AN ELECTRONIC TACHOMETER FOR MEASURING THE RELATIVE ANGULAR DISPLACEMENT OF ROTATING MACHINES

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INTRODUCTION

Laboratory experiments involving power selsyns indicated a need for a measuring device capable of showing relative positions of the generator and motor under various conditions of speed and load in order to determine accurately the performance of the system. Such a device would also be extremely useful in studies of servo-mechanisms in general, as well as synchronous machinery investigations where stroboscopic apparatus is now commonly employed.

For wide application of such a device, the following characteristics are desirable: 1) It should be applicable to rotating machines separated by a reasonable distance such as is encountered most frequently in practice. 2) The device should in no way coerce the system under investigation; friction and moment of inertia must be held to a minimum. 3) The response should be linear with relative angle, for both transient and steady state conditions, and should be independent of speed over the wide range which may be encountered in practice. 4) The indication should be available for direct viewing during transients, and some means of

recording provided.

The first requirement, remote operation, is best met by an electrical system wherein a signal of low power corresponding to the instantaneous position of each machine may be transmitted to a comparing and indicating device. Such a system, making use of "selsyns," "synchros," or similar self-synchronous devices, is now available. However, these devices have relatively low maximum continuous speeds, and are inherently limited in maximum speed and speed of response in their present form by practical exciting frequencies. The inertia must be relatively high due to the rotating component of the magnetic circuit.

Stroboscopic systems, while meeting all other requirements, offer no means of following or recording transient conditions.

Several considerations led to the conclusion that a photoelectric system could best meet the requirements set forth. The only moving element in such a system is a revolving shutter by which a light beam may be modulated as some function of the speed or position of the rotating machine under test. No external forces are imposed on such a shutter so it may be made light in weight and friction may be reduced to a minimum. Thus it will follow transitory changes with negligible

loading on the machine.

Indicator requirements may be met by a direct inking oscillograph, or a cathode-ray oscilloscope for transient conditions. In case the oscilloscope is used, a long persistence screen is almost essential, since in most cases the transients will be non-repetitive.

GENERAL

The use of a system wherein intelligence is superimposed on a carrier frequency is common practice. In this application such a scheme was selected for the following reasons. If the device is to operate over a wide range of speeds, amplification must be uniform over the entire range. Such response is difficult to obtain with conventional amplifiers, and a direct-coupled amplifier would be the only alternative. Since the phototube signal is weak, high gain is necessary, and considering the problem of instability in high gain direct-coupled amplifiers, the carrier system seems most promising. This is believed to be accepted practice in similar phototube amplifiers.

The pickup head will be in contact with a moving machine and is unavoidably subject to vibration. Phototubes and low-level amplifiers are particularly subject to microphonics, and it was found that a comparatively large signal was generated due to vibration. However, this signal adds linearly to the carrier voltage and results in very little modulation, hence is not passed through the carrier amplifiers.

Special precautions must be taken with the current source for the exciter lamp in a true direct-current

system to avoid fluctuations of light intensity. The use of a carrier frequency on the exciter lamp therefore imposes no additional problems, and may even be simpler.

The basic system selected is illustrated by the block diagram, Figure 1. A pickup head located at each machine contains an exciter lamp operated at a carrier frequency, a phototube and preamplifier, and a rotating disc, mechanically driven by the machine, by which the light striking the phototube is modulated as some function of the speed and angular position of the machine. The resulting modulated carrier is transmitted by means of a cable to a central amplifier unit where it is further amplified and detected. A comparison or integrator unit combines the signals from the two pickups and generates a signal proportional to the angular difference between the two machines. The indicator plots the angular difference as a function of time.

In order to provide for as wide an application as possible, two distinct methods of modulating the carrier and combining the resultant signals were developed, each having its particular advantages and disadvantages. A pulse integrator system is provided to measure rapid, large angle transients. Its response is linear, but it will not measure steady-state deviations. The phase

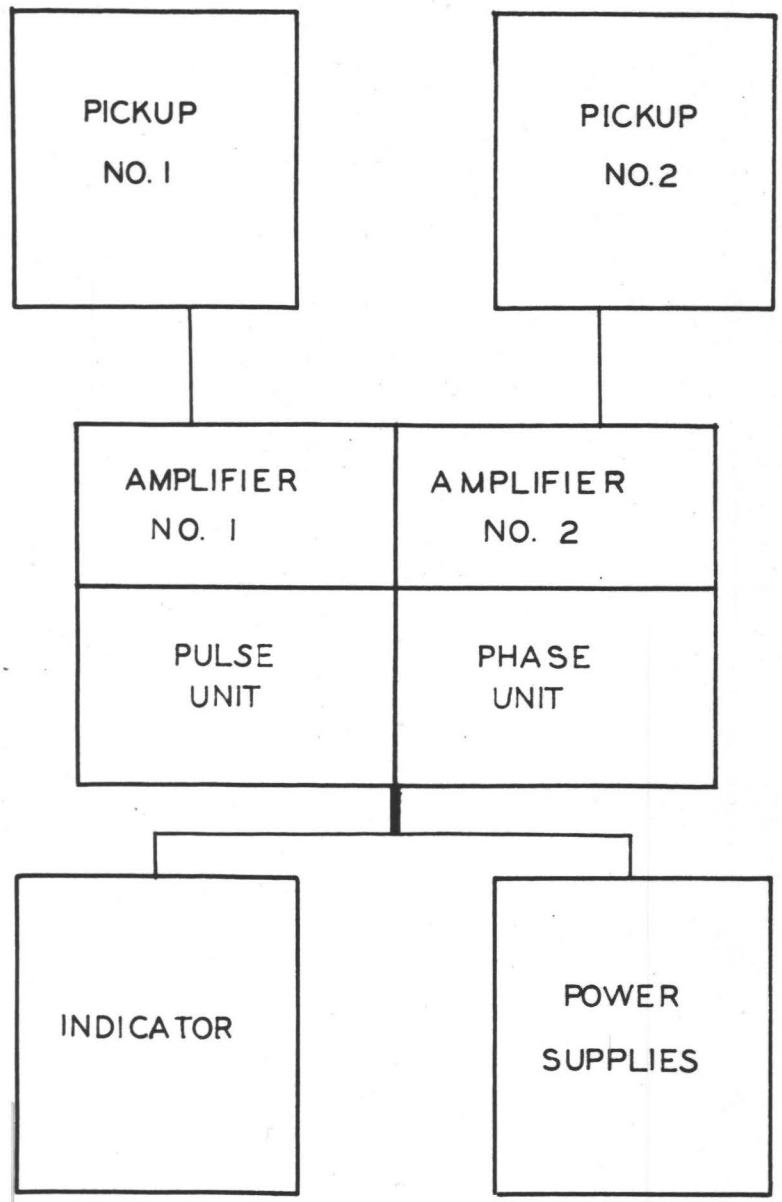


FIGURE 1

BLOCK DIAGRAM

comparison system has an approximately linear response for small angles, will follow relatively slow transients, and will indicate steady state conditions.

The basic carrier system is common to both of the above methods, and will be discussed in detail before proceeding to the detailed discussion of the pulse integrator and phase comparison methods.

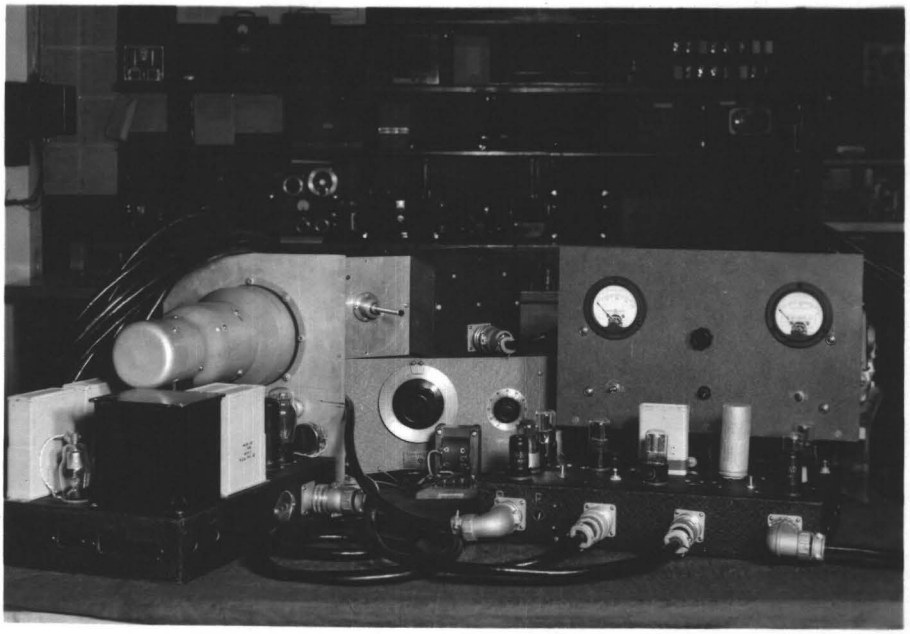
THE BASIC CARRIER SYSTEM

Two identical independent carrier channels, each complete within itself, are provided to produce and amplify the signals from the two machines. Physically, the apparatus consists of two pickup units and an amplifier unit, and interconnecting cables. The assembled units are shown in Figure 2.

The pickup unit, Figure 3, consists of a standard gas phototube excited at carrier frequency by a neon glow lamp. Light striking the photocell is modulated by a rotating shutter placed between the exciter lamp and the phototube.

The exciter lamp is operated at a frequency of about 20,000 cycles per second with a direct bias superimposed on the alternating component of voltage. This is accomplished as shown in the wiring diagram, Figure 5. The exciter lamp is shown with the amplifier unit rather than the pickup for greater clarity. By using the lamp, L_1, as the plate resistance of a triode, the intensity can be made to vary approximately sinusoidally at the desired frequency by driving the grid of the triode with an audio oscillator.

The exciter frequency is not critical, the lower limit being determined by the maximum modulation



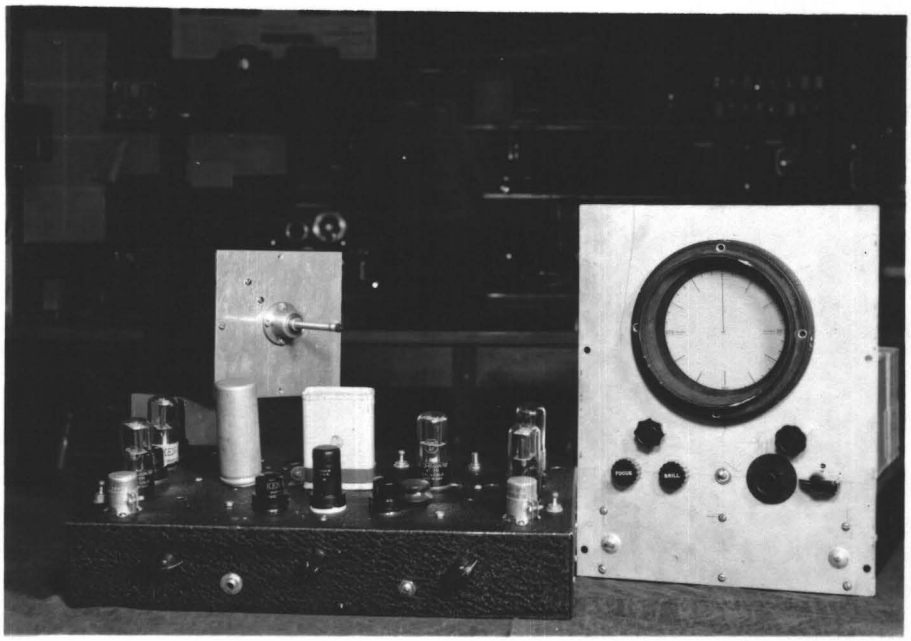
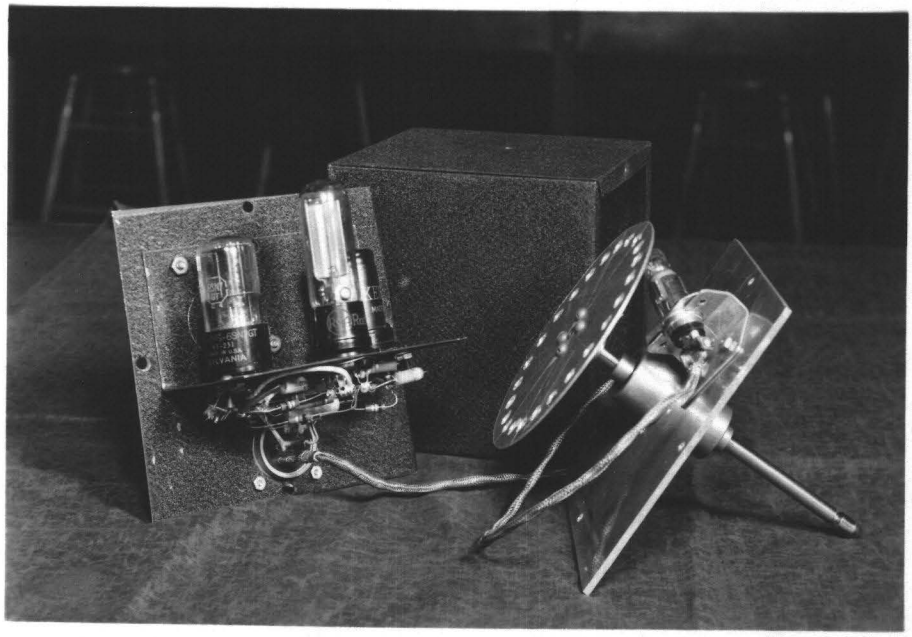
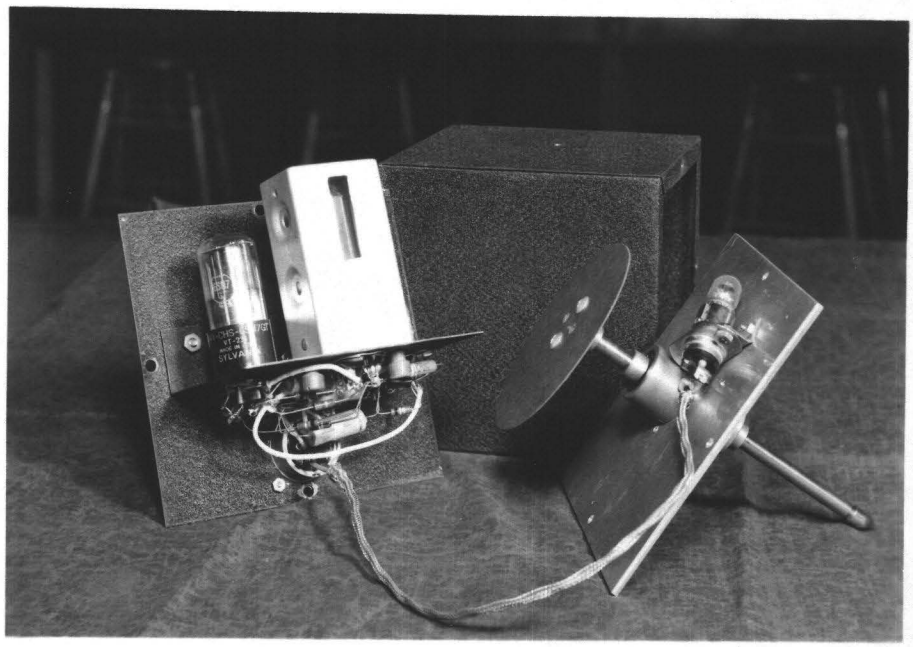


Figure 2.

Assembled Units and Related Equipment.



(a) Pulse Pickup.



(b) Phase Pickup.

Figure 3.

frequency and the upper limit by the combined response of the phototube and the exciter lamp. Both the latter are gas-filled devices and high-frequency response is limited by deionization time. 20,000 cycles was selected as a reasonable value and has been found to be entirely satisfactory.

A three-stage preamplifier is located in the pick-up to raise the signal level to a value that can be satisfactorily transmitted through the relatively long cable. A cathode-follower (2, p. 164-174; 3, p. 430-431) is used to match the high impedance phototube circuit into a pentode voltage amplifier as shown in the wiring diagram, Figure 4. A second cathode-follower is used to minimize the attenuation of the high-frequency signal by the large shunt capacitance of the shielded cable leading to the amplifier unit.

In the central amplifier unit, Figure 5, another pentode voltage amplifier is followed by a triode working into a diode detector of conventional design. One triode stage of audio amplification follows the detector, and the output may be switched to either the phase comparison or pulse integrator unit as desired.

Resistance-capacitance coupling, designed for high-frequency response only, is used throughout the carrier-frequency stages because of its simplicity and

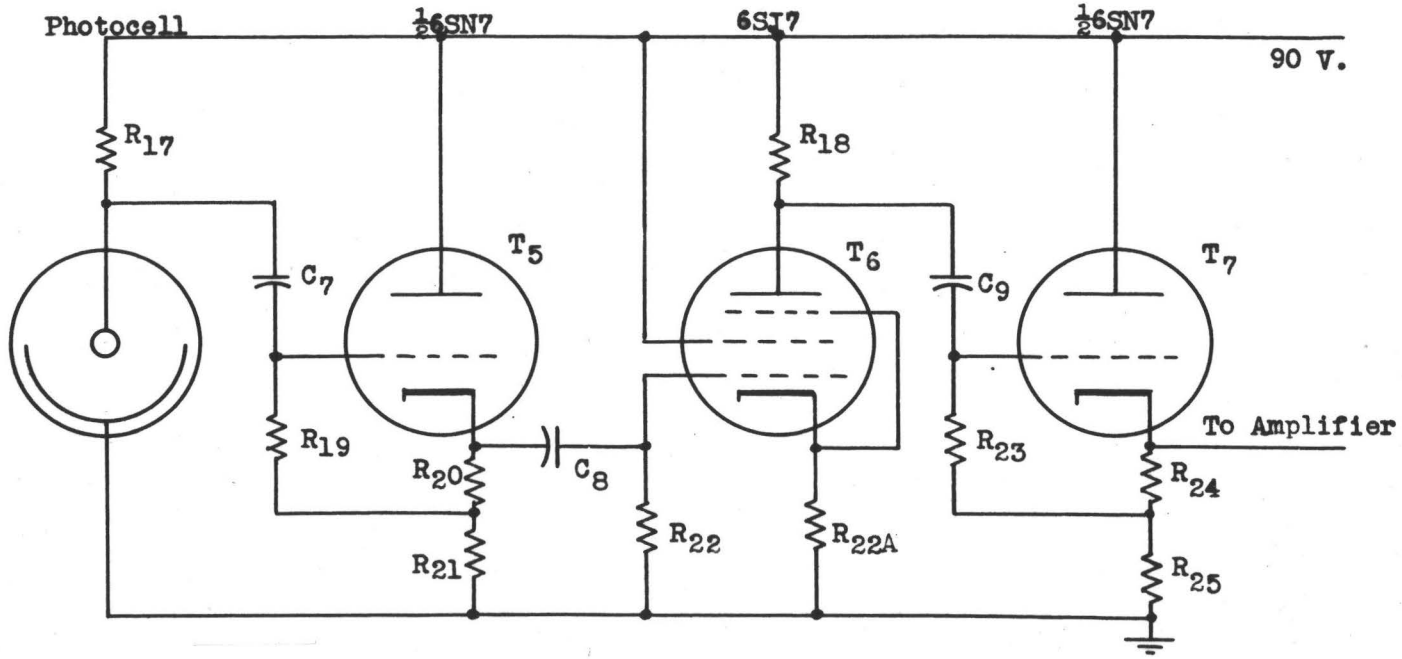


Figure 4.

Pickup Circuit Diagram

(Two Units Required)

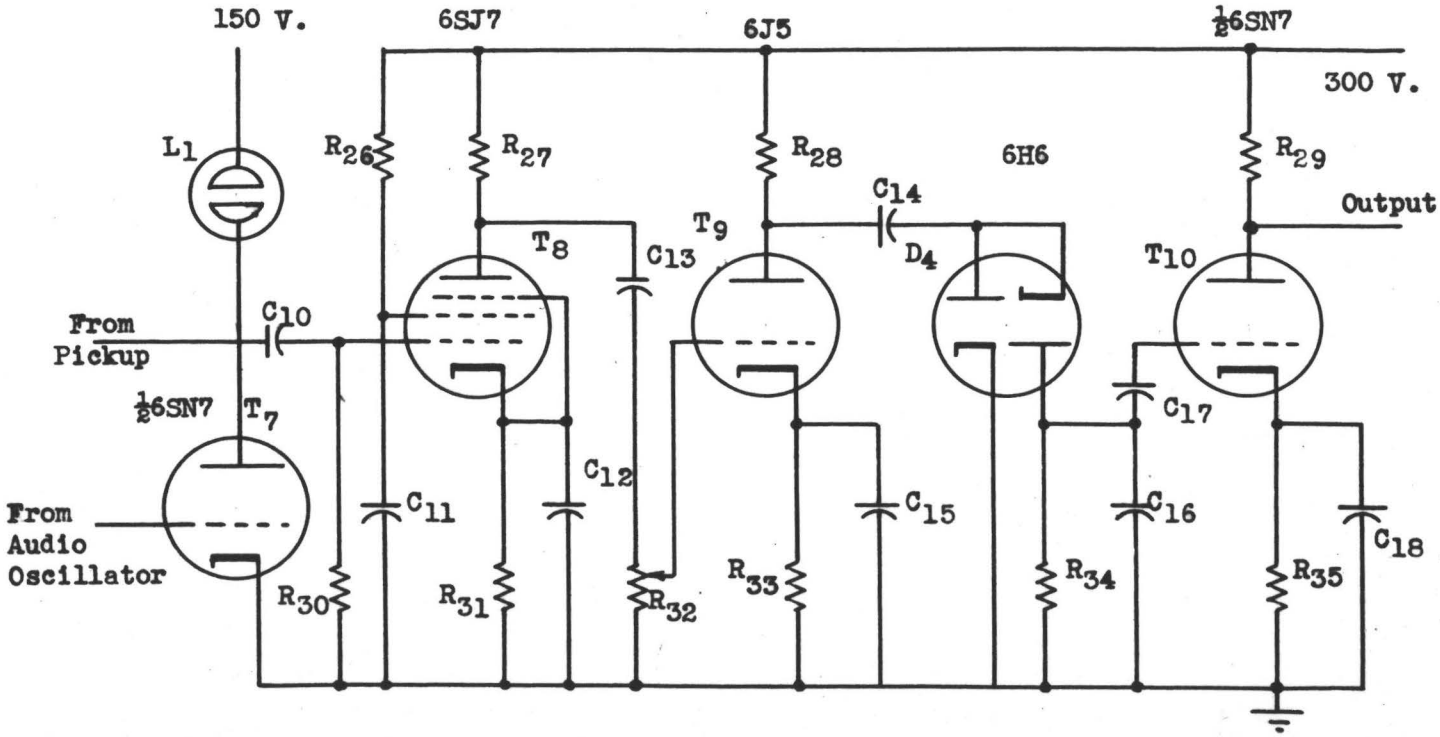


Figure 5.

Amplifier Unit and Exciter Lamp Circuit Diagram

(Two Units Required)

adaptability for experimental purposes. Special transformer or tuned impedance coupling might improve the amplifier characteristics if carrier frequency could be held constant.

Plate voltage for all stages is supplied by an external heavy duty electronically regulated power supply operated at 300 volts. Lower voltages unless otherwise indicated are obtained from tapped bleeders. Heater circuits are not shown on the diagrams in order to maintain greatest simplicity. All supply voltages are brought into the system through one multi-conductor cable to keep connections as simple as possible.

THE PULSE INTEGRATOR CIRCUIT

THEORY. The angular position, θ, at any time, t, of a shaft rotating at angular velocity ω may be represented as follows:

$$\theta = \int \omega \, dt \qquad (1)$$

and for the difference between two shafts,

$$\theta_1 - \theta_2 = \int (\omega_1 - \omega_2) dt \qquad (2)$$

Also the charge Q on a condenser of capacitance C and at voltage E is (1, p. 182)

$$Q = \int i dt = CE \qquad (3)$$

or

$$E = (1/C) \int i dt \qquad (4)$$

Thus if a current which is directly proportional to the angular velocity of one machine may be made to charge a condenser while another current proportional to the angular velocity of the other machine is made to discharge the same condenser, the net voltage on the condenser will be a function of the angular displacement of one shaft with respect to the other at any instant of time.

The integrating circuit of Figure 6 was devised to perform the functions outlined above. The rotating shutter in the pickup previously described modulates the carrier in the form of pulses at a rate proportional to

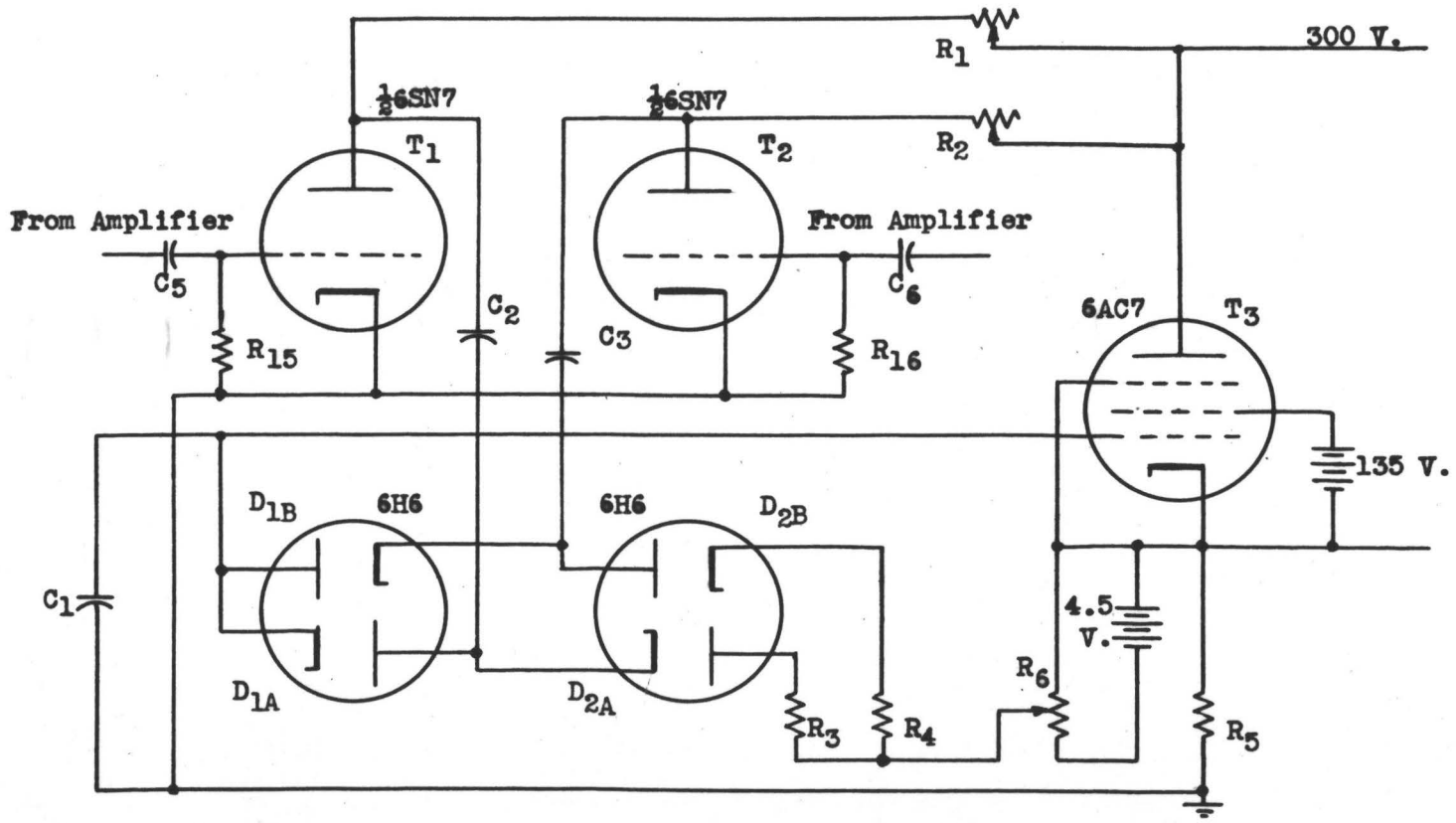


Figure 6.

Pulse Integrator Circuit.

the angular velocity. These pulses, amplified and detected provide a voltage wave sufficient to overdrive the triode T_1, resulting in a square wave of voltage of constant amplitude on the plate. The positive swing of the square wave of voltage charges C_1 and C_2 in series through the diode D_{1A}. From equation (4) it is seen that the voltage divides inversely as the capacitance, and since C_1 is large compared to C_2 the voltage on the former changes in small steps. On the negative swing, C_2 discharges through D_{2A} and R_3 to cathode potential. By a similar process condenser C_1 is discharged through C_3 by the negative swing of the pulse from the other pickup. Thus the charging and discharging current through C_1 is metered in definite increments and decrements by the fixed input voltage changes occurring at rates proportional to the angular velocities of the shafts, and with the two signals balanced by means of R_1 and R_2, the change in voltage on C_1 is a linear function of the change of relative angle between the two machines.

Since the condenser C_1 must be both charged and discharged and the condensers C_2 and C_3 must be restored to quiescent charge between pulses, a direct leakage path tending to discharge C_1 is always present. A long discharge time constant exclusive of the circuits through

C_2 and C_3 must be provided to give good response to very slow transients, but short time constants through C_2 and C_3 are essential to follow high angular velocities. To meet these conflicting requirements two characteristics of the cathode-follower amplifier were used, namely the apparent high input resistance and low output resistance. These may be expressed approximately as follows: (2, p. 164-174; 3, p. 430-431)

$$R_i = \frac{r_g}{1 - A_f} \tag{5}$$

where

$$A_f = \frac{gm\ R_L}{1 + gm\ R_L} \tag{6}$$

and

$$R_o = 1/gm \tag{7}$$

For the circuit shown, using a high-gain pentode with a mutual conductance of 9000 micromhos and a load resistance of 100,000 ohms, a theoretical amplification of 0.999 is obtained. This indicates that the apparent resistance shunting C_1 is 1000 times R_4.

However, experiment has shown that the discharge rate of C_1 is determined to a large extent by grid current, which limits the range over which the above relationship applies.

The output resistance of the stage, theoretically 110 ohms, is sufficiently low that no indication of the discharge current of C_2 and C_3 passing through the load resistor R_5 may be observed.

The relationships between circuit constants and performance may be derived as follows: Let n represent the number of pulses, or modulation cycles, per revolution of the shutter, s the speed of the machine in revolutions per minute, f the frequency of the square wave input to the integrator, e the peak to peak amplitude of the square wave, and E the voltage change in C_1 per revolution. Then assuming C_2 very small compared to C_1, the voltage change on C_1 per pulse is

$$E/n = eC_2/C_1 \qquad (8)$$

and

$$f = ns/60 \qquad (9)$$

To insure complete discharge of C_2 after each pulse, the discharge time constant should be a maximum of 1/5 the discharge period, or

$$C_2R_3 = 1/10f \qquad (10)$$

assuming R_3 is the limiting factor. Then

$$C_2R_3 = 60/10ns \qquad (11)$$

Combining with equation (8)

$$C_2R_3 = \frac{60eC_2}{10sEC_1} \qquad (12)$$

or

$$C_1R_3 = \frac{60e}{10sE} \qquad (13)$$

and

$$s = \frac{60e}{10C_1R_3E} \qquad (14)$$

Thus for a given discharge time constant (C_1R_3) there is a maximum speed for which linear calibration obtains. Practical limitations hold e to about 200 volts, E, assuming a maximum deflection of plus or minus 360 degrees, should be on the order of 5 volts for maximum stability, and operation to at least 3600 revolutions per minute is desirable. For these conditions C_1R_3 becomes 0.066 if C_1 is taken as 1 microfarad. By equation (5) the theoretical discharge time constant is 66 seconds, which is large compared to the limitation imposed by grid current.

The internal impedance of the overdriven amplifier has heretofore been neglected, but actually is a practical limitation of the circuit as shown. Vacuum tube T_2 is cut off during the recovery period of C_3, presenting an internal impedance of approximately 100,000 ohms, which becomes an appreciable part of the discharge resistance. This limits operation of the device in its present form to about 1000 revolutions per minute, but this limitation may be removed by including low-impedance

drivers in addition to T_1 and T_2. Cathode-follower amplifiers seem best suited for this purpose.

The equations above indicate that the value of C_1, rather than the internal impedance of the amplifiers, may be reduced to improve high-speed response. It was found, however, that grid current set the minimum size of C_1 at approximately 1 microfarad for a reasonable discharge rate. The discharge time constant was found to be approximately 30 seconds for these conditions.

For experimental purposes n was set at 24, being limited primarily by the degree of mechanical and optical refinement of the photoelectric pickup. C_2 and C_3 are then specified by equation (8) as 0.001 microfarads.

PERFORMANCE. Figure 7 shows the output waveform on an expanded time scale. This represents a shaft speed of approximately 500 revolutions per minute on each pickup, with the charge and discharge pulses occurring at equal intervals. Figure 8 shows the output for simulated conditions where the relative angular velocity jumps instantaneously from zero at the start to a value equal to the steady-state angular velocity of either machine, and back to the steady state value of 500 revolutions per minute. The total angular displacement may be determined from the number of steps required for

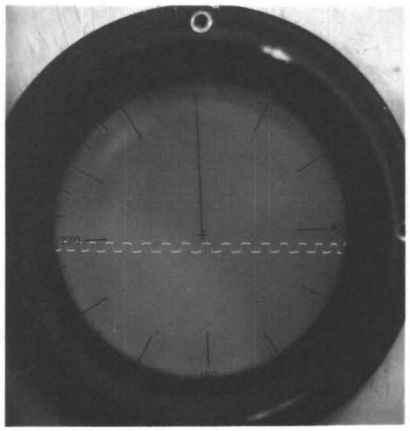


Figure 7.

Steady State Output with
Expanded Time Scale.

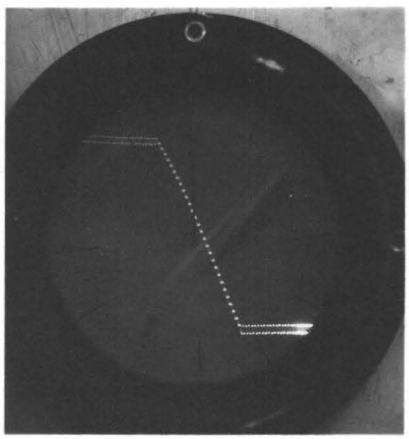


Figure 8.

Output for Relative Angular Velocity of
500 Revolutions per Minute.

the change. Note the negligible rate of decay toward the steady-state position after balance has been restored.

Figure 9 shows simulated transient conditions of an abrupt nature. The sharp corners of the wave form indicate an excellent high-frequency response. Figure 10 represents a less extreme rate of change of angle, corresponding to speeds of 400 and 500 revolutions per minute during the change. The time scale is greatly expanded to show the way in which the separate pulses combine in the output.

The definition of the system as outlined may be stated as 15 degrees, but the practical accuracy may be greatly improved over this value by careful interpretation of the output waveform, and interpolation between steps.

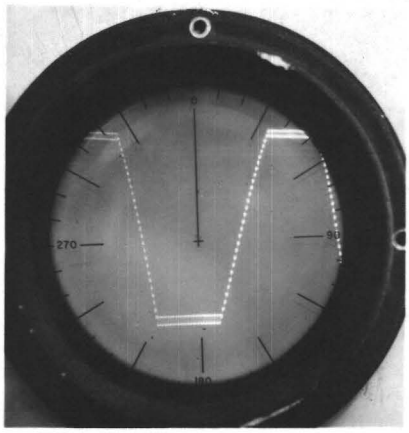


Figure 9.

Simulated Oscillatory Transient.

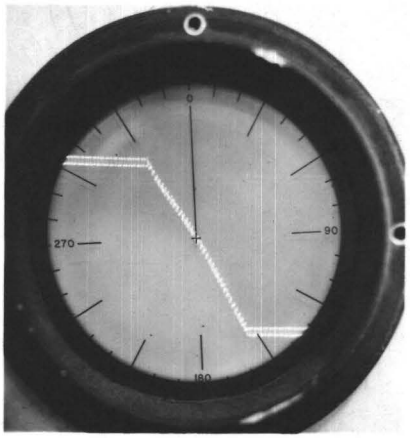


Figure 10.

Output for Angular Velocities of 400 and 500 Revolutions per Minute.

THE PHASE COMPARISON SYSTEM

THEORY. If two sinusoidal voltages of equal frequency and magnitude are added together, the magnitude of the sum is a function of the phase angle or time displacement between the two voltages. This may be represented vectorially as shown in Figure 11. The relative magnitude of the sum as a function of the angle is also shown. This is seen to be nearly linear for the range between 0 and 90 degrees, but departs rapidly from the original slope for greater angles.

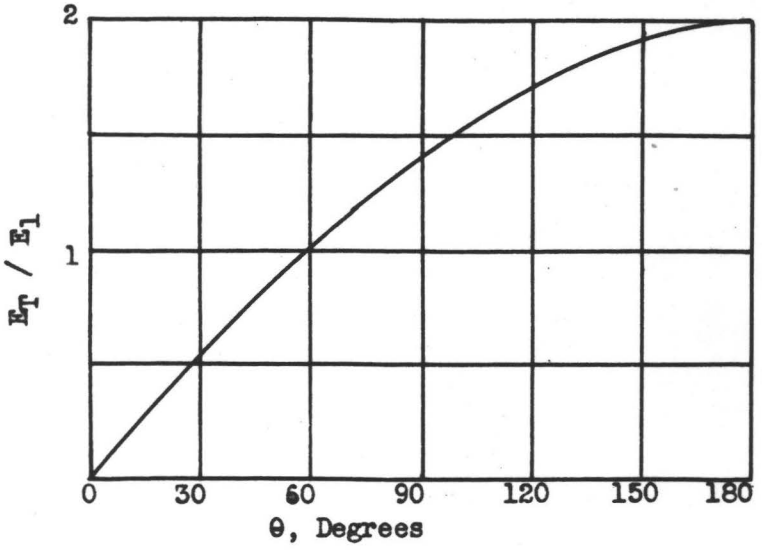
Voltages may be combined linearly in a resistive network such as that composed of R_7, R_8, and R_9 in Figure 12. Assume that R_{11} is very large compared to R_9. Then by the superposition principle, the voltage across R_9 due to the voltage e_1 is

$$e_{1R9} = e_1 \frac{\frac{R_7 R_9}{R_7 + R_9}}{R_8 + \frac{R_7 R_9}{R_7 + R_9}}$$

Similarly

$$e_{2R9} = e_2 \frac{\frac{R_8 R_9}{R_8 + R_9}}{R_7 + \frac{R_8 R_9}{R_8 + R_9}}$$

and if R_7 is made equal to R_8, the total voltage across R_9 is



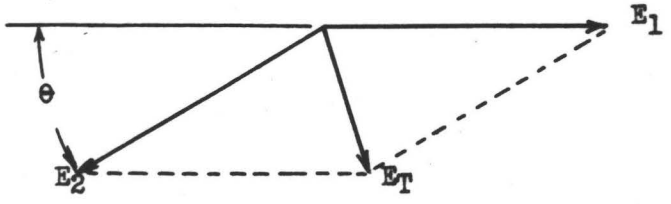


Figure 11.

Vector Sum of Equal Sinusoidal Voltages

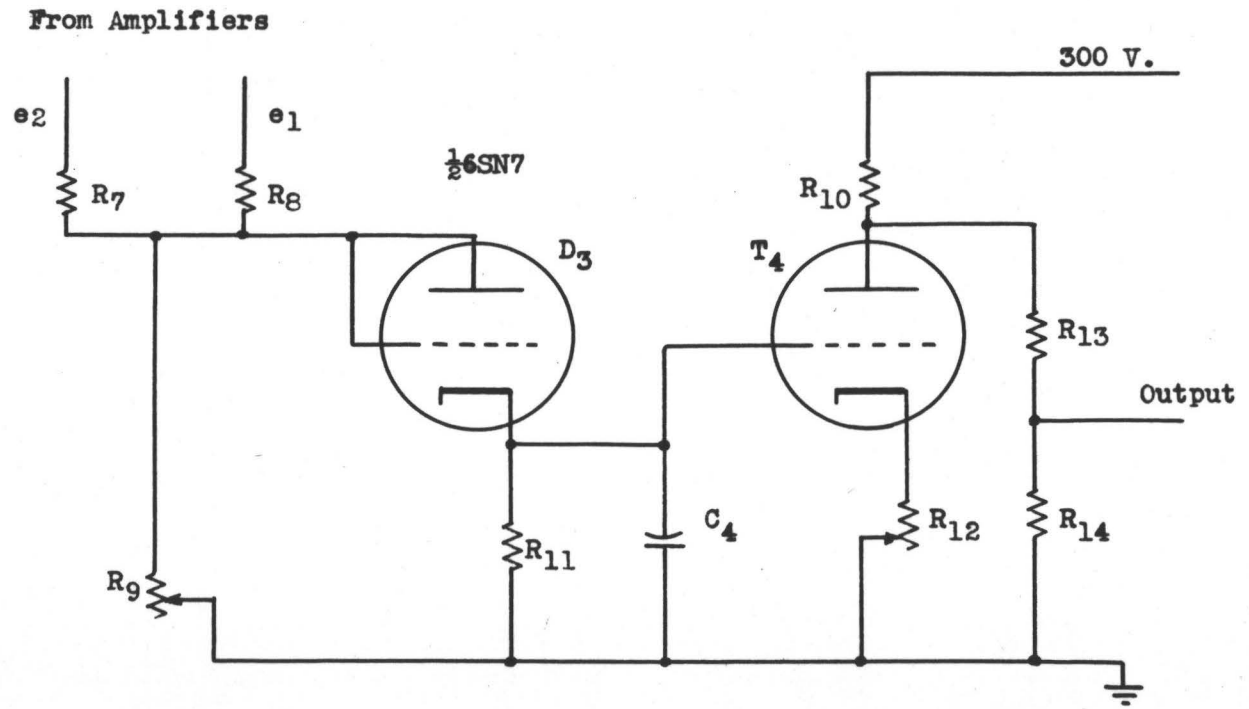


Figure 12.

The Phase Comparison Circuit

$$e_{R9} = (e_1 + e_2) \times \text{constant}$$

or is directly proportional to the sum of the input voltages.

For this system, the illuminated area of the photocell in the pickup is varied as a sinusoidal function of the angular position of the machine to which it is attached. The radius of the shutter varies sinusoidally, and when projected over a slit admitting light to the photocell, causes the illuminated area to be varied similarly. Thus the carrier is modulated sinusoidally at constant amplitude and at a frequency proportional to the angular velocity of the machine. When the carrier is amplified and detected, an alternating voltage results, the relative phase of which depends on the relative angular position of the machine.

The two voltages, one from each pickup, are fed into the network described, and the amplitude of the output voltage is related to the angular displacement by the function shown in Figure 11. This, however, is an alternating voltage and a direct voltage proportional to the instantaneous r. m. s. value of the alternating voltage is desired for convenient indication.

The signal is rectified by the diode D_3 and filtered by R_{11} and C_4. Choice of the filter condenser, C_4, is limited by two conflicting requirements. For a

ripple-free output the condenser should be large, making the time constant of $R_{11}C_4$ large with respect to the half period of the input voltage. For maximum frequency response, the time constant must be short compared to the period of the most rapid transient to be measured. Under transient conditions the voltage wave is similar to that of a 100% modulated carrier, and it has been shown (3, p.555) that under this condition any filtering whatever will introduce distortion.

In practice the ratio of the input to transient frequencies may be low, on the order of 10 to one or less, so it is impossible to satisfy completely the conditions mentioned above, ripple will always be present in the output. The best solution seems to be to provide a range of filter condensers, the proper value to be selected by trial for each specific application. If the approximate speed of the machine is known, good transient response can be assured by selecting the condenser to make the filter time constant equal to the half period of the input frequency. Using the symbols previously defined,

$$2R_{11}C_4 = 1/f = 60/sn$$

If R_{11} is one megohm

$$C_4 = 30/sn \text{ microfarads}$$

This value results in a peak to peak ripple voltage of over 50% of the signal. For all but the most rapid transients a value of at least twice that above may be used satisfactorily with much improvement in the output waveform.

The amplifier stage shown in Figure 12 is used to amplify and match the signal to the indicator. Direct coupling is used for maximum low-frequency response, and the voltage divider circuit, R_{13} and R_{14}, is used to permit operation of the amplifier over the best plate voltage range and still maintain the proper quiescent level on the indicator amplifier. R_{12} provides a fine adjustment on this quiescent level.

PERFORMANCE. Steady-state calibration of the device was found to follow closely the theoretical curve shown in Figure 11. Some non-linearity, approximately 5% of full scale, was observed at the lower end of the curve due to second-harmonic distortion generated in the amplifier stages. In effect this offsets the zero reading, but does not seriously affect the accuracy.

No readily attainable means was found to check the transient characteristics of the device, but it is felt that the circuit applications are sufficiently conventional and well established that additional proof of the theory is unnecessary.

This device makes no distinction between directions of angular displacement. The indication is always in the positive direction. This may lead to confusion, particularly if the displacement is more than 180 degrees and is oscillatory. However, with some understanding of the probable behavior of the devices under test, and a knowledge of the nature of the calibration curve, the proper interpretation should be readily deduced.

Care must be exercised in interpreting waveforms. The ripple voltage is a complex function, varying in relative magnitude with modulation, but the peaks accurately define the modulation envelope and should be used in calibration and measurement. Some distortion in the nodes of the waveform where the phase swings through zero is unavoidable, and it may be necessary to obtain transient readings in this region by extrapolation.

THE INDICATOR

An oscilloscope using a cathode-ray tube with a long-persistence screen is now under development, and was used in connection with these experiments. The use of such a tube permits direct observation of non-repetitive transients and photographic recording where desired. Figures 7, 8, 9, and 10 show waveforms photographed on this instrument.

A type 5FP7 cathode-ray tube is used, and the magnetic focussing and deflection together with a high accelerating voltage, approximately 6000 volts, results in very good definition at high intensities. The push-pull deflection amplifiers are direct-coupled to the input source to obtain the required low-frequency response. A single-trace sweep circuit provides sweep durations from about 0.5 seconds to 20 seconds with automatic intensification.

No circuit diagram for this unit is included since it is still in the experimental stage.

RECOMMENDATIONS

The following recommendations are offered for the improvement of the device to better meet requirements for accuracy, convenience, and operation over the widest possible range of conditions:

1. The use of a more refined optical system in the pickup for increased accuracy and better definition.

2. The incorporation of a stable fixed-frequency oscillator for the exciter system and the use of tuned coupling circuits in the carrier amplifiers to eliminate an external oscillator and minimize noise voltages.

3. The use of low-impedance drivers for the pulse integrator circuit to extend the operating range.

4. The investigation of better detector circuits for the phase comparison circuit to improve response to transitory changes.

5. The control of heater voltage in the pulse integrator circuit to minimize drift due to line voltage changes.

6. The development of a timing system to automatically coordinate the initiation of the transient and indicator sweep, and operation of the recording camera.

7. Provisions for timing markers to be superimposed on the output to facilitate timing of transients.

CONCLUSIONS

This investigation leads to the following conclusions:

1. The basic carrier system developed is well adapted to this particular application. Reasonable distances between machines constitute no limitation on its operation; the photoelectric pickup imposes negligible burden on the system under test, thus making possible measurements essentially undistorted by test equipment.

2. The combination of the two methods presented permits measurements over a wide range of conditions even though each method has definite limitations. The pulse integrator will follow rapid transitory changes with linear response over wide angles throughout the range of operating speeds commonly encountered. The phase comparison method is best suited to steady state measurements of angles less than ninety degrees, but its use may be extended to transient conditions and greater angles at a sacrifice of ready interpretation of results.

3. The long-persistence cathode-ray tube gives excellent results in connection with this apparatus. The brilliance and definition of the image, and flat frequency response well beyond the desired range make it ideally suited to this application.

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APPENDIX

TABLE OF CIRCUIT CONSTANTS

R_1, R_2, R_9, 100,000 ohm potentiometer.

R_3, R_4, R_5, R_7, R_8, R_{15}, R_{16}, R_{19}, R_{22}, R_{23}, R_{27}, R_{34}, 100,000 ohm resistor.

R_6, 100 ohm resistor.

R_{10}, R_{18}, R_{28}, R_{29}, 50,000 ohm resistor.

R_{11}, 1.0 megohm resistor.

R_{12}, 10,000 ohm potentiometer.

R_{13}, 33,000 ohm resistor.

R_{14}, 68,000 ohm resistor.

R_{17}, 2.2 megohm resistor.

R_{20}, R_{24}, R_{33}, R_{35}, 1000 ohm resistor.

R_{21}, R_{25}, 24,000 ohm resistor.

R_{26}, 390,000 ohm resistor.

R_{30}, 560,000 ohm resistor.

R_{31}, 500 ohm resistor.

R_{32}, 500,000 ohm potentiometer.

C_1, 1.0 microfarad capacitor.

C_2, C_3, C_{14}, 0.001 microfarad capacitor.

C_4, see text.

C_5, C_6, 0.25 microfarad capacitor.

C_7, C_8, C_9, C_{10}, 0.00025 microfarad capacitor.

C_{11}, C_{12}, C_{15}, 0.1 microfarad capacitor.

C_{13}, C_{16}, 0.0025 microfarad capacitor.

C_{17}, 0.5 microfarad capacitor.

C_{18}, 50 microfarad capacitor.