[illegible]
6	"	1[illegible],[illegible]	[illegible].[illegible]45	"	"	126[illegible]
7	"	"	4.[illegible]	"	"	12[illegible]
						7)[illegible]
						1271

Mean = 1271 m/s Mean Deviation = [illegible] m/s

Accepted Value = 12[illegible] m/s Percent Difference = 1.01

VI. CONCLUSIONS

A. Sources of Error with Their Magnitudes

The following are the sources of error which can be recognized more specifically, the magnitude of each immediately following in parenthesis:

1. Inaccuracy of Vernier Caliper (± .1mm = .1 to .[illegible] percent error for the ΔL's used).
2. Internal errors of strobocon (± .05 percent) plus reading error of dial on strobocon (± .058 percent) yield (± .108 percent) total error.
3. Short time audio oscillator drift (± .1 percent).
4. Temperature fluctuations of (± .25°C) while taking velocity measurements plus thermometer reading error of (± .1°C) would amount to (± .15 percent).

More detail concerning these last two sources of error will undoubtedly make things clearer. As was previously mentioned, the more stable of the two audio oscillators was used for making the Lissajous figures with the trigger pulse signal. Nevertheless, repeated checks of this oscillator made by means of the strobocon in conjunction with the other oscillator showed that a small amount of drift did sometimes occur. Calculations based on the maximum observed drift showed that a small amount of drift of the system may occur. Calculations based on the amount of observed drift showed that the most this error could amount to was ± .1 percent. Because no constant temperature bath was used, the temperature of some of the liquids was observed to fluctuate somewhat while velocity measurements were being made. However, since .25°C was the largest change noted for a given velocity determination, this error, when added to the .1°C thermometer reading error, becomes about .15 percent (it varies with the temperature coefficient of velocity for each liquid).

C. Other Probable Sources of Error with Unknown Magnitudes

The following list contains probable or observed errors which for one reason or another cannot be estimated as to size:

1. Inability to accurately judge size of trigger pulse when viewed on oscilloscope, plus two percent oscilloscope inaccuracy.
2. Instability of circuit components and (or) fluctuations in the sound field within the medium itself.
3. Play between U-shaped blocks which hold transducers and grooved horizontal bar in which they slide.
4. Impurities in the liquid samples.
5. Non-uniformity of the beam pattern.

The errors introduced by the first three of these sources cannot be isolated very well, because often the shape, size, and clarity of the signal change simultaneously. This can happen when the transducers are clamped securely in place as well as when either one is being translated or rotated. Part of the cause of these changes which take place when the crystals are being adjusted is due to the third reason listed, but the sound beam pattern's lack of uniformity probably plays some role here too.[16] There were times when the signal remained quite constant in shape and clarity; during such periods it was occasionally observed that the frequency remained independent of trigger pulse magnitude within a range of fifty percent change; in other instances the slightest variation in size caused significant frequency fluctuations. Apparently the leading edge of the pulse had a steeper slope for the former case; for the latter, not only was the leading edge more gradual, but the multivibrator might have been triggering at a point on the leading edge either near the bottom or top, where the slope is even less steep. Naturally it would be best to attempt to trigger at a point somewhere half way up the slope, but this cannot always be done because of circuit instability. At best the location is very uncertain; all that can be done is to set the trigger bias dial about half-way between where the multivibrator first starts to operate properly and where it cuts off due to insufficient pulse voltage.

C. Suggestions for Improvement

Some of the things which could be done to increase the accuracy of the instrument will be mentioned. They are enumerated and described by number so as to be better systematized:

1. The most obvious improvement would be the elimination of the vernier caliper. Gauge blocks used in conjunction with a micrometer screw could reduce this error by a factor of 10. A traveling vernier of some sort would be still better, because with such a device the transducer holders would have no play and could therefore be firmly fixed while being moved; this would undoubtedly eliminate some of the fluctuations in signal size, shape, and clarity occurring when the path length between crystals was being changed.

2. A counter type frequency measuring instrument which has an accuracy of one part in 100,000 would rule out frequency errors due to the Strobocon and audio oscillators.

3. An automatic volume control placed in the amplifier would solve the problems inherent in keeping the size of the trigger input pulse constant; it might also improve the stability of the amplifier's electronic circuits.

4. [illegible] trigger bias resistors would be worthwhile, because any fixed values in their values will automatically change the amount of trigger voltage necessary to actuate the multivibrator; this causes a subsequent variation in delay time.

5. The importance of using a constant temperature bath can be seen from scanning the [illegible] [illegible].

6. Working at higher frequencies, if possible with the method of crystal excitation in use, would give a better beam pattern; in other words, the infinite medium situation would be more closely approximated.

7. Very pure liquids would have to be obtained.

8. The crystal holders should be repositioned so that the axis of rotation (the vertical arm) would pass through the center of the crystal face, rather than [illegible] at present [illegible]. Large scale geometrical drawings showed that the ΔL error caused by this when the crystals were misaligned was less than .1 percent, but [illegible] should be eliminated for very accurate work.

9. If all the above improvements were made, with the result that the readings were very consistent but still low (or high) by an amount which was a constant

for all liquids (or different for various groups of liquids), then perhaps a correction factor could be introduced which would make the instrument quite precise.

SUMMARY

The method for measuring sound velocities in liquids by means of the "Sing-Around Circuit" has been demonstrated. The few electronic circuits necessary to accomplish this are very simple and inexpensive. This indicates that the method might be useful in industrial applications. Considering the accuracy of the measuring instruments used, the deviations of individual readings from the mean by usually not more than one percent seems very hopeful. It appears possible to perfect the method to such a degree of precision that it might allow very accurate measurements.

BIBLIOGRAPHY

1. [illegible], [illegible] and [illegible], [illegible] German Patent Application (1940). Quoted after E. Hiedemann in the FIAT Review of German Science, 1939 - 1946, Volume: Physics of Solids, Part I, page 1[illegible]0. Wiesbaden, Germany, 1947.

2. Koch, [illegible] U. S. Patent 2,400,30[illegible], Appl. for Oct. 31, 1941.

3. [illegible], [illegible] and [illegible], Jr. [illegible] Proc. I. R. E. 7[illegible] (July, 1947).

4. Holbrook, R. D. "A Pulse Method for Measuring Small Changes in Ultrasonic Velocity in Solids with Temperature"; Jour. Acous. Soc. Amer. [illegible] (July, 1948).

5. [illegible], [illegible] "Applications of the Acoustic Sing-Around Circuit"; Prog. Acous. Soc. Amer. Meetg. 11 (Nov., 19[illegible]).

6. Pellam, J. R. and Galt, J. "Ultrasonic Propagation in Liquids"; (Technical Report No. 4, June 30, 1946) Research Laboratory of Electronics, MIT.

7. Radar Electronic Fundamentals; (A War Department Technical Manual: [illegible]) June, 1944.

8. Electronic Circuits and Tubes; (by the Cruft Electronics Staff of Harvard University) McGraw-Hill Book Co., Inc., New York, 1947.

9. Schreuer, E. "Präzisionsmessungen der Ultraschallgeschwindigkeit in verschiedenen Flüssigkeiten und ihre Bedeutung für die Frage der Schalldispersion, sowie für die Methodik der Ultraschallgeschwindigkeitsmessungen"; "Akustische Zeitschrift, vol. 4, 215 (1939).

10. Bergmann, L. Der Ultraschall und Seine Anwendung In Wissenschaft und Technik; S. Hirzel Verlag Zurich, 1949.

11. Schaaffs, W. "Schallgeschwindigkeit und Molekülstruktur in Flüssigkeiten"; Ergebnisse der Exakten Naturwissenschaften, Vol. 25, 110; Springer-Verlag, Berlin, 1951.

1[illegible]. [illegible], [illegible]. und [illegible], [illegible]. "[illegible] von Schallamplitudenfeldern mittels [illegible] der [illegible]"; [illegible] Jubilee Volume, *Proceedings of the Indian Academy of Sciences*, Vol. [illegible], [illegible], (19[illegible]).