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A SONAR TRANSDUCER SIMULATOR

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A SONAR TRANSDUCER SIMULATOR

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January 19, 1950

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ABSTRACT

A transducer simulator was developed in order to facilitate accurate laboratory testing of certain types of sonar equipment. This instrument simulates the electrical outputs of a multisection, submerged sonar transducer receiving a signal from a source anywhere within its sound beam. It enables complete phase-characteristic tests of phase-sensitive receiving devices (such as sector scan indicators and their associated coupling and combining units) to be made within the laboratory, reducing the work load on overtaxed underwater facilities.

PROBLEM STATUS

The device reported on was developed to facilitate the work on certain phases of the problem; work on the overall problem is continuing.

AUTHORIZATION

NRL Problem S07-01R
NR 527-010

A SONAR TRANSDUCER SIMULATOR

INTRODUCTION

The transducer simulator, which is the subject of this report, is designed to duplicate the phase relationships between the electrical outputs of a four-section sonar transducer receiving a signal from a source anywhere within its sound beam. This instrument facilitates the testing of phase-sensitive receiving devices, such as sector scan indicators and their associated coupling and combining units, when no transducer is available or when it is desired to evaluate electronic performance independent of transducer influence. The simulator is calibrated in electrical degrees of phase angle rather than mechanical degrees of transducer motion so that the calibration will be independent of the beamwidth of the transducer being simulated.

DESCRIPTION

This transducer simulator, shown in Figure 1, has been constructed sufficiently rugged and lightweight to be portable. It measures 14 in. wide, 9 in. high, and 16 in. deep, and weighs 38 pounds.

The two flush-type control knobs, located on the panel, control the phase relationship of the four output signals which simulate electrical outputs of the quadrants of a horizontally and vertically split type of transducer. The dials associated with the controls are visible through the plastic windows adjacent to each control. These dials, labeled UP—DOWN and LEFT—RIGHT, indicate directly the phase relationship of the output signals. The UP—DOWN dial indicates the phase angle between the two outputs representing the upper half of the transducer and the two outputs representing the lower half of the transducer. Likewise, the LEFT—RIGHT dial indicates the phase angle between the outputs representing the right half of the transducer and the two outputs representing the left half of the transducer.

The four output terminals at the rear of the simulator are shown in Figure 2. The simulator chassis removed from the case is shown in Figure 3. Shafts with the self-aligning couplings connect the control mechanism at the front of the case with the four special phase shifters. The oscillator stage and the components of the phase shifting network are shown in the view of the chassis with the control mechanism removed (Figure 4). The control mechanism with the dust cover removed is shown in Figure 5 and a rear view of the simulator chassis (Figure 6) shows the four converter and output stages. The four phase shifters can be partially seen behind the converter sub-chassis. A view of the converter sub-chassis removed from the main chassis is given in Figure 7, showing the low-pass filters; and Figure 8 is an underneath view of the chassis showing the manner in which the four channels are completely shielded.

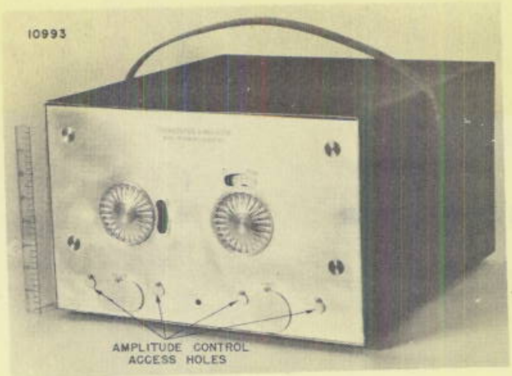


Figure 1 - Transducer simulator

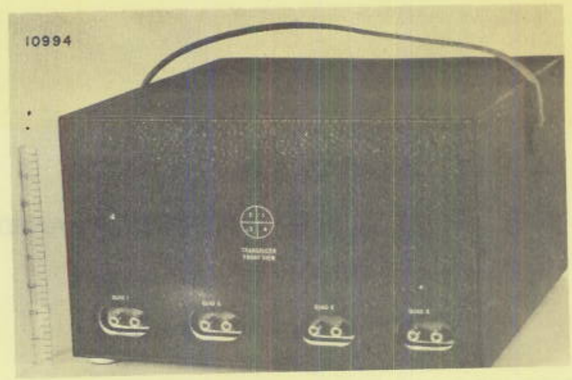


Figure 2 - Rear view of simulator

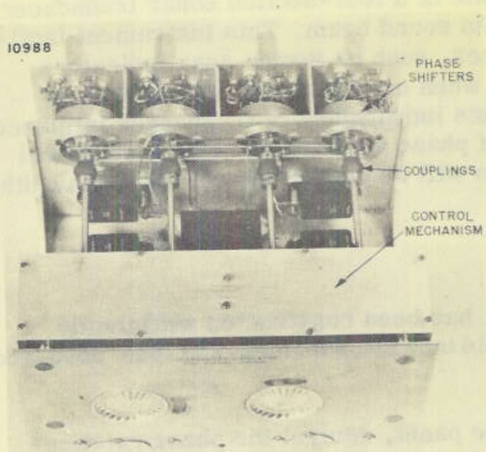


Figure 3 - Front view of chassis

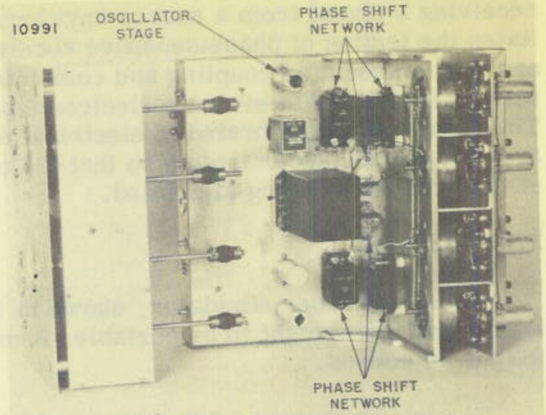


Figure 4 - Control mechanism removed from chassis

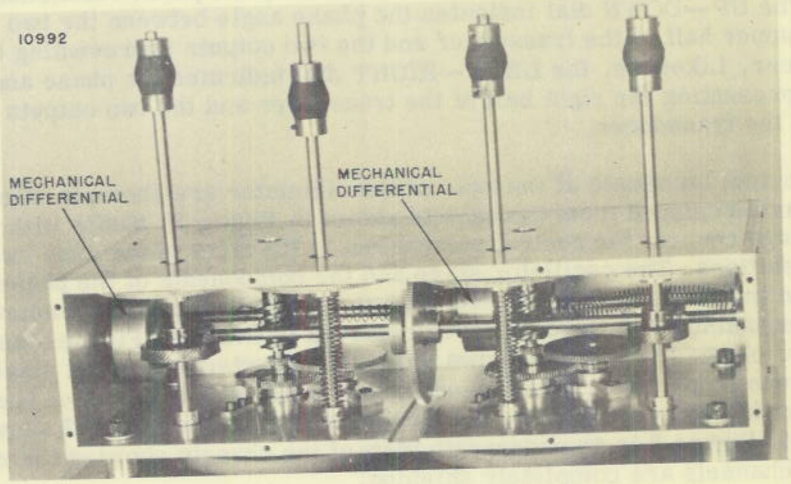


Figure 5 - Control mechanism

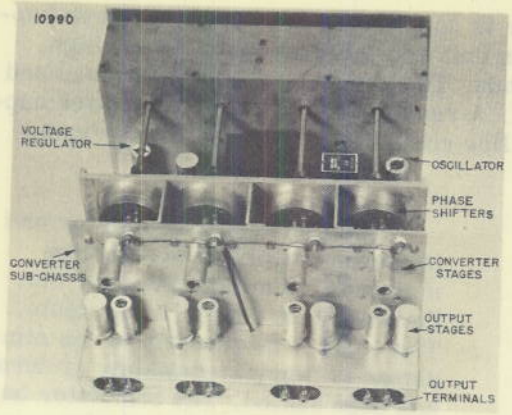


Figure 6 - Rear view of chassis

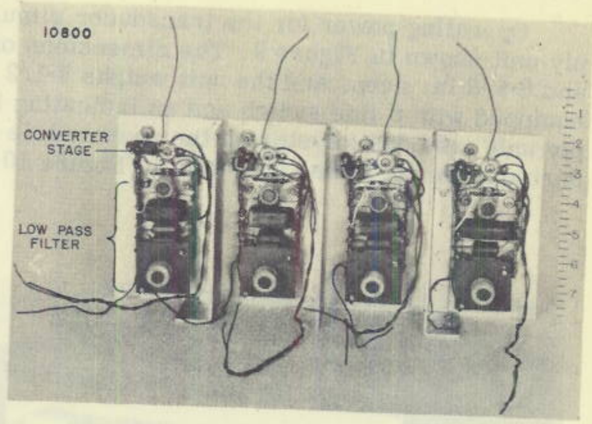


Figure 7 - Converter sub-chassis

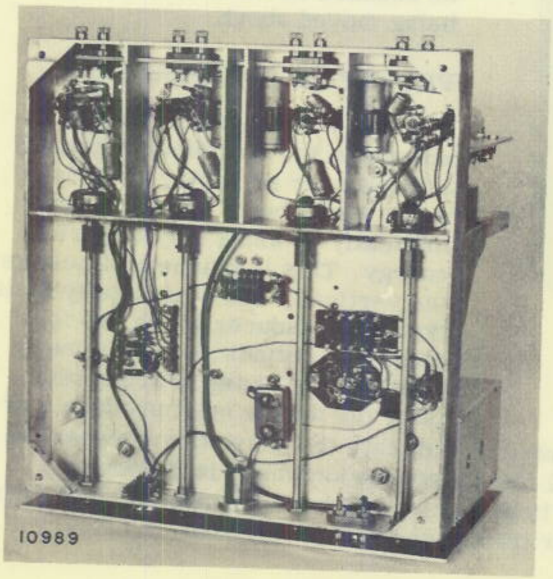


Figure 8 - Underneath view of chassis

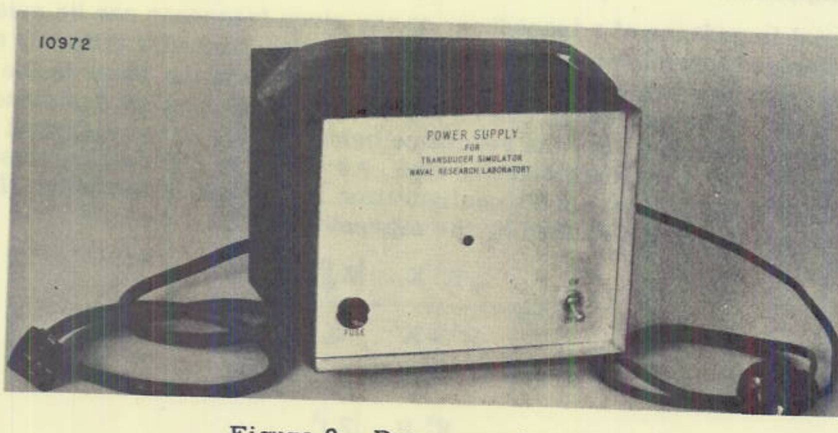


Figure 9 - Power supply unit

Operating power for the transducer simulator is supplied by the separate power supply unit shown in Figure 9. The dimensions of this unit are 7-1/8 in. wide, 6 in. high, and 6-5/8 in. deep, and the unit weighs 8-1/2 pounds. The power supply unit is fused and equipped with a line switch and an indicating light. A recess in the rear of the power supply unit provides for storing the power cable and line cord when the unit is being transported or is not in use as shown in Figure 10.

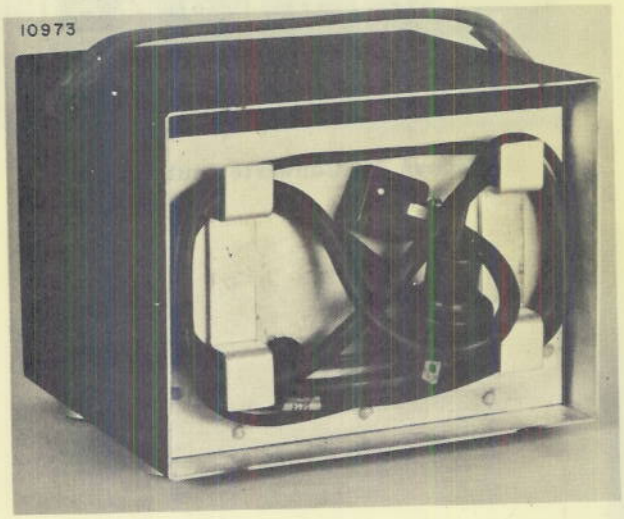


Figure 10 - Rear view of power supply

The transducer simulator and its power supply are fabricated mainly of aluminum in order that the weight be kept to a minimum. The control mechanism of the simulator is fabricated mainly of dural and dust sealed. The simulator has no protruding knobs, jacks, switches, or other parts that could be knocked off or broken when being moved about.

PRINCIPLES OF OPERATION

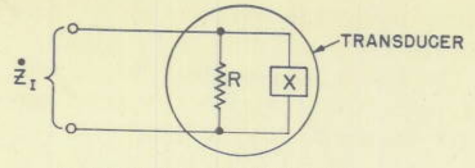
The transducer simulator simulates the electrical outputs of a transducer receiving an ultrasonic signal but it does this synthetically by using only electrical energy. This instrument simulates the vertically and horizontally split type of transducer which has four electrical outputs, one from each quadrant. In order to accomplish this, the device must produce four outputs whose phase relationships can be adjusted to duplicate those existing between the four outputs of a transducer receiving a signal from a source anywhere in its sound beam. In addition, it must permit making the impedance of each output identical with that of the corresponding quadrant of the particular transducer being simulated.

Transducer Impedance

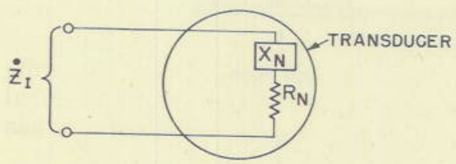
The internal impedance of a transducer at any given frequency can be measured on a bridge. The clamped impedance and the dynamic impedance usually differ by some amount, but the dynamic impedance of the transducer when in the water is the one usually of interest. This impedance can be represented as a parallel resistance and reactance, as shown in Figure 11a, the reactance being capacitive for a crystal transducer and inductive for a magnetostrictive type. As shown in Figure 11b, this parallel configuration has an equivalent series configuration in which Z is the same. The parallel and series configurations are related by the expressions:

$$X_N = \frac{R^2 X}{R^2 + X^2} = \frac{|Z_1|^2}{X}$$

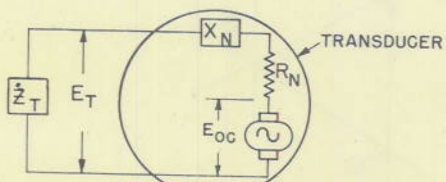
$$X_N = \frac{X^2 R}{R^2 + X^2} = \frac{|Z_1|^2}{R}$$



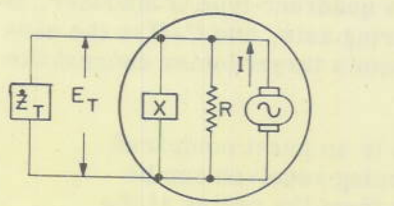
a. PARALLEL CONFIGURATION



b. SERIES CONFIGURATION EQUIVALENT TO a.



c. CONSTANT VOLTAGE GENERATOR CIRCUIT EQUIVALENT TO TRANSDUCER.



d. CONSTANT CURRENT GENERATOR CIRCUIT EQUIVALENT TO TRANSDUCER.

Figure 11 - Transducer equivalent circuits

A transducer can be represented by the circuit shown in Figure 11c. For a constant sound pressure on the transducer of a given frequency, the voltage across the terminating impedance, E_T, can be predicted from this circuit where the generator voltage (E_{OC}) of Figure 11c is the open circuit voltage of the transducer. For any given transducer at a particular frequency, E_{OC} depends only on the sound pressure. This arrangement is known as the constant-voltage generator circuit. The circuit shown in Figure 11d can also be used to represent the transducer if the generator is made a constant-current generator whose current I is dependent only on the sound pressure for any given transducer at any given frequency, and $I = \frac{E_{OC}}{X} + \frac{E_{OC}}{R}$ where $\dot{E}_{OC}$ is the open circuit voltage. Thus the terminating voltage is

$$\dot{E}_T = (\dot{I})\, \frac{R\cdot jX\cdot \dot{Z}_T}{RjX + R\dot{Z}_T + jX\dot{Z}_T}\,.$$

It will be found that the two circuits, the parallel and its equivalent series, will react identically with equivalent terminating impedances, in voltage and phase relationship, if the open circuit voltage (E_{OC}) of each is the same and all the other relationships shown are true. Any parallel configuration of terminating impedance used to parallel terminate a transducer will have an equivalent series configuration of terminating impedance which can be used to series terminate the transducer. These equivalent terminating impedances will be related by the same relations given above for Figure 11.

In the transducer simulator, the circuit configuration of Figure 11d is actually used. A 6AH6 tube is used as the constant current generator since the internal impedance of this tube and its associated circuit is so high, compared with the impedance of the R and X in parallel with it, that it produces for all practical purposes a constant current. When the proper values of R and X are introduced into the output circuit of the simulator, the voltage and phase across any given terminating impedance, as compared with the open circuit voltage and phase, will very accurately duplicate the results that would be obtained with the real transducer as compared with its open circuit voltage and phase.

Phase Relationship

A brief examination of the phase relationship of the electrical outputs of the quadrants of a sonar transducer receiving a signal will be useful in describing the operation

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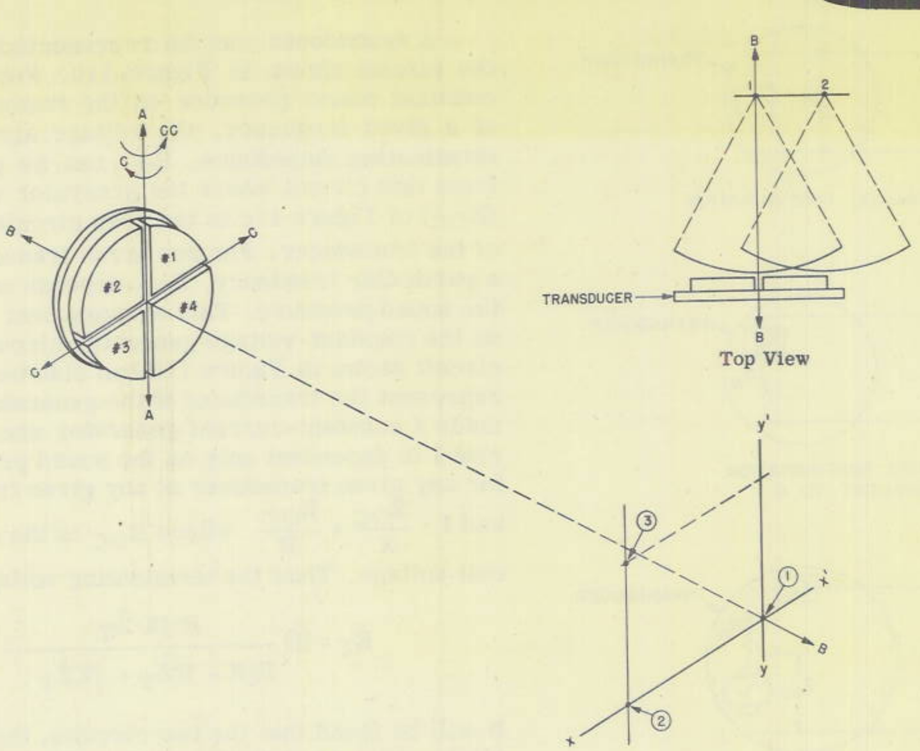

Figure 12 - Section transducer

of the transducer simulator. In Figure 12, a drawing of a quadrant-type transducer, B-B is the sound beam axis of the transducer, A-A is the bearing axis, and C-C is the elevation axis. When the transducer is receiving a signal from a target (noise source) the following assumption is made:

> The distance from the transducer to the target is so great compared to the transducer diameter that sound energy being received can be considered a plane wave front normal to a line from the center of the transducer to the center of the target.

This assumption is valid for current transducers and practices. When a signal is being received from a target which is on the axis B-B at point 1, the energy reaches all quadrants at the same time and hence the four output voltages will be in phase. If the sound source moves off the axis along the line toward x, quadrants 2 and 3 will receive the energy before 1 and 4; hence the phase of the output voltage of 2 and 3 will lead 1 and 4. The reverse will be true if the target moves back across the axis B-B toward x'.

The same type of reasoning holds when the target moves above and below the axis, along y-y'. Now assume that the target has moved along x-x' over to point 2 and consequently the outputs of 2 and 3 lead the outputs of 1 and 4 by a certain amount. Now, if the sound source is moved up to point 3, 1 and 2 must advance in phase relative to 3 and 4, and 2 and 3 must still lead 1 and 4 by the same amount as when the target was at position 2.

[redacted]

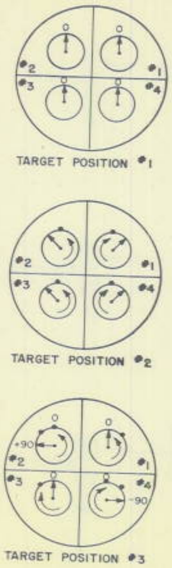

Figure 13 - Phase relationship of electrical outputs of the four quadrants

Figure 13 shows by vectors the phase relations of the four quadrants for the three consecutive positions. It is assumed for simplicity that target movement from position 1 to 2 gives rise to a 90° difference in phase between the voltages of the left and right halves, and the movement from position 2 to 3 also gives a 90° phase difference between the upper and lower halves.

It can be seen from an examination of the above process that the voltage vectors of quadrants 1 and 3 always move in opposite directions, and the vectors of 2 and 4 always move in opposite directions, regardless of target movement. However, when the target moves right or left, the vectors of 1 and 2 move opposite to each other, as do also 3 and 4, but when the target moves up and down 1 and 2 must move in the same direction; also 3 and 4 must move in the same direction, but opposite to 1 and 2, of course.

In the transducer simulator, four mechanically rotated phase shifters, each phase shifter representing one quadrant, are used to obtain the proper phase relationship of the output voltages. In these phase shifters one degree of mechanical motion gives one degree of electrical phase shift. A simplified schematic of the phase shifters and mechanical control mechanism is given in Figure 14. The phase shifters are numbered according to the quadrant they represent. According to the above explanation, 1 and 3 are geared together so that they always move in opposite directions, and 2 and 4 are geared together so that they also always move in opposite directions. A pair of mechanical differentials are arranged so that when the RIGHT—LEFT knob is rotated, 1 and 2 move in opposite directions, but when the UP—DOWN knob is rotated, 1 and 2 move in the same direction. The dial geared to the RIGHT—LEFT knob indicates the phase angle between 1 and 2, which is also the phase angle between 3 and 4. The dial geared to the UP—DOWN knob indicates the phase angle between 1 and 4, which is also the phase angle between 2 and 3. Each dial is graduated to indicate from 180° maximum one way through 0 to 180° maximum the other way.

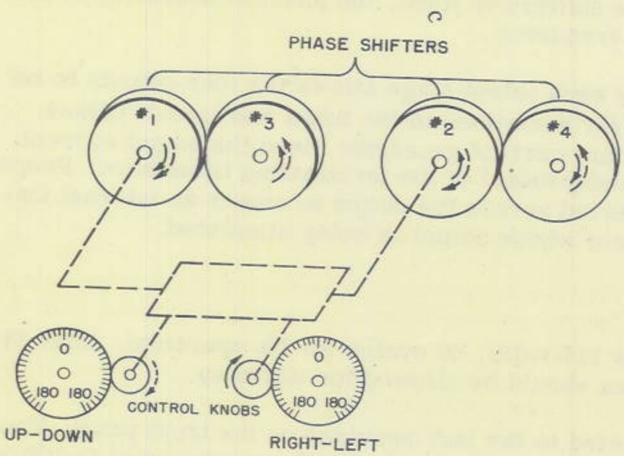

Figure 14 - Control mechanism, simplified schematic

Block Diagram

A block diagram of the simulator is shown in Figure 15. A crystal controlled oscillator generates a 100-kc signal which goes through a buffer stage into a phase shift network. This network results in four voltages, equal in amplitude but spaced 90° apart in phase, which are fed into the phase shifters whose output is a 100-kc signal whose phase angle depends on the position of the rotor shaft. As shown on the diagram, the phase shifter rotors are mechanically coupled with the control mechanism. The four outputs of the phase shifters go into converter stages where

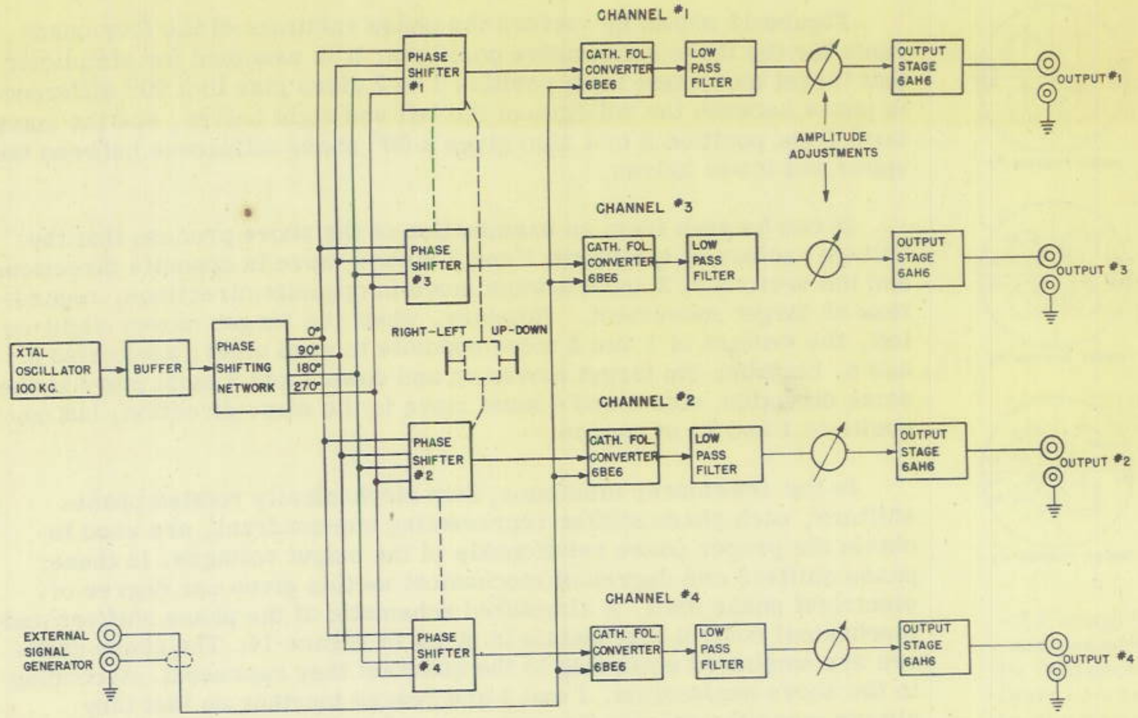

Figure 15 - Block diagram of transducer simulator

they are mixed with a signal from an external signal generator, a low-pass filter at the converter stage output rejecting all but the difference frequency component of each output. Because the same external signal is applied to all converters, and since phases add in converters, the four difference frequency components coming out of the converters will have phase relationships identical to that of the four phase-shifter outputs. Since the frequency of the signal through the phase shifters is fixed, the phase relationship of the four outputs does not change with output frequency.

The amplitude adjustment preceding each output stage allows the four outputs to be made equal in amplitude, compensating for variations in the tubes and circuit values. The output stage is equivalent to a constant current generator since the output current depends only on the grid voltage and is independent of the terminating impedance. Proper values of X and R in parallel can be inserted across the output to create an internal impedance the same as that of the transducer whose output is being simulated.

OPERATION

This transducer simulator requires 117 volts, 60 cycles for its operation. After the instrument is turned on, several minutes should be allowed for warm-up.

A signal generator should be connected to the jack provided on the front panel. The frequency range of this generator should enable it to produce a frequency equal to 100 kc plus the desired ultrasonic output frequency since the internal oscillator of the simulator is set at 100 kc. The generator should be capable of producing about 1 volt. It is desirable that the signal generator have an output attenuator, or other amplitude control, since this makes a convenient way to vary simultaneously the amplitude of all four outputs of the simulator an identical amount. This is often necessary since the output level must be placed within the dynamic input range of the receiving device being tested. The outputs of the simulator are labeled as to the transducer quadrants they represent. A parallel combination of resistance and reactance can be externally connected across each output to make the output impedance equal to the dynamic internal impedance of the corresponding quadrant of the transducer. The degree of exactness used in making the impedance of the output equal to the impedance of the transducer will determine the faithfulness with which the simulator output duplicates the transducer output in its reaction to a terminating impedance.

If the instrument is properly adjusted, the four output currents will be precisely equal. Thus, if the four characteristic impedances connected across the four outputs are not identical, the voltage amplitudes will not be identical. If it is desired to make them identical they can be adjusted by means of the amplitude adjustment potentiometers.

When the instrument is ready to operate—with the signal generator set to proper frequency and amplitude—the phase relationship of the outputs can be adjusted by the front panel controls. The dials indicate the phase angle between the respective halves of the transducer. When the RIGHT—LEFT dial is rotated counterclockwise, by rotating the control counterclockwise, the dial reads RIGHT and the outputs correspond to a target (noise source) to the right of the transducer axis, i.e., the transducer would have to be trained to the right (clockwise, increasing in bearing) to bring the sound beam axis of the transducer back on the target, and, in this case, quadrants 2 and 3 would lead 1 and 4 by the amount read on the dial. Also, when the UP—DOWN dial is rotated clockwise the dial reads UP and the outputs correspond to a target above the transducer sound beam axis. In this case, quadrants 1 and 2 would lead 4 and 3 by the angle indicated by the dial. The transducer would have to be elevated to bring it back on the target.

Since the dials read the phase angle between the output voltages of the halves of the transducer, there is actually no indication of the angle, in degrees of rotation, or tilt, between the simulated transducer's sound beam axis and the target. A simple approximation can be used to determine the angle, in degrees, through which the transducer* would have to be rotated, or tilted, to bring it back on the target. The approximation is:

$$\alpha = \frac{\theta B}{360},$$

where α is the angle between the sound beam axis of the transducer and the target, in degrees rotation or degrees tilt, depending on θ;

θ is the dial reading. If θ is RIGHT, α will be the angle that the target is to the right of the transducer axis. If θ is UP, α will be the angle that the target is above the transducer axis; and

B is the angle between the first null points in the response pattern of the whole transducer whose receiving performance is being simulated. If θ is the RIGHT—LEFT dial reading, the horizontal beam pattern should be used to determine B, and if θ is the UP—DOWN dial reading, the vertical beam pattern should be used to determine B. B varies, of course, with frequency.

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* See appendix for the derivation of the exact relation and the limitations of the above approximation.

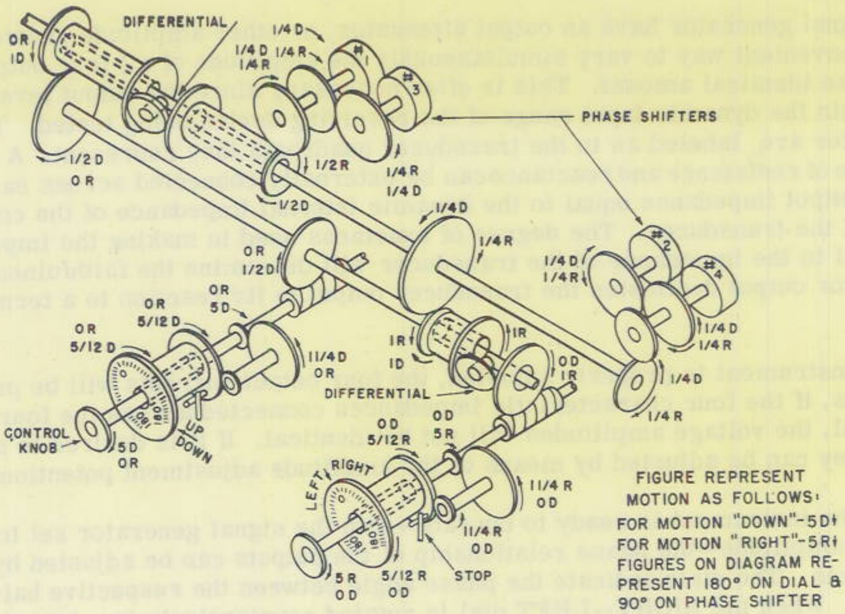

Figure 16 - Transducer simulator mechanism (schematic)

In summary, the characteristics of the transducer simulator are:

a. Frequency range of output signal—10 to 60 kc.

b. Dial indication—within ±1 degree of the actual phase angle.

c. Output amplitude variation—no more than ±2-1/2% with variation of the phase controls.

d. Output current—approximately 20μ amps with one volt of external input signal. The magnitude of the current is proportional to the external input signal amplitude.

CONTROL MECHANISM

A schematic of the control mechanism is shown in Figure 16. As explained in the section "Principles of Operation," phase shifters numbered 1 and 3 are geared together, 2 and 4 are geared together, and the two differentials are arranged so that when the RIGHT–LEFT control is turned, 1 and 2 rotate in opposite directions, but when the UP–DOWN control is turned, phase shifters 1 and 2 rotate in the same direction. Five revolutions of the control move the associated dial 180° in graduation, which is 5/12 of a revolution and rotate the phase shifters 90°. Thus each control can independently move the phase shifters 180°, representing 10 revolutions of the control and 5/6 of a revolution of the dial from 180° through 0 to 180°. Stops on the dials limit the system within this range. Both controls together can move the phase shifters 360°. The combination of the worm drive used and a frictional drag on each dial makes the two controls independent. Movement of one control will not disturb the setting of the other control. Four helical springs in the mechanism perform the dual purpose of reducing backlash to a minimum and, at the same time, imparting an even "feel" to the finger controls. On the schematic, numbers followed by R indicate rotation resulting from 5 revolutions clockwise of the RIGHT—LEFT control, and numbers followed by D indicate rotation resulting from 5 revolutions clockwise of the UP—DOWN dial.

ELECTRICAL CIRCUIT

The electrical circuit is shown in Figure 17. The output of the 100-kc oscillator is coupled through a buffer stage, which is connected as a cathode follower, into a transformer which matches the cathode follower output impedance to the impedance of the phase shift network. The phase shift network supplies four voltages at 90° intervals in phase to the four stator plates of the phase shifters, which are special phase shifting capacitors whose rotor plate picks up voltage components from two or three stator sections simultaneously. The voltage at the output of each phase shifter is the vector sum of these components. The plates of these phase shifters are shaped so that the output voltage is of constant amplitude, and rotation through one degree mechanically changes the output phase one electrical degree. General Radio precision type resistors shunted across the secondary of the transformer reduces the amount of unbalance due to stray capacity in the transformer and associated circuit.

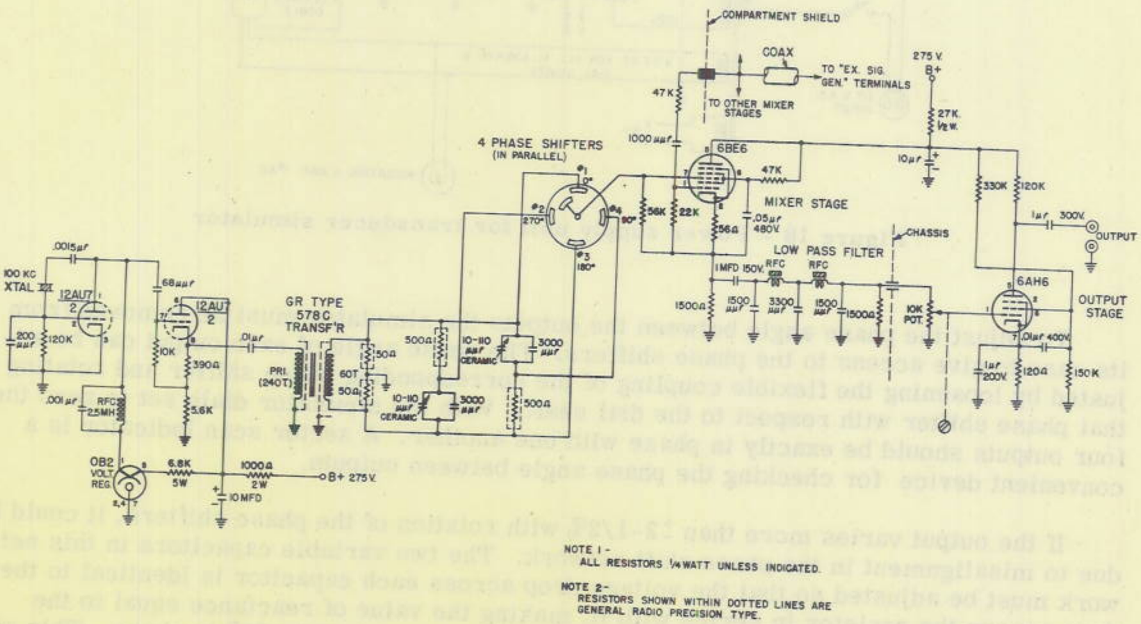

Figure 17 - Transducer simulator—oscillator, buffer, and phase shift network—mixer and output stages

The resistors R_1 and R_2 are also GR precision type. It is necessary to use precise components in this circuit since the slightest unbalance will alter the voltage and phase relationships at the four stator plates. Wiring and mounting of the components in this section of the transducer simulator is very critical.

The outputs of the phase shifters are connected to the converter stages where they are mixed with the signal from the external signal generator. This stage is connected as a cathode follower to match the low characteristic impedance of the low-pass filter.

The circuit diagram of the power supply unit is shown in Figure 18. This unit supplies 275 volts of well-filtered d.c. at 60 milliamperes for the B+ requirements of the simulator. It also supplies 6.3 volts a.c. for filament power.

The amplitude of the outputs can be adjusted by the four screwdriver-type potentiometers located behind the small access holes in the front panel. By using the same load resistor across each output, a suggested value being 10,000 ohms, the output currents can be made equal by making the voltages equal. The output contains 100 kc and external signal components which will affect the meter reading. An additional low-pass filter, or tuned circuit, between the output and the meter will aid in removing these components if the absolute value of the output must be determined.

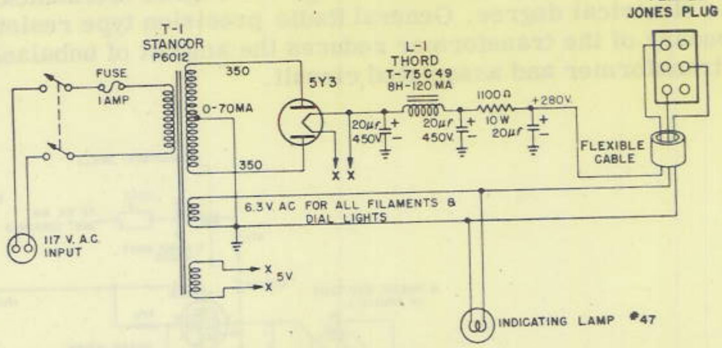

Figure 18 - Power supply unit for transducer simulator

To adjust the phase angle between the outputs the simulator must be removed from its case to give access to the phase shifters. The phase angle of each output can be adjusted by loosening the flexible coupling of the corresponding phase shifter and rotating that phase shifter with respect to the dial shaft. With the simulator dials set to zero the four outputs should be exactly in phase with one another. A sector scan indicator is a convenient device for checking the phase angle between outputs.

If the output varies more than $\pm 2\text{-}1/2\%$ with rotation of the phase shifters, it could be due to misalignment in the phase shift network. The two variable capacitors in this network must be adjusted so that the voltage drop across each capacitor is identical to the drop across the resistor in series with it, making the value of reactance equal to the resistance—thus insuring that the four outputs are spaced exactly 90° in phase. This adjustment is rather critical, but should seldom be necessary.

* * *

APPENDIX

Since the dials of the transducer simulator are graduated in electrical degrees, the actual angle between the sound beam axis of the transducer whose outputs are being simulated and the apparent target, in degrees of rotation or tilt, must be calculated. The dials read the phase angle between the electrical outputs representing the vertically divided halves and the horizontal divided halves of the transducer. To calculate the angle between the axis and the target, certain assumptions must be made, namely:

a. The distance between the transducer and the target is so great compared to the transducer diameter that the sound energy being received can be considered a plane wave front normal to a line between the transducer and the target.

b. The diameter of the transducer is so large compared to the longest wavelength of the sound energy to be received that the apparent electrical center of each of the transducer sections remains the same for a target anywhere within the beamwidth of the transducer.

These assumptions are valid for current transducers and practices.

Referring to Figure 19,

λ = wavelength of sound energy being received,

$\beta = 1/2$ beamwidth of transducer for frequency being received.

Thus, distance $(y_1) = \frac{\lambda}{2}$. Now

α = angle between target and transducer sound beam axis,

d = distance between apparent electrical centers of the two halves of transducer,

$r = \frac{d}{2}$, and

θ = dial reading of either dial of transducer simulator which is the phase angle between voltages at a and a′ for a transducer angle of α away from target bearing.

Then,

$$\text{distance } (y_3) = r \sin\alpha, \tag{1}$$

$$\text{distance } (y_2) = 2r \sin\alpha = d \sin\alpha, \tag{2}$$

$$\text{distance } (y_1) = \frac{\lambda}{2} = d \sin\beta. \tag{3}$$

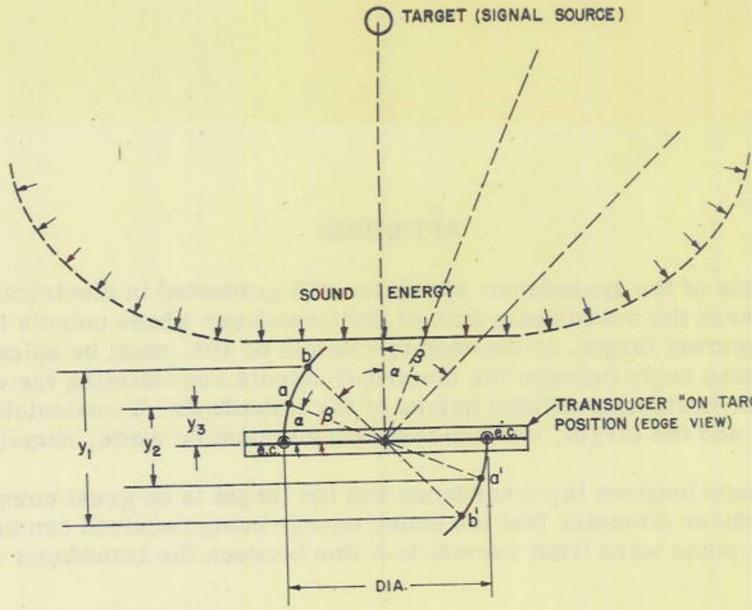

Figure 19

Now, $$(y_2) = \frac{(\theta)}{360}(\lambda). \tag{4}$$

From (3), $$\lambda = 2d \sin \beta. \tag{5}$$

Substituting (5) into (4),

$$(y_2) = \frac{(\theta)}{360} 2d \sin \beta. \tag{6}$$

Substituting (6) into (2),

$$\frac{(\theta)}{360} 2d \sin \beta = d \sin \alpha,$$

$$\frac{\theta \sin \beta}{180} = \sin \alpha,$$

$$\alpha = \sin^{-1} \frac{(\theta \sin \beta)}{180}. \tag{7}$$

Thus α is the angle between the transducer sound beam axis and the target in the plane represented by the dial whose reading is substituted for θ in Equation (7).

For all practical purposes, the following approximation can be used:

$$\text{Since } -1 \leqq \frac{\theta}{180} \leqq +1,$$

then $\alpha \cong \frac{\theta\beta}{180}$.

If B = beamwidth at frequency being received, then $\beta = \frac{1}{2}B$, and

$$\alpha \cong \frac{\theta B}{360} \qquad (8)$$

If the beamwidth of transducer at the frequency being received is 28° less, the approximation (Equation (8)) will always be within 1 percent or less of the correct angle, the maximum error occurring at the very low dial readings.

The above formula (Equation (8)) will give in degrees rotation or tilt the transducer angle off of the target bearing.

* * *

then, $\alpha = \frac{\theta\phi}{180}$

If B = bandwidth at frequency being received, then $\phi = \frac{1}{2}B$, and

$$\alpha = \frac{\theta B}{360} \qquad (8)$$

If the bandwidth of transducers at the frequency being received is 180° or less, the approximation (Equation (8)) will always be within 1 percent or less of the correct angle, the maximum error occurring in the very low dial readings.

The above formula (Equation (8)) will give in degrees rotation or tilt the transducer angle off of the target bearing.

* * *