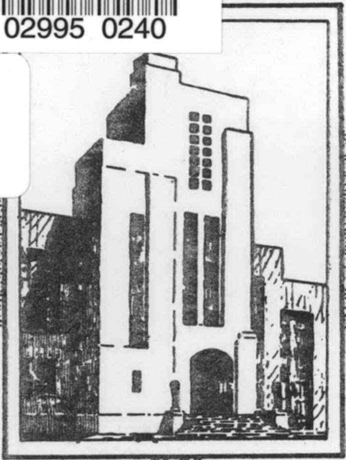
NAVY DEPARTMENT

DAVID TAYLOR MODEL BASIN



HYDROMECHANICS

○

AERODYNAMICS

○

STRUCTURAL MECHANICS

○

APPLIED MATHEMATICS

A PHASE-COMPONENT MEASUREMENT SYSTEM

[redacted]

by

R.G. Tuckerman

[redacted]

INSTRUMENTATION DIVISION

RESEARCH AND DEVELOPMENT REPORT

April 1958

Report 1139

PRNC-TMB-648 (11-56)

DEPARTMENT OF THE NAVY
DAVID TAYLOR MODEL BASIN
WASHINGTON 7, D.C.

IN REPLY REFER TO
S87
A9/1
(230:FBB:lcb)
25 April 1958

From: Commanding Officer and Director
To: Chief, Bureau of Ships (312)

Subj: A phase-component measurement system; forwarding of report on

Encl: (1) TMB Report 1139 - 12 copies

1. Enclosure (1) describes an instrumentation system developed to indicate directly the first-order Fourier coefficients of the heaving force and pitching moment acting on a ship model when it is forcibly displaced. Provision is made for indicating the coefficients of the second or the third harmonics when desired. Direct recording of the force and moment signals is also provided. The report includes schematic diagrams, photographs, and operating instructions.

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Versuchsanstalt, Bramfelder Str. 164, Hamburg 33, Germany
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A PHASE-COMPONENT MEASUREMENT SYSTEM

by

R.G. Tuckerman

April 1958 Report 1139

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ABSTRACT

This report describes an instrumentation system developed to indicate directly the first-order Fourier coefficients of the heaving force and pitching moment acting on a ship model when it is forcibly displaced. Provision is made for indicating the coefficients of the second or the third harmonics when desired. Direct recording of the force and moment signals is also provided. The report includes schematic diagrams, photographs, and operating instructions.

INTRODUCTION

Model-testing programs at the David Taylor Model Basin for the study of ships' motions require the measurement of heaving force and pitching moment of the model when it is being driven in heaving and pitching motions by a displacement oscillator.[1] In instrumentation used in such tests in the past, these force and moment signals have been recorded graphically, and the amplitudes and phase shifts of the signals were determined by a tedious point-by-point analysis and measurement of the records. This analysis was complicated by the presence of harmonics, by signals produced by the natural frequency of the model and dynamometer suspension, and by high amplitude extraneous noise signals. In addition, the time required to analyze the records made it necessary to carry out the analysis after the test operations had been completed, precluding the ready checking of questionable data points or the acquisition of additional points as might be dictated by the analysis results.

For these reasons, the Seaworthiness Division of the Hydromechanics Laboratory requested the Instrumentation Division to study the feasibility of designing instrumentation to measure and indicate directly the Fourier coefficients of the complex force and moment signals. This would yield the essential data immediately, as the test is in progress.

The requirements set up for the instrumentation were as follows:

1. The force and moment signals will be obtained from a multicomponent force balance, utilizing strain-gage bridge transducers with all four arms active.

2. The frequency of displacement will be from 1/3 cycle per second to 3 cycles per second.

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[1] References are listed on page 22.

3. The first-order Fourier coefficients of the force and moment signals should be indicated directly on meters or other devices. Provision should be made for indicating also the second- and third-order coefficients of components of the force and moment signals. Accuracy of measurement of any selected component should not be affected by the presence of harmonics of the signal frequency.

4. Superimposed noise caused by the natural frequency of the model and other apparatus should not affect the accuracy of the indications.

5. The maximum pitching angle of the model will be 3 degrees and the maximum speed will be 4 knots. This will produce a maximum strain of 1000 microinches per inch per strain gage, giving an equivalent signal of 4000 microinches per inch for each bridge.

6. Direct recording of the force and moment signals is to be provided.

A study of various means of obtaining the Fourier coefficients was made. Among methods which at first appeared to be adaptable was a system used at NACA.[2] In this system the coefficients are obtained by utilizing a strain-gage bridge as a combination force-signal source and multiplier. The resultant output voltage from the bridge is averaged by the action of a highly damped galvanometer. The system also utilizes a strain-gage bridge as the source of a sine-multiplying voltage. The cosine-multiplying voltage is obtained by electronic integration of the sine voltage. Although this system appears very satisfactory for the intended application, it exhibits two disadvantages as far as our application was concerned: (1) low-level d-c amplifiers would be required to amplify the small low-frequency signals, and (2) no simple means of obtaining the second- and third-order coefficients was apparent.

Another system considered was that used in the TMB Vibration Analyzer Type 165-A. This system obtains the same results by direct measurement of the component of the input signal that is in phase with an injected reference signal, which can be either a sine or cosine voltage. Voltages proportional to the desired coefficients may be obtained by averaging the output of special phase-sensitive demodulators. Indication is on a highly damped galvanometer. This system also failed to meet our requirements, primarily because the additive process, by which the coefficient voltages are obtained, results in an indication which is affected by the magnitude of higher order coefficients.

Further study led to the choice of the system described in this report. In this system the instrumentation carries out the operations involved in solving the functions representing force or moment signals for the Fourier coefficients. The individual function is multiplied electrically by a cosine function of the drive frequency, then integrated and averaged (divided by time) to obtain the inphase coefficient; or is multiplied by a sine function, integrated, and averaged, to obtain the quadrature coefficient. By a similar process, the inphase and quadrature coefficients of any selected harmonic may also be obtained. The coefficients are indicated as meter readings; if desired, they could also be read through a digital recording. Provisions are also made for simultaneous graphic recording of the force and moment signals.

This system was proposed by an Instrumentation Division memorandum[2] of 31 January 1956 to the Hydromechanics Laboratory, and was authorized by the Laboratory for design and construction in March 1956. The final instrument, which has now been in use for about a year, is shown in Figure 1.

MEASUREMENT SYSTEM

DESCRIPTION

The instrumentation described in this report is the TMB Type 278 Phase-Component Indicating System. This system is composed of several distinct units, each of which is discussed separately in detail. The overall operation of the system can best be described by referring to the block diagram (Figure 2) and following the action through the blocks.

A drive motor (A) is mounted on the towing carriage and through gears and a scotch yoke (B) drives the model (C) up and down in a sinusoidol pitching motion. A towing strut which is attached to the carriage is coupled mechanically to the model through a strain-gage force balance (D). The strain-gage bridge is excited with a 2000-cycle signal from the carrier oscillator (I). When the model is forced up and down, the strain-gage balance produces a signal f(t) which is fed to the carrier amplifier and demodulator (E). The output from the carrier amplifier and demodulator is a varying d-c signal proportional to the force exerted on the strain-gage balance.

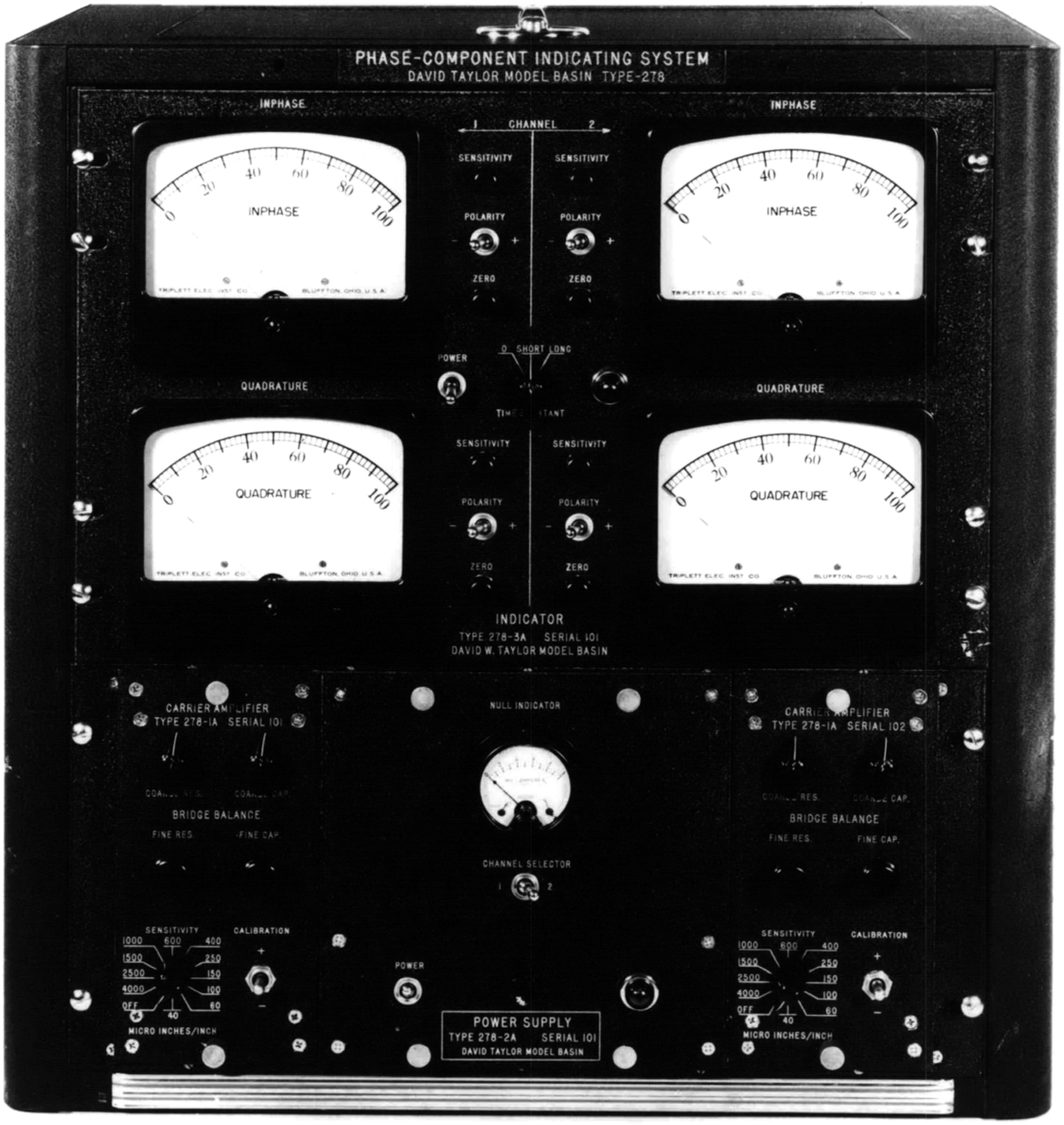

Figure 1 - Front View, Phase-Component Indicating System

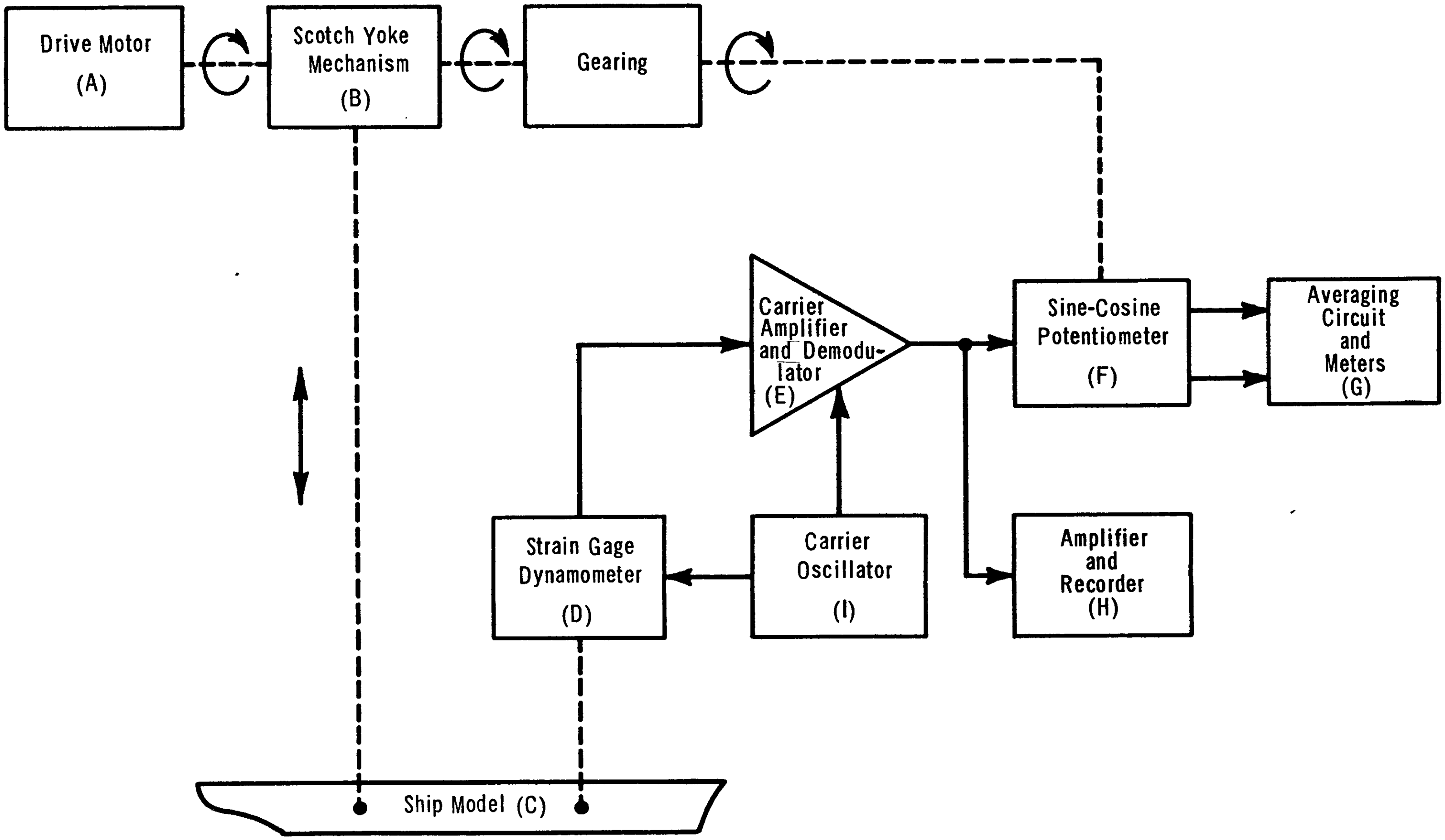

Figure 2 - Block Diagram of Phase-Component Indicating System

This d-c signal is fed to an amplifier and direct-writing recorder (H), which produces a graphic record of the forces being applied to the balance.

The output signal from the carrier amplifier and demodulator is also fed to the sine-cosine potentiometer (F). The wiper arms of the potentiometer are rotated, through a gear system, at the same frequency as the pitching motion of the model, or in the study of second or third harmonics, at twice or three times the frequency of pitching, respectively. The wiper arms are properly phased so that one wiper produces an output signal $f(t) \sin \omega t$ while the other wiper produces a signal $f(t) \cos \omega t$. These two signals are fed to separate averaging and metering circuits (G), where the average inphase and quadrature components of the force and moment signals are indicated.

THEORY OF OPERATION

The force (or moment) signal obtained from the strain-gage balance is a complex voltage signal composed of components of the driving frequency, harmonics of the driving frequency, natural frequencies of mechanical structures, and other extraneous noise signals. After demodulation, the voltage wave form may be expressed as,

$$E_1 (t) = A \cos (\omega t + \phi) + B \cos (n\omega t + \gamma) + C \cos x\omega t \quad [1]$$

where ω is the angular driving frequency
$n\omega$ is any harmonic of ω ($n = 1, 2, 3, \ldots.$)
$x\omega$ is any other angular frequency (usually higher than ω and not harmonically related)
ϕ is the phase angle between the force (or moment) signal and the displacement
γ is the time phase of the nth harmonic
A, B, and C are amplitude constants.

The function of the instrument system is to separately compute and indicate the amplitudes of the inphase and quadrature components of the first term, and to neglect all other terms, or if desired, to perform the same operation on the second term, neglecting all others. This operation is equivalent to finding the Fourier coefficients of these terms. The process, mathematically, consists of multiplication of the function, first by $\cos \omega t$ and integrating over a period 2π of the multiplying function, then multiplying by $\sin \omega t$ and integrating over the same period, to obtain the first-order coefficients, a_1 and b_1, respectively.

First, in order to simulate the mathematical process of multiplication, the complex signal voltage, E_1 (t) is applied to a sine-cosine potentiometer, which is mechanically rotated at the displacement frequency, ω. The outputs of the potentiometer are then simultaneously:

$$E_1 (t) \cos \omega t, \text{ and } E_1 (t) \sin \omega t. \qquad [2]$$

Considering first only the cosine component:

$$E_2 (t) = A \cos (\omega t + \phi) \cos \omega t + B \cos (n\omega t + \gamma)$$

$$\cos \omega t + C \cos x\omega t \cos \omega t, \text{ where}$$

$$E_2 (t) = E_1 (t) \cos \omega t. \qquad [3]$$

Expanding

$$E_2 (t) = [\cos \omega t \cos \phi - \sin \omega t \sin \phi] \cos \omega t$$

$$+ \text{ other terms.} \qquad [4]$$

Integrating over an interval, 0 to T,

$$\int_0^T E_2 (t)\, dt = \int_0^T A \cos \phi \cos^2 \omega t\, dt \qquad [5]$$

$$- \int_0^T A \sin \phi \sin \omega t \cos \omega t\, dt + \int_0^T (\text{other terms})\, dt$$

Since all definite integrals above, with the exception of the first term, vanish if T is chosen as an integral number of periods of the frequency ω, then

$$\int_0^T E_2 (t)\, dt = \int_0^T A \cos \phi \cos^2 \omega t\, dt$$

$$= A \cos \phi \left[\frac{t}{2} + \frac{\sin 2\omega t}{4\omega}\right]_0^T$$

$$= A \cos \phi \,(n\pi) \qquad [6]$$

Dividing through by T (which is n 2π)

$$\frac{\int_0^T E_2 (t)\, dt}{T} = \frac{A \cos \phi\, (n\pi)}{n2\pi} = \frac{A \cos \phi}{2} = a_1 \qquad [7]$$

By identical process, the sine component of Equation [2] yields

$$\frac{A \sin \phi}{2} = b_1. \qquad [8]$$

The terms a_1 and b_1 are proportional to the first order coefficients.

The action of the R-C circuits and meter movements is to perform an operation of averaging which can be made very nearly equivalent to the foregoing integration and division by the time base, if the time constant R-C is properly chosen in relation to the lowest frequency ω that is of interest, and if the time of averaging can be permitted to extend over many periods. The voltages corresponding to a_1 and b_1 are indicated on the respective meters, as the inphase and quadrature components, respectively.

Similarly, if the sine-cosine potentiometers are geared to rotate at a frequency $n\omega$, (where n is an integer), the n^{th} order coefficients can be measured and indicated to the exclusion of all other components, including those of the fundamental frequency ω.

In actual model tests, nonlinearities give rise to various harmonic components in the force (or moment) signal. In addition, other extraneous vibrations and noise signals contaminate the signal. It is in this respect that the instrument achieves its worth. Since the nature of the operations performed closely approximates the true mathematical operations of multiplication and integration, all voltage components except the one being measured automatically become zero and produce no indication on the coefficient indicating meters.

DYNAMOMETER (FORCE BALANCE)

This instrumentation was designed to be used with strain-gage type dynamometers using a four-arm bridge. The dynamometers which were used in the initial test conducted with the equipment had strain-gage bridges with all four arms active. Each gage arm was 120Ω and the gage factor was 2.00. By proper application, other types of resistance-gaging elements, such as potentiometers, may be used.

The system may be adapted to the use of variable reluctance-type gaging elements by replacing the plug-in carrier amplifier units, Type 278-1A, with a similar unit designed to balance and power the variable reluctance-type gaging elements.

CARRIER AMPLIFIER, TYPE 278-1A

The carrier amplifier unit performs several functions in the system. It has balancing circuits used to correct any initial unbalances in the strain-gage bridge. A secondary calibration of the system is accomplished within this unit by switching a shunt resistor across either side of the bridge to ground, producing a known tension (+) or compression (-) signal. The size of the calibration signal is dependent upon the setting of an eleven-step attenuator which provides sensitivity settings from 40 microinches per inch to 4000 microinches per inch for full-scale deflection of the recording apparatus.

The bridge circuits are followed by amplifiers and a demodulator. The output of the demodulator is filtered to remove any of the carrier frequency that remains and is then fed to the output terminals of the carrier amplifier unit.

The carrier amplifier, Type 278-1A, is built in a plug-in chassis which plugs into Rack, Type 278-4A. All components are mounted so that they are readily accessible when the unit is removed from the rack, as shown in Figures 3 and 4. Two carrier amplifiers are used in the complete system to provide for the handling of signals from two separate dynamometers. The schematic diagram is shown as Figure 5.

POWER SUPPLY, TYPE 278-2A

The Power Supply, Type 278-2A, provides 200 volts regulated d-c and 6.3-volt a-c filament voltage for itself and for the two carrier amplifiers. It contains the necessary power supply circuits and electronic regulators, as well as a 2000-cycle-per-second oscillator and a null indicator. The oscillator is used to drive the strain-gage bridges and provides the injection voltage for the demodulators in the carrier amplifiers. The null indicator provides an indication of the state of balance of the strain-gage bridges. A switch is provided so that either of two bridges may be monitored.

This unit is built on a plug-in chassis which plugs into the rack. All components are readily accessible for servicing

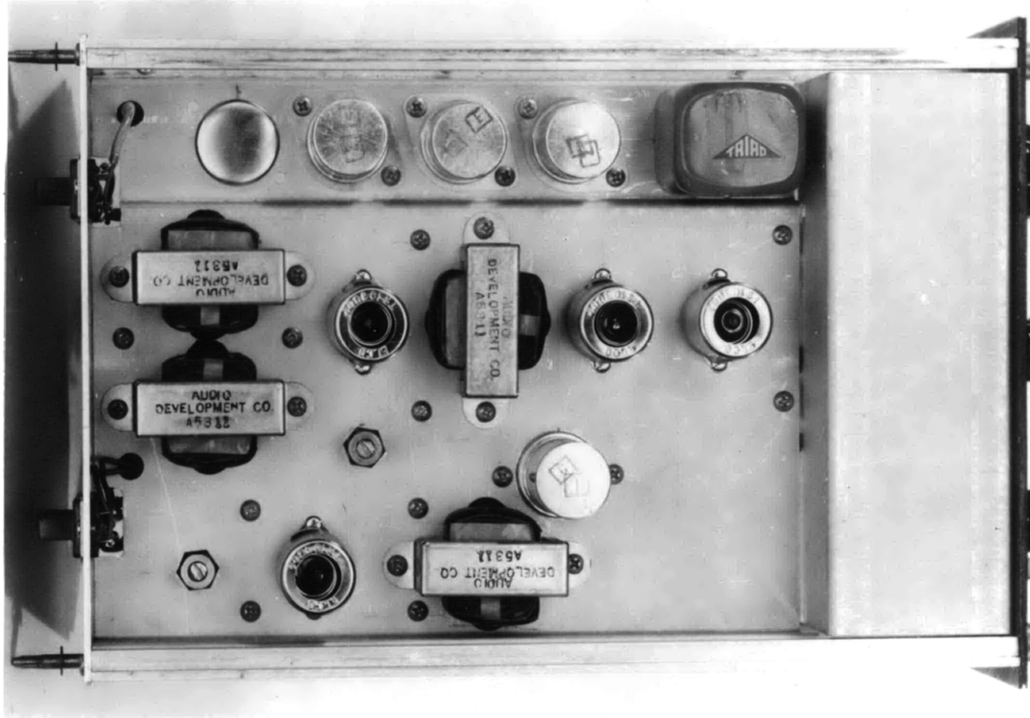

Figure 3 - Side No. 1, Carrier Amplifier, Type 278-1A

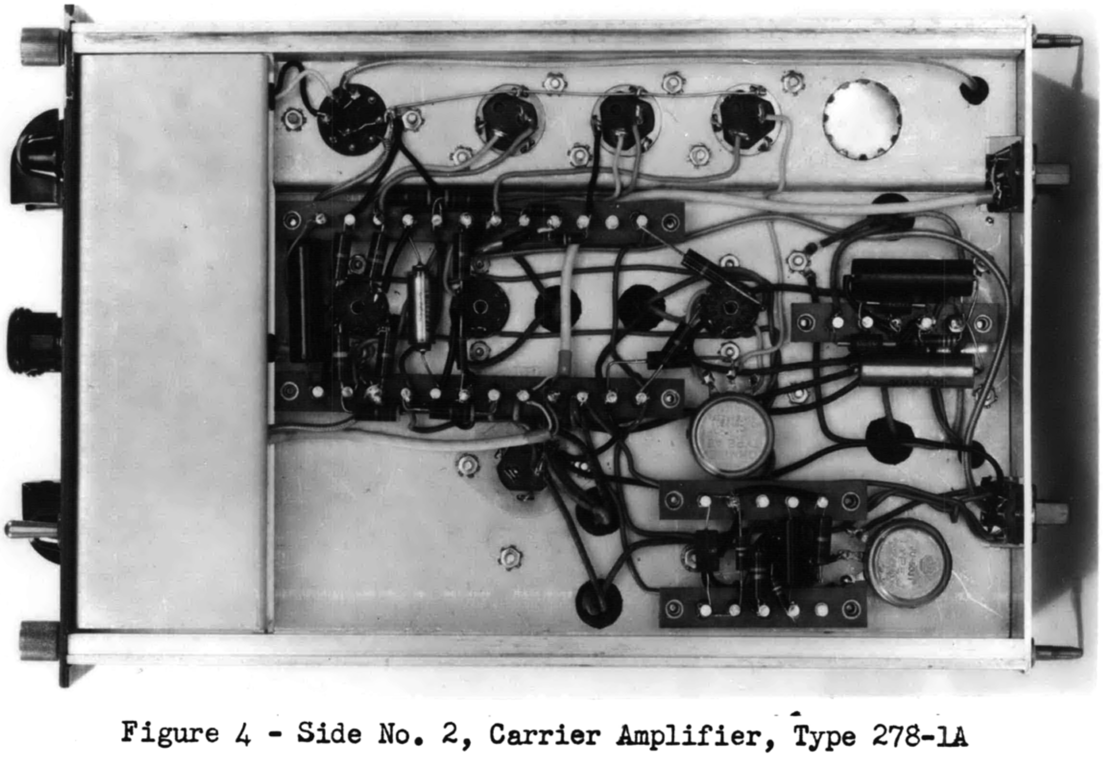

Figure 4 - Side No. 2, Carrier Amplifier, Type 278-1A

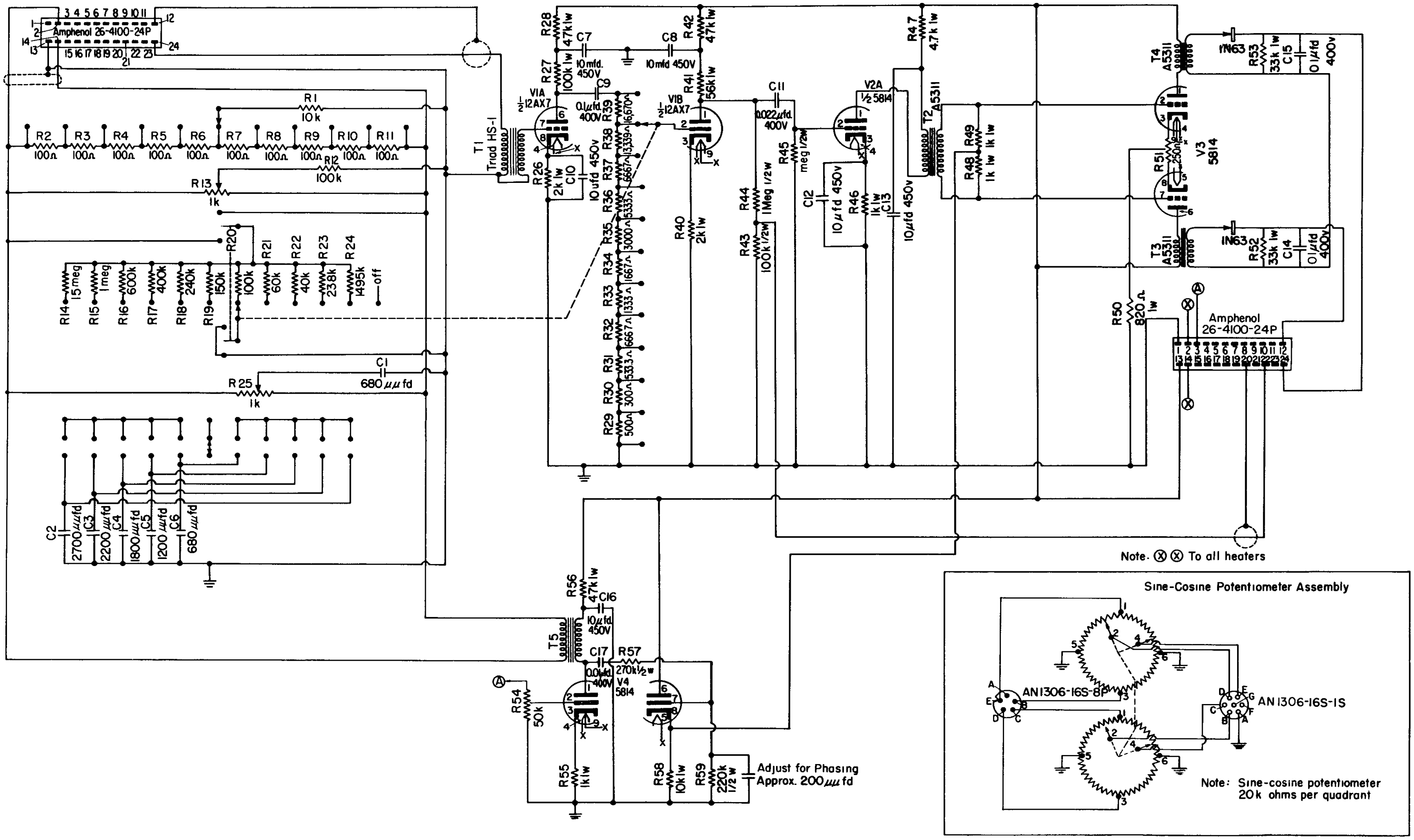

Figure 5 - Schematic Diagram, Type 278-1A

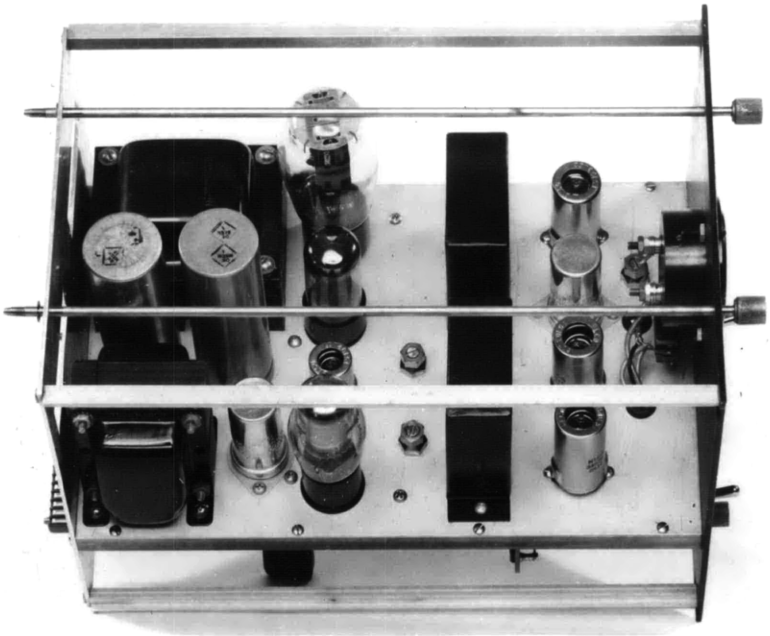

Figure 6 - Top View, Power Supply, Type 278-2A

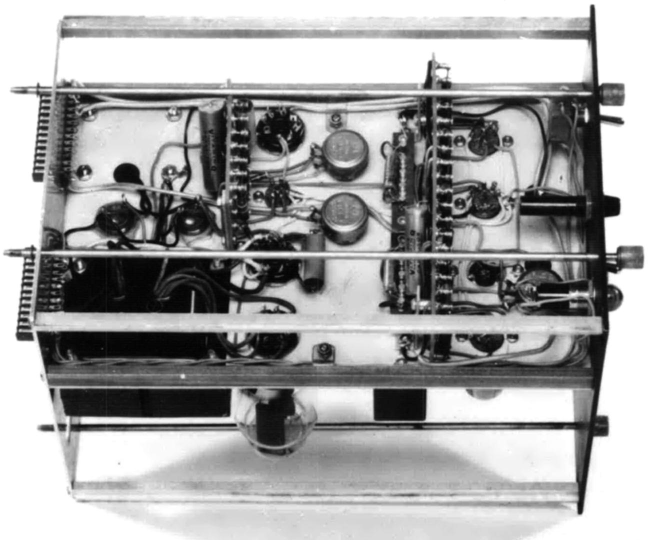

Figure 7 - Bottom View, Power Supply, Type 278-2A

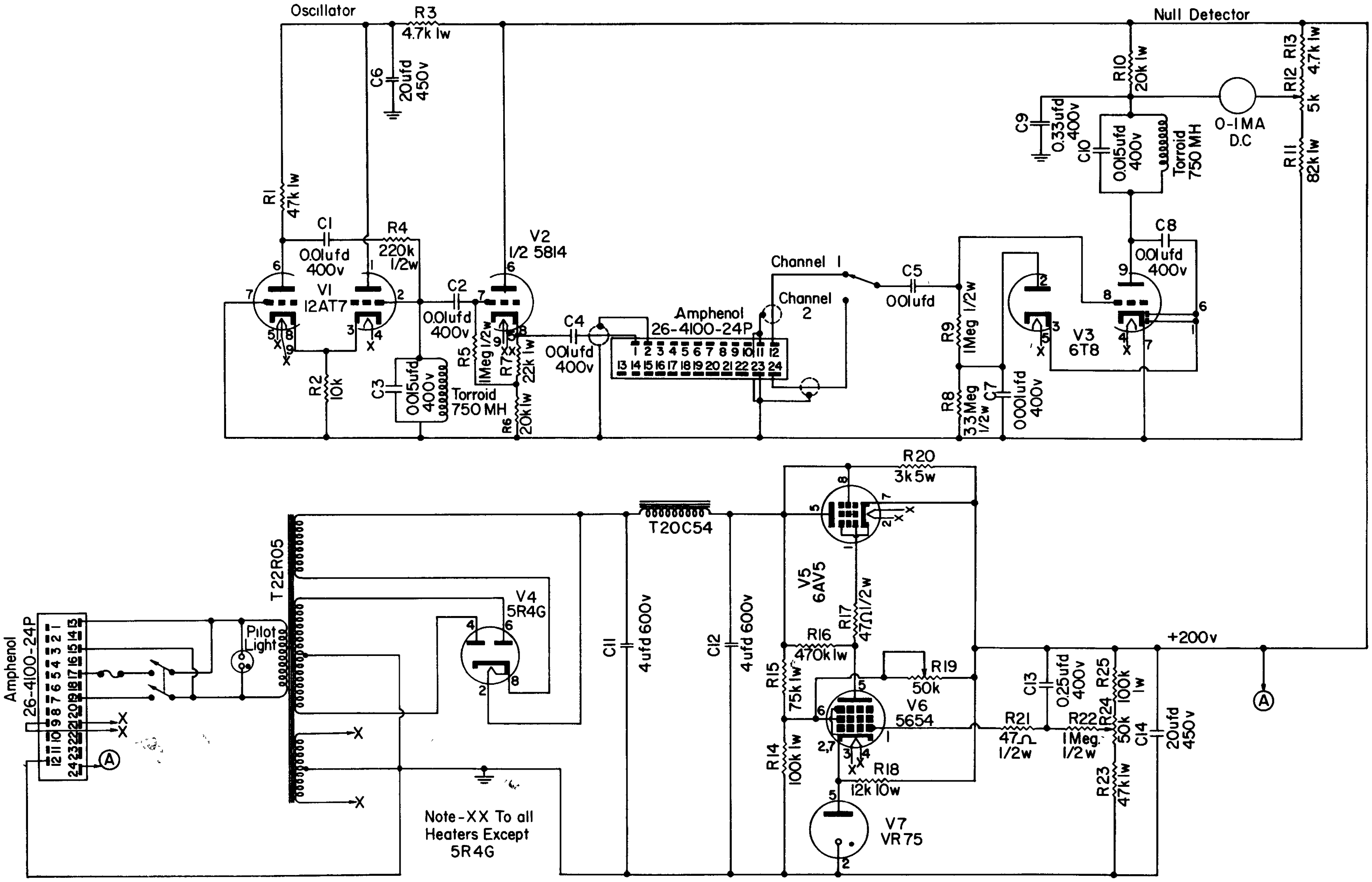

Figure 8 - Schematic Diagram, Power Supply, Type 278-2A

when the unit is removed from the rack, as shown in Figures 6 and 7. The schematic diagram of this unit is shown in Figure 8.

INDICATOR, TYPE 278-3A

The Indicator, Type 278-3A, contains four identical but separate averaging and metering circuits. The unit also contains its own power supply which furnishes 200 volts d-c and filament voltage to the tubes in the metering circuits. The meter circuits receive varying d-c signals from the sine-cosine potentiometers. These signals are passed through R-C averaging circuits to cathode followers which drive the indicating meters. A choice of three time constants is available for the averaging circuits by means of a selector switch on the front panel. The "0" position is used when making adjustments of the meter zeroes and sensitivity, the "SHORT" position is used for input frequencies above 2 cycles per second, and the "LONG" position for frequencies between 1/3 cycle per second and 2 cycles per second. Each indicating meter has its related zero control, sensitivity control, and polarity reversing switch. Input to the indicator unit is received through a connector on the back panel of the chassis. Placement of components in this unit can be readily seen in Figures 9 and 10. A circuit diagram is shown in Figure 11.

RACK, TYPE 278-4A

The Rack, Type 278-4A, provides plug-in connections for the two carrier amplifiers and the power supply. It provides interconnections between the aforementioned units and has connectors on the back panel for inputs from the strain-gage bridge and outputs to the sine-cosine potentiometer and the graphic recorder. A circuit diagram is shown in Figure 12.

GRAPHIC RECORDER AND ASSOCIATED AMPLIFIERS

A two-channel Sanborn Recorder and two Sanborn D-C Amplifiers are used to record the force-and-moment signals. A marker pen on this recorder may be connected to a switch which closes once per revolution of the main drive shaft, so that correlation of the phase shift in the output signals may be obtained. Other types of recording devices could be adapted to recording these signals, provided they have a high impedance input and the necessary amplification to drive the recording device.

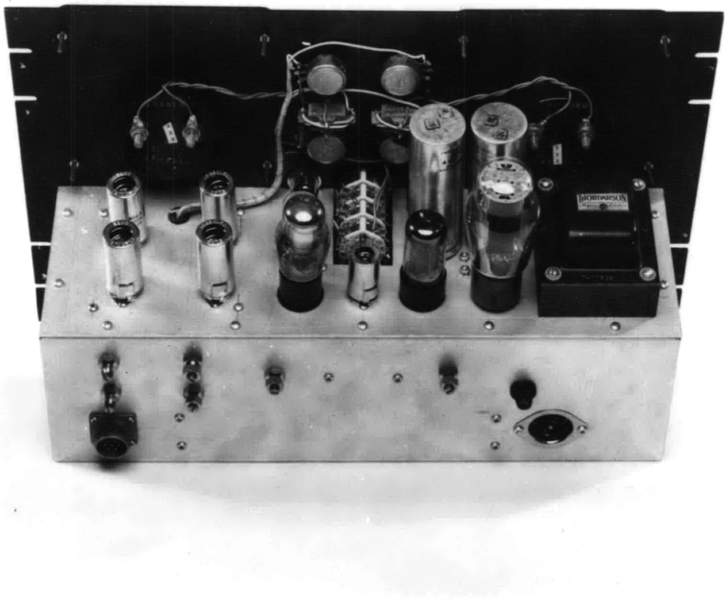

Figure 9 - Top View, Indicator, Type 278-3A

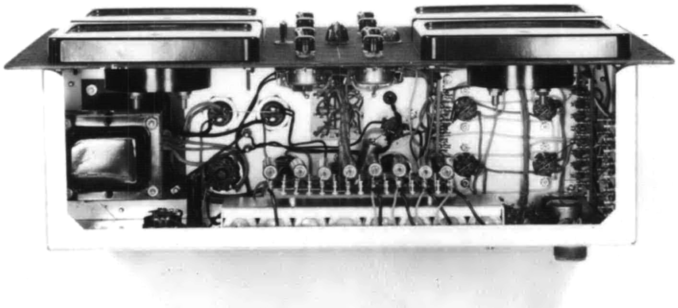

Figure 10 - Bottom View, Indicator, Type 278-3A

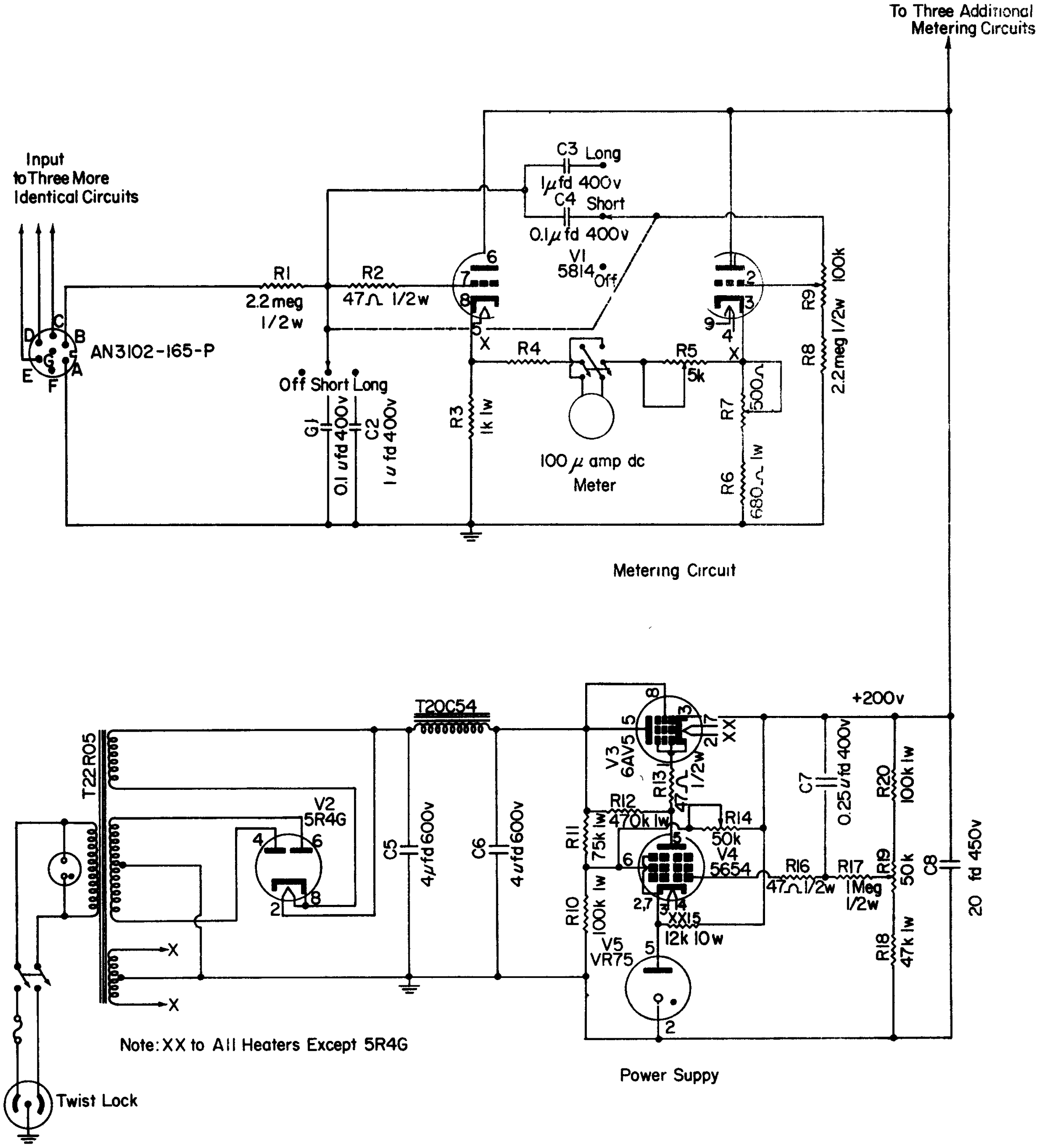

Figure 11 - Schematic Diagram, Indicator, Type 278-3A

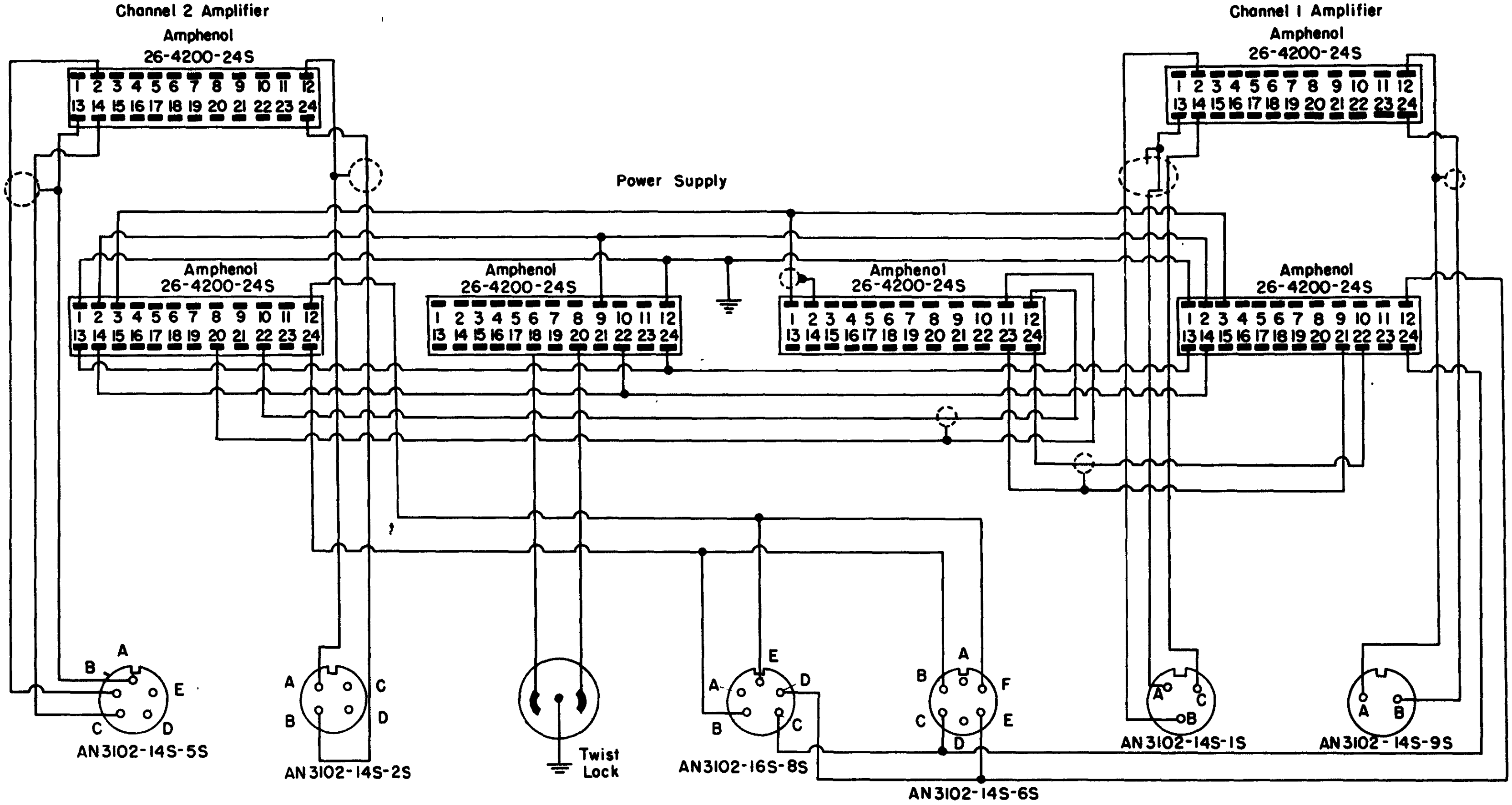

Figure 12 - Schematic Diagram, Rack, Type 278-4A

SINE-COSINE POTENTIOMETER ASSEMBLY

The sine-cosine potentiometer assembly is mounted on the pitch-and-heave oscillator and gear driven from the shaft which operates the scotch yoke mechanism. An interchangeable Metron speed changer is used between the main drive shaft and the sine-cosine potentiometer. Three speed-changer ratios are used: 6:1, 3:1, and 2:1. The 6:1 ratio is used when measurements are being made of components of the fundamental frequency. The 3:1 and 2:1 are used for measurements of the second and third harmonic components, respectively.

OPERATING INSTRUCTIONS

1. Connect all cables to the instrument and the sine-cosine potentiometer.

2. Place the SENSITIVITY controls on the carrier amplifiers to the OFF position.

3. Turn on the two POWER switches and allow the equipment to warm up about 15 minutes.

4. Place the pitch-and-heave oscillator in its "ZERO" position, i.e., midway on its downward stroke.

5. Place the CHANNEL SELECTOR switch in Position 1.

6. Turn the SENSITIVITY control on the Channel 1 carrier amplifier clockwise until an unbalance is indicated by a downswing of the null indicator. Using the BRIDGE BALANCE controls, adjust for maximum deflection of the NULL INDICATOR. Advance the SENSITIVITY control to the 40 microinches per inch setting, making adjustments as necessary so that balance is obtained on this step. Return the SENSITIVITY control to the OFF position.

7. Place the CHANNEL SELECTOR switch in position^3 and repeat Step 6, now using the corresponding controls on the panel of the Channel 2 carrier amplifier.

8. Place the SENSITIVITY control of the No. 1 carrier amplifier at the approximate operating position. Turn the TIME CONSTANT switch to the "O" position and the POLARITY switches of the related meters to their + positions. Adjust the ZERO controls so that the meters read zero.

9. Next lift the CALIBRATION switch and adjust QUADRATURE meter SENSITIVITY control until a full-scale reading is obtained. Recheck the meter zero and full-scale readings.

10. Repeat Steps 8 and 9, using Channel 2.

11. Rotate the pitch-and-heave oscillator 90 degrees and perform Steps 8, 9, and 10, using this time the INPHASE meter and its related controls.

12. Place the SENSITIVITY controls of both carrier amplifiers to the OFF position. Place the TIME CONSTANT switch on the SHORT or LONG position as appropriate for the frequency at which the pitch-and-heave oscillator will be operated. Start the pitch-and-heave oscillator.

13. Adjust the ZERO control of each meter until the meters read zero. Advance the SENSITIVITY controls on the carrier amplifiers to their operating position. The equipment is now ready for measurements to be made.

INSTALLATION AND ADJUSTMENT

The phase-component indicating system may be placed at any convenient location on the towing carriage. Cable lengths to the gages and the sine-cosine potentiometer are not critical, and the cables that are furnished with the unit permit location of the instrumentation as far as 50 feet from the dynamometers. Care is required in the initial adjustment of the sine-cosine potentiometer assembly to assure that correct readings are obtained.

SINE-COSINE POTENTIOMETER

The procedure listed below will completely check the alignment of the sine-cosine potentiometer.

1. Place dummy gages in the gage input connectors in place of the cable from the dynamometers.

2. Turn on the equipment and balance the carrier amplifiers, as outlined in Steps 3, 4, and 5 of the Operating Instructions.

3. Check to be sure that the pitch-and-heave oscillator is exactly midway on its down stroke.

4. Place the SENSITIVITY switch of the No. 1 carrier amplifier to any of the low-sensitivity steps. Push the CALIBRATION switch to the + position. A plus reading should appear on the QUADRATURE meter and no movement should be evident on the INPHASE meter. If the above readings are not obtained, loosen the shaft of the sine-cosine potentiometer from its gear drive and rotate the shaft until the above conditions are met. Retighten the sine-cosine potentiometer shaft to its gear drive.

5. Slowly rotate the pitch-and-heave oscillator in the normal direction of rotation. A decrease in the reading on the QUADRATURE meter and an increasing reading in the positive direction on the INPHASE meter should be noted. When the QUADRATURE meter reaches zero, the INPHASE meter will reach

its maximum positive swing. Continued rotation of the pitch-and-heave oscillator will result in a negative reading on the QUADRATURE and a decreasing reading on the INPHASE meter.

STRAIN-GAGE DYNAMOMETER

Various strain-gage dynamometers may be used with this system, provided they contain a four-arm bridge with a resistance of 120Ω per arm. The gage elements may be located as much as 50 feet from the instrumentation with the cables that are provided. Longer gage cables may be used if necessary.

In the interest of standardization and for ease of analysis of data, an upward force on the model will give the same indication on the meter and recorder as pushing the CALIBRATION switch to its + position. If the opposite indication occurs, the gage pickup wires should be reversed.

CONCLUSIONS

The Type 278 Phase-Component Measurement System has been used in Model Basin test programs during the past year, and has successfully met all the requirements for Fourier analysis of heaving force and pitching moment signals which had been set forth in the request for the system.

Although designed primarily for the type of tests described in the report, this system could be modified for Fourier analysis of other types of inputs and testing set-ups. The carrier amplifiers are plug-in and could be replaced by units specifically designed for transducers other than strain gages, such as differential transformers or reluctance gages. This system does depend, however, on a mechanical rotary motion to drive the sine-cosine potentiometer multiplying device, and in its present form, must be used with a test set-up where this motion is available and synchronized with the driving forces being applied.

It should be noted that because of the nature of the multiplying system used, an exact null balance of the gaging element is not important. Any initial unbalance will be cancelled out in the multiplying process. However, precaution should be taken to assure that the unbalance signal is not so large as to approach overload conditions for the amplifier.

PERSONNEL AND ACKNOWLEDGMENTS

The conception and basic design of the measuring system herein described were the work of several members of the Instrumentation Division. Final circuit design and testing were the work of the author, who also participated in the initial applications of the system to model testing. The section on theory of operation is the work of Mr. W.S. Campbell.

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