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AUTOMATIC REDUCTION OF WIND TUNNEL DATA

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Final Report

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FINAL REPORT

AUTOMATIC REDUCTION OF WIND TUNNEL DATA

1. INTRODUCTION

This report describes the work carried out by the Instrumentation Laboratory of the Department of Aeronautical Engineering, University of Michigan, under Department of the Air Force Contract No. AF 33(038)-20806 with the Engineering Research Institute of the University. The work was started on February 17, 1951. This report consists of new material and edited excerpts from the progress reports; however, reference to the progress reports will not be made since this report is complete in itself.

2. PURPOSE

There exists a need for a system which would automatically reduce raw data, obtained during wind tunnel tests, to quantities which would indicate the characteristics of the system being tested. These quantities would be dimensionless coefficients such as lift coefficient, drag coefficient, pressure coefficient and center of pressure. At present many man-hours are required to reduce the data taken during a single run in a wind tunnel. The research carried out on this project had as its purpose the development of a system which would take the raw data, operate on it, and produce the above mentioned quantities as its output. This conversion of the raw data to the desired quantities would be achieved instantaneously while the run was being made, thereby eliminating any time lag between the testing and the viewing of the results.

More precisely, the purpose of the research performed on this project was to develop a breadboard fabrication of an analogue type computer, for the automatic reduction of wind tunnel data, which would:

1) Compute normal force, pitching moment, center of pressure and chord force from static wind tunnel tests.
2) Compute pressure coefficient directly from static wind tunnel tests.
3) Have self-balancing of all reduction and computing equipment.
4) Obtain items 1 and 2 above for various angles of attack during one run.
5) Compute normal force, chord force, and moment coefficient directly from static wind tunnel tests.
6) Obtain items 1 and 2 above for various Mach numbers during one run.

3. THEORY OF OPERATION

The basic principles of operation of this system of automatic data reduction are:

1) Convert the quantities detected into a d-c voltage.
2) Combine and operate on these d-c voltages in such a manner that the desired calculated quantities appear at the output of the system in the form of d-c voltages. These voltages can then be used to drive a recording device to obtain traces of the calculated quantities.

The system used to obtain a d-c voltage which is proportional to the quantity being measured is the following. A constant amplitude a-c voltage is applied across some type of transducer - an instrument which converts mechanical signals to electrical signals - such that the voltage becomes an amplitude-modulated carrier with two sidebands. The modulated carrier is then amplified and rectified to produce a d-c signal which is proportional to the quantity being detected and of such a magnitude that it can easily be utilized. During the calibration procedure the gain of each channel of information is adjusted to provide the constant of proportionality desired. In addition to the above, to facilitate ease of operation, each information channel contains its own servo zero-balancing loop which automatically adjusts the d-c output to zero when no signal is applied to the transducer. This assumes that the transducer has been manually adjusted to the range of error correctable by the servo system.

Assume, now, that the d-c voltages are available and consider only (2) above. The operations indicated, in the case of wind tunnel data, consist of correcting the detected quantities for location and tare and then combining these corrected quantities in such a manner that the proper calculated quantities appear at the output. The tare corrections are usually multiplications by a constant or summations, hence they are easily made as will be shown a little later in this discussion.

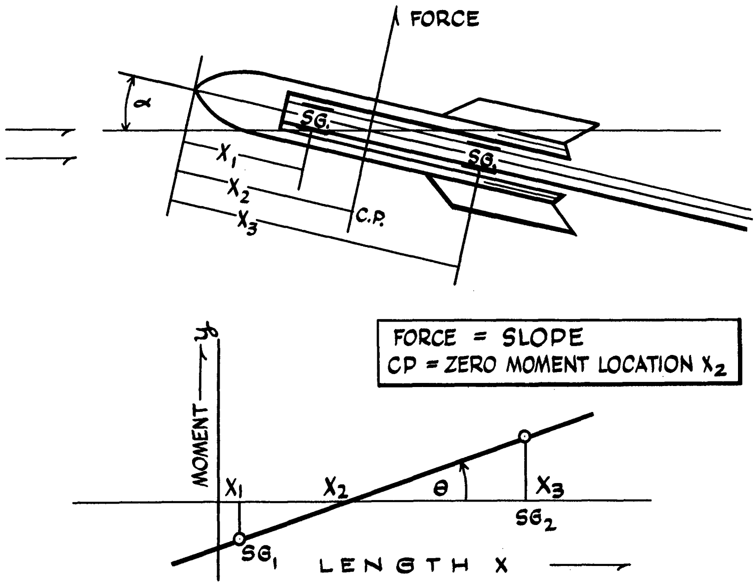


Fig. 3.1 Typical Force-Moment Measuring System

In the case of a force system, the sensing elements are usually strain gages attached at various stations along the sting, Fig. 3.1. The gage outputs are proportional to the moments existing at its center. Now, the moment at any point along the sting is given by

$$M = A + BX \quad , \qquad (3.1)$$

where: M = moment at any point,

A = moment at origin of X coordinate,

B = normal force,

X = coordinate along the sting with arbitrary origin.

The quantities actually desired are A and B because B is the normal force and - A/B is the center of pressure. These quantities are readily obtained by the method of least squares. Assuming that strain gages are located at n stations along the sting the expressions for A and B are as follows:

$$A = \frac{\sum_{m=1}^{n} X_m^2 \sum_{m=1}^{n} M_{0_m} - \sum_{m=1}^{n} X_m \sum_{m=1}^{n} (XM_0)_m}{n \sum_{m=1}^{n} X_m^2 - \left(\sum_{m=1}^{n} X_m\right)^2} \tag{3.2}$$

$$B = \frac{n \sum_{m=1}^{n} (XM_0)_m - \sum_{m=1}^{n} X_m \sum_{m=1}^{n} M_{0_m}}{n \sum_{m=1}^{n} X_m^2 - \left(\sum_{m=1}^{n} X_m\right)^2}$$

where M_{0_m} is the observed moment at station m.

In these equations the values of X are determined by the choice of origin and relative positions of the gages from this origin. Therefore all values of X are known, hence the following substitution can be made

$$\sum_{m=1}^{n} X_m = K_1$$

$$\sum_{m=1}^{n} X_m^2 = K_2 \tag{3.3}$$

$$\left(\sum_{m=1}^{n} X_m\right)^2 = K_1^2$$

where K_1 and K_2 are constants for any particular test configuration. Substituting equation (3.3) into equation (3.2), we get

$$A = \frac{K_2 \sum_{m=1}^{n} M_{0_m} - K_1 \sum_{m=1}^{n} (XM_0)_m}{nK_2 - K_1^2}$$

$$B = \frac{n \sum_{m=1}^{n} (XM_0)_m - K_1 \sum_{m=1}^{n} M_{0_m}}{nK_2 - K_1^2} \qquad (3.4)$$

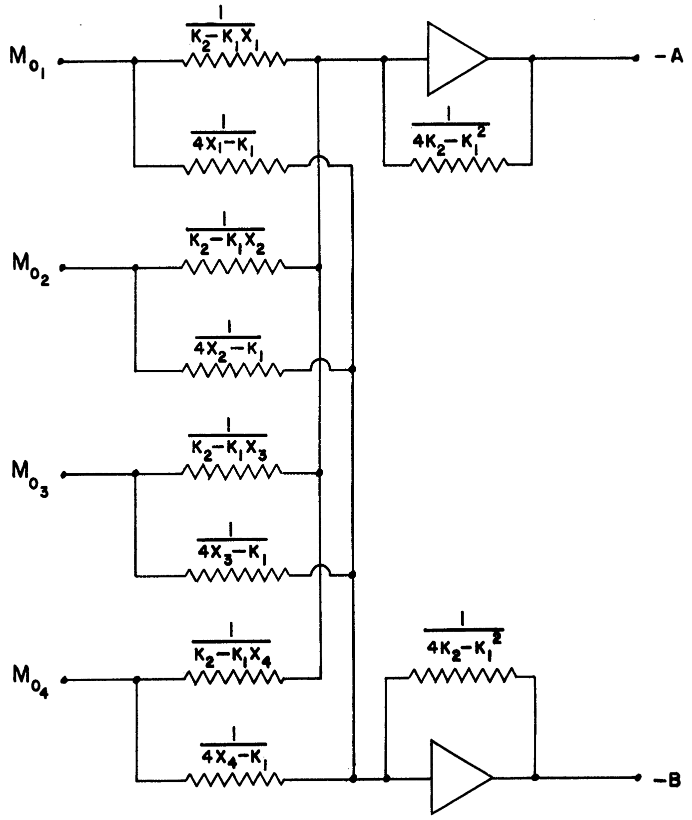
From equation (3.4) it can be seen that A and B are determined by summation and multiplication by a constant. These operations are easily performed by d-c operational amplifiers similar to those used in electronic differential analyzers (analogue computers). The theory of operational amplifiers is reviewed in Section 3.3.2.

If it is assumed that four stations are present along the sting, then equations (3.4) become

$$A = \frac{K_2\left(M_{0_1} + M_{0_2} + M_{0_3} + M_{0_4}\right) - K_1\left(X_1M_{0_1} + X_2M_{0_2} + X_3M_{0_3} + X_4M_{0_4}\right)}{4K_2 - K_1^2}$$

$$B = \frac{4\left(X_1M_{0_1} + X_2M_{0_2} + X_3M_{0_3} + X_4M_{0_4}\right) - K_1\left(M_{0_1} + M_{0_2} + M_{0_3} + M_{0_4}\right)}{4K_2 - K_1^2} \qquad (3.5)$$

The d-c operational amplifier arrangement for such a system would be the following



It has been shown that the most desirable location for the X coordinate origin is at the centroid of the stations (1). With this origin location

$$\sum_{m=1}^{n} X_m = K_1 = 0$$

and

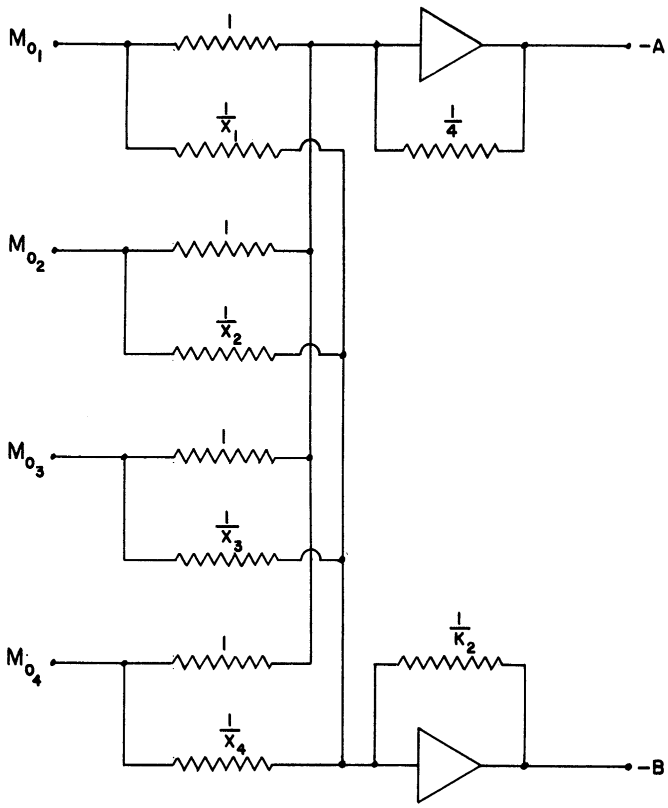
$$\sum_{m=1}^{n} X_m{}^2 = K_2 \text{ is a minimum.}$$

Applying this to equations (3.5) we get

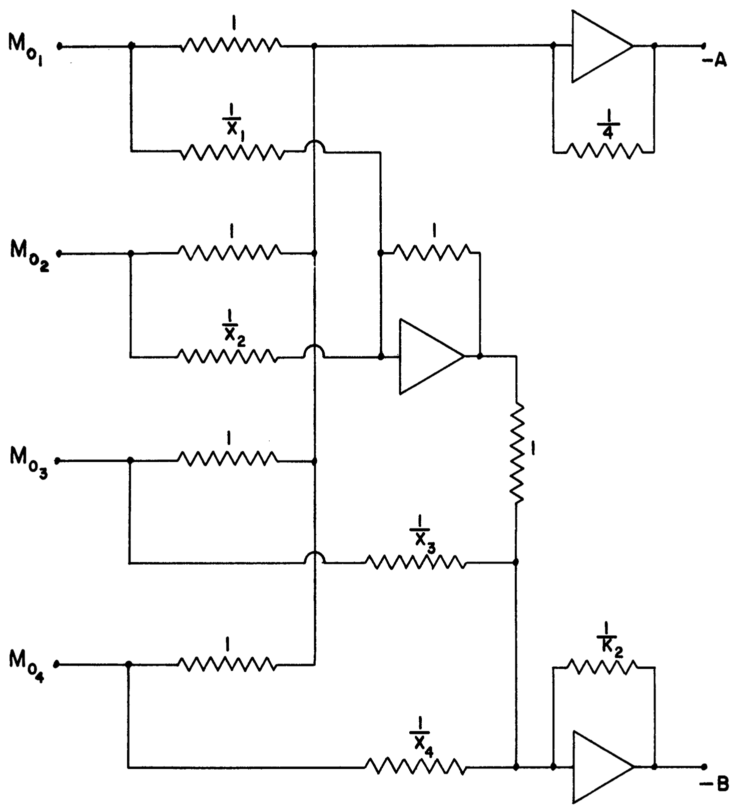
$$A = \frac{M_{0_1} + M_{0_2} + M_{0_3} + M_{0_4}}{4}$$

$$B = \frac{X_1M_{0_1} + X_2M_{0_2} + X_3M_{0_3} + X_4M_{0_4}}{K_2} \qquad (3.6)$$

The d-c operational amplifier arrangement for this system would then be

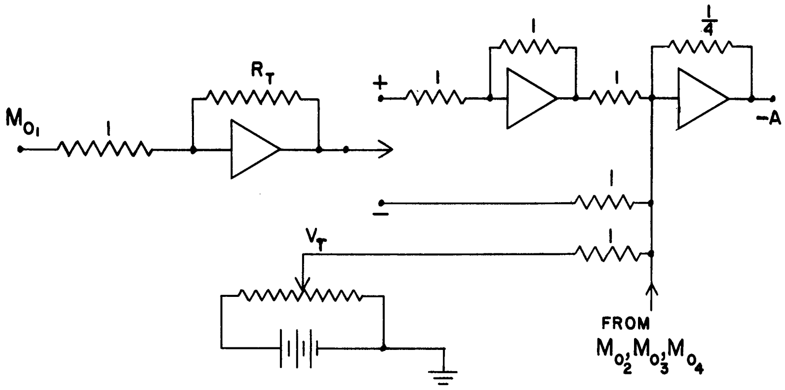


Whenever any of the constants are negative an additional amplifier must be used as a sign changing amplifier. This is illustrated in the following figure where X_1 and X_2 are assumed to be negative.



Thus the d-c outputs of the system would represent the normal force on the sting and the moment about the centroid of the gages.

The tare corrections mentioned previously are applied before the above computation is performed by adjustment of the gain of the signal amplifier. In the case of multiplication by a constant an additional operational amplifier must be placed in each information channel, and in the case of summations a fixed voltage of appropriate sign must be summed into each channel. Consider the case where both types of tare corrections must be applied to M_{0_1}. Its circuit would then appear as follows:



R_T = Tare multiplication factor

V_T = Tare summation factor

In the case of the determination of pressure coefficient, the calculations indicated by the equation

$$C_{p_n} = \frac{P_n - P_a}{\frac{\gamma}{2} P_b M^2} \tag{3.7}$$

are performed by the same operational amplifiers. The pressure sensing element considered is a pressure capsule utilizing a Schaevitz Differential Transformer. The output of this element is proportional to the difference between a fixed reference pressure and the unknown pressure. Therefore, assuming the capsule has a linear response, the unknown pressure, in terms of volts, is given by:

$$P_n = P_r + K(P_n - P_r) = P_r + P_{G_n} \tag{3.8}$$

where P_n = unknown pressure in volts

P_r = reference pressure in volts

K = proportionality constant of capsule

P_{G_n} = input to operational amplifier in volts.

Substituting equation (3.8) into equation (3.7) and nondimensionalizing by dividing each term by P_b, the barometric pressure, we get:

$$C_{p_n} = \frac{\dfrac{P_r + P_{G_n}}{P_b} - \dfrac{P_a}{P_b}}{\dfrac{\gamma}{2} \dfrac{P_a}{P_b} M^2} , \tag{3.9}$$

where γ is the ratio of specific heats and M is the Mach number.

Depending upon the characteristics of the particular wind tunnel this equation will be composed of essentially one variable quantity, P_G , and a number of quantities which are functions only of orifice location, Mach number or both. These latter quantities, therefore, are constants for any particular wind tunnel configuration. In the University of Michigan Supersonic Wind Tunnel the following relationships exist:

$$\frac{P_a}{P_b} = f(L,M) \quad , \quad \frac{\gamma}{2} M^2 = f(M)$$

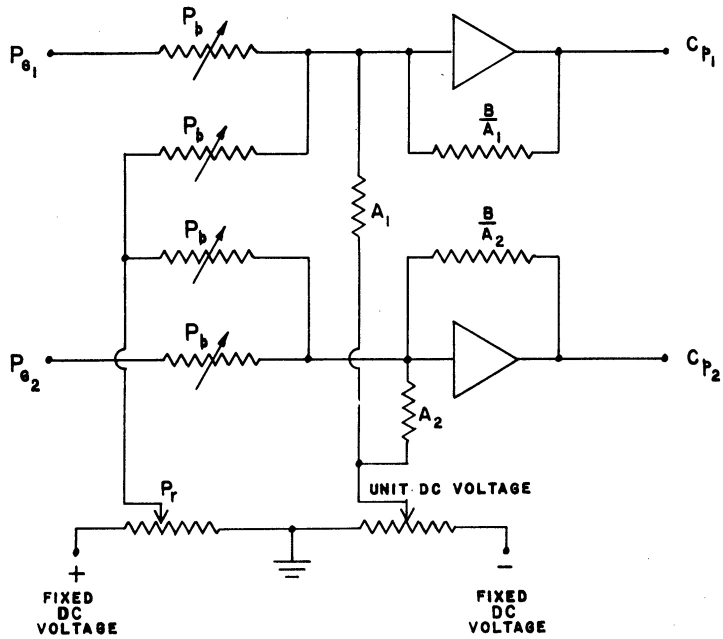
where L signifies location and M Mach number (2). Therefore if we assign constants to these quantities in the following manner,

$$\frac{P_a}{P_b} = A \quad , \quad \frac{2}{\gamma M^2} = B$$

we obtain the following relationship:

$$C_{p_n} = \frac{B}{A_n}\left[\frac{P_{G_n}}{P_b} + \frac{P_r}{P_b} - A_n\right] \tag{3.10}$$

If we now consider two pressure measurements, the following schematic indicates the type of operational amplifier system needed to compute C_p.



So far it has been shown how the d-c voltage equivalent of a measurement can be operated on to obtain desired coefficients and other quantities. By using additional operational amplifiers these coefficients and other quantities can be combined to make additional computations. The type and number of additional computations that can be performed is almost unlimited especially if some type of multiplier is available in sufficient numbers to multiply variable quantities by other variable quantities. This extended utilization of d-c operational amplifiers is simply a straightforward application of d-c operational amplifiers and analogue principles, hence it will not be covered here.

4. BACKGROUND

As mentioned previously, this system of data reduction uses the analogue method of computation for calculation of desired measurements in wind tunnel work. The system will take the output of sensing units, operate on them, correct for tares, position, etc., and produce either the desired measurement or coefficient to be applied to some type of d-c voltage sensing recorder. It is thought that it might be valuable to apply a digital conversion to this analogue output, but this is not part of this contract.

In studying a sample computation, let us assume that we have two strain gage elements on a cantilever sting of a balance system. The output of these two units will be proportional to moments while the desired measurements are force and center of pressure. Each of these strain gage elements will become the end instruments for a separate channel of information. The gages will be incorporated into bridges, supplied with a 2-kc voltage, and the output will be an amplitude-modulated carrier with a 180-degree phase reversal for negative or positive forces. Fig. 4.1 is a block diagram of this system.

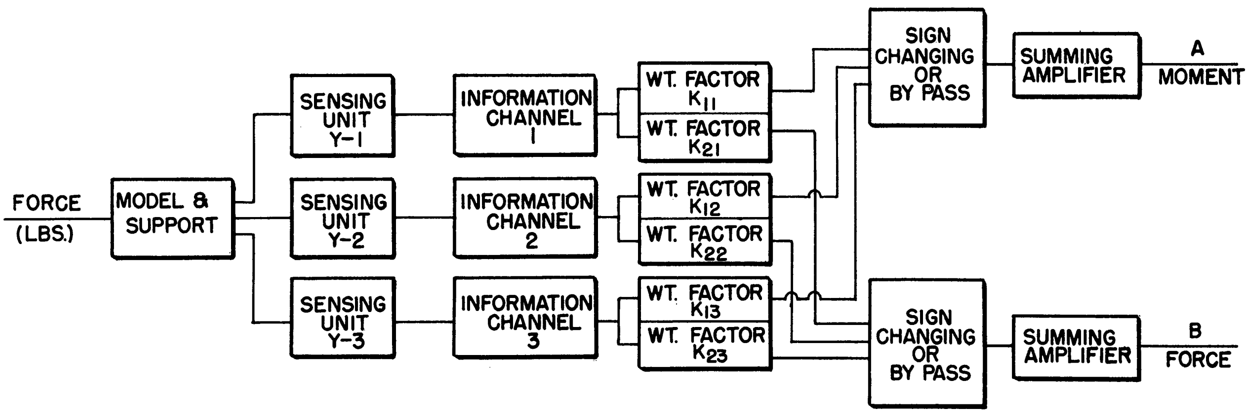


Fig. 4.1 Block Diagram of Force System

This signal will be amplified through the signal amplifier of which the gain control will represent a composite of constant multiplying terms determined by calibration for each new test setup. This composite multiplying term can be determined by applying a known force and varying the gain of each channel until its output directly represents the applied force or moment.

The output will be summed with a carrier so that the total output will be amplitude modulated without phase reversal. This summed signal then will be rectified directly. At the same time, a carrier equal to that summed in will be rectified through a separate channel and subtracted from the above rectified signal. This yields a d-c voltage proportional to the actuating quantity times a lumped constant of the system.

This d-c signal will be applied through weighting factors to a d-c operational amplifier used for summing the two hypothetical parallel channels. The weighting factors will be determined by the position from a reference point on the sting, tares, tunnel corrections, and the decision of whether moment at the origin or force is desired. The output of the d-c operational amplifier will be the desired quantity. It is possible to perform both calculations simultaneously by utilizing two d-c amplifiers, as shown schematically in Fig. 4.1.

Balance in normal strain-gage bridges and other sensing units will be accomplished in two steps. The first will be the initial correction which will be applied directly to the strain-gage bridge to bring the zero point within the limits of the automatic balancing system and will be manual in the initial test setup. The second step will take any normal unbalances due to temperature and other causes and correct for them by changes in the bias voltage. This will be accomplished when the channel is not computing. The d-c output of the rectifiers, will be sensed, chopped and amplified. This error signal will then be applied to a servo motor which will vary the bias to bring the error signal to zero.

When differential transformers are used, as in the case of the pressure capsule, the above discussion also applies. As the measured pressure changes from a value less than the reference pressure to a value greater than the reference pressure, the voltage output will shift phase by 180 degrees. Thus, with the reference pressure as the zero-output position, the voltage output will be proportional to the difference between the measured pressure and the reference pressure. Therefore a fixed voltage, proportional to the reference pressure, must be added to the output to obtain the equivalent of the measured pressure.

Balance is accomplished in two steps, as discussed above. The differential transformer is mechanically adjusted to zero by displacing the core until the output of the transformer is zero when the pressures on each side of the capsule diaphram are the same. After this adjustment is completed the automatic zero-balancing loop will adjust the d-c output of the information channel to zero when no signal is applied to the pressure capsule.

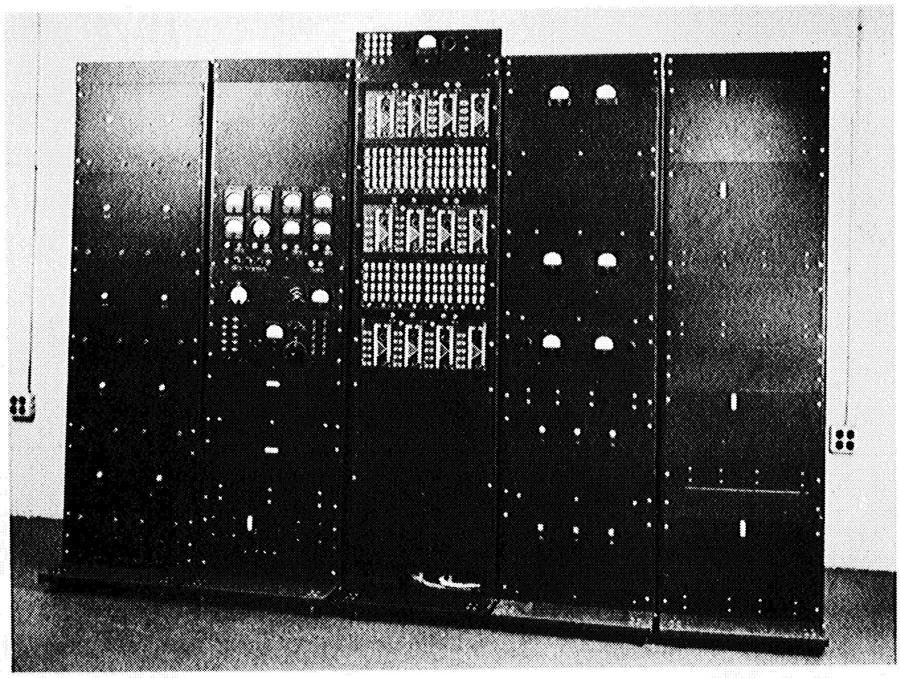


Fig. 5.1 Computer for Automatic Reduction of Wind Tunnel Data

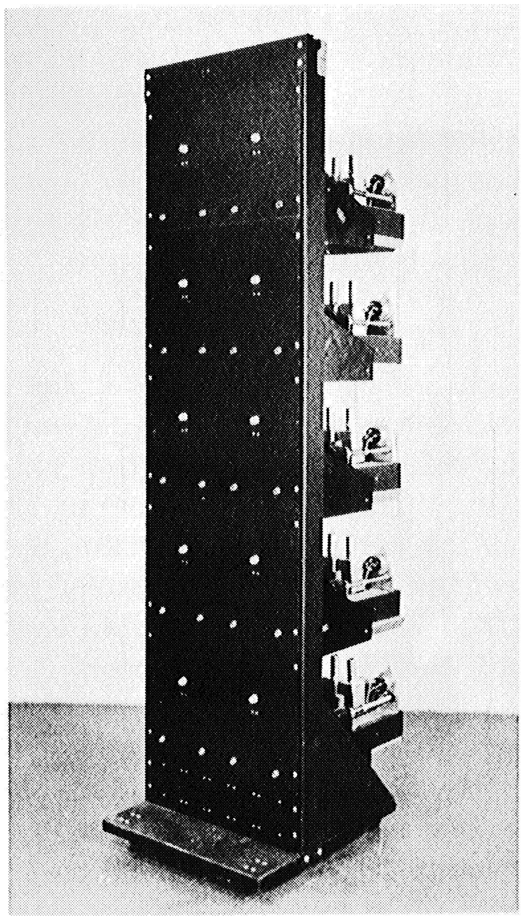


Fig. 5.2 Information Channel Rack

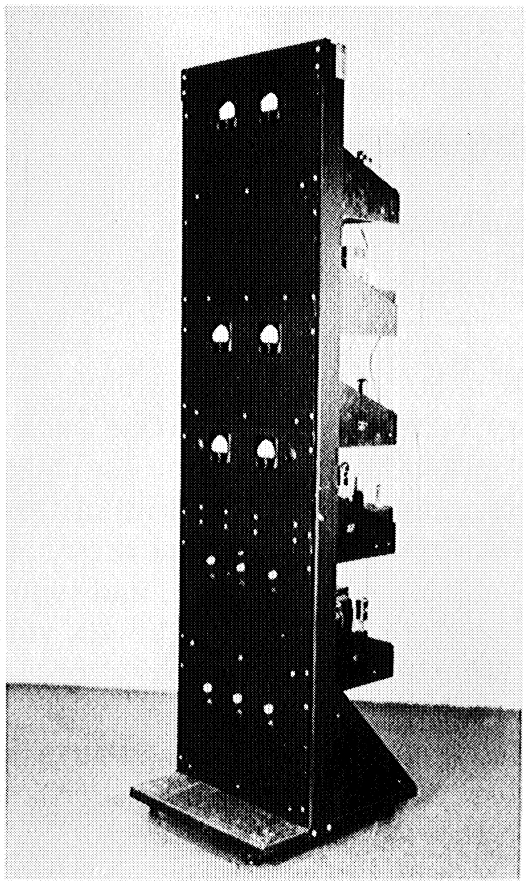


Fig. 5.3 Oscillator Rack

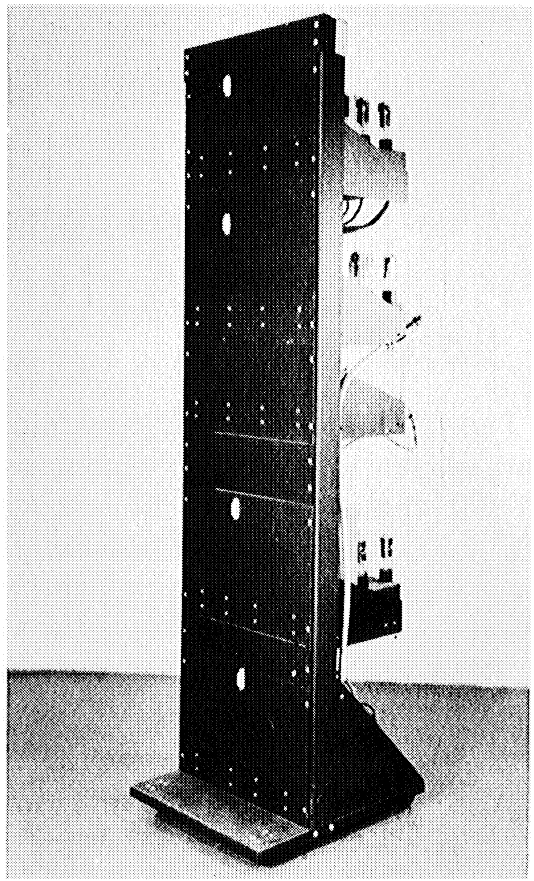


Fig. 5.4 Power Supply Rack

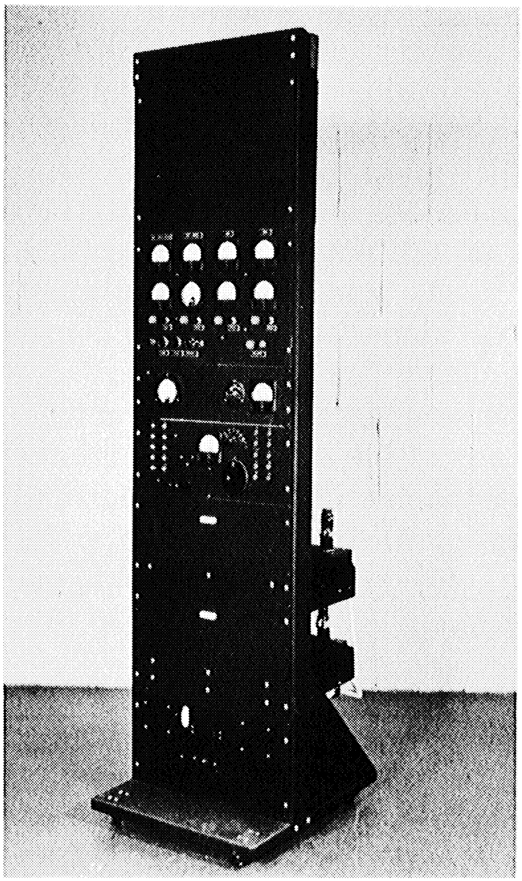


Fig. 5.5 Master Control Rack

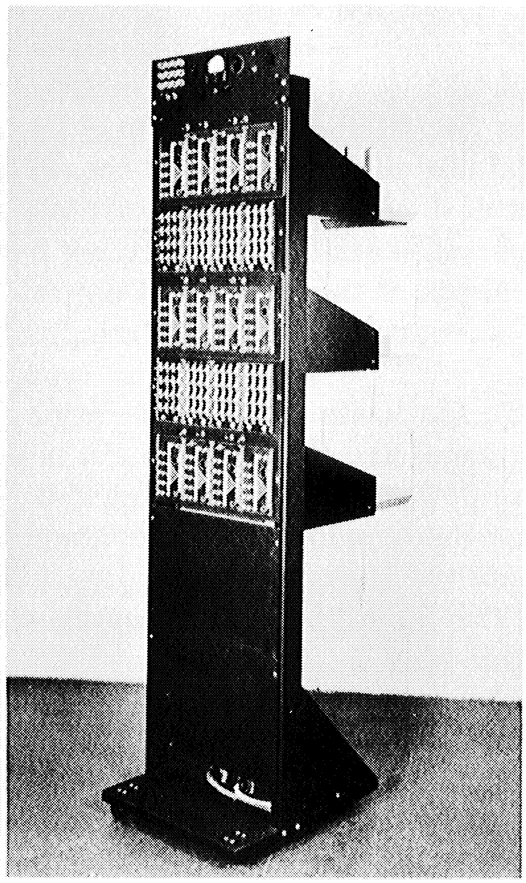


Fig. 5.6 Operational Amplifier Rack

5. COMPUTER AND ITS COMPONENTS

5.1 General

The present computer consists of five relay racks, (Fig. 5.1). One rack contains ten information channels, (Fig. 5.2); in another is mounted the 2-kc and 400-cps oscillators along with their power supplies and output amplifiers, (Fig. 5.3); the third contains the power supplies for all units except the oscillators, (Fig. 5.4); in the fourth is contained the master control panel and junction box, the voltage regulation units for the main power supplies and the six volt a-c filament supplies, (Fig. 5.5); the fifth rack contains the d-c operational amplifiers, (Fig. 5.6). All racks are interconnected by shielded cables of sufficient length to permit the power supplies and oscillators to be located at some distance from the remainder of the equipment. This is done in order to prevent stray pickup due to radiation from the former units. The racks are mounted on casters so that they can be easily moved to any desired location. One of the goals of this project was to develop a computer which would be as portable as possible to facilitate the use of it in any test setup thereby increasing its utility.

In addition to the units mentioned above a line voltage regulator and a 12 volts d-c filament supply may be used with the computer. If a line voltage regulator is necessary, it should have a capacity of approximately 5 KVA. The 12 volt d-c supply, which furnishes the voltage for the d-c operational amplifiers and their drift stabilizing units, must be of sufficient capacity to fulfill the needs of the number of operationals being used. Each operational amplifier and associated drift stabilizing unit requires 1.2 amperes at 12 volts d-c.

To facilitate ease of operation, a master control panel was constructed. On this panel are mounted all the monitoring meters of the d-c voltages from the main power supplies and the a-c voltages from the oscillators. In addition to these the overload indicators and reset buttons for all the d-c supply voltages, except the 12 volts d-c supply, are also located on this panel. The main operating switches, namely, the start, operate and balance switches, are also placed on this panel.

Below the master control panel is the signal monitoring circuit for the information channels. By means of a multi-position switch the d-c output from any information channel can be read on a vacuum tube voltmeter located in the panel. This circuit is shown schematically in Fig. 9.14.

5.2 Information Channel

5.2.1 General

The information channel contains all the units necessary to convert the amplitude-modulated carrier output of the transducer to a d-c voltage. In addition, it contains the automatic zero-balancing loop. A block diagram is shown in Fig. 5.7. More precisely, on any one of the ten information channel chasses, are contained the following main units (see Fig. 5.8); input transformer, 60-cps filter, signal amplifier, phase shifting network, two diode bridge rectifiers, 400-cps chopper, servo amplifier and output transformer, servo motor and a ten-turn potentiometer.

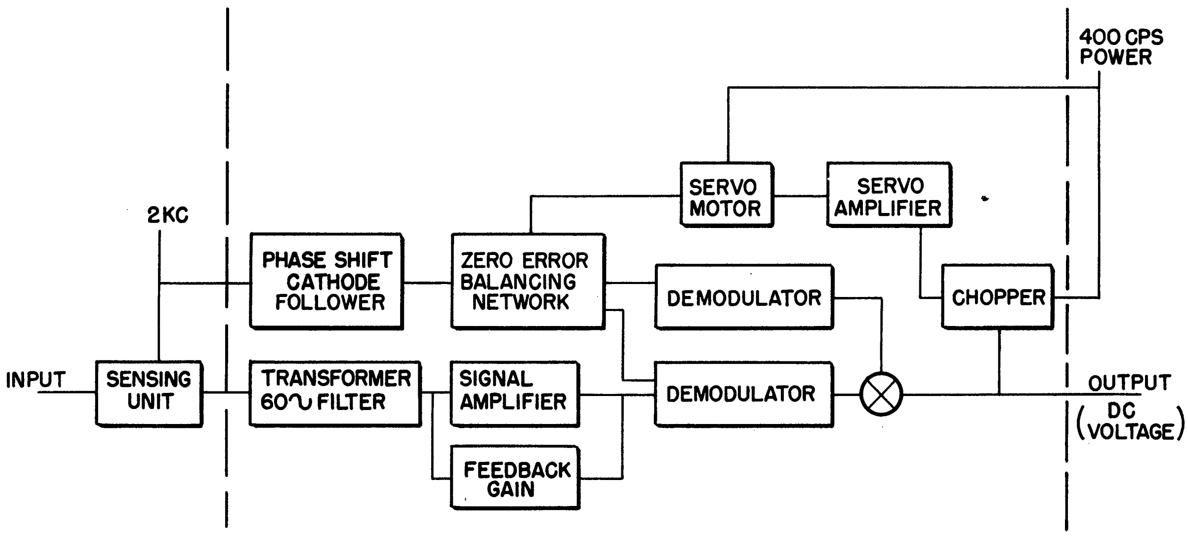


Fig. 5.7 Block Diagram of One Channel of Information

Each channel is a plug-in unit which is completely interchangeable with all other channels. All power is brought in through the plug at the front, while the signal input and output plugs are located at the rear of the chassis. Fig. 9.1 is the information channel chassis wiring diagram. The adapter box, shown at the rear of the chassis, (Fig. 5.9), is used when forces are to be measured. It contains two nonactive arms of a Wheatstone bridge, the other two arms are strain gages. This arrangement was necessary to use the computer with the University of Michigan Supersonic Wind Tunnel. One of the arms contained in

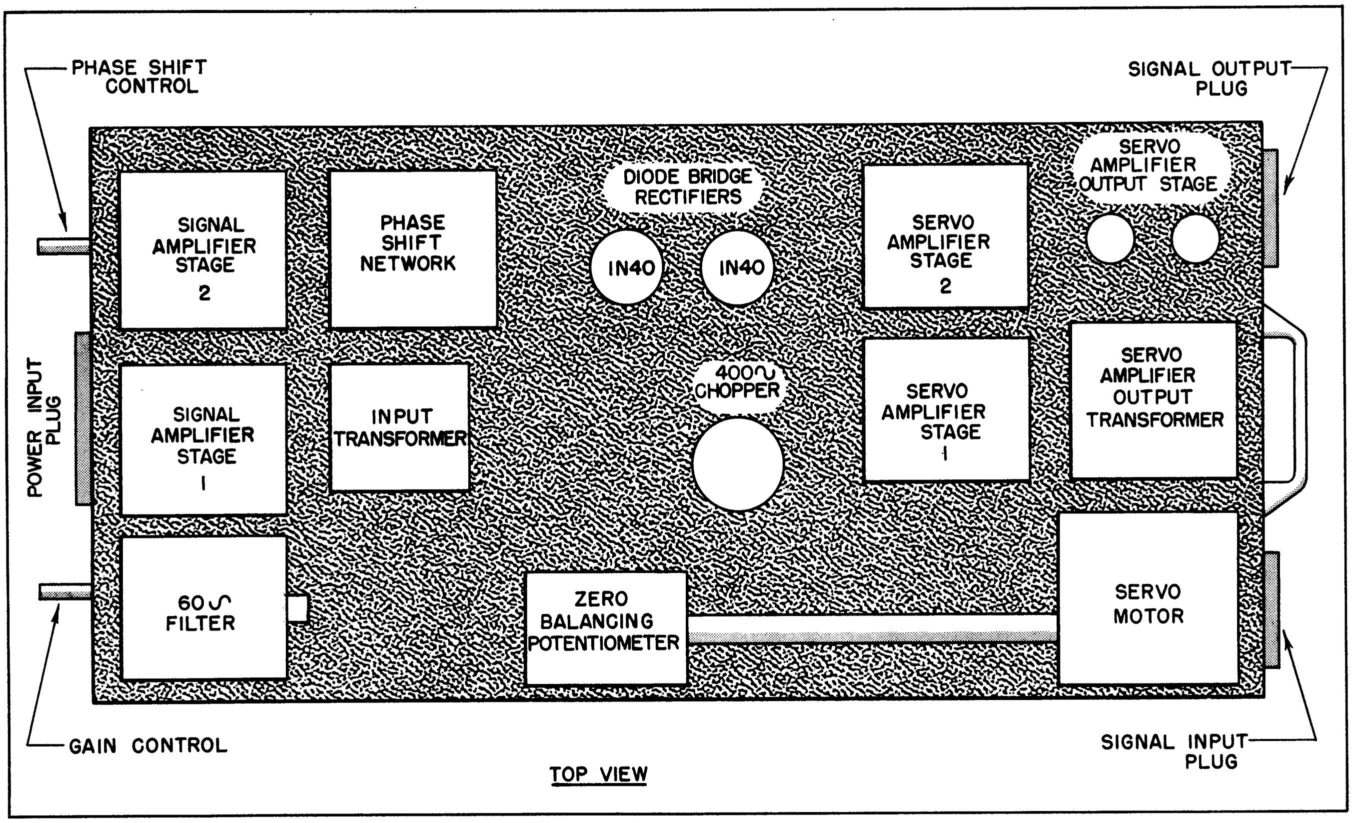


Fig. 5.8 Information Channel Layout

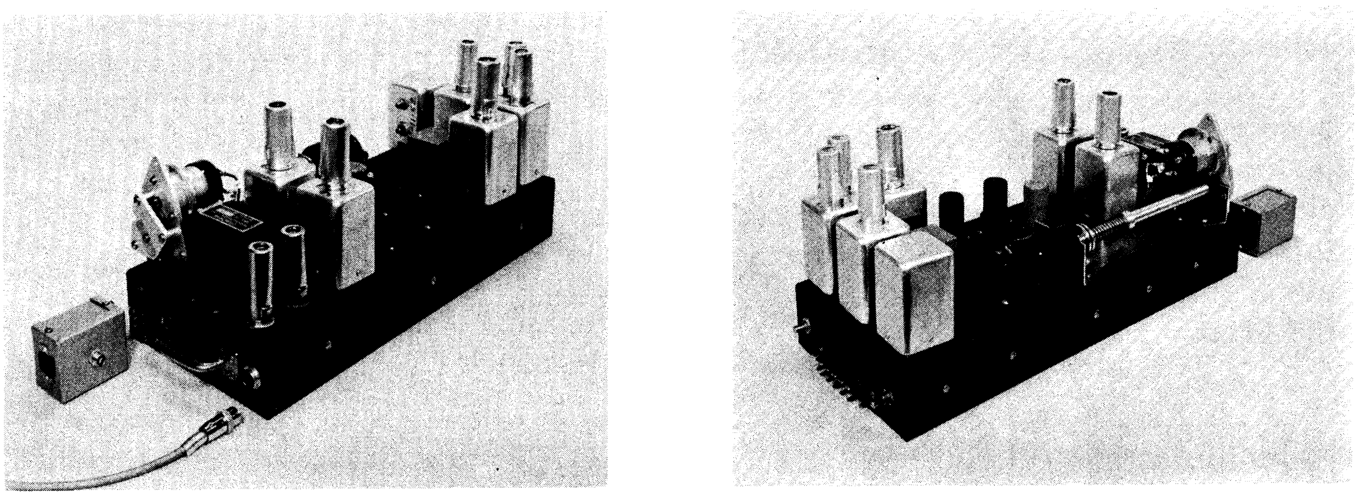


Fig. 5.9 Photographs of an Information Channel

the box is a variable resistance which provides a manual adjustment for balancing the bridge initially. Variable condensers can also be mounted here to eliminate capacitive unbalance in the bridge. When a pressure-sensing unit is employed, the adapter box is not used. It should be noted that the input to the adapter box is a four-prong socket, while the input to the chassis is a six-prong socket. By using a four-prong plug for the strain gages and a six-prong plug for the pressure-sensing element the possibility of employing a partial bridge for force measurement was eliminated. The information channel accepts signals from a strain-gage Wheatstone bridge or a Schaevitz Differential Transformer (pressure-sensing element) with equal facility. In general, any sensing unit which will produce a 2-kc amplitude-modulated carrier can be used.

It might be noted here that the type of strain-gage bridge having two fixed arms is not the only type that can be used with this system. If the wind tunnel test configuration is of such a nature that four active gages can be used, certain advantages are obtained. Among these are increased bridge sensitivity - a factor of four if four active gages are used instead of one - and the possibility of measuring differential strains, i.e., comparison of the strains at two points. A very important advantage is obtained due to the symmetry of a bridge having four active elements. Generally the resistive and reactive unbalance is small since all arms are nearly identical and are subjected to the same environmental conditions. Also, the associated leads are not part of the active bridge, hence do not contribute to the characteristics of the bridge. Basically, it is better engineering practice to make use of four active gages whenever possible, due to the fact that all adverse effects are minimized when this configuration is used.

As can be seen from Fig. 5.9, Vector turrets have been used wherever possible to make identical components of each information channel completely interchangeable. The use of these plug-in units greatly decreases the loss of running time due to breakdown of an information channel. If a channel should become faulty, it can be replaced immediately by a spare channel, thereby making the complete system operative again. The plug-in units of the faulty channel can then be tested individually and the inoperative unit repaired at the leisure of the operator or technician concerned. These cans are color-coded along with the octal sockets in the chassis to assist in replacing the units in the proper socket.

In addition to the above considerations, the cans were used to reduce pickup within the information channel not only by restraining the entrance of stray voltages into a particular unit but also by reducing the amount of radiation from the units themselves. In short, the cans have greatly reduced the possibility of crosstalk among individual units and in doing so have aided in the suppression of positive feedback, which can be bothersome in relatively high-gain amplifiers.

The signal amplifier gain and phase-shift controls are located adjacent to the power plug at the front end of the information channel chassis. These controls are screwdriver adjustments which are accessible through holes in the rack panel. This configuration, it is believed, will prevent the setting of either control from being accidentally changed at any time. A change in the position of one of these controls, especially the gain control, will necessitate a complete recalibration of that channel since it will no longer be zero-balanced. It should be noted that a change in the gain of any unit in the information channel, except the servo-motor amplifier, will introduce a shift in the zero-balance position. Therefore, the system must be rebalanced before accurate results can be obtained.

An indicator light is placed in the rack panel immediately ahead of each information channel. This light is lighted when the output voltage of the servo amplifier is sufficient to operate the servo motor. Therefore the light is on while the motor is attempting to bring the output to zero. When the balance position has been achieved, the light will be extinguished. If, after a sufficient length of time, the light is not extinguished it will undoubtedly be due to the fact that the balance potentiometer has reached the limit of its travel and a manual rebalancing of the sensing element is necessary to bring the balance point of the potentiometer within the limits of its travel.

5.2.2 60-cps Parallel "T" Filter

The problem of eliminating 60-cps pickup from the output signal of the sensing unit was considered important enough to take precautionary steps before any trouble was experienced. It was realized that any pickup originating in the sensing units or their associated leads would not modulate the 2-kc carrier but would simply be superposed upon it. This meant that a filter which had a very sharply tuned null frequency would be required because no appreciable attenuation could be tolerated in the neighborhood of the carrier frequency and especially if this attenuation were not constant in this region.

The filter appearing to have the desired characteristics was a parallel "T" filter tuned for 60 cps. This type filter has a very sharp null at the chosen frequency, but the attenuation at frequencies differing from the null frequency by a factor of three or four is very slight. It was also decided to place this filter as far forward as possible in the information channel, namely, between the input transformer and the signal amplifier; a 60-cps parallel "T" filter having the required impedance was then designed. The schematic of this filter is shown in Fig. 9.2.

As can be seen in the circuit diagram, this filter has two variable resistors which are used to tune the filter for 60 cps. These two controls are varied by means of screwdriver adjustments on the exterior of the can in which the filter is mounted. This method of mounting was chosen to eliminate the possibility of accidentally detuning the filter once it has been properly adjusted. The schematic diagram of the can is shown in Fig. 9.3.

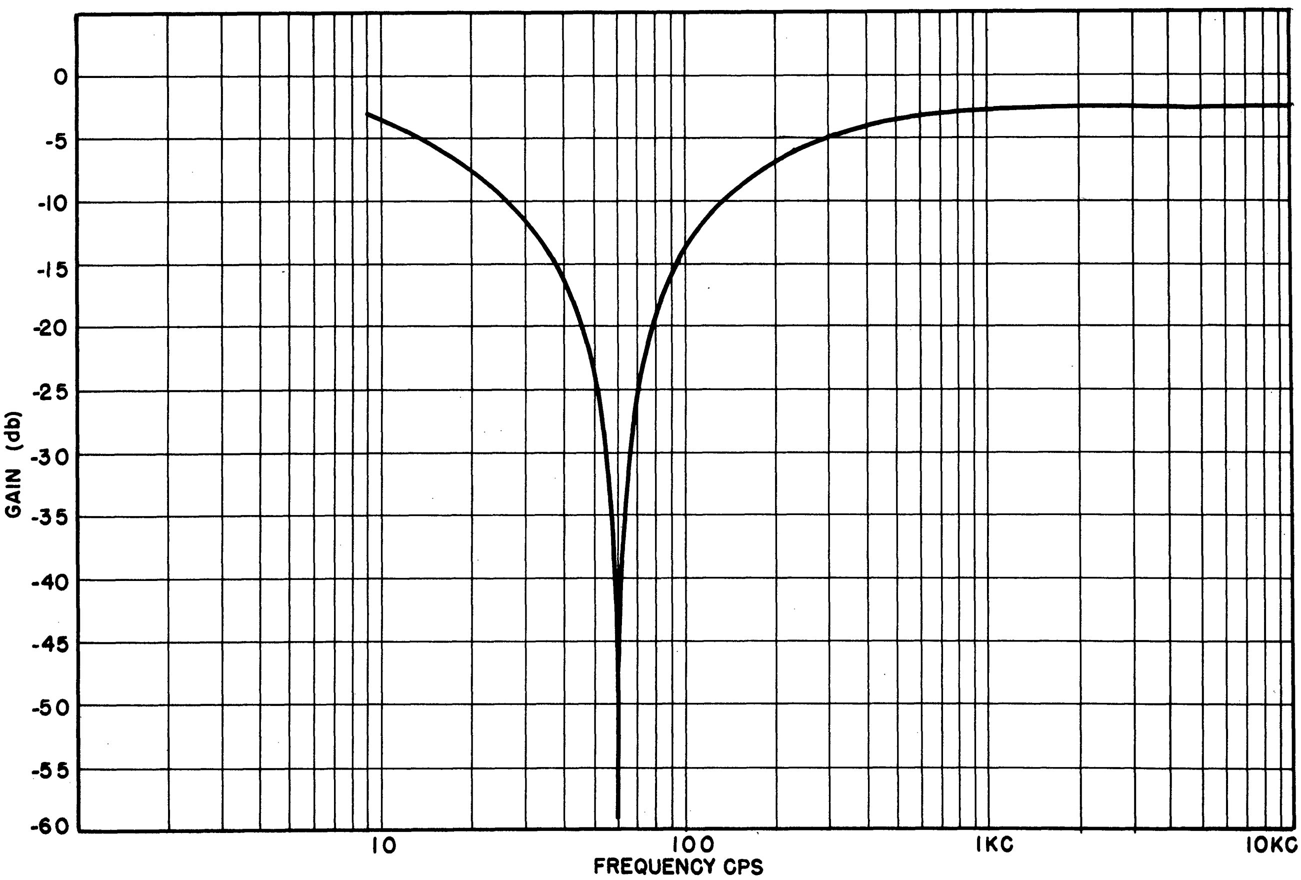


Fig. 5.10 Frequency Response of 60-cps Filter

The frequency response of the parallel "T" filter is shown in Fig. 5.10. It has an attenuation of approximately 60 db at 60 cps, while frequencies greater than 1 kc have a constant attenuation of approximately 2.5 db. Thus the side-bands of any signal will be attenuated very little in passing through the filter.

A question may arise concerning 120-cps pickup. It is true that the filtering action is relatively poor at this frequency, but the magnitude of any pickup of this frequency will probably be small compared to the magnitude of the 60-cps pickup.

5.2.3 Signal Amplifier

Preliminary investigations into the output voltages of the sensing unit led to the estimation that the maximum output would be of the order of 10 millivolts. Hence, assuming that the desired maximum input to the d-c operational amplifiers be of the order of 50 volts, the desired gain of the signal amplifier would have to be 5000, or 74 db. This value was exceeded by the class A type signal amplifier shown schematically in Fig. 5.11. As indicated in Fig. 5.12, the maximum open-loop gain is approximately 80 db at 1000 cps and with the 1:10 input transformer the over-all open-loop gain is approximately 100 db. This is approximately 25 db more gain than was thought necessary, but with this additional gain the amplifier can be operated with negative feedback at all times. The use of the amplifier in this manner provides a frequency response which is flat over a greater range of frequencies than that required by the expected bandwidth. In addition to improving the frequency response, the linearity of the system is improved by the use of increased negative feedback. Hence the excess gain of the amplifier provides a means of improving the characteristics of the system.

The components used in the feedback loop were such that the maximum negative feedback obtainable in the amplifier is approximately 48 db. However, the stability of the prototype was checked using approximately 65 db of negative feedback; no instability occurred. With this margin of safety, it is reasonable to expect this system to remain stable for normal changes of tube characteristics and circuit variations.

The gain control is located in the cathode circuit of the first stage (see Fig. 5.11). Minimum over-all gain is obtained when the negative feedback is fed directly into the cathode, and maximum gain when the feedback loop is grounded at the cathode. The cathode follower output stage is employed as an impedance matching stage to prevent the amplifier from being overloaded by the network into which it operates.

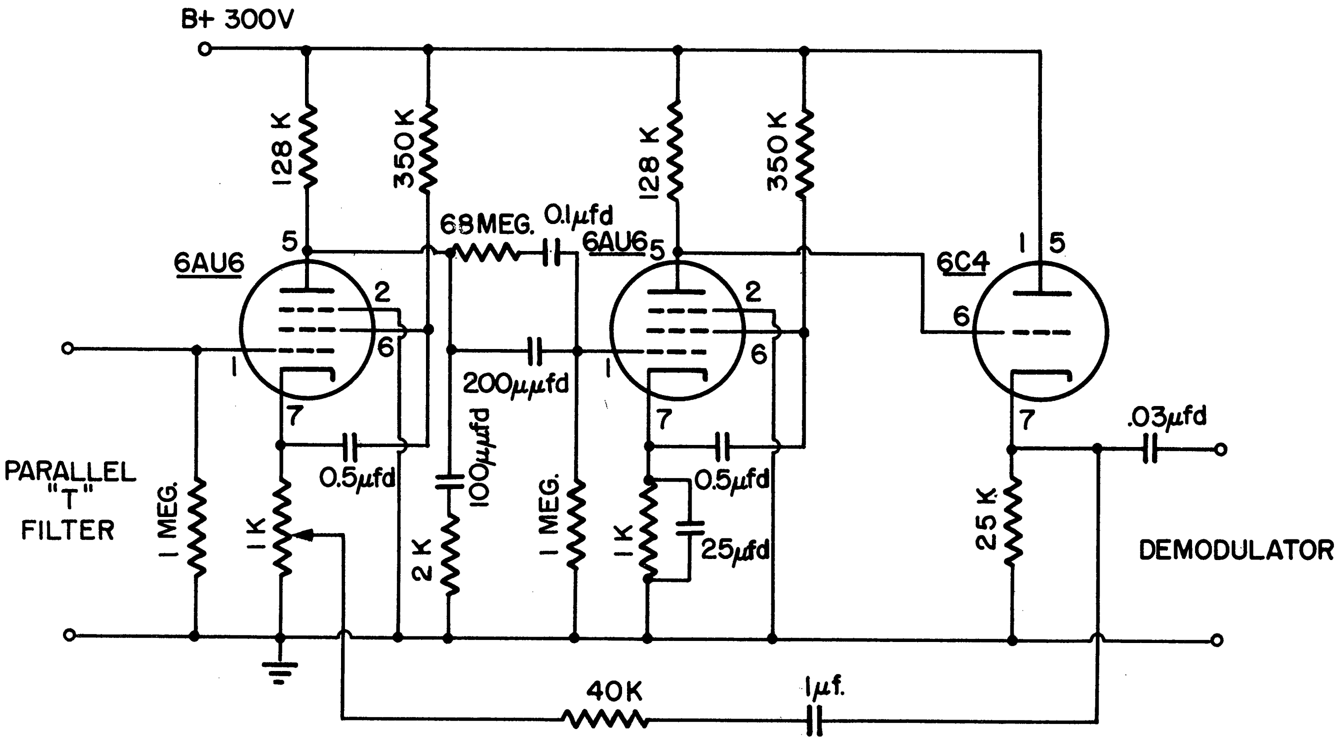


Fig. 5.11 Schematic Diagram of Signal Amplifier

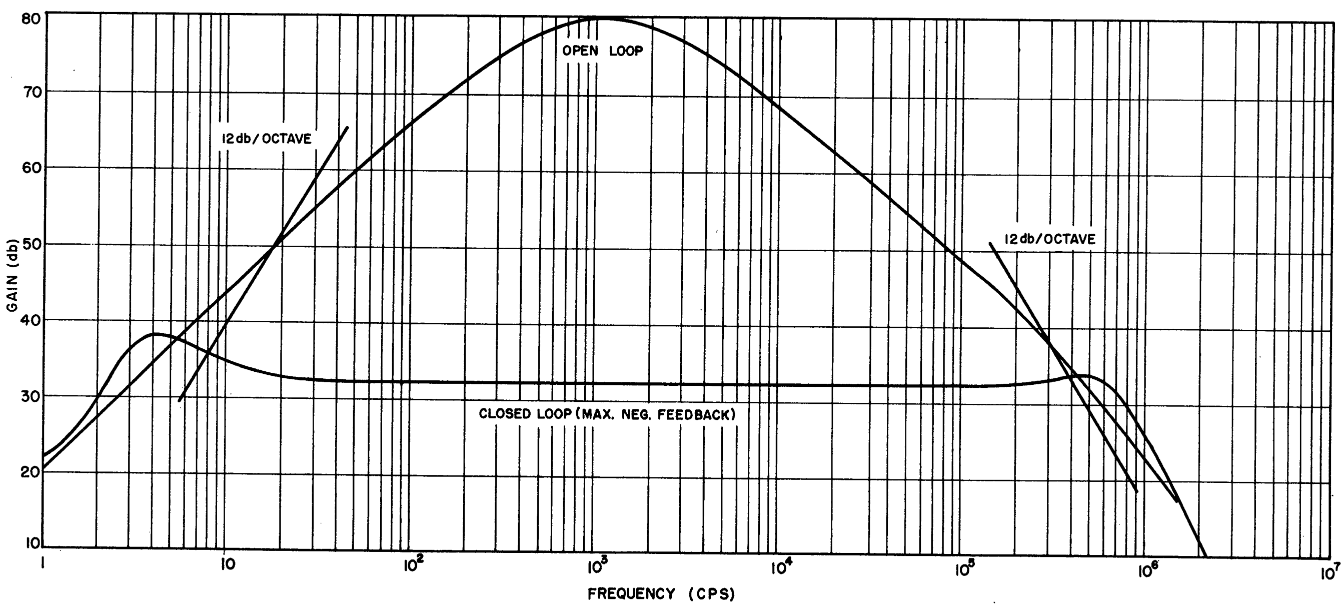


Fig. 5.12 Frequency Response of Signal Amplifier

In the expected operating frequency range, the maximum undistorted output is approximately 80 volts peak, which is well beyond the maximum desired output voltage, namely 50 volts peak.

It must be kept in mind that the gain of the signal amplifier must remain fixed after the system has been balanced, since this amplifier is not located in the closed-loop balancing network, and any change in gain will appear as a change in error signal at the output of the information channel. It is expected that this will introduce no hardship, since the gain of the amplifier will be adjusted during calibration and will then be allowed to remain at a fixed setting over a relatively long period of time, whereas the balance circuit will be activated before and after each run.

The signal amplifier occupies two Vector turret cans. The first can contains the first stage and the second can contains the second stage and the cathode follower. These two cans are shown schematically in Figs. 9.4 and 9.5.

5.2.4 Bias Summing

The output of the sensing units will have a phase reversal of 180 degrees when passing through the zero-actuating balance point. However, the diode-bridge rectifier is not a phase-sensitive device; its d-c output will have the same polarity regardless of the phase of the input a-c signal. It is therefore necessary to add a 2-kc signal as bias at the output of the a-c signal amplifier. This bias carrier is in phase with the signal carrier for positive signals and of sufficient amplitude to keep the input to the rectifier in phase with the bias carrier regardless of the phase of the a-c signal amplifier output, thus yielding a biased signal that does not require a phase-sensitive rectifier.

The d-c output of the diode-bridge rectifier will be linearly proportional to the magnitude of this biased signal. The d-c equivalent of the 2-kc bias carrier is obtained by applying the 2-kc bias carrier to a separate diode bridge. This d-c output is then subtracted from the d-c equivalent of the biased signal, giving a d-c voltage linearly proportional to the input signal. The bias summing network is shown in Fig. 5.13.

5.2.5 Diode-Bridge Rectifiers

To rectify the 2-kc voltages a full wave diode-bridge rectifier was chosen. The initial problem was to find a rectifier which would be linear over the range

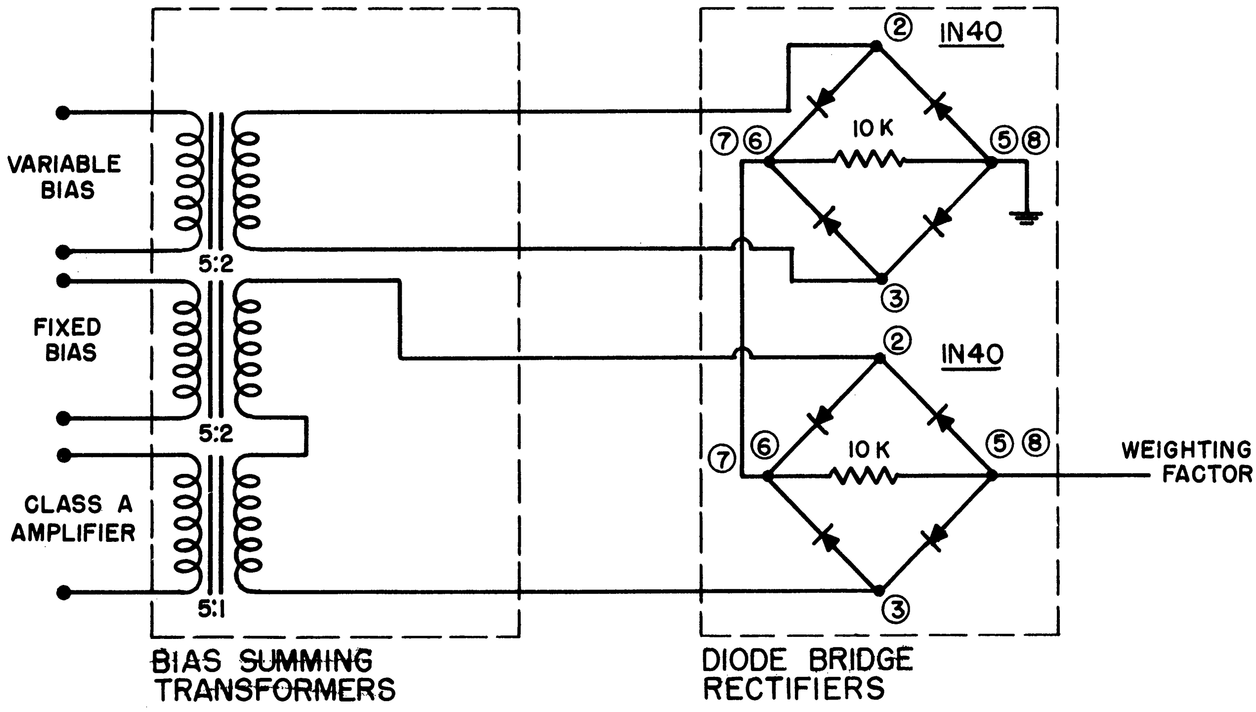


Fig. 5.13 Schematic Diagram of Bias Summing Transformers and Diode Bridge Rectifiers

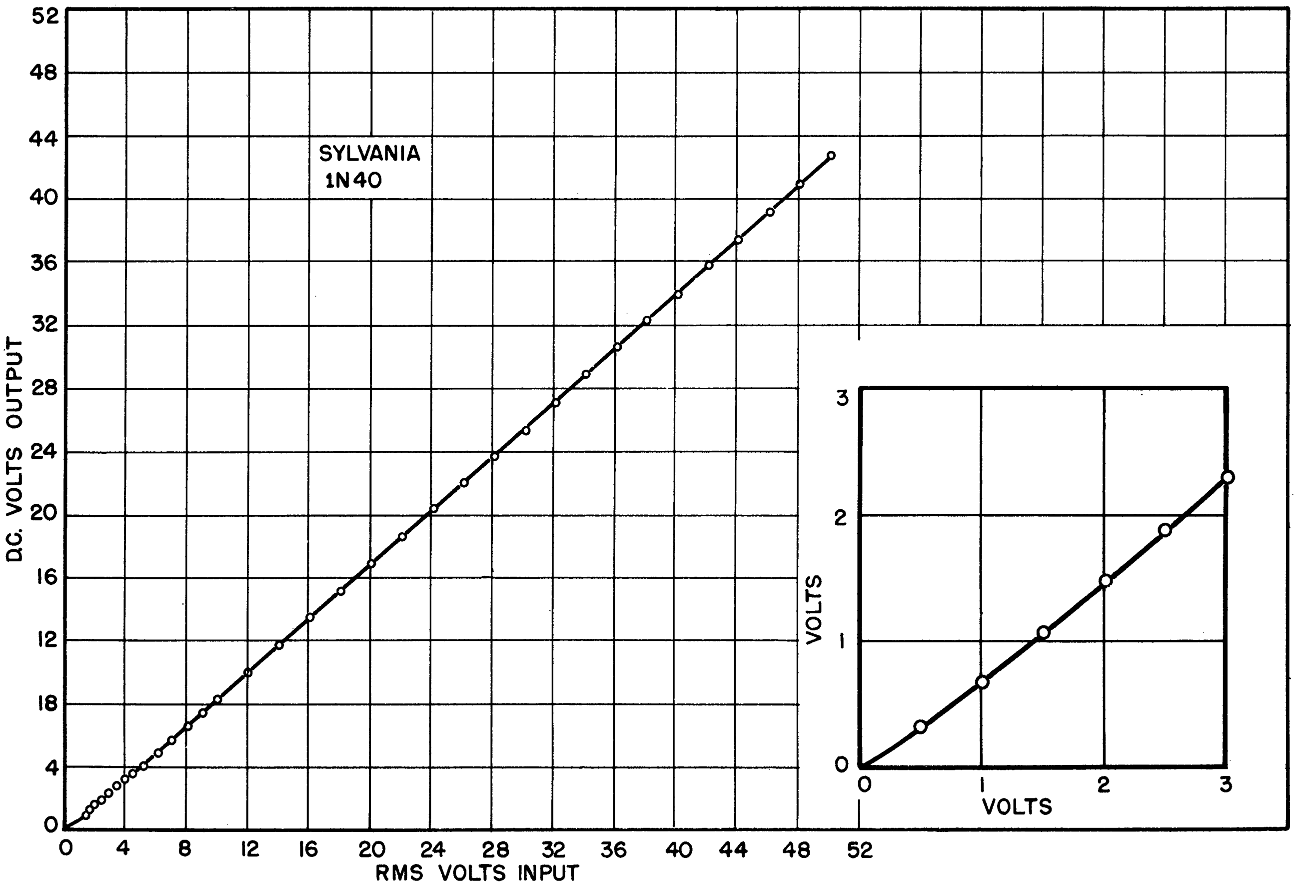


Fig. 5.14 Diode Bridge Characteristics with 10,000-Ohm Load

of voltages likely to appear on the secondary of the bias summing transformers. In the present system this voltage range is from approximately 2 volts to approximately 22 volts. The rectifier finally chosen was the Sylvania 1N40 Germanium Diode Bridge. After testing the diode bridge with a series of resistive loads across it, it was found that 10,000 ohms appeared to give the best linearity characteristics. Fig. 5.14 shows the linearity characteristics of two randomly chosen 1N40's with a 10,000 ohm resistive load across the bridge. With a 2-kc input, the linearity is better than 1 per cent between input voltages of 2 and 50 volts. Agreement between the two units tested is better than the plotting accuracy.

5.2.6 Phase Shifting

Due to the possibility of small phase shifts occurring between the transducer and the output of the signal amplifier a phase-shifting network (Fig. 5.15) was placed in the bias circuit. By means of this adjustable network the phase of the bias voltage can be adjusted during calibration so that it is identical with the amplitude-modulated carrier at the output of the signal amplifier. This network has an attenuation factor of two and it remains very nearly constant over the entire range of phase-angle settings.

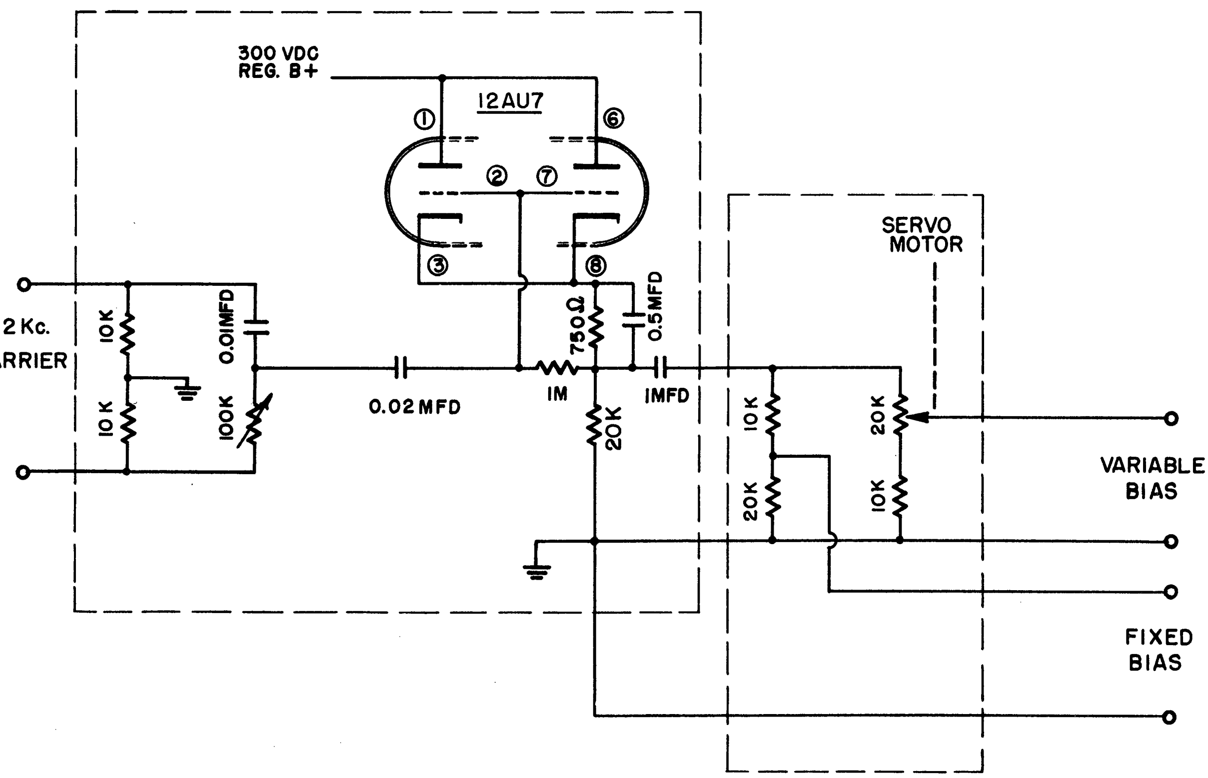


Fig. 5.15 Schematic Diagram of Phase Shifting and Zero-Balancing Networks

If the phase-shifting network were operating into an infinite impedance it would theoretically have a total range of 180 degrees. The input impedance of the bias circuit is approximately 15,000 ohms. This reduces the range to approximately 90 degrees. Therefore a cathode follower was placed at the output of the passive phase-shifting network to improve the impedance matching. This increases the range to approximately 170 degrees, that is, from 0 degrees to 170 degrees phase shift between the output and input of the phase-shifting network. The maximum undistorted output of the cathode follower is approximately 100 volts peak.

In keeping with the general practice on this project, the phase-shifting network and cathode follower were placed in a Vector turret can. A schematic diagram of this can is shown in Fig. 9.6.

5.2.7 Zero-Error Balancing

For the condition of no signal input to the transducer, the d-c output of the information channel should also be zero. If unbalance exists in the system the d-c output will not be zero. Therefore a zero-error balancing loop was incorporated in each information channel to adjust the d-c output to zero when there is no signal input to the information channel. This is accomplished by varying the amplitude of the bias voltage which is rectified and then subtracted from the d-c signal-plus-bias voltage to give the d-c voltage representing the signal input to the information channel.

A 400-cps chopper is located at the output of the information channel. This unit converts the d-c output to a 400-cps signal which is then amplified and applied across the variable phase of a 400-cps servo motor. The motor, in turn, drives a ten-turn potentiometer which varies the amplitude of the variable bias voltage. If there is an unbalance in the system, the motor will continue to drive the potentiometer until the d-c output is brought to zero. When this occurs the motor will stop and the output d-c voltage will remain at zero volts.

The bias network - both fixed and variable - and the zero-balancing network are shown schematically in Fig. 5.15.

5.2.8 400-cps, DC-AC Chopper

The selection of a chopper or converter for the servo-balancing system was based on four major requirements. These four requirements were 400-cps output, break-before-make contacts, long life and a high amount of phase stability. Additional desirable requirements were that the unit be compact and inexpensive, require low driving power, have a single-pole double-throw contact arrangement and possess a moderately low output noise level.

After considerable investigation it was decided to use Stevens-Arnold Type 268 DC-AC choppers. This unit requires approximately 0.75 watts of 400-cps power at 6 volts.

A test was conducted using two types of choppers that most nearly met the above requirements. One unit of each manufacturer was run for over 1200 hours continuous operation at 400 cps. The voltage chopped was 1.5 volts and the circuit was arranged such that 300 microamperes was conducted across the contacts. At the conclusion of the test both units were operating satisfactorily.

The Stevens-Arnold unit had about 4 millivolts of noise at the end of the test. This was less than half that of the other unit tested. The phase stability appeared to be excellent throughout the test. This unit also required much less driving power than the second type tested.

A phase-shift network is incorporated in the 400-cps power input network. This is required to correct for phase shifts introduced by the chopper and amplifier, and supply a quadrature error signal to the servo motor.

5.2.9 Servo Amplifier

The servo amplifier, Fig. 9.7, is a class AB_1 amplifier consisting of three stages of voltage amplification, a phase-inverter stage and a push-pull power amplification stage. A transformer is used to match the output impedance of the amplifier to the impedance of the variable phase of the servo amplifier.

In Fig. 5.16 is shown the frequency response of the servo amplifier with a 250-ohm load on the output. The maximum gain is approximately 67 db and remains at this value for all frequencies between 100 cps and 10 kc.

Since it requires approximately 9 volts rms on the variable phase of the servo motor to set that motor in motion, the d-c output of the information channel will be balanced to within 1.4 millivolts d-c by the servo-balancing loop. This was deemed satisfactory to provide the necessary accuracy since it is only 0.014 per cent of the proposed maximum d-c output, namely 10 volts.

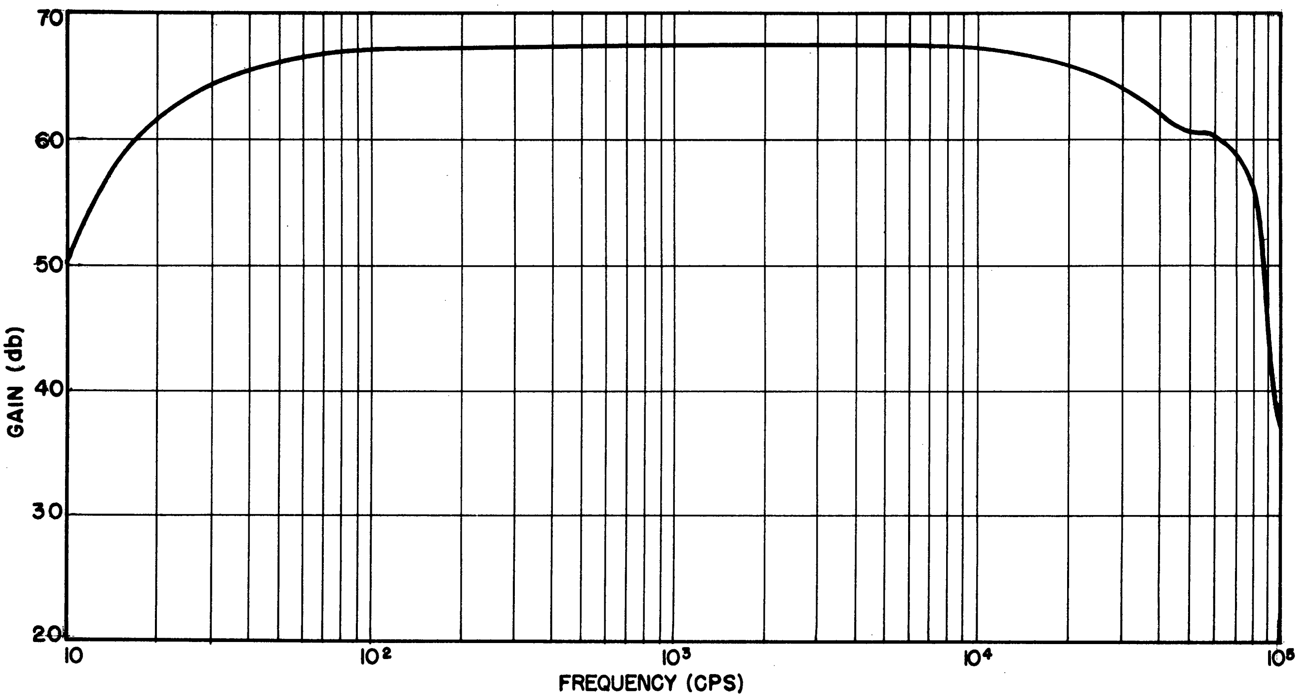


Fig. 5.16 Frequency Response of Servo Amplifier

To reduce the possibility of introducing an error in the d-c output signal due to high-level spurious noise, the B^+ voltage is not applied to the servo amplifier when the balance system is not energized.

Vector turret cans were used to house part of the servo amplifier. The first can contains two stages of amplification and the second can contains the third amplification stage and the phase inverter. These cans are shown schematically in Figs. 9.8 and 9.9. The push-pull stage is mounted on the channel chassis.

5.2.10 Servo Motor

After examining the characteristics of several motors, it was determined that the Bendix Eclipse Pioneer CK-2 motor (Signal Corps No. M0-18A) had the desired characteristics. This motor is a two-phase 400-cps low inertia motor having rated voltages of 26 volts on the fixed phase and 0-40 volts on the variable phase. The measured impedances of the two windings of the motor were approximately 41 ohms and 190 ohms at 400 cps for the fixed and variable phases, respectively. With 26 volts at 400 cps on the fixed phase, the voltage required on the variable phase, to drive the potentiometer, is approximately 9 volts.

The 20,000-ohm Micropot potentiometer is driven by the motor through a reduction gear having a reduction ratio of approximately 200:1. The torque is transmitted through the reduction gear to a clutched shaft approximately 8 inches long. The length of the shaft enables the potentiometer to be placed remotely from the motor thereby preventing any 400-cps pickup from being introduced by the potentiometer. The clutch provides protection for the Micropot when a large unbalance causes the motor to drive the potentiometer to the end of its travel. If this should happen, the clutch, which can be adjusted to transmit a fairly large range of torques, allows the motor to continue turning without placing undue strain on the mechanical stops of the Micropot.

The servo-balancing system is slightly underdamped. This was believed to be desirable; therefore no additional electronic or mechanical damping was placed in the servo loop. The balancing error due to the finite gain of the servo amplifier is approximately ±1.4 millivolts out of a full scale output of ±10 volts. This error is negligible if an error of 0.1 per cent is considered satisfactory.

5.3 Drift-Stabilized D-C Operational Amplifier

5.3.1 General

In order to carry on the necessary computations in the wind tunnel data reduction system, it is necessary to employ a number of d-c operational amplifiers similar to those used in electronic differential analyzers (analogue computers). At first it was thought that REAC (Reeves Electronic Analogue Computer) amplifiers, which incorporate the necessary a-c drift-stabilizing loop, could be used. One such amplifier was ordered for test purposes. The d-c performance of the amplifier was satisfactory, but the a-c frequency response (see Fig. 5.19) was not considered sufficient for the ultimate requirements of the wind tunnel system. Hence, a new d-c operational amplifier was designed.

5.3.2 Theory of Operational Amplifiers

Before describing the new amplifier, it might be well to review briefly the theory of operational amplifiers. The block diagram in Fig. 5.17 shows the essential components of the operational amplifier; a high gain d-c amplifier (gain = $-\mu$, an input impedance Z_i and a feedback impedance Z_f).

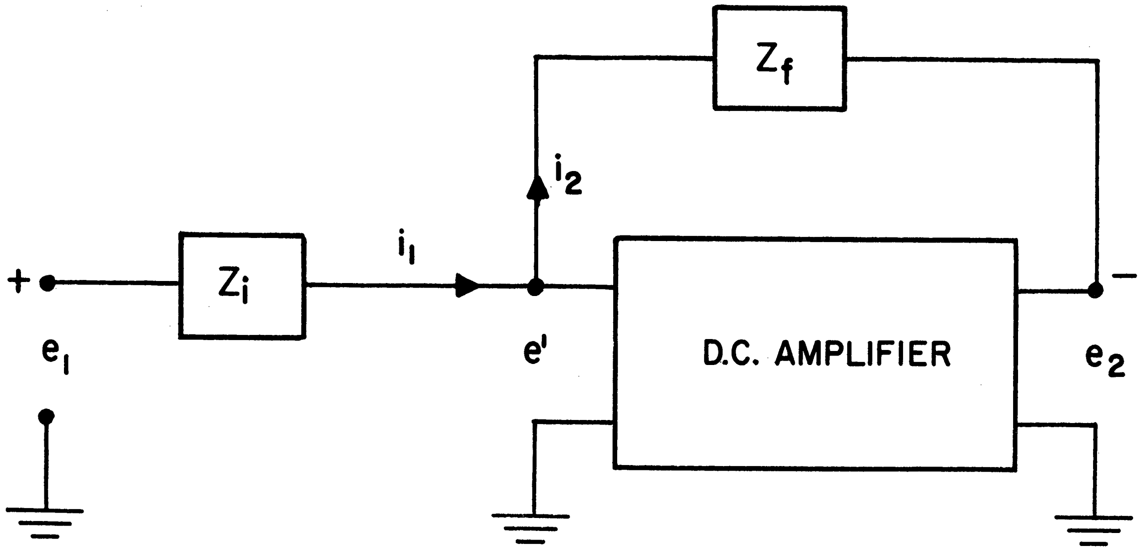


Fig. 5.17 Block Diagram of an Operational Amplifier

The output voltage e_2 is by definition equal to $-\mu e'$ where e' is the input to the high-gain amplifier. If we neglect the current into the high-gain amplifier (i.e., neglect any grid current of the input tube) it follows that $i_1 = i_2$. Hence:

$$\frac{e_1 - e'}{Z_i} = \frac{e' - e_2}{Z_f} \tag{5.1}$$

Substituting $e' = -e_2/\mu$ into equation (5.1), we can solve for the output voltage e_2 as a function of the input voltage e_1. Thus

$$e_2 = -\frac{Z_f}{Z_i} \frac{\mu}{\mu + \left(1 + \frac{Z_f}{Z_i}\right)} e_1 \tag{5.2}$$

If $\mu \gg 1 + Z_f/Z_i$, then

$$e_2 \cong - \frac{Z_f}{Z_i} e_1 \qquad (5.3)$$

which is the fundamental equation governing the behavior of the operational amplifier. If Z_i and Z_f are resistors R_i and R_f respectively, then the operational amplifier multiplies any input voltage e_1 by a constant $- R_f/R_i$. If Z_i is resistor R and Z_f is a capacitor C, then

$$e_2 = - \frac{Z_f}{Z_i} e_1 = - \frac{\frac{1}{CP}}{R} e_1 = \frac{-1}{RC} \int e_1 dt \qquad (5.4)$$

that is, the operational amplifier output voltage e_2 is the time integral of the input voltage e_1. By introducing any number of input voltages through separate input resistors, the operational amplifier can be used to sum voltages.

The above analysis assumes that $\mu \gg 1 + Z_f/Z_i$ in order for equation (5.3) to hold. Actually, the d-c amplifier gain, μ, is a function of frequency ω, or more generally, a function of the operator P. For high frequencies the gain, μ, will fall off until it is equal to or less than $1 + Z_f/Z_i$ and we must return to the original equation (5.2) to study the stability of the system. When $\mu(P) = -(1 + Z_f/Z_i)$ the denominator of equation (5.2) becomes zero. This means that if we make a Nyquist plot in the complex, μ, plane to determine stability, the critical point will be $-(1 + Z_f/Z_i) + j0$. According to Bode's minimum phase-shift criteria, the critical point will not be encircled in the μ plane and we will have a stable system if the amplitude of $\mu(j\omega)$ does not fall off faster than 12 db per octave before $\mu < 1 + Z_f/Z_i$. The most feedback occurs when $Z_f = 0$ so that our d-c amplifier frequency response should be designed to fall off at less than 12 db per frequency octave until $\mu < 1$. In order to provide a safe margin of stability, the order of 8 db per octave or less is desirable.

5.3.3 Design of Operational Amplifier

The general design procedure, then, is to decide first on a d-c circuit for the amplifier; after the amplifier is built, capacitors or resistor-capacitor combinations are inserted into the circuit in the proper locations so that the gain μ falls off at a rate considerably less than 12 db per frequency octave.

The d-c amplifier circuit that was finally arrived at is shown in Fig. 5.18. There are three stages of amplification, giving the necessary 180 degrees

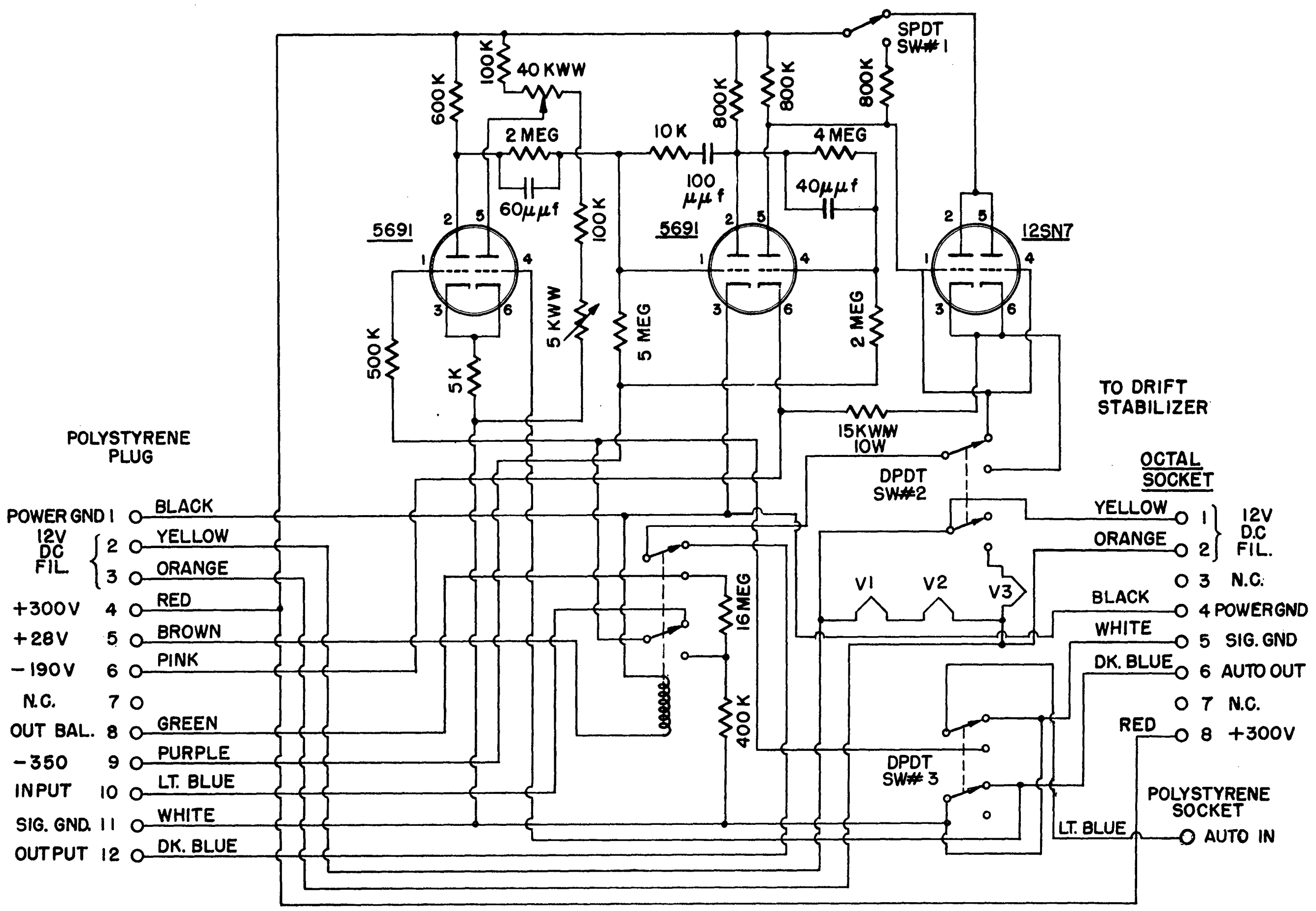


Fig. 5.18 Schematic Diagram of Operational Amplifier

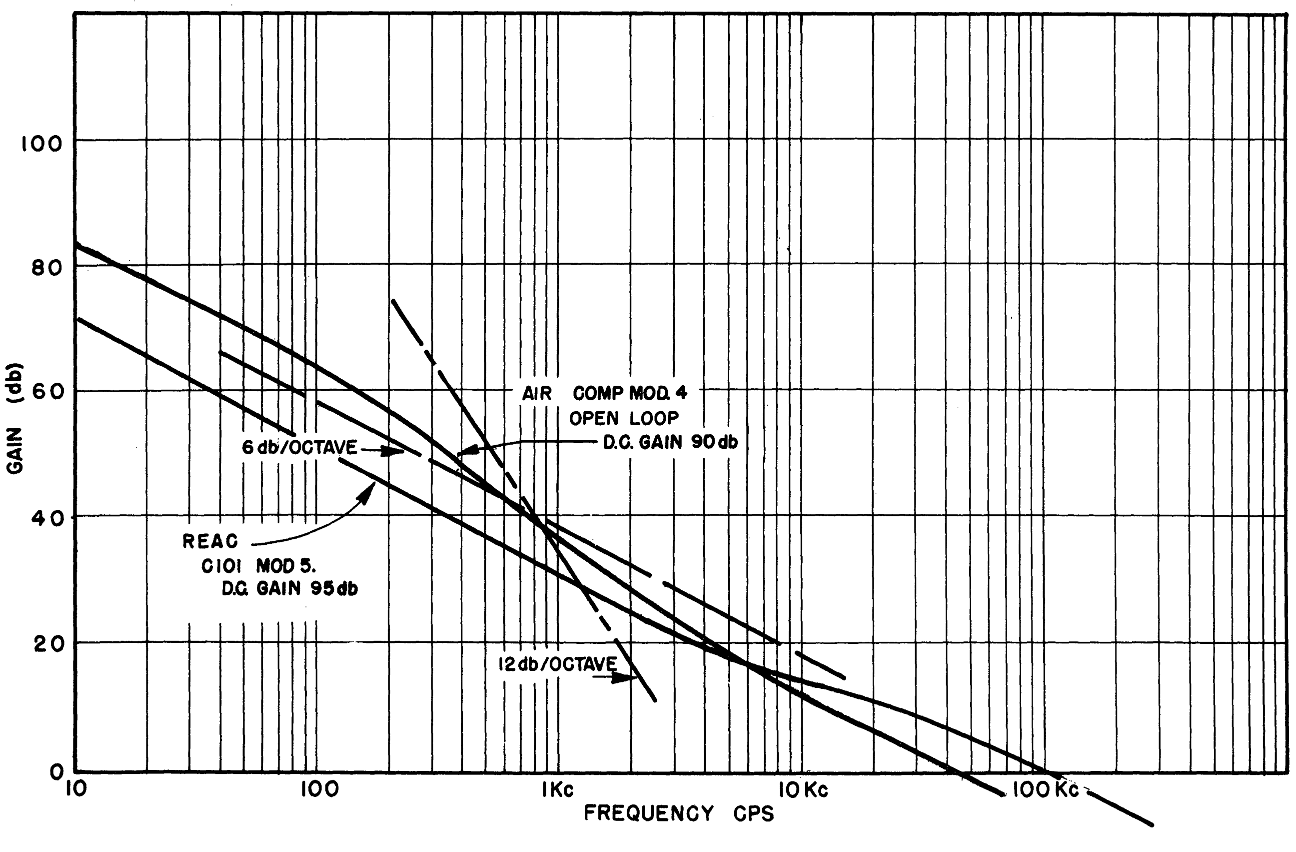


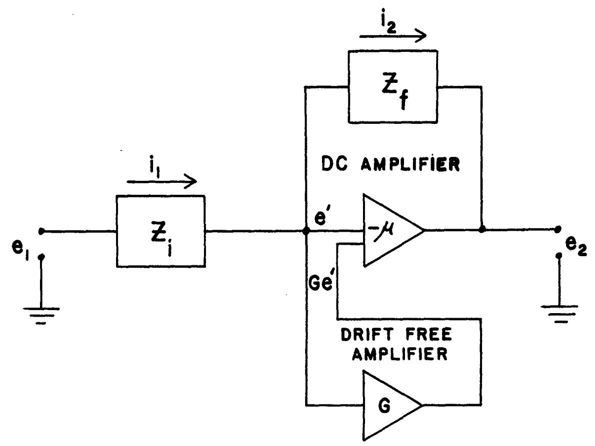
Fig. 5.19 Frequency Response of Operational Amplifier

phase shift, and a cathode-follower output is provided. The gain of the amplifier is 90 db or about 30,000. The circuit employs two 5691 twin triodes (these are RCA red base tube equivalents of the 6SL7) for the d-c balancing circuit and the three stages of amplification. The cathode-follower output is provided by a 12SN7, which can operate into a 20K load. Provision is made in the second half of 5691#1 for manual or automatic (drift-stabilized) balance. In order to check the balance of the amplifier a 28-volt relay is provided. When energized, this relay disconnects the external feedback and input impedances Z_f and Z_i and introduces a 40:1 ratio of feedback to input resistance. One per cent precision resistors are used throughout the amplifier. The power input to the amplifier include 12 volts d-c for filaments and B supply voltages of + 300, - 190, and - 350.

The frequency response of the d-c amplifier is compared with the REAC amplifier in Fig. 5.19. The response of the AIR Comp Mod 4 computer amplifier falls off considerably less than 12 db per octave over the entire range down to zero db, and over the lower region of the curve (which is the most important, since $1 + Z_f/Z_i$ is seldom greater than 20 db) the response falls off at approximately 6 db per octave. Square-wave response of the operational amplifier with all possible ratios of Z_f/Z_i indicates complete stability with practically no overshoot in the transient.

5.3.4 Drift Stabilization

One of the difficulties inherent with any d-c amplifier is the zero-drift problem, and the operational amplifiers used with electronic differential analyzers are no exception. Since the operational amplifiers employ a large amount of feedback, the zero-drift is very much less than it would be with an open-loop d-c amplifier, yet it can still be appreciable. To cite a specific example, it has been found that with an electronically regulated power supply (VR tube reference), an operational amplifier with a gain of unity (input resistor equal to feedback resistor) will drift the order of 0.01 volt per hour after it has been thoroughly warmed up. Naturally this figure is very approximate, but it gives an idea of the amount of drift which can be expected. This drift can be reduced by a large factor by using the additional drift-free a-c amplifier of gain G as shown in Fig. 5.20. In this drift-stabilizing amplifier the input voltage e' is chopped into a-c by a 60-cycle vibrator. The a-c signal is amplified through capacitor-coupled stages and then reconverted to a d-c output, Ge', by the same 60-cycle vibrator. Since the actual amplification is accomplished by an a-c amplifier, there is no d-c drift introduced. The output, Ge', of the drift-free amplifier is fed into the main d-c amplifier along with



Note: Ground connections on amplifiers omitted for clarity.

Fig. 5.20 Block Diagram of Drift-Stabilized Operational Amplifier

e' , so that the net input into the amplifier is $e'(1 + G)$. The output voltage, e_2, is $-\mu(1 + G)e'$, where $-\mu$ is the gain of the main d-c amplifier. Thus by using the auxiliary drift-free amplifier we have increased the gain e_2/e' of the open-loop system by a factor $1 + G$ without introducing any additional d-c drift.

If the currents into the amplifiers are negligible when compared with the currents i_1 and i_2 through the input and feedback impedances, respectively, then $i_1 = i_2$, and

$$\frac{e_1 - e'}{Z_i} = \frac{e' - e_2}{Z_f} \quad . \tag{5.5}$$

Remembering that $e_2 = -\mu(1 + G)e'$, we have

$$e_2 = - \frac{Z_f}{Z_i} \frac{1}{1 + \frac{1}{\mu(1+G)}\left(1 + \frac{Z_f}{Z_i}\right)} e_1 . \tag{5.6}$$

For the actual drift-stabilized amplifier which will be used, μ = 30,000 and G = 330, so that the total d-c gain $\mu(1 + G) = 10^7$. Hence it is evident that for Z_f/Z_i the order of 100 or less

$$e_2 = - \frac{Z_f}{Z_i} e_1 , \tag{5.7}$$

to a high degree of approximation.

5.3.5 Effect of Drift-Stabilizing Amplifier on D-C Unbalance

In order to assess accurately the effectiveness of the additional a-c stabilizing loop in reducing the d-c unbalance or drift, we must write down the equations for the output e_2 of the operational amplifier for zero input ($e_1 = 0$). In general, this output will not be zero, due to unbalance in the d-c amplifier proper as well as unbalance in the drift-stabilizing loop. The latter results from any a-c pickup at the chopping frequency (60 cycles in our case) coming either from the chopper contacts themselves (contact potentials), the chopper-driving coil, or the B^+ supply voltages for the a-c amplifier tubes. Since d-c is used for the filaments, no pickup should be introduced by the heaters. Any 60-cps a-c pickup gets amplified in the a-c amplifier and converted to a d-c signal before being fed back into the main operational amplifier. This d-c unbalance will be constant as long as the pickups causing it remain constant.

Let the d-c unbalance of the drift-free amplifier, referred to its input, be c volts. If e' is the input to the amplifier, then its output is $Ge' + Gc$, where G is the gain of the drift-free amplifier. Also let b volts be the d-c unbalance referred to the input of the main d-c amplifier so that its output e_2 is given by

$$e_2 = - \mu\,(e' + Ge' + b + Gc) . \tag{5.8}$$

Eliminating e' from equations (5.5) and (5.8), we have

$$e_2 = -\frac{Z_f}{Z_i}\frac{1}{1+\frac{1}{\mu(1+G)}\left(1+\frac{Z_f}{Z_i}\right)}e_1 - \left(\frac{b}{1+G}+c\right)\left(1+\frac{Z_f}{Z_i}\right). \qquad (5.9)$$

The first term above is just the output which was derived earlier in equation (5.6); the second term is the unbalance in the output because of the d-c amplifier unbalance of b volts and the drift-free amplifier unbalance of c volts (both referred to the respective inputs). For no drift stabilization (G = 0) the unbalance in the output reduces to $b(1 + Z_f/Z_i)$. The addition of the drift-stabilizing loop decreases this unbalance by a factor of 1 + G, where G is the gain of the drift-stabilizing amplifier; it also introduces an additional unbalance c due to a-c pickup which gets converted to d-c.

By increasing the gain G of the drift-stabilizing amplifier, the effect of unbalance b in the main d-c amplifier is proportionately reduced, but the unbalance c in the drift-stabilizing amplifier will not be reduced. Thus there is no advantage in making G so large that $b/(1 + G) \ll c$ for the values of d-c amplifier unbalance b normally encountered. Our experience has been that b is the order of 0.01 volt after sufficient warm-up time, while c is the order of 0.0001 volt for the drift-stabilizing circuits encountered. Evidently a value of G of 100 will reduce the drift b in the main d-c amplifier to the same order as the steady unbalance c (or 0.0001 volt). Higher values of G will reduce further the effect of drifts in b but will not change the intrinsic unbalance c. It is often feasible to adjust manually the unbalance b in the main d-c amplifier so that the net unbalance $[b/(1 + G) + c](1 + Z_f/Z_i)$ is zero at the output.

5.3.6 Drift-Stabilizing Amplifier

The circuit developed for the drift-stabilizing amplifier is shown in Fig. 5.21. The d-c input is passed through a low-pass filter before being chopped into a-c by a Leeds and Northrup Std. 3338-1 converter. The a-c input signal is amplified by a 6AU6 pentode and one-half of 12AX7 twin triode. The a-c output is reconverted to d-c by the chopper and then passed through another low-pass filter. The input and output filters are similar to those given by Vance et al. for the typhoon amplifiers. The second-half of the 12AX7 is available for additional a-c amplification of the error signal if an external indication of excess error signal is incorporated later.

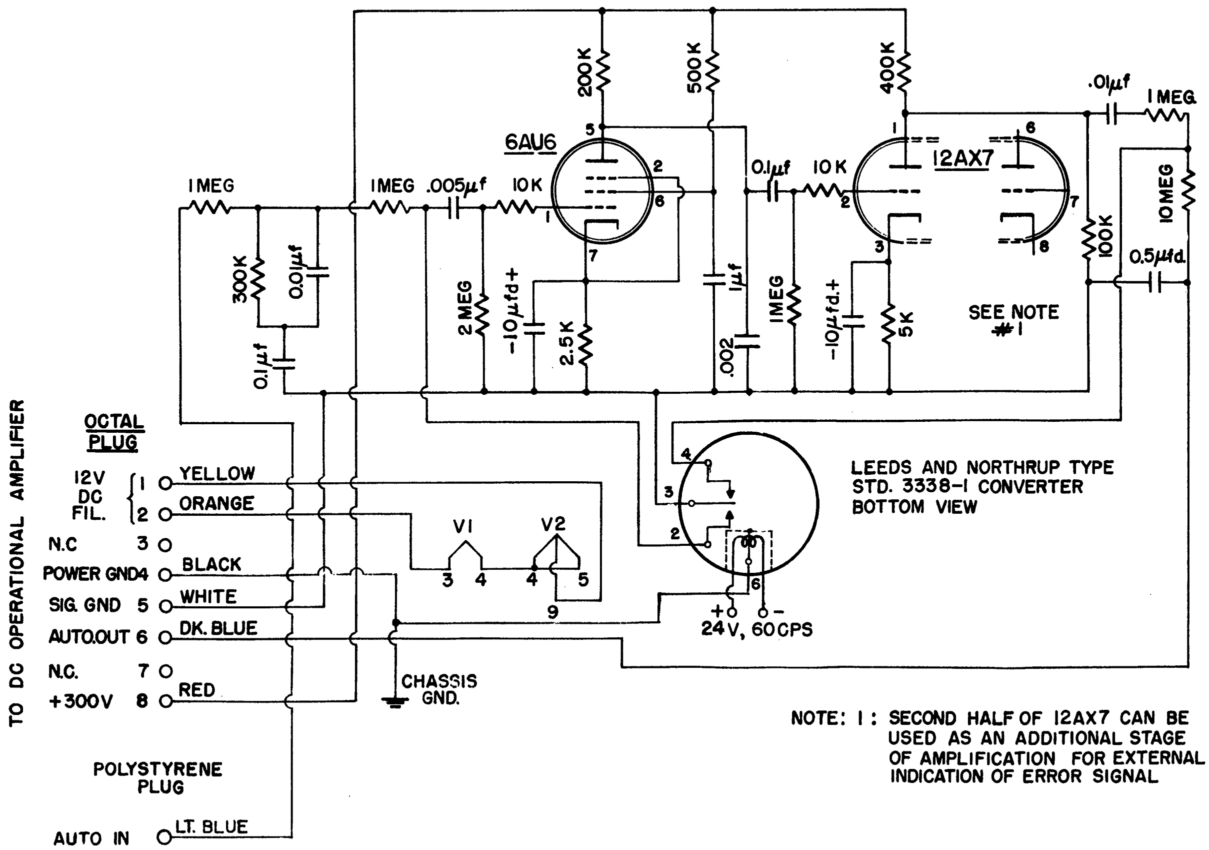


Fig. 5.21 Schematic Diagram of Drift Stabilizer

The over-all gain of the drift-stabilizing system is 330, from d-c in to d-c out. The d-c unbalance c referred to input is of the order of 0.0001 volt. The unit operates very satisfactorily with the d-c operational amplifier shown schematically in Fig. 5.18. For an operational gain of unity the unbalance in the output voltage remained within 300 microvolts of zero over a test period of 16 hours.

5.4 Oscillators

5.4.1 General

The 2-kc carrier system and the 400-cps power system are mounted in one relay rack and as such form a self-contained unit. The rack contains six chasses. On one of these are mounted both the 2-kc and 400 cps oscillators and associated control loop and driver amplifier of the former and voltage amplifier and buffer stage of the latter. On another are placed the B^+ power supplies for the above mentioned oscillators and associated units. Of the remaining four chasses, two are used to house the 2-kc power amplifier and its B^+ supply and the other two contain identical units for the 400-cps system.

There are three potentiometers located on the oscillator chassis. One is used to adjust the amplitude of the 2-kc carrier, another performs the same function for the 400-cps power and the remaining one provides a means of adjusting the amount of d-c bias supplied to the amplitude-control loop.

The power supplies which furnish the B voltages for the oscillators and associated stages are described in detail in the Power Supplies section of this report. Here only a general description will be given.

Two d-c voltages are supplied, namely, - 190 VDC and + 300 VDC. Both are regulated supplies which have good regulation and ripple characteristics. Each supply has two control potentiometers. One provides a means of adjusting the d-c output of the particular regulated supply and by means of the other control the gain of the regulation loop can be varied by adjusting the screen voltage of the amplifier tube. In addition to the above two controls, the - 190 VDC has a potentiometer which permits the magnitude of the d-c reference voltage, to the 2-kc amplitude-control loop, to be varied.

5.4.2 2-kc Voltage Supply

Due to the fact that the accuracy of the entire Wind Tunnel Data Reduction System depends directly upon the stability and accuracy of the transducer output, it is necessary that the amplitude stability of the carrier be one order of magnitude greater than the desired accuracy of the system. The type of oscillator chosen was a Wien Bridge oscillator because of its relatively great stability in amplitude and frequency. It was thought that the amplitude control of this unit would be sufficient to give the accuracy required of the equipment. However, it was decided that increased accuracy would be obtained if a closed-loop servo system were added to the 2-kc oscillator section. This would give added assurance that the over-all design accuracy of 1 per cent could be obtained. The fundamental idea in this control involves driving a triode to cut off and filtering out all frequency components but the first harmonic to yield a sine wave of good amplitude stability.

The complete system, shown as a block diagram in Fig. 5.22, accomplishes the desired amplitude stability by slicing the sine wave generated by the Wien Bridge oscillator, passing the resultant wave through a low-pass filter and amplifying the carrier to the desired amplitude and power level. The output

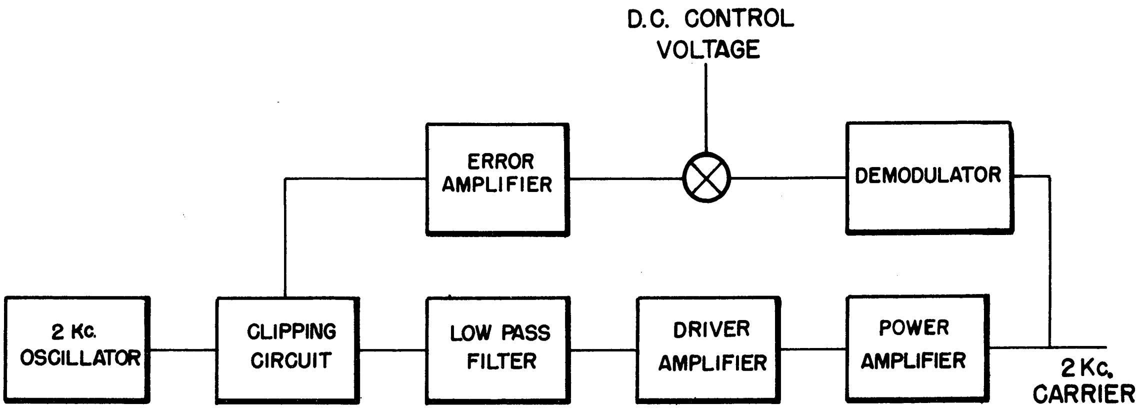


Fig. 5.22 Block Diagram of 2-kc Voltage Amplitude Control

of the power amplifier, i.e., the carrier to be applied to the transducer, is also applied to a diode-bridge rectifier through a step-down transformer and compared to a variable d-c reference. The error signal is then amplified by a d-c amplifier which governs the plate supply of the slicer, and therefore regulates the amplitude of the carrier.

The system, as constructed, is shown schematically in Figs. 9.10, 9.11, and 9.12.

The control available by full variation of a 22-1/2 volt d-c reference is better than 20 per cent of the normal operating value of the output to the transducers. In addition to this, the system was tested with the loop closed by applying a step variation of the output of the oscillator into the slicer and noting the variation of output to the transducers. These step variations were twice the normal output and half the normal output of the oscillator; they yielded no measurable variation of the output on meters that would show a 1 per cent change in the output. Variations of the 110-volt a-c power to the power amplifier B^+ supply of better than 10 per cent also yielded no variation in the output.

The results of tests have indicated that the present output transformers in the power amplifiers do not have sufficient capacitive balance with respect to ground. Future plans for this equipment include using either single capacity balanced transformers on each bridge or replacing the present output transformers with capacity balanced units.

To provide the power necessary to drive the transducers and bias networks at the proper voltage level, the power amplifier, operating class AB_2, has three push-pull parallel stages (Fig. 9.11). The three output transformers have multiple-tap secondaries which permit an impedance match to be obtained with practically any load.

The B^+ supply for this amplifier is shown schematically in Fig. 9.12. It is an unregulated power supply which furnishes B^+ power only to this power amplifier. A separate B^+ supply was employed to prevent the superposition of 2-kc on any other signal due to feedback through the power supply.

5.4.3 400-cps Power

400-cps power is used to drive the choppers and the fixed phase of the servo motors. This system has the same general circuit design as that used for the 2-kc carrier system, except that the amplitude control requirements are not as stringent and therefore a servo-control loop is not employed.

Amplitude control on the 400-cps power system is not critical because amplitude variations will affect the information channel only by reducing the sensitivity of the zero-balancing loop, thereby permitting a variation of the zero-balancing error. The sensitivity of this loop is an order of magnitude greater than that required to reduce a given error to such a value that it is well within the design accuracy. Therefore, the normal amplitude control of the oscillator is sufficient.

The over-all system is composed of a Wien Bridge oscillator, class A amplifier and buffer stage, Fig. 9.13, and a class AB_2 power amplifier (Fig. 9.11) which is identical to the one used in the 2-kc system. Again, this power amplifier has its own B^+ power supply (Fig. 9.12).

5.5 Power Supplies

5.5.1 General

A total of eight power supplies are present in the Automatic Reduction of Wind Tunnel Data system. Two of these, namely, the + 300 VDC supplies for the 2-kc and 400-cps power amplifiers have already been mentioned and therefore will not be covered here. The remaining six consist of - 190 VDC and + 300 VDC regulated supplies for the oscillators, a + 300 VDC regulated supply for the information channels and operational amplifiers, - 190 VDC and - 350 VDC regulated supplies for the operational amplifiers alone and a

+ 300 VDC unregulated supply for the servo amplifiers in the information channel. Power supplies for the information channels and operational amplifiers occupy one relay rack and the associated regulation circuits are located in the control relay rack. The regulation circuits were not placed in the power supply rack to eliminate the effects of radiation from the power supplies upon the regulation system.

After considering the voltage regulation requirements of the system, it was decided that super-regulation was not needed in the + 300, - 350 and - 190 VDC supplies, since the signal amplifier is operated with a relatively large amount of negative feedback, the cathode follower is relatively insensitive to B^+ fluctuations and the d-c operational amplifier is drift stabilized. Therefore just an A regulation loop - voltage-regulating tube reference - is used in the B^+ supplies of the above mentioned components. Variation of the B^+ voltage of the servo amplifier will simply cause the sensitivity of the balancing system to vary. This will not greatly affect the balancing of the system; therefore, the B^+ voltage for the servo amplifiers has no regulation except that provided by a choke-input filter located at the output of the power supply.

All of the power supplies are equipped with the proper fuses, each of which has a neon lamp in parallel with it. If any fuse should burn-out, due to overload, the neon lamp in parallel with that particular fuse will be lighted, indicating the destroyed fuse. In addition to the fuses, the - 190, - 350 and + 300 VDC regulated and the + 300 VDC unregulated supplies have overload relays, which are set to open the particular circuit when the current exceeds the value for which that power supply was designed. The particular overload relay that has been energized by an overload is indicated by a light on the Master Control Panel. Adjacent to this light is a reset button for the overload relay.

5.5.2 <u>+ 300 VDC Regulated Power Supply</u>

The + 300 VDC regulated power supply is shown schematically in Fig. 9.15. It was designed to supply a maximum current of approximately 700 ma at 300 volts d-c. The basic power supply and first filter stage occupy one chassis in the power supply relay rack; the second filter stage, which was added when it was found that the ripple characteristics were undesirable, occupies another chassis in the above mentioned rack. The regulation chassis is located in the control rack. The latter chassis contains the control for adjusting the magnitude of the d-c output.

The characteristics of this power supply, when set to give rated voltage with a load of 500 ma, are given in Table A. (110 volts, 60-cps line)

TABLE A

Characteristics of + 300 VDC Regulated Supply

LOAD (ma)	ERROR (VDC)	RIPPLE (mv RMS)
150	+ 1.82	9.5
200	+ 1.59	9.5
250	+ 1.23	9.5
300	+ 1.00	9.0
350	+ 0.71	9.0
400	+ 0.49	9.0
450	+ 0.26	9.0
500	0	10.0
550	- 0.35	10.0
600	- 0.81	12.0
650	- 1.30	15.0
700	- 1.88	20.0

It was found that, with the supply set to give 700 ma at 300 VDC, the output voltage was regulated to within - 2 VDC for all line voltages above 105 VAC.

5.5.3 + 300 VDC Unregulated Power Supply

The + 300 VDC unregulated power supply is shown schematically in Fig. 9.17. It was designed to supply a maximum current of approximately 1.5 amperes at + 300 volts d-c. The power transformers are located on one chassis in the power supply rack and the rectifier tubes and filter section are located on another chassis in the same rack. To provide the proper voltage output several bucking transformers have been placed in series with the primary windings of the power transformers.

The characteristics of this power supply are given in Table B. (110 volts, 60-cps line)

TABLE B

Characteristics of + 300 VDC Unregulated Supply

LOAD (ma)	OUTPUT (VDC)	RIPPLE (volts RMS)
400	358	4.2
600	345	4.3
800	332	4.4
1000	317	4.5

It may appear that the ripple content is quite high. This may be true for most applications, but in this case, where only a servo motor is driven by the output of an amplifier, a ripple of only approximately one per cent on the B^+, supplying the amplifier will not influence the operation of the system.

5.5.4 - 190 VDC Regulated Power Supply

This power supply is shown schematically in Fig. 9.16. It was designed to furnish rated voltage at a maximum current of approximately 450 ma d-c. The basic power supplies of the - 190 and - 350 VDC systems occupy one chassis together in the power supply rack and the regulation circuits for these two supplies jointly occupy one chassis in the control rack. On the regulation chassis is a control to vary the magnitude of the d-c output.

Table C gives the characteristics of this power supply when set to furnish - 190 VDC with 300 ma load. (110 volts, 60-cps line)

TABLE C

Characteristics of - 190 VDC Regulated Supply

LOAD (ma)	ERROR (VDC)	RIPPLE (mv RMS)
100	+ 1.00	11.0
150	+ 0.70	17.0
200	+ 0.45	16.0

TABLE C (continued)

LOAD (ma)	ERROR (VDC)	RIPPLE (mv RMS)
250	+ 0.20	14.0
300	0	13.0
350	- 0.30	12.0
400	- 0.55	15.0
450	- 0.80	23.0

This power supply will regulate the output to within - 2 volts d-c of rated voltage at maximum load current for all line voltages above 90 VAC.

5.5.5 - 350 VDC Regulated Power Supply

The - 350 VDC regulated power supply is shown schematically in Fig. 9.16. It was designed to supply a maximum current of 100 ma at a rated voltage of - 350 VDC. As mentioned above, the basic power supply occupies one chassis of the power supply rack jointly with the - 190 VDC supply; and one chassis of the control rack is occupied jointly by the regulation circuits of these basic supplies. As in the previously mentioned power supplies, the control for varying the magnitude of the d-c output, is located on the regulation chassis.

Since the power required by the d-c operational amplifiers at - 350 VDC is very small, a fixed resistive load was placed across the output of the - 350 VDC supply. This load is of such a magnitude that a fixed current of approximately 50 ma will be drawn from the supply at all times, thereby placing the operating point of this power supply in a region where desirable characteristics are obtained.

Table D gives the characteristics of this power supply when it is set to furnish the rated voltage of - 350 VDC at a current load of 50 ma. (110 volts, 60-cps line)

TABLE D

Characteristics of - 350 VDC Regulated Supply

LOAD (ma)	ERROR (VDC)	RIPPLE (mv RMS)
15	+ 0.55	3.0
20	+ 0.45	2.9
25	+ 0.35	2.8
30	+ 0.30	2.8
35	+ 0.25	2.7
40	+ 0.20	2.7
45	+ 0.10	2.7
50	0	2.6
55	- 0.05	2.6
60	- 0.10	2.6
65	- 0.15	2.7
70	- 0.25	2.7
75	- 0.35	2.7
80	- 0.40	2.8
85	- 0.50	2.8
90	- 0.55	2.9
95	- 0.60	3.0
100	- 0.65	3.0

This power supply will furnish 50 ma load current at a voltage which remains within - 1 VDC of the rates voltage of - 350 VDC for all line voltages above 80 VAC.

5.5.6 + 300 VDC Regulated Power Supply for Oscillators

The schematic diagram of this regulated power supply is given in Fig. 9.18. This supply was designed to furnish a maximum current of 120 ma at the rated voltage of + 300 VDC. The basic power supply and regulation circuit of this unit and the - 190 VDC supply occupy one chassis in the oscillator relay rack. Two control potentiometers are furnished. One controls the screen voltage of the d-c amplifier tube and therefore is a gain adjustment for the amplifier section of the regulator. This control is valuable for minimizing the ripple for a particular current load on the power supply. The other control provides a means of setting the d-c output of the power supply to the desired value. This is accomplished by adjusting the bias voltage on the control grid of the amplifier section.

Table E gives the operating characteristics of this power supply when it has been adjusted to furnish 75 ma at the rated voltage of + 300 VDC. The screen grid voltage was 100 VDC with respect to the cathode. (110 volts, 60-cps line)

TABLE E

Characteristics of + 300 VDC Regulated Supply for Oscillators

LOAD (ma)	ERROR (VDC)	RIPPLE (mv RMS)
40	+ 0.28	1.7
50	+ 0.18	1.8
60	+ 0.08	1.9
70	+ 0.03	1.9
75	0	1.9
80	- 0.02	1.9
90	- 0.02	1.9
100	- 0.02	2.0
110	- 0.02	2.0
120	- 0.03	2.0

This power supply will furnish a load current of 100 ma at a voltage which remains within - 1 VDC of the rated voltage of + 300 VDC for all line voltages above 100 VAC.

5.5.7 - 190 VDC Regulated Power Supply for Oscillators

This regulated power supply is shown schematically in Fig. 9.18. It was designed to furnish a maximum current of 70 ma at the rated voltage of - 190 VDC. As mentioned above, the basic power supply and regulation circuit of this unit and the + 300 VDC supply occupy one chassis in the oscillator relay rack. Two control potentiometers are located in the circuit. One controls the gain of the d-c amplifier section, by controlling the screen grid voltage, and the other controls the magnitude of the d-c output of the power supply by adjustment of the d-c bias on the control grid of the d-c amplifier section. A third potentiometer provides a means of varying the magnitude of the d-c reference voltage supplied to the amplitude-control loop of the 2-kc system.

Table F shows the operating characteristics of this power supply when it has been set to furnish 50 ma at the rated voltage of - 190 VDC. The screen voltage was 81 VDC with respect to the cathode - the value which provided minimum ripple. (110 volts, 60-cps line)

TABLE F

Characteristics of - 190 VDC Regulated Supply for Oscillators

LOAD (ma)	ERROR (VDC)	RIPPLE (mv RMS)
25	+ 0.26	0.54
30	+ 0.20	0.54
35	+ 0.15	0.55
40	+ 0.11	0.60
45	+ 0.04	0.65
50	0	0.70
55	- 0.04	0.85
60	- 0.11	1.00
65	- 0.23	1.60
70	- 0.48	5.00

This power supply furnished 70 ma at a voltage which remained within - 1 VDC of the rated voltage of - 190 VDC for all line voltages above 100 VAC.

5.6 Controls

5.6.1 General

In designing this equipment, considerable effort was exerted to minimize the number of adjustments necessary to place the system into operation. At the same time, simplicity and safety were incorporated to the highest possible degree. In general, control simplicity, circuit simplicity and foolproofness are not compatible. Simple controls do not necessarily imply simple circuitry and the same holds true for foolproofness and circuit simplicity. Realizing these facts, the design of this computer system incorporated what was believed to be the best compromises of the three above mentioned factors whenever compromise was necessary.

In addition to the above considerations, an attempt was made to centralize the controls as much as possible. This led to the construction of the Master Control Panel which is described in Section 5.6.5. This panel is contained in the Control Rack which as a unit contains all the voltage controls except those of the oscillators. For a particular test configuration, the initial alignment of the system may involve several additional adjustments which when set should not have to be touched again until the test configuration is changed. These adjustments consist of B^+ voltage corrections, correction of the 2-kc carrier and 400-cps power voltages for the number of information channels being used and null adjustments of the sensing elements. In addition to these, the gain of each signal amplifier must be set to the desired value and the phase of the bias voltage must be made to coincide with that of the amplitude-modulated carrier. After the above steps have been taken the system can be balanced automatically by means of the servo-balancing loop in each information channel.

The d-c operational amplifiers contain the drift-stabilizing amplifier which greatly reduces any unbalances, but they should be manually balanced periodically to minimize the error due to d-c unbalance.

5.6.2 Power Supply Controls

The power supply controls consist of potentiometers located on the respective voltage regulation chassis. As previously mentioned in Section 5.5, these potentiometers provide a means of adjusting the d-c voltage output of the power supply to the desired value. In addition to this control, each of the power supplies for the oscillators has a potentiometer which varies the gain of the d-c amplifier section of the voltage regulator and thereby provides a means of minimizing the ripple on the d-c output.

Located on the Master Control Panel are d-c voltmeters and d-c ammeters, which indicate the output voltage and load current, respectively, of each of the main power supplies. These meters provide a means of conveniently monitoring all the voltages supplied to the information channels and the d-c operational amplifiers.

Another control on all the power supplies, except the power supplies for the oscillators, is an overload relay. The potentiometer associated with the overload relay can be set so that the d-c voltage circuit from the respective power supply will be opened if the current in the circuit exceeds a predetermined value. These relays are located in the junction box and have been set so that they will be energized by magnitudes of current slightly below the rated maximum currents of the respective power supplies.

The four overload relays incorporated in the system are interconnected such that an overload on any one of the main power supplies immediately disconnects all the B supply voltages from every unit in the entire system except the oscillators. The particular power supply that has been overloaded is indicated by a light on the Master Control Panel. Adjacent to this light is a button for remotely resetting the overload relay.

5.6.3 Oscillator Controls

The two oscillator-amplitude controls are located on the oscillator chassis. The 400-cps voltage is adjusted by a gain-control potentiometer in the grid circuit of the voltage amplification stage.

The amplitude of the 2-kc voltage is adjusted by a potentiometer setting the d-c control voltage. This voltage controls the clipping level of the 2-kc slicer. A gain potentiometer is located in the grid circuit of the voltage amplification stage. This control has the effect of increasing or decreasing the regulation sensitivity.

5.6.4 Information Channel Controls

On the information channel chassis are mounted two potentiometers. One allows the gain of the signal amplifier to be varied and the other shifts the phase of the 2-kc bias carrier with respect to the 2-kc signal carrier. Viewing the chassis from the power-plug end, the gain control is located on the right and the phase-shift control on the left, adjacent to the power plug. Both controls are screwdriver adjustments and are accessible through holes in the front panels of the Information Channel rack.

The remaining controls associated with the information channels are located in the adapter box for the strain-gage bridges and on the sensing elements themselves in the case of pressure measurements. In the adapter box, a potentiometer provides a means of manually balancing the bridge to bring the unbalance within the range of the automatic-balancing system. In addition to this, one or two variable condensers may be installed to compensate for capacitive unbalance in the sensing element and associated leads. Any capacitive unbalance introduces a signal which is 90 degrees out of phase with the carrier. Therefore, the output of the bridge is the vector sum of the applied signal and that produced by the capacitive unbalance. Unless eliminated this introduces the difficulty of attempting to adjust the phase of the bias carrier correctly for all magnitudes of input signal, because the phase of the bridge output varies slightly for different signal magnitudes and the bridge cannot be balanced. Hence, the amplitude-modulated carrier is not always either in phase or 180 degrees out of phase with the bias carrier. This results in a rather complicated summation of the two carriers.

At this point it might be mentioned that with the present 2-kc signal carrier system additional controls must be employed to manually balance the transducer.

First, a Wagner ground must be used to center-tap the signal carrier to ground and secondly an additional capacitive balance must be employed to eliminate the capacitive unbalance in the output transformer. In the present design these controls are located in the adapter box.

5.6.5 Master Controls

After the controls mentioned above have been adjusted to their proper settings, all remaining controls used to operate the entire system are located on the Master Control Panel. These controls consist of three switches and an automatic time delay relay.

The "Start" switch controls a mercury relay which in turn switches line voltage to the power supplies, oscillators and filament transformers. To allow the tubes in the information channels and operational amplifiers sufficient time to become warm before the B supply voltages are applied, a time delay relay, which operates on 6 VAC, is placed in series with the B supply voltage switch. The B supply voltage switch is called the "Operate" switch. This switch and the time delay relay control the operation of the 4-pole "Operate" relay, which has one set of contacts in the output circuit of each of the main power supplies. With this system, the minimum length of time between the application of filament voltages and B supply voltages is approximately 60 seconds.

Also in series with the "Operate" switch and time delay relay are the contacts of each of the power supply overload relays. This arrangement, shown in Fig. 9.19, provides a means of disconnecting all the B supply voltages when one of the power supplies is overloaded.

The "Balance" switch activates a double-pole relay which in turn switches the B^+ voltage to the servo amplifier and the 400 cps to the fixed phase of the servo motor. The B^+ side of this relay is in series with the "Operate" relay, therefore the automatic balancing system cannot be energized unless both the "Operate" and "Balance" relays are actuated.

To indicate when the "Start" switch, time delay relay, "Operate" relay and "Balance" relay have been actuated, lights have been provided on the Master Control Panel. In the cases of the above mentioned relays, the lights are not energized by the respective switches but by the relays themselves.

5.6.6 Operational-Amplifier Controls

The only control located in an operational amplifier is the d-c balance control. By means of this control the d-c output of the amplifier can be brought to zero when the input is grounded thereby eliminating any extraneous voltages originating within the amplifier itself.

In reality, this control consists of two potentiometers. One potentiometer, the coarse-balance control, is located on top of the amplifier chassis and the second potentiometer, the fine-balance control, is located on the front face of the amplifier chassis and projects through the rack panel when the amplifier is placed in position. In order to provide a convenient method of balancing each of the operational amplifiers in a particular relay rack, an output socket is located on the top left-hand corner of the front of the relay rack and a push-button switch is located in the rack panel face plate of each amplifier. To balance an amplifier, the button is pressed and the output voltage is adjusted to zero volts by means of either of the controls mentioned previously. The output voltage can be observed by connecting a voltmeter between the output socket and ground.

The push-button switch energizes the relay mentioned in Section 5.3.3. When the relay is closed the amplifier has a gain of 40, hence, the actual unbalance in an amplifier is less than that appearing on the output by a factor of 40.

6. OPERATING PROCEDURE

6.1 Assembly of Components

The present Computer for Automatic Reduction of Wind Tunnel Data was designed such that each chassis had a specific location in a particular relay rack. Below is given the location of each chassis of the computer. In the case of each relay rack the chassis as listed are located from top to bottom, respectively.

Following this is given the procedure recommended for placing the computer into operation. It is believed that the procedure as given should be strictly adhered to in order that the possibility of damaging the equipment be reduced to a minimum.

6.1.1 Location of Chasses

a) Power-Supply Rack (See Fig. 5.4)

1) - 190 VDC and - 350 VDC Power Supplies
2) Second Section of 300 VDC Unregulated Power Supply
3) Second Filter Section of 300 VDC Regulated Power Supply
4) 300 VDC Regulated Power Supply
5) First Section of 300 VDC Unregulated Power Supply

b) Oscillator Rack (See Fig. 5.3)

1) 2-kc Power Amplifier
2) 2-kc and 400-cps Oscillators
3) 400-cps Power Amplifier
4) Oscillator Power Supplies

5) Power Supply for 400-cps Power Amplifier

6) Power Supply for 2-kc Power Amplifier

c) Information Channel Rack (See Fig. 5.2)

1) Five Shelves of Two Information Channels Each

2) Impedance Matching Condensers for 400-cps Power

d) Master Control Rack (See Fig. 5.5)

1) Junction Box

2) Master Control Panel

3) Information Channel Output Monitoring Panel

4) 300 VDC Regulation

5) - 190 VDC and - 350 VDC Regulation

6) 6 VAC Supply

e) Operational Amplifier Rack (See Fig. 5.6)

1) Four Operational Amplifiers

2) Resistor Selection Panel

3) Four Operational Amplifiers

4) Resistor Selection Panel

6.1.2 Cable Assembly

a) Chassis Connections

When the computer is assembled as indicated above, the necessary chassis connectors are conveniently located at the rear of each shelf. These connectors provide all the required inter-chassis connections for proper introduction of the various components into the computer.

b) Inter-Rack Cabling

At the top of each relay rack suitable connectors are provided to permit proper interconnection of relay racks.

Fig. 9.20 indicates the inter-rack connections and therefore serves as a guide when assembling the computer.

6.2 Operating Instructions

1) With all Information Channels in place, insert a dummy load plug into the signal input socket of each channel.
2) Connect output of each Information Channel to appropriate socket on the Monitor Panel by means of leads provided.
3) Supply the system with at least 110 VAC, preferably 115 VAC, from a source capable of supplying a minimum of 20 amperes.
4) Place "Start" switch on "On" position. "Ready" light must be energized by time delay relay before operating procedure can be continued.
5) Observe meters on Oscillator rack for possible overload condition.
6) Place "Operate" switch in "On" position.
7) Observe meters on Master Control Panel for possible overload condition.
8) Adjust d-c voltages to proper values by means of controls on respective regulation chassis.
9) Adjust 2-kc Bias voltage to 100 volts. While making this adjustment observe milliammeters on face of 2-kc power amplifier chassis. These meters should have nearly identical readings. If this is not the case, check bias batteries and output tubes of driver amplifier located on oscillator chassis.
10) Place "Balance" switch in "On" position.
11) Maximized 400-cps voltage by means of control on oscillator chassis. While making this adjustment observe milliammeters on face of 400-cps power amplifier chassis. If meters do not have nearly identical readings carry out investigation indicated in Step 9.
12) Observe lights on face of Information Channel rack. If all are not extinguished, indicating balance, check unbalanced channels for possible defects.

13) Return "Balance" switch to "Off" position.

14) Having determined impedance of transducers, insert equivalent dummy load across 2-kc voltage contacts in signal input socket. Then select appropriate winding of output transformer in the 2-kc power amplifier to produce the desired voltage across the dummy load .

15) After the entire system has been energized for several hours recheck all voltages. It is suggested that the d-c regulated voltages be adjusted using a well-calibrated voltmeter. The wave shape of the 2-kc voltages should also be investigated by means of an oscilloscope.

16) Assign each of the transducers to a specific channel and align each of these channels in the manner described in the following steps.

17) Remove the Information Channel from its position in the rack and attach the test-power cable provided. Connect the appropriate transducer to the channel.

18) Connect the output of the signal amplifier to the vertical axis of a cathode-ray oscilloscope. Connect the output of the cathode follower in the phase-shift network to the horizontal axis of the oscilloscope.

19) Manually adjust the balance of the transducer so that the output of the amplifier is a minimum. The gain of the amplifier should be adjusted to maximum gain.

20) If the previous step does not produce a satisfactory null, the transducer undoubtedly will have to be capacitively balanced also. Directions for doing this can be found in any text on electrical measurements.

21) Having obtained a satisfactory balance manually, a small fixed positive signal is applied to the transducer. Then observing the Lissajous figure on the oscilloscope, the phase-shift control is adjusted to the position at which the bias and signal carriers are exactly in phase.

22) Apply positive and negative signals to the transducer. If the Lissajous figure remains closed for all signals the transducer system is capacitively balanced.

23) Return the Information Channel to its position in the rack.

24) In general, the gain of each channel should be as large as permissible within the linear range of the system. In the case of force-moment measurements on a sting, the channel, in which the maximum signal input is anticipated, should be adjusted to the maximum allowable gain permitted by the linear range of the channel. All other channels will then have gain settings approximately equal to that of the channel of maximum signal and exactly determined by the calibration of the wind tunnel balance system. The voltage output of each channel will be proportional to the moment at the corresponding station on the sting. This constant of proportionality must be identical for all channels. In the case of pressure measurements the same general procedure is followed. The channel having maximum input signal should be adjusted to maximum allowable gain. Since there may be a relatively wide range of pressures in a given test configuration, channels having relatively low signal inputs may require additional gain to produce outputs which lie within the upper region of their respective linear ranges. In general, an attempt should always be made to keep all output signals within the top half of the linear range of the channels. Regardless of the type of transducer being used, the gain of any channel may be increased if it is believed that the signal level is too low. In such cases, the gain of the Information Channels should be increased by integral values so that the gain of the operational amplifiers receiving signals from these channels can be conveniently reduced by the same factors.

25) Connect a vacuum-tube voltmeter to the balance output socket in the Operational Amplifier rack.

26) Balance each of the operational amplifiers by pressing the button and adjusting the position of the potentiometers. (See Section 5.6.6)

27) Having aligned all the Information Channels to be used, connect the output of each to the appropriate terminal on the Monitor Panel.

28) Place the "Balance" switch in the "On" position.

29) Check balance of each channel by means of meter on the Monitor Panel.

30) Return "Balance" switch to "Off" position.

31) Set up desired computing problem on operational amplifiers.

32) Apply input signals to operational amplifiers by connecting between the Monitor Panel and appropriate terminals on the operational amplifiers.

33) It is suggested that the balance of the information channels and operational amplifiers be checked periodically.

34) To secure the entire unit return the "Operate" and "Start" switches to the "Off" position in the order mentioned.

7. CONCLUSIONS

The Computer for Automatic Reduction of Wind Tunnel Data, in its present form, will perform the operations indicated in Section 2. The major problem solved was the accurate and reliable transformation of a physical measurement into an equivalent d-c voltage. Utilization of this d-c voltage in the application of analogue techniques permits the desired computations to be made.

Improvements can be made on the present prototype model. These improvements, in general, would enhance the operating characteristics of the system. The present system appears to be feasible in all respects when performing the tasks for which it was designed.

The use of analogue computing techniques is conveniently applicable to wind tunnel testing. Accuracies of approximately 1 per cent are readily obtained. Extremely accurate test and computational equipment is always desired, but there must be a balance. This balance should consider cost; time required to attain this accuracy; errors introduced into the over-all system, starting with transducers and basic theory and ending with the method of recording; and last but not least, the accuracy required of the results. Such a balance is obtained in the present equipment.

Complete operational tests have not been completed. Linearity and repeatability tests are being conducted at the present time with promising results. The results will be published at some future date.

Success in the present phase of data reduction has resulted in the belief that additional effort should be exerted to utilize this system in dynamic investigations. Frequencies below 500 cps can be handled with the same ease as steady-state conditions, the only limitations being those of the recording system. Extensive advances may be possible in experimental dynamic testing by the use of this system.

It is felt that additional effort should be expended in completely evaluating the system as a whole and determining the extent to which it can be utilized by installations other than wind tunnels. In this way interest will be cultivated with the result that applications, not evident at the present, may be introduced. The initial step has been taken; now it is a matter of perfecting and expanding the techniques.

8. RECOMMENDATIONS

In the process of placing the computer into operation, it was discovered that a number of desirable modifications could be incorporated in the present system. These modifications would not only improve the operation of the computer but also facilitate an easier and more rapid alignment for any particular test configuration. Before the present computer is employed in any extensive program it is strongly recommended that at least some of the following alterations be made. The order in which the recommended changes are given is considered as the order of importance of these alterations.

1) The present method of supplying 2-kc voltages to the bias circuit and the transducer can be greatly improved in the following manner. A single 2-kc voltage should be supplied to each Information Channel. This voltage should come directly from the power amplifier and have the amplitude required by the bias circuit, approximately 100 volts peak. To supply the transducers, an additional transformer should be located in each Information Channel. It will act as an isolation transformer and possess a turns ratio such that the proper voltage is supplied to the transducer. It should be electrostaticly shielded and have a capacitively balanced secondary winding. In addition to these requirements it may have a number of secondary taps to accommodate transducers of various impedances.

   In addition to the above, it is suggested that approximately 20 db of negative feedback be fed from the secondary of the 2-kc power output transformer to the input stage of the driver amplifier. This feedback around the driver and power amplifiers will aid in reducing any fluctuations in the 2-kc voltage due to changes in load or in the operating characteristics of the amplifiers themselves.

2) To improve the method of adjusting the phase-shift network it is suggested that several test points be installed on the rear face of each information channel chassis. One of these test points would provide a means of monitoring the output of the cathode follower in the phase-shift network. Another would be connected to the output of the signal amplifier. The third would be at ground potential. By means of these test points an oscilloscope and voltmeter could be used to align the channel without removing it from its position in the relay rack.

3) The gain control now used in the signal amplifier is a linear potentiometer. Since the gain of the amplifier does not vary linearly with position of the potentiometer, it would be advantageous to replace the present potentiometer with one whose resistance varies nonlinearly, i.e., a tapered potentiometer. Utilization of a tapered potentiometer would allow the gain to be adjusted more easily.

4) To eliminate all 400-cps voltage from the Information Channels when they are not balancing, it is recommended that the existing DPST "Balance" relay be replaced by a 3PST relay. The 400-cps output transformer is center-tapped to ground, therefore both sides of the 400-cps line should be broken when power is to be removed from the chasses. If this is not done a 400-cps voltage will still be developed in the Information Channels between the unbroken side of the line and ground.

   If a more extensive modification proves feasible, it is recommended that instead of breaking both sides of the 400-cps line the B^+ voltage be removed from the 400-cps power amplifier. This would completely eliminate the presence of any 400-cps voltages thereby removing the possibility of introducing pickup from this source into the signal channel. One half of the present DPST relay could operate another relay in the power amplifier chassis. The latter relay would then switch the B^+ voltage to the amplifier.

5) The present adaptor box is somewhat cumbersome and also does not fulfill all the requirements that it should. For example, in the present system no provision is made for capacitively balancing a differential transformer. This may be very necessary in some applications, hence it should be incorporated in each information channel.

Using the present Information Channel chasses, a box similar to the present one would be attached to the near face of each chassis. Within the box would be two circuits, one for a resistive transducer the other for a reactive transducer. On the exterior of the box would be mounted a socket for each circuit and appropriate components for manually balancing the transducer of each circuit.

If additional Information Channels are constructed in the future, it is suggested that a larger chassis be used. This would permit the adaptor box to be eliminated and its contents to be placed within the channel chassis.

6) It is believed that the present maximum output of the cathode follower in the phase-shift network may not be adequate for all applications. This output at present cannot be increased beyond approximately 100 volts without the wave form becoming distorted. Therefore if the bias voltage should prove to be inadequate it is recommended that - 190 VDC be supplied to the lower end of the cathode resistor in the cathode follower circuit. Of course, the value of this cathode resistor will have to be changed due to the added voltage drop across the circuit.

The additional pin in the power plug required to do the above would be available as a result of the first modification.

7) The characteristics of the Information Channel could be improved by replacing the summing transformers. Three such transformers are located in each Information Channel. Each of the present transformers has available two secondary windings which provide voltage ratios of 5:1 and 5:2. In the present system the signal is attenuated by a factor of five between the signal amplifier and the rectifier. This attenuation was used because of the ratings of the rectifier. Recently it was learned, from the manufacturer of these units, that for the present application the maximum a-c voltage supplied to the rectifiers could be 50 volts RMS without damaging the units. In view of this it is suggested that the present summing transformers be replaced by 2:1 transformers. The advantages gained in doing this would be the result of an increased d-c output for a given signal and gain setting on the signal amplifier. Also with less attenuation after the signal amplifier,

for a given signal and d-c output, the amplifier could be operated with more negative feedback thereby improving its characteristics.

Since the maximum gain of the signal amplifier would not have to be as great as before, the amplifier could be altered in such a manner that the minimum negative feedback would be approximately 20 db. This could be accomplished by placing a fixed resistor between the lower end of the gain potentiometer and ground.

8) To expedite the alignment of the computer for a particular application it is strongly recommended that all transducers be approximately balanced, resistively and reactively, before their initial use with the computer. Elimination of large unbalances in the transducers will greatly reduce the effort exerted in setting up the computer.

9. ADDITIONAL FIGURES

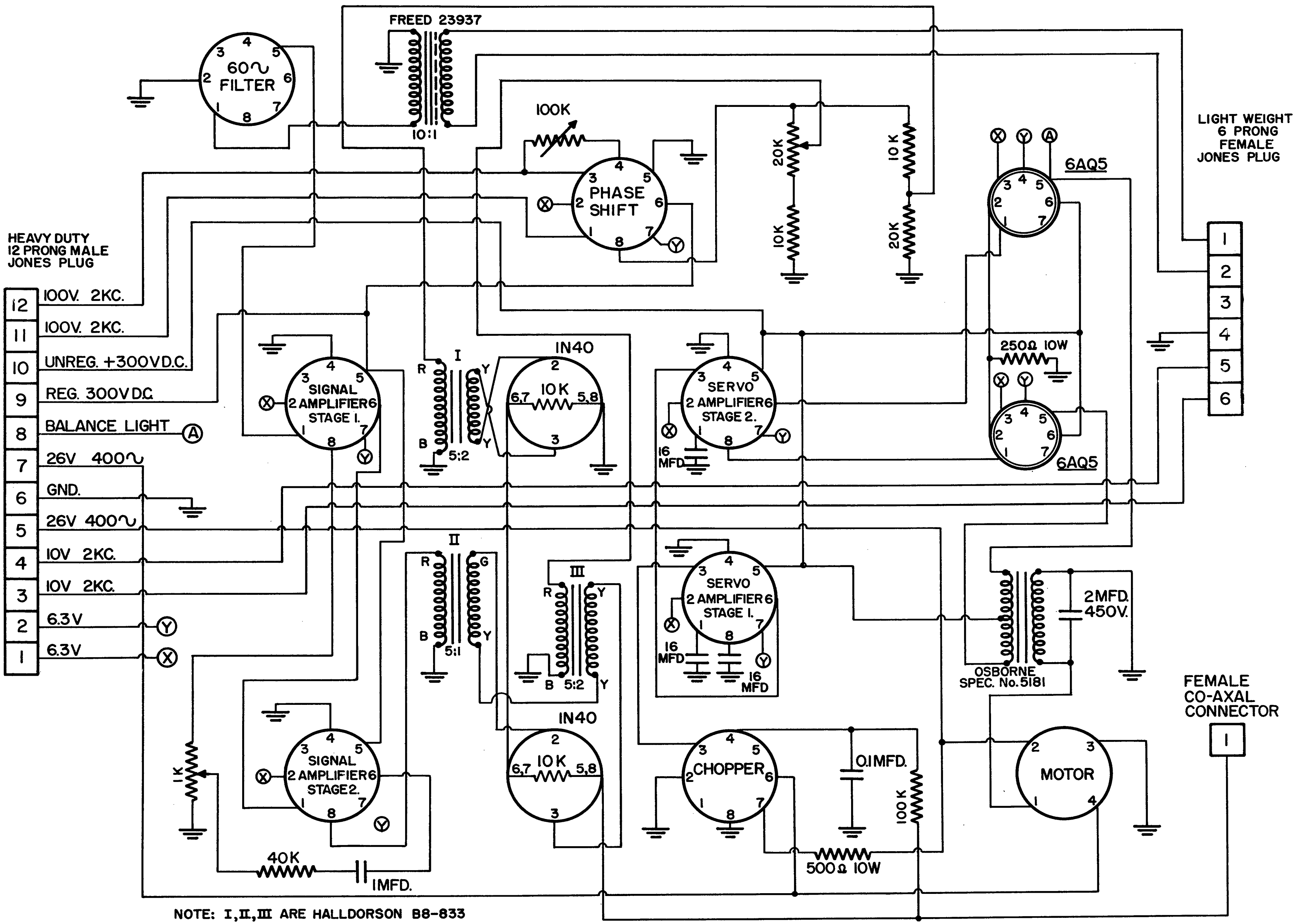


Fig. 9.1 Schematic Diagram of Information Channel

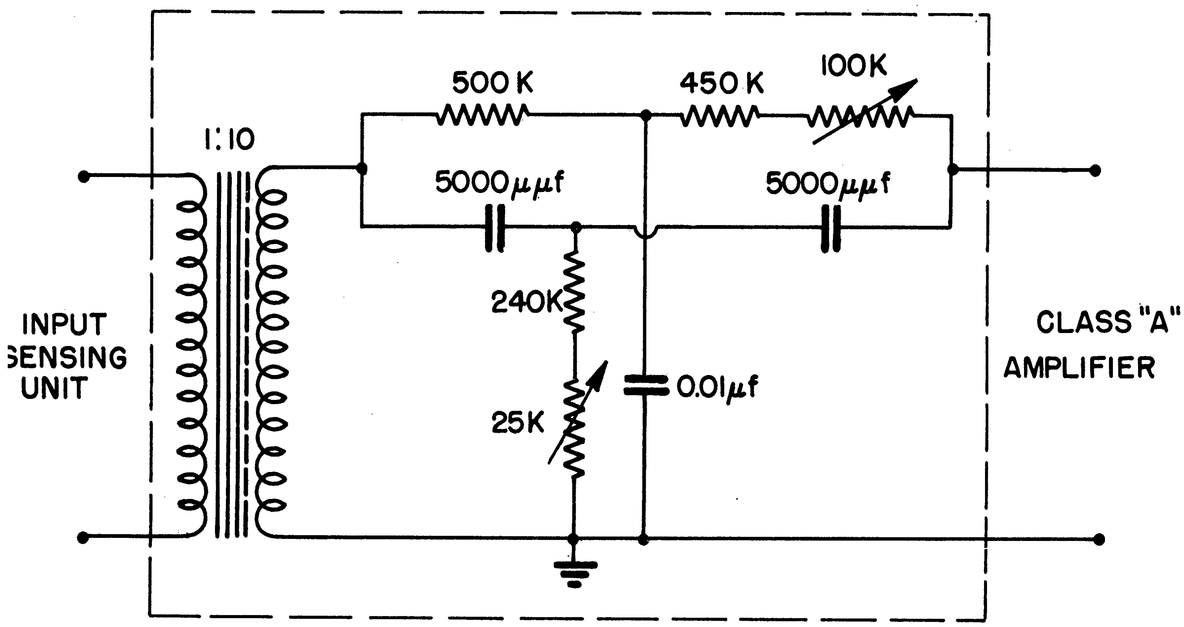


Fig. 9.2 Schematic Diagram of 60-cps Filter

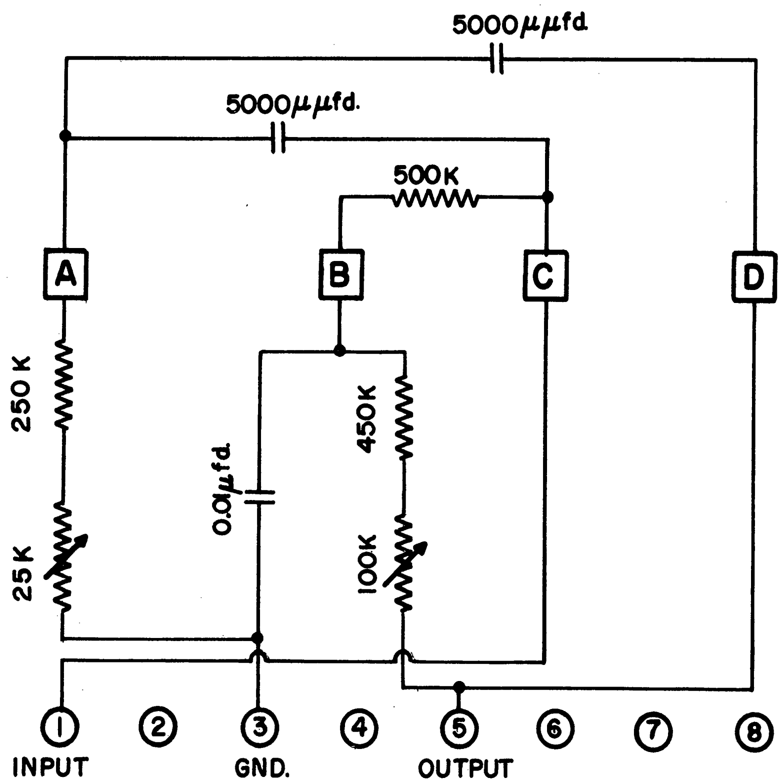


Fig. 9.3 Vector Can Layout of 60-cps Filter

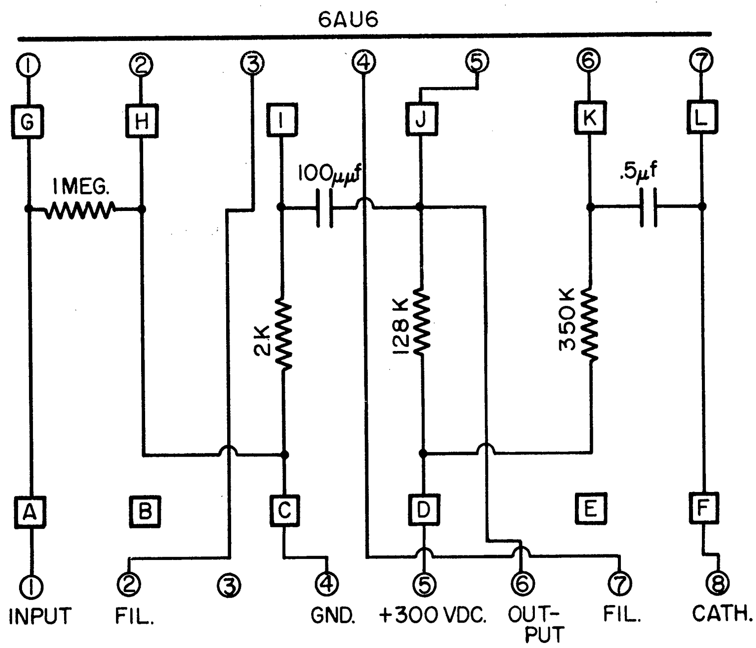


Fig. 9.4 Vector Can Layout of First Stage of Signal Amplifier

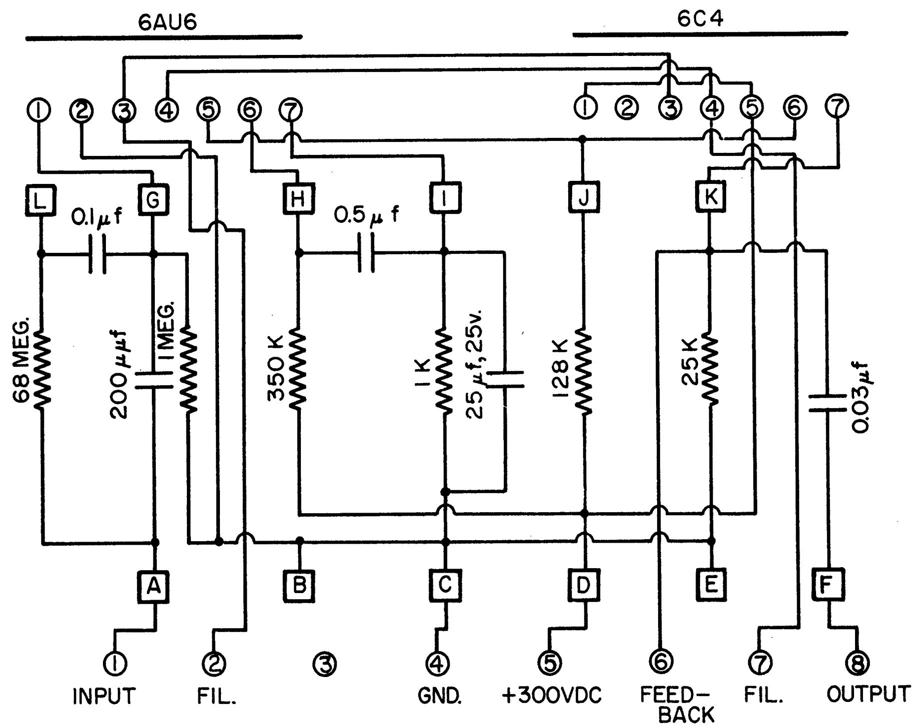


Fig. 9.5 Vector Can Layout of Second Stage of Signal Amplifier

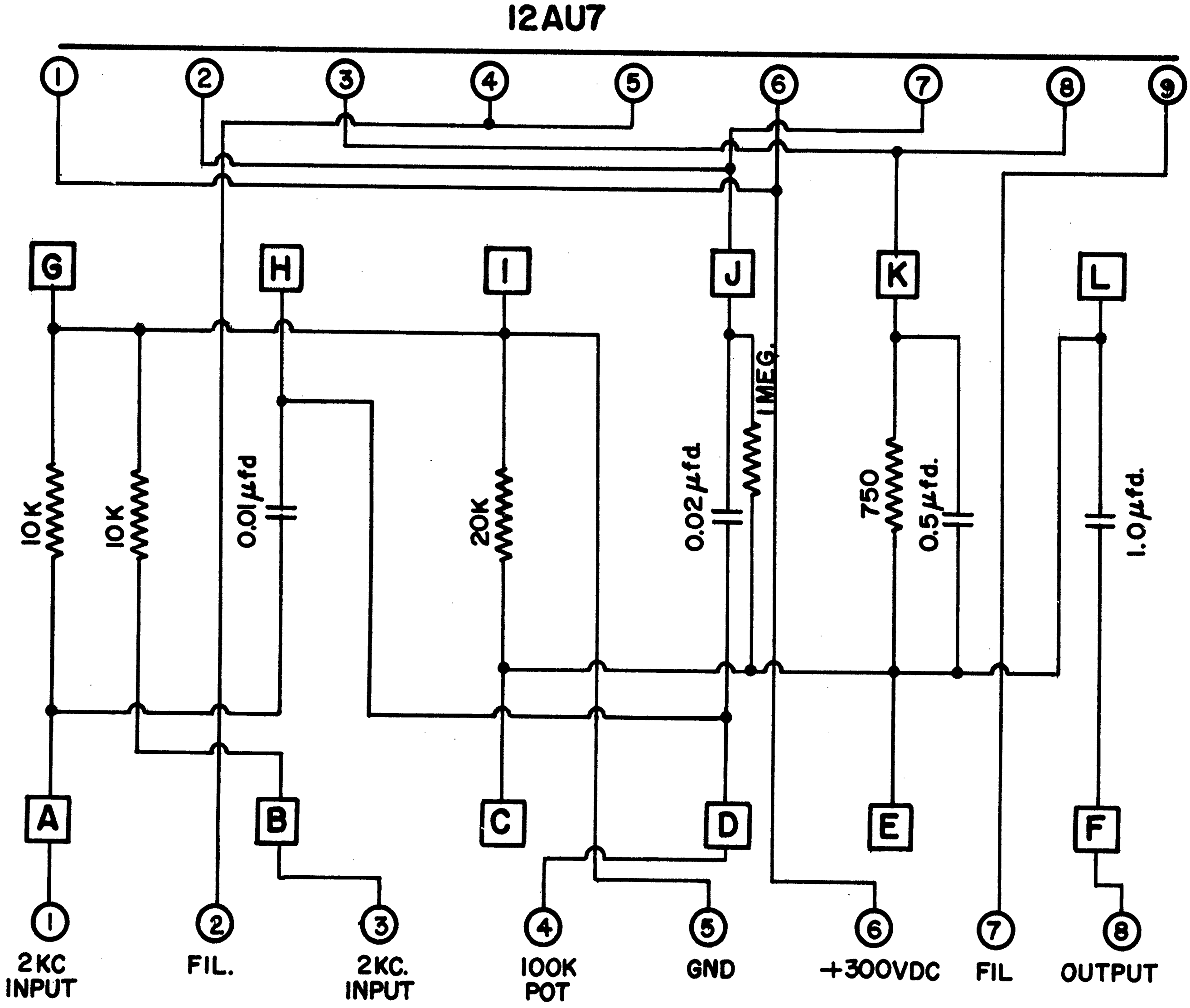


Fig. 9.6 Vector Can Layout of Phase-Shift Network

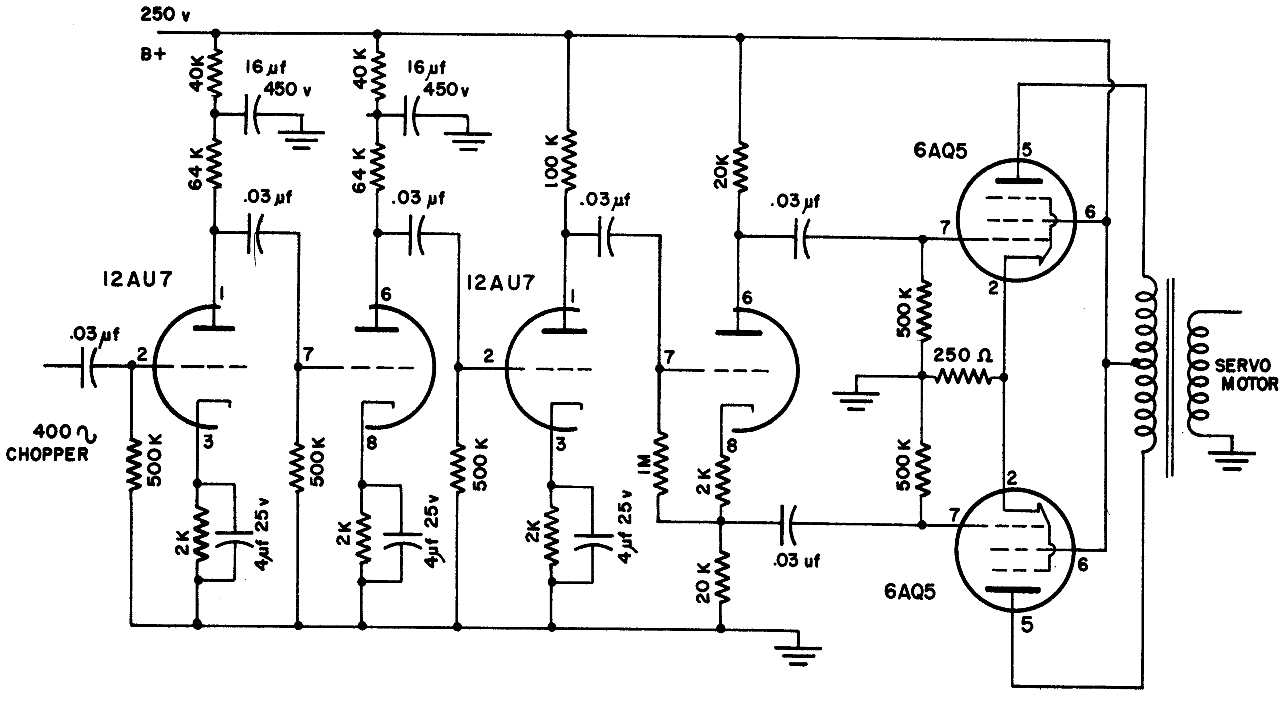


Fig. 9.7 Schematic Diagram of Servo Amplifier

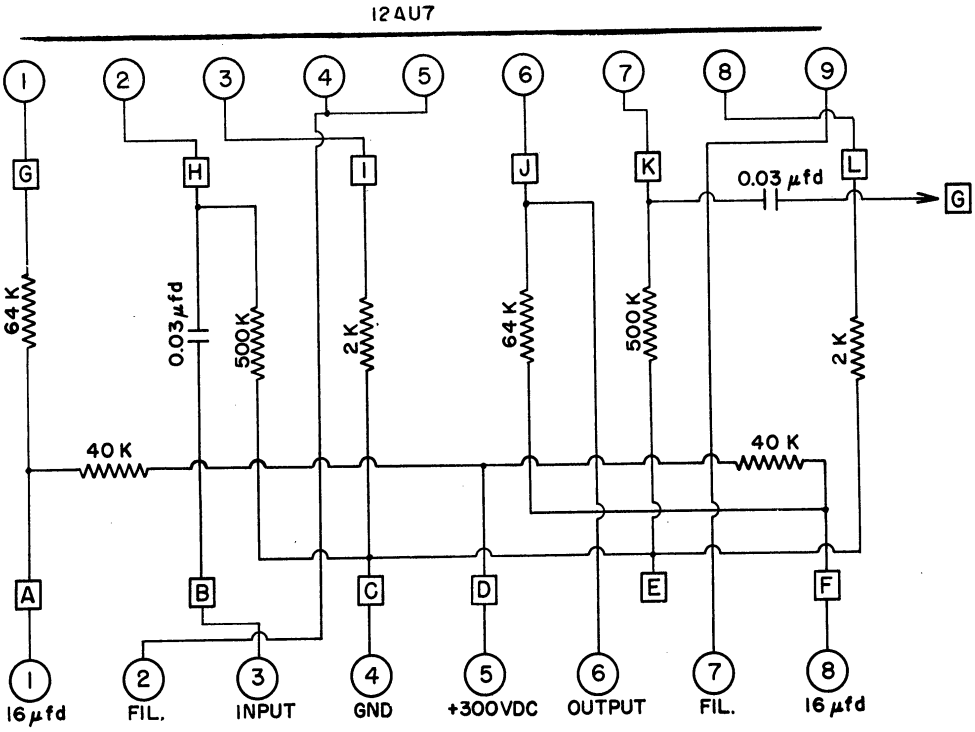


Fig. 9.8 Vector Can Layout of First Stage of Servo Amplifier

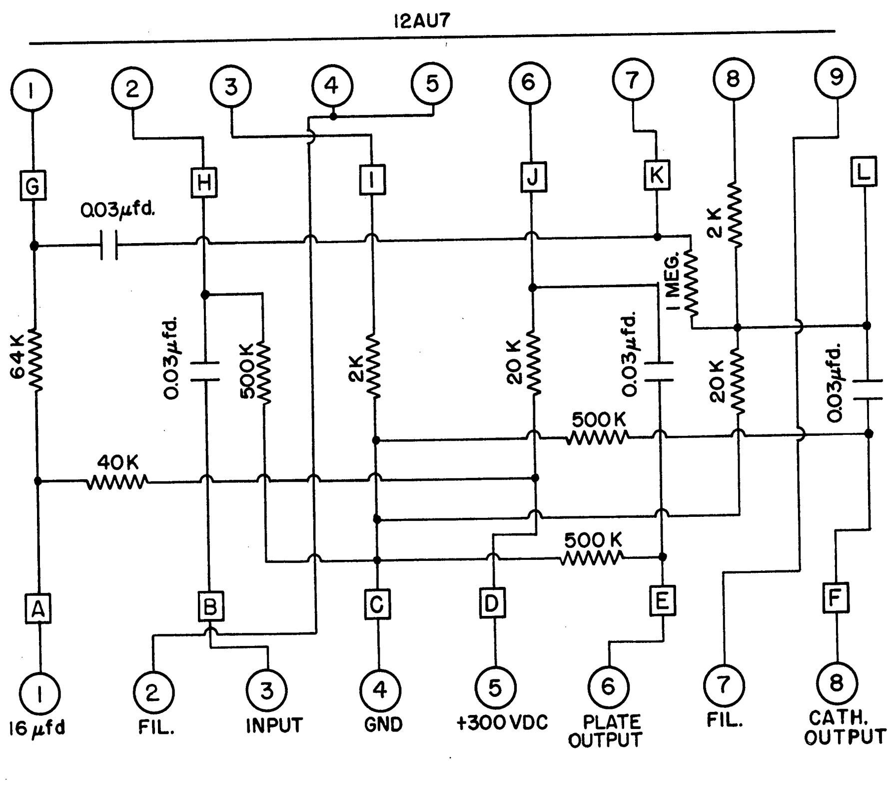


Fig. 9.9 Vector Can Layout of Second Stage of Servo Amplifier

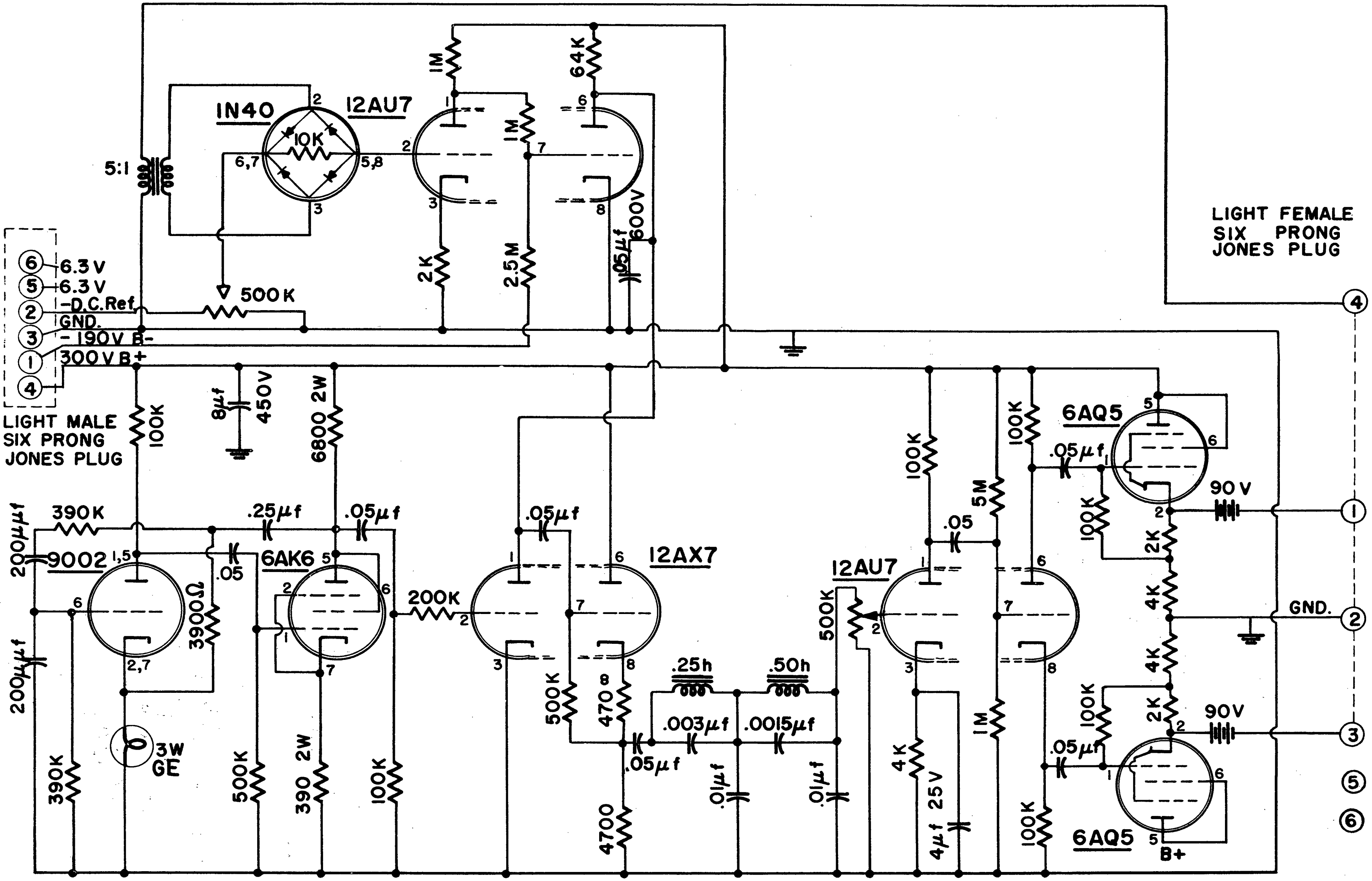


Fig. 9.10 Schematic Diagram of 2-kc Oscillator and Amplitude Control

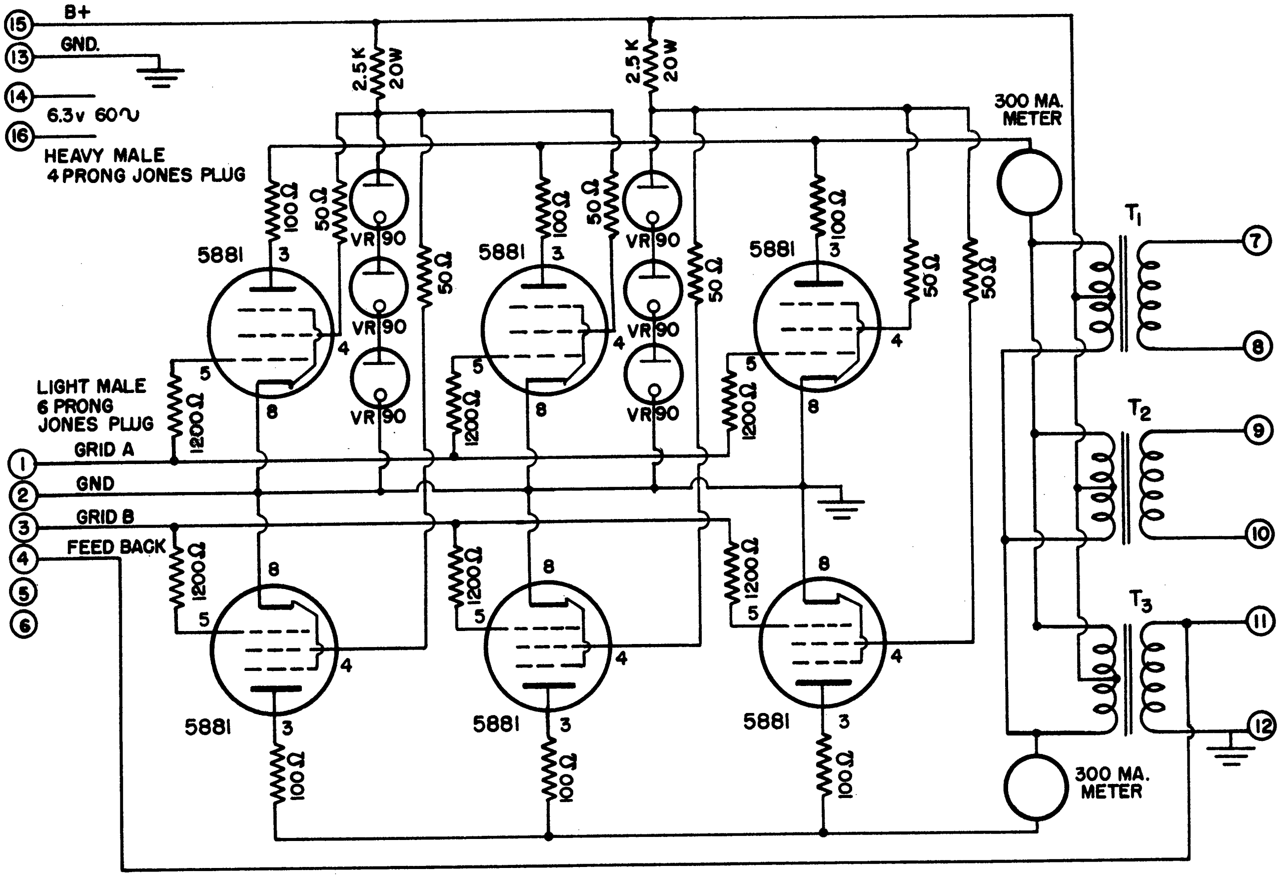


Fig. 9.11 Schematic Diagram of Power Amplifier

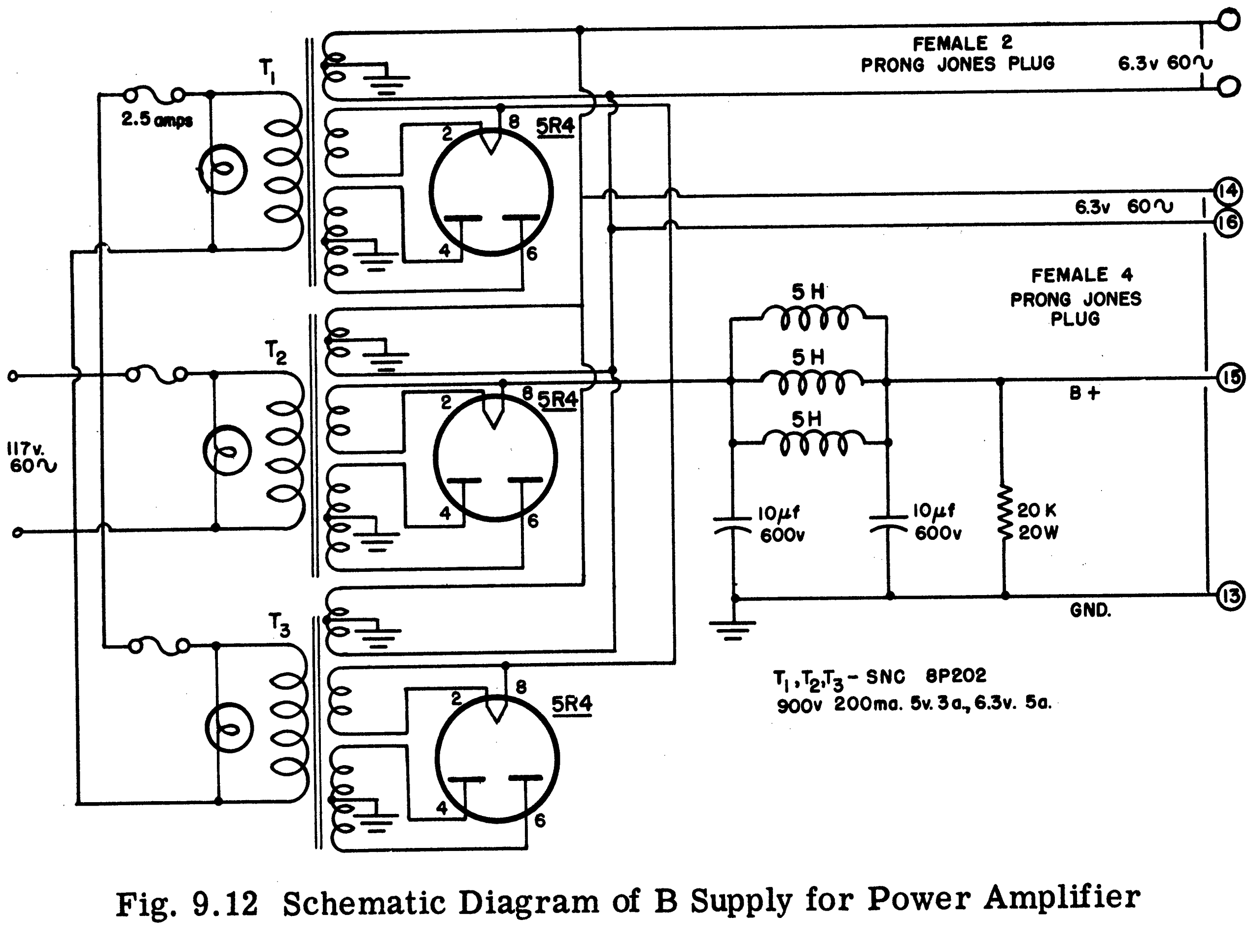


Fig. 9.12 Schematic Diagram of B Supply for Power Amplifier

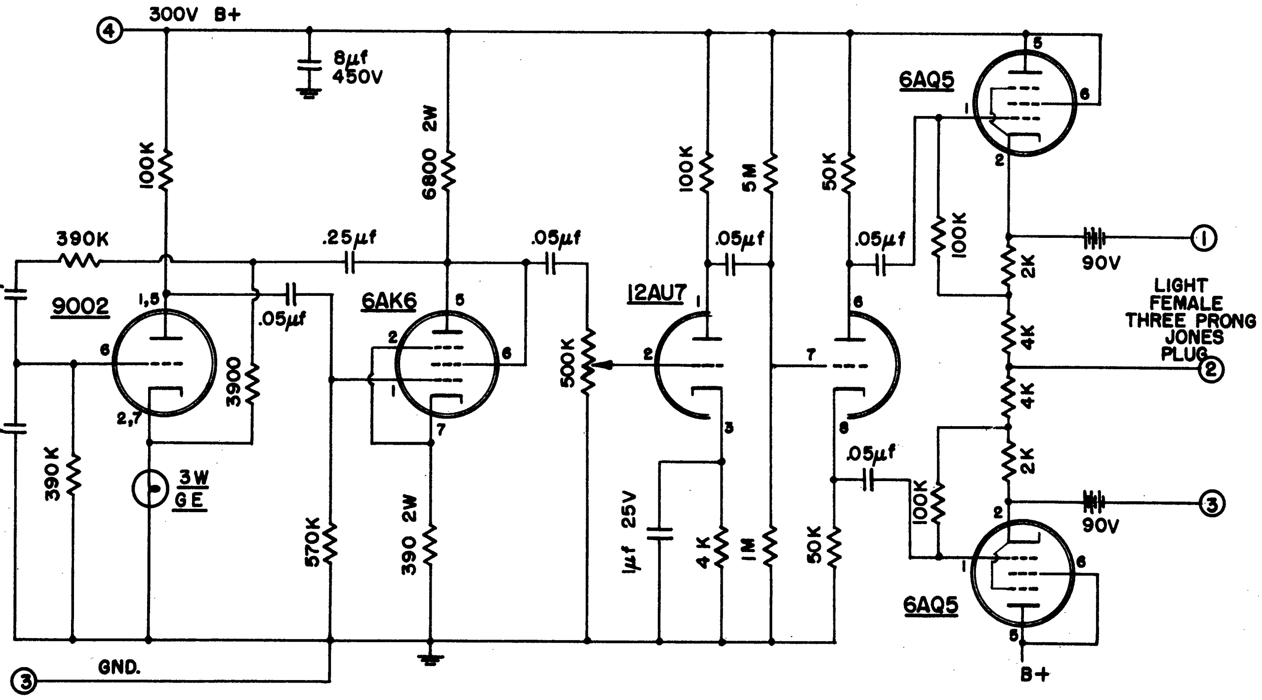


Fig. 9.13 Schematic Diagram of 400-cps Oscillator and Driver Amplifier

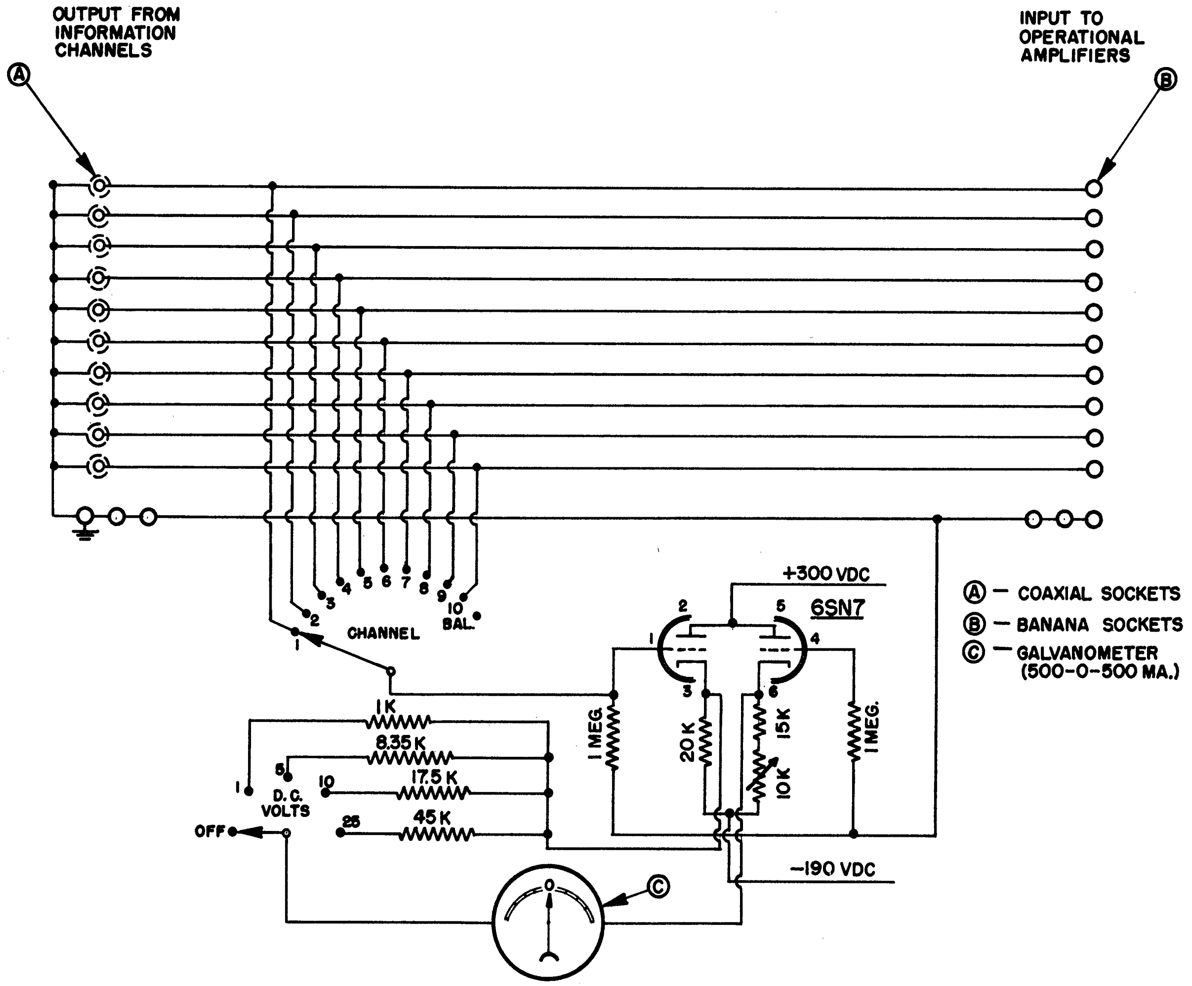


Fig. 9.14 Schematic Diagram of Information Channel Output Monitoring Circuit

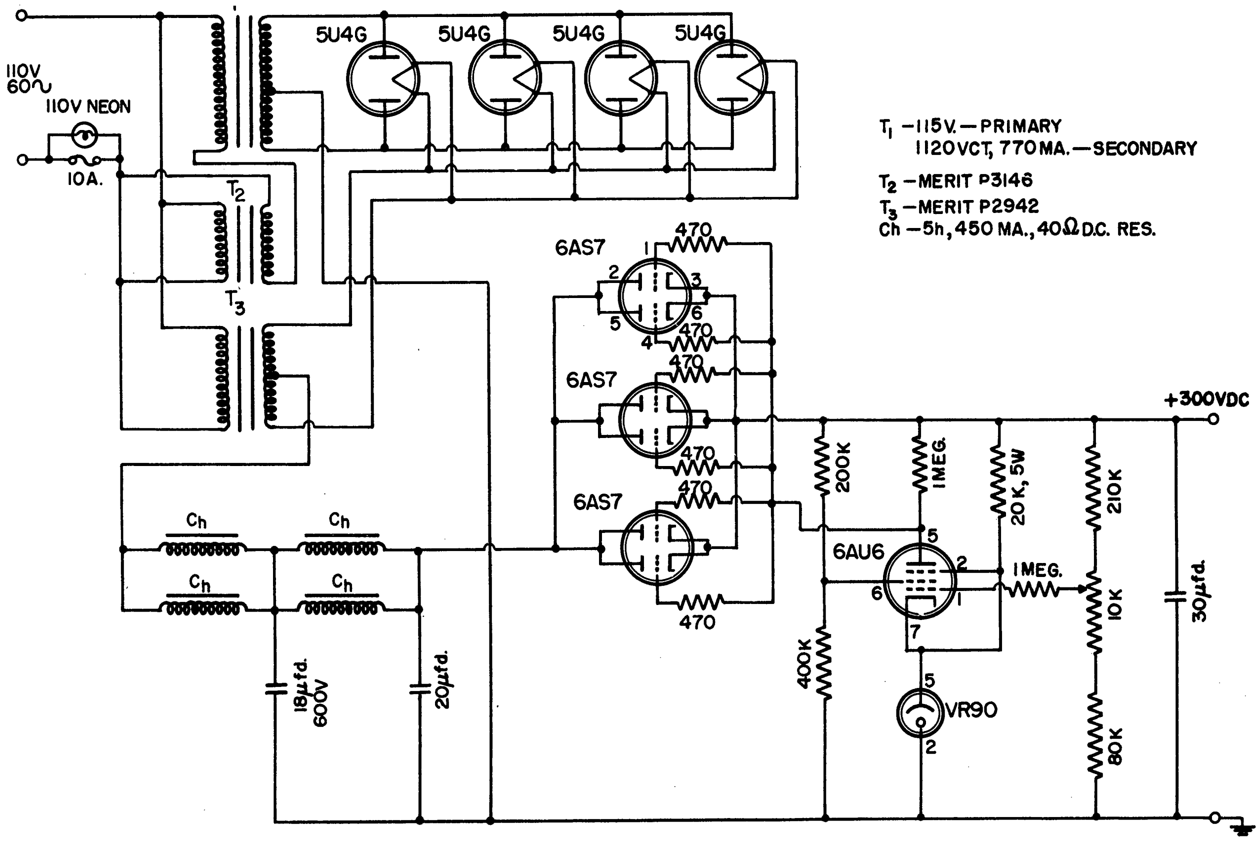


Fig. 9.15 Schematic Diagram of + 300 VDC Regulated Power Supply

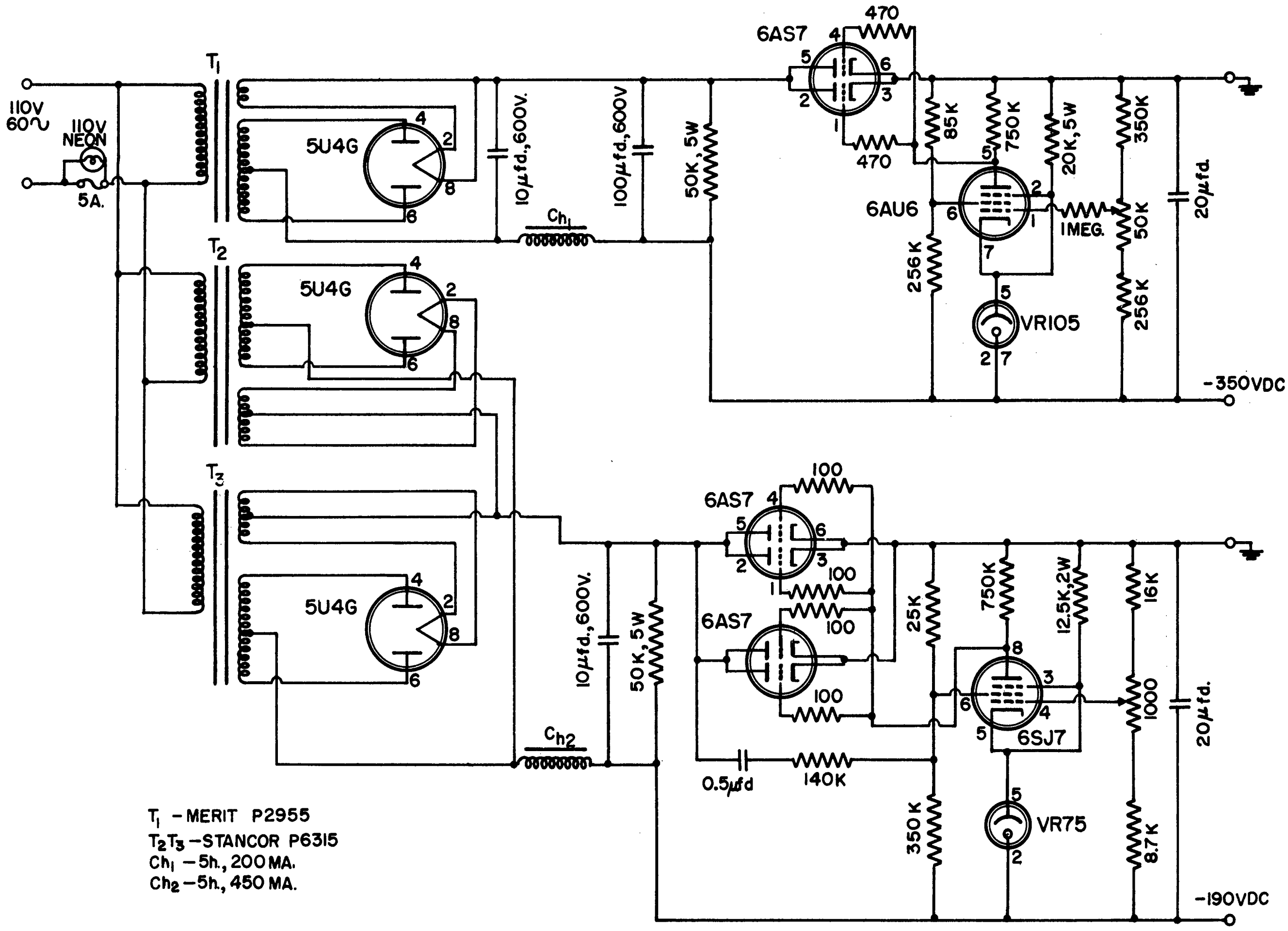


Fig. 9.16 Schematic Diagram of - 190 VDC and - 350 VDC Regulated Power Supplies

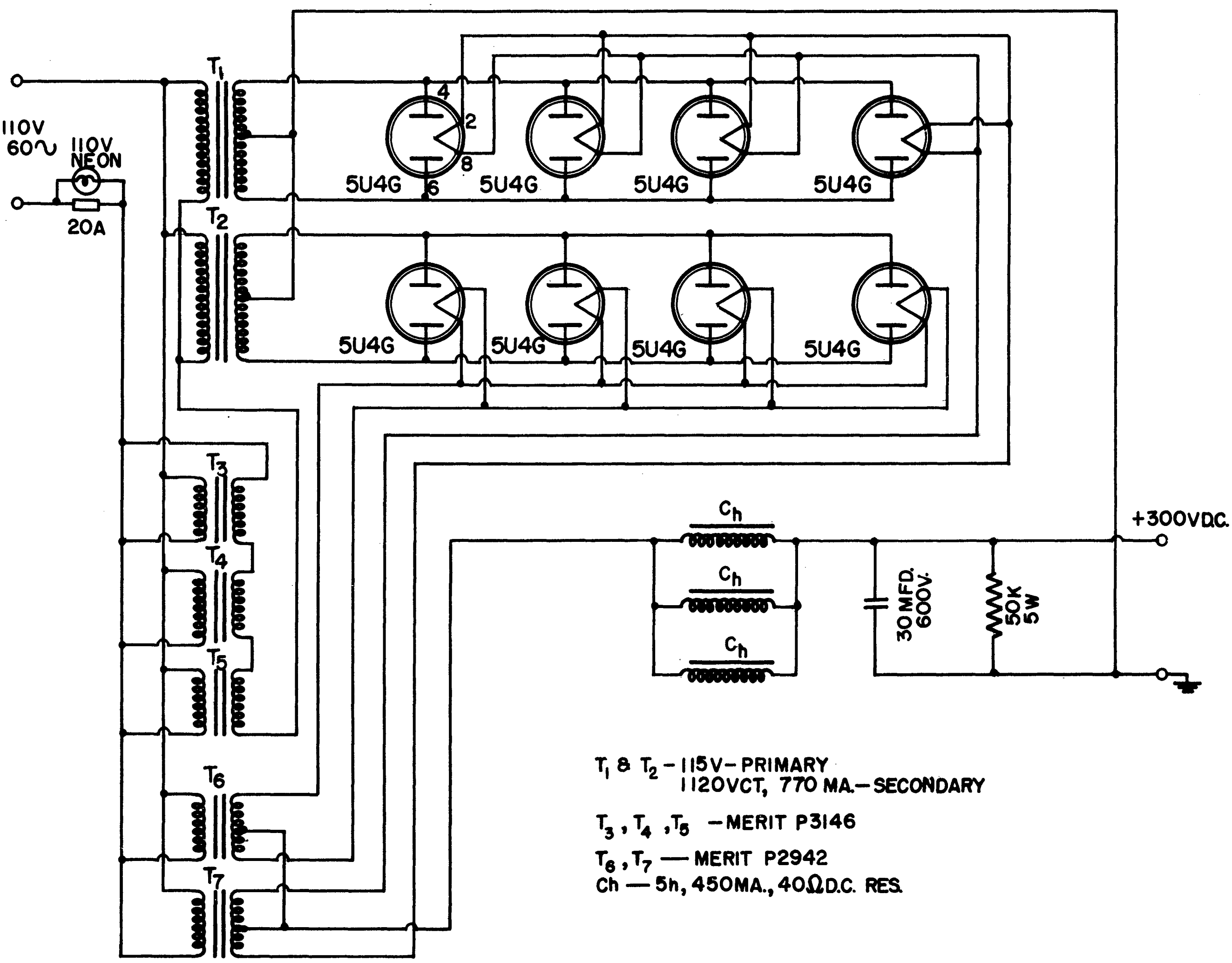


Fig. 9.17 Schematic Diagram of + 300 VDC Unregulated Power Supply

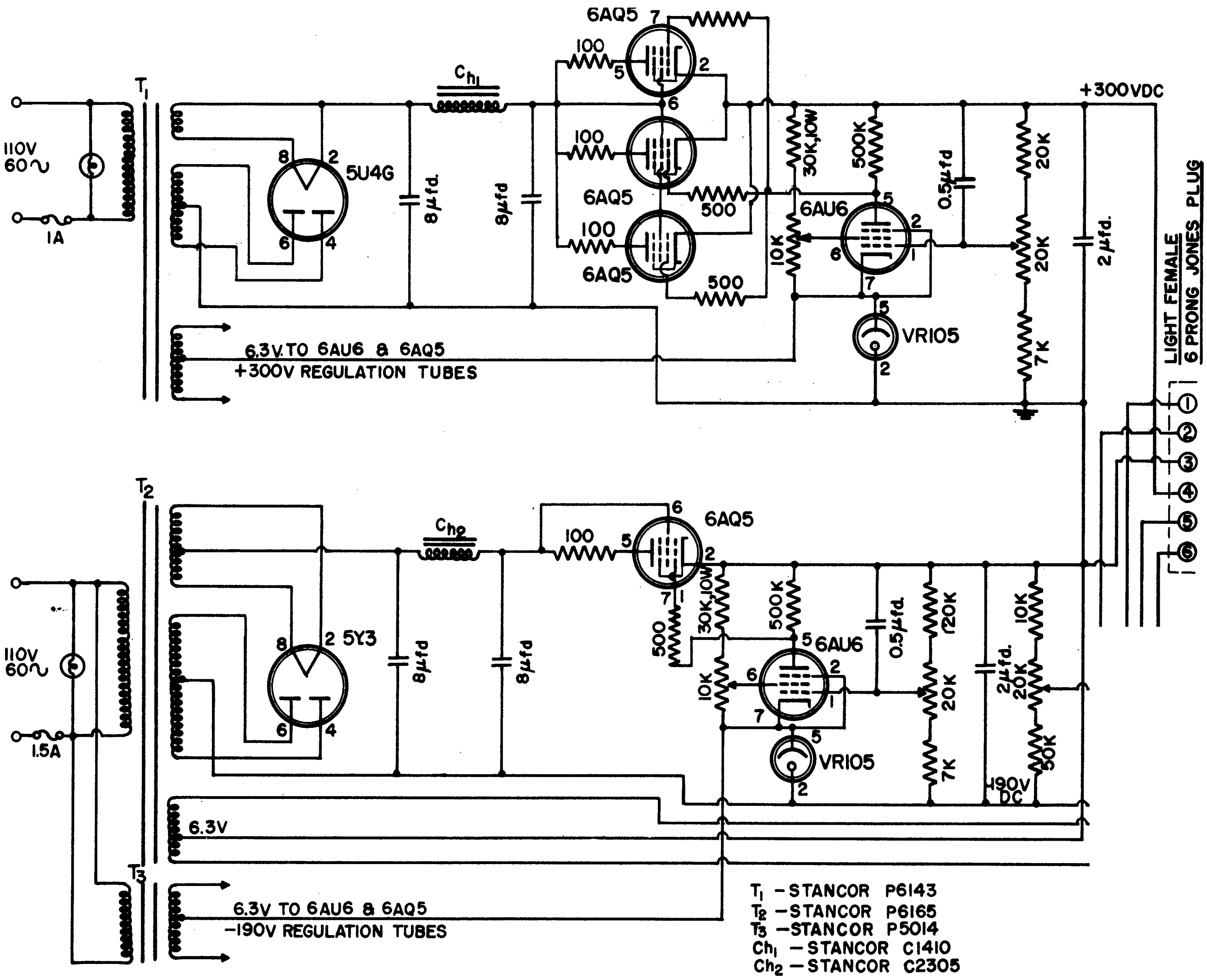


Fig. 9.18 Schematic Diagram of - 190 VDC and + 300 VDC Regulated Power Supplies for Oscillators

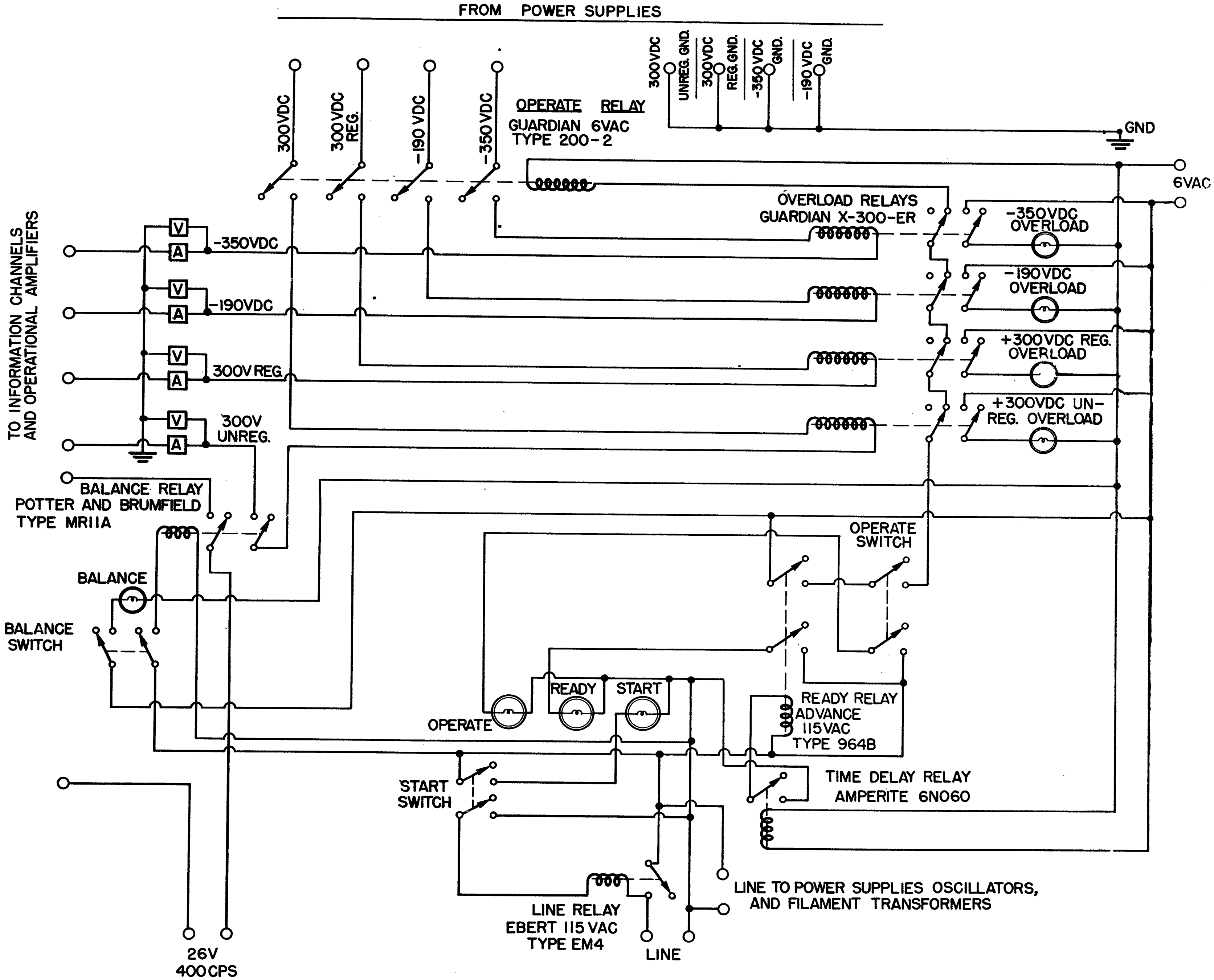


Fig. 9.19 Schematic Diagram of Master Control Circuit

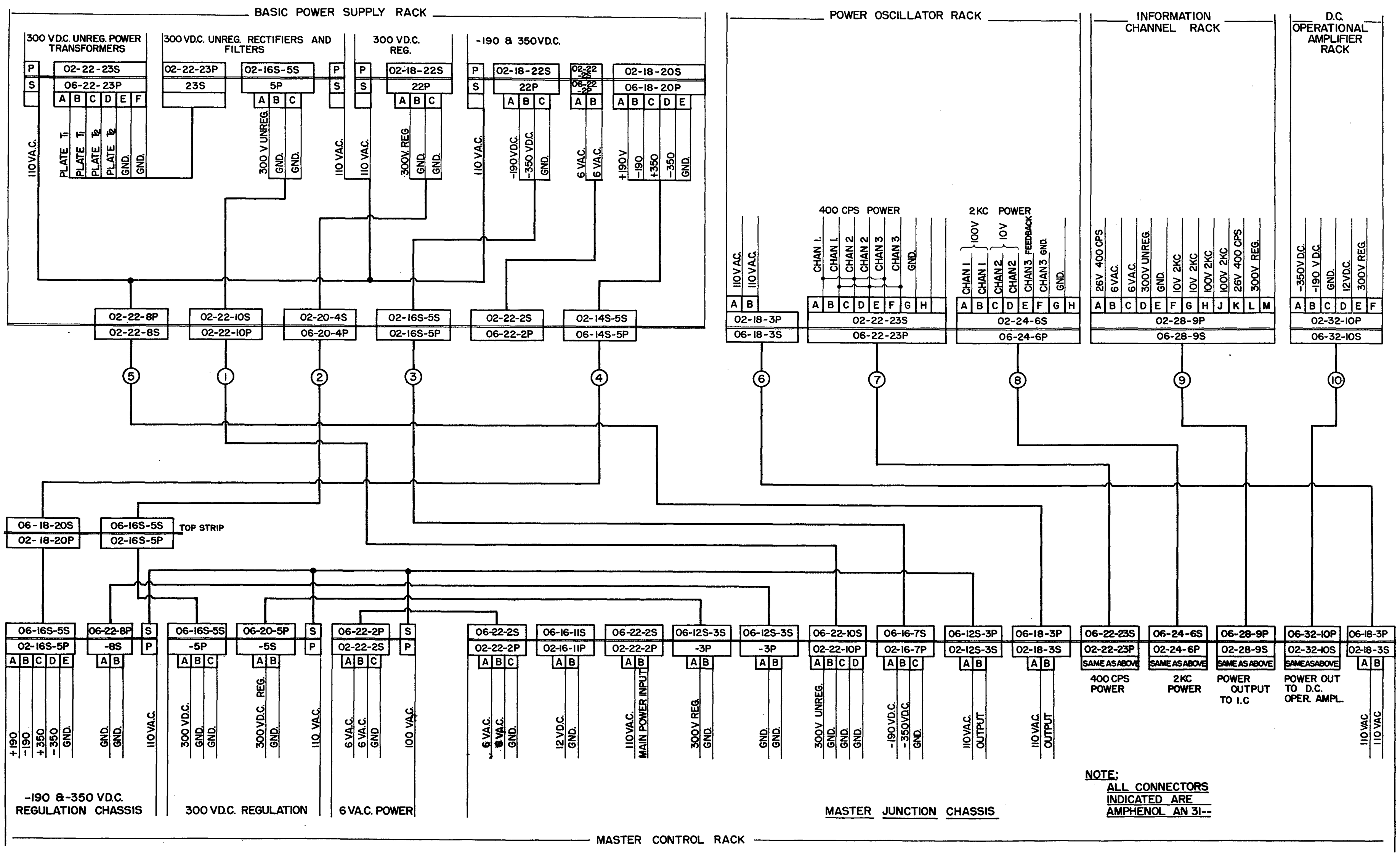


Fig. 9.20 Cable Wiring Diagram

10. ACKNOWLEDGMENTS

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