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SERVO SYSTEMS

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CHAPTER 1

INTRODUCTION TO SERVO SYSTEMS

Section I. GENERAL

1. SCOPE

This manual covers the basic theory, operation, and characteristics of servo systems and their associated equipments. Particular emphasis is placed on the use and practical applications of these systems by presenting a detailed analysis of the operations of typical servo systems of present day military equipments. Specifically, the subject material covered in subsequent chapters includes: basic servo systems, stability and error considerations, actuators, controllers, modulators and phase-sensitive devices, sensing elements and synchros, resolvers and potentiometers, auxiliary servo elements, and typical servo systems.

2. PURPOSE

The purpose of this manual is to give you a basic understanding of the fundamental principles of servo systems. With one exception, the emphasis is on the general theory and characteristics of servo systems rather than a detailed knowledge of any one system, so that you will be able to understand the operation of any servo system. The one exception is the detailed discussion of the servo systems, used in the antenna-positioning components of Radio Set SCR-584 and Radar Set AN/MPQ-10, which is intended to represent typical applications of servo systems in military equipment.

Section II. BASIC SERVO CONCEPTS

3. DEFINITION OF A SERVO

A servo loop, servo system, or servomechanism, the three terms being synonymous, is a device by which the action of a load may be controlled by an external order. The external order is the desired result that the movement of the load is to attain. When such an order is received, the servo compares the desired result with existing conditions of the load, determines the requirement, and applies power accordingly, automatically correcting for any tendency toward error which occurs during the process. The servo system is characterized by its ability to apply the necessary power automatically, at the proper time, and to the degree regulated by the need at each particular moment.

4. EXAMPLES OF SERVOS

The following examples of servos are based on controlling the speed of an engine. The complete servo is shown in figure 1. The engine drives the tachometer, which produces a signal that indicates the speed of the engine. An external speed order is received by way of a data-transmission system, which is not shown. A sensing element compares the actual speed with the speed order and develops a speed-error signal which is the difference between the ordered speed and the actual speed. The speed-error signal controls a throttle adjuster which alters the throttle setting, and so changes engine speed. The nature of the various signals is not important to the discussion at this point. What must be emphasized is the loop configuration of the complete servo, in which the speed-error signal acts through the throttle adjuster and the throttle to alter the engine speed. The engine speed, then, alters the tachometer signal and changes the resulting value of the speed error until it becomes zero. The complete loop may be formed in a number of ways, some of which are discussed in subsequent paragraphs.

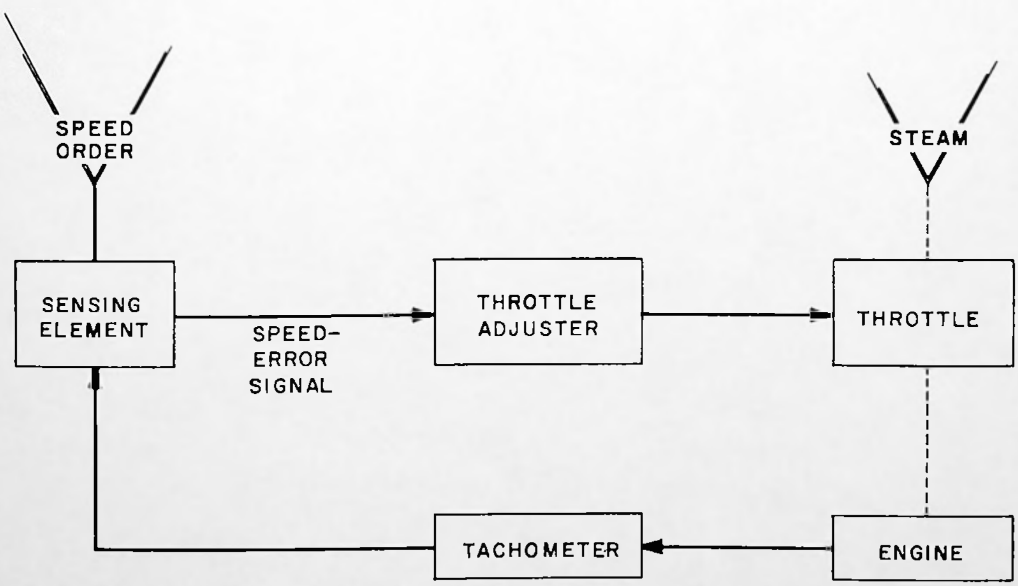


Figure 1. Basic servo loop.

a. Basic Servo Loop With Manual Control. In the servo system illustrated in figure 2, a human operator functions as the sensing element of the system. The operation of this system is initiated by the speed order which is received by the operator, who in turn observes the actual speed by looking at the tachometer dial, and then makes an appropriate throttle setting. Thus, the operator manually controls the speed of the engine by setting the throttle to the difference between the speed order and the actual speed of the engine.

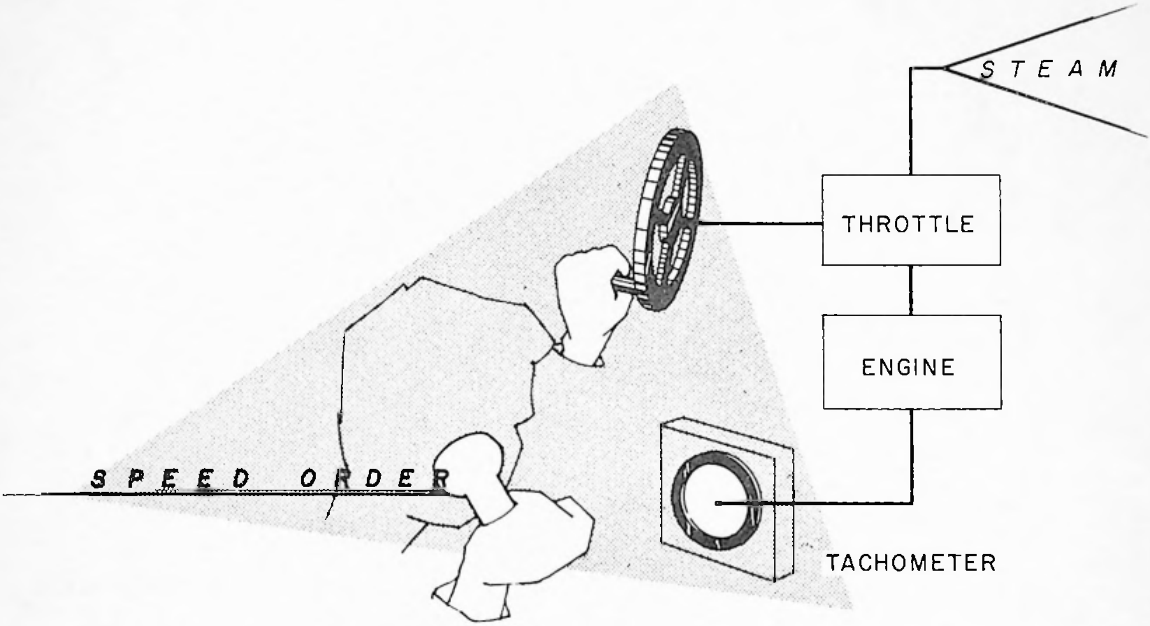


Figure 2. Basic servo loop with operator as sensing element.

b. Automatic Servo Loop. The servo loop shown in figure 3 illustrates an automatic system controlling the speed of an engine from the bridge of a ship. A speed order originates on the bridge of the ship and is converted to a proportional voltage signal by the potentiometer across a dc voltage source. This signal is then applied to the sensing element. The output of a tachometer generator, a voltage signal that indicates the actual speed of the engine, also is applied to the sensing element. The speed-indicator voltmeter provides a visual indication of the speed of the engine. The function of the sensing element is similar to a comparator in that its output is a speed-error signal consisting of a difference between the voltages of the speed order and the actual speed of the engine. This error signal is sent back to the engine room through a motor controller and a throttle-adjusting motor. The output of the motor controls the opening or closing of the throttle valve until the engine speed equals that of the speed order. When the output of the tachometer generator is equal to the voltage signal of the speed order, the output of the sensing element is zero.

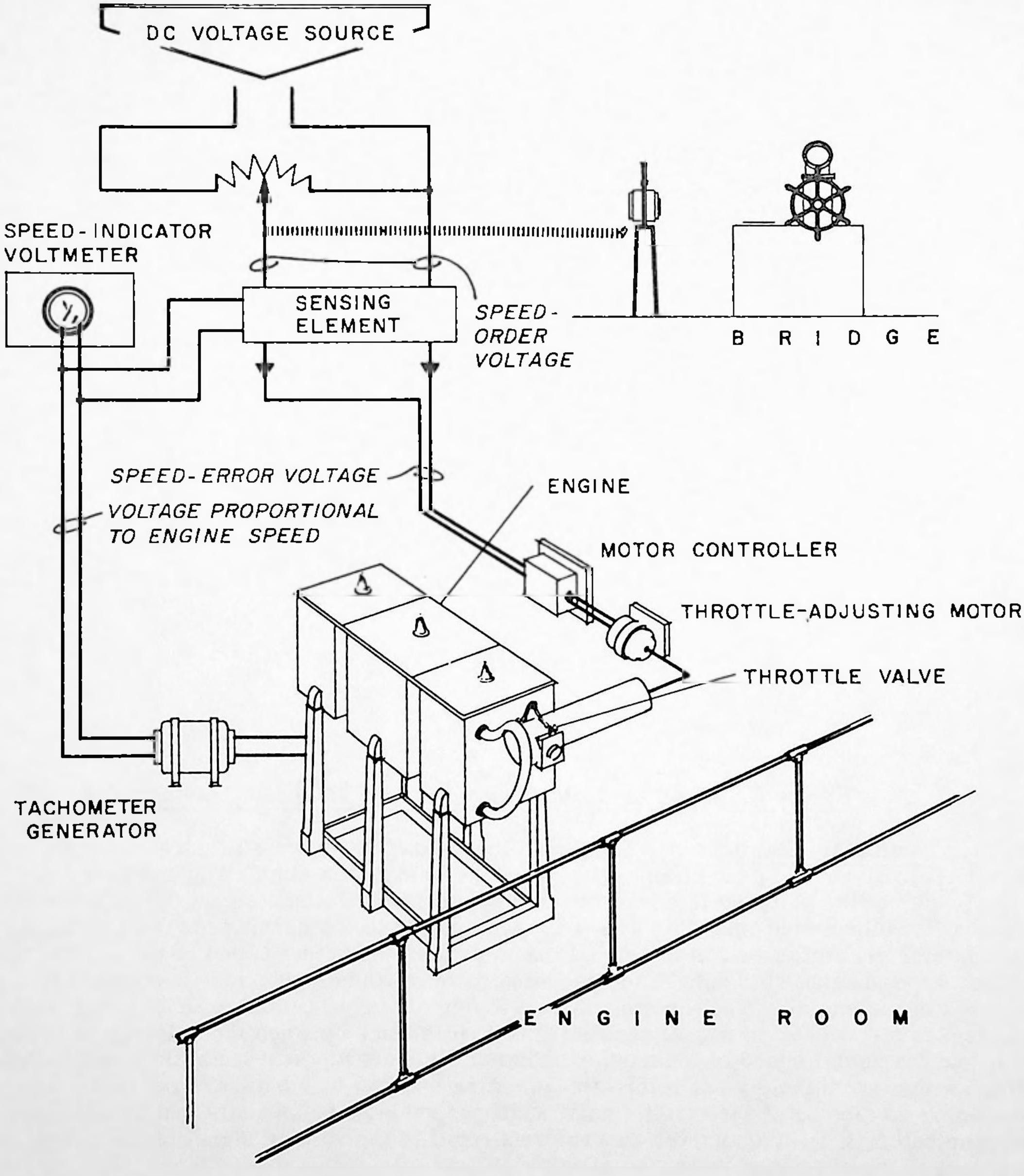


Figure 3. Automatic servo loop.

Section III. CONTROL SYSTEMS

5. NEED FOR CONTROL SYSTEMS

A human operator can accomplish certain actions, such as driving an automobile, better than any control systems of reasonable size and complexity. In many actions, however, a control system can assist an operator to carry out his work faster or more precisely. In many applications, automatic control systems can dispense with the human operator completely. A servo is a special type of automatic control system.

a. Movement of Heavy Load. An operator can control the movement of a heavy load with the assistance of a control system. One example is a control system consisting of a hoisting engine and its operating controls. The crane operator cannot lift the load, which may amount to several hundred tons, without the assistance of the hoisting engine, but it is easy for him to operate the engine controls.

b. Precise Positioning. Automatic control systems are used in some applications because they operate with greater precision than human operators. Figure 4 shows a ship-mounted radar antenna designed to continuously track a target aircraft within its range. One or more operators sometimes position the radar antenna, either directly by moving it manually, or with the assistance of positioning control systems; however, this is difficult since it is necessary to compensate continuously for the rolling and pitching of the ship. A much better job is done by automatic control systems that operate in response to changes in the output of the radar and require no human assistance.

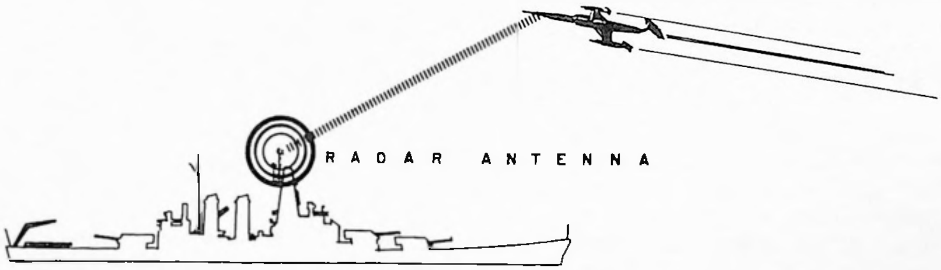


Figure 4. Automatic controls keep radar antennas pointed at target.

c. Control of Nonmechanical Quantities. Consider the problem of heating a house. If the house temperature is too low, there is nothing a human operator can do to raise it, since he is limited to the performance of mechanical work, such as moving and lifting. With the assistance of a furnace, however, he can control the house temperature easily. The furnace is part of the temperature-control system which, like the hoisting engine, assists the operator to do a job he cannot do alone. The operator of the hoisting engine, however, is unable to lift the load only because it is too heavy for him. He is able to lift lighter loads and, in general, can do the same work as the hoisting engine. However, he is unable to heat a house without the furnace, even if it is only a small house. The control system in the first instance extends the existing capability of the operator; in the second, the furnace gives him a completely new capability. The control system, therefore, may supplement the ability of the operator, it may give the operator new abilities, or, as in the example of the ship-mounted radar, it may replace the operator completely.

d. Control at a Distance. The control system may aid the operator in controlling an operation remote from his location. An example is the control system that changes the path of a guided missile. The operator gives the control orders that are sent over a data-transmission system to the missile. A servo system in the missile moves the guiding controls in response to those orders. The complete control system, therefore, includes the operator, the data-transmission system, and the servo system controlling the guiding controls in the missile.

6. OPEN AND CLOSED SYSTEMS

There are two basic types of control systems, open and closed. It is not always easy to make a distinction between these two basic systems; an open system may be part of a larger system that is closed, or a closed control system may be part of a larger system that is open. The distinction between the two systems lies in whether or not the action of the control is affected by the result of its earlier action. A system that operates only in response to external orders, paying no attention to the result of its action, is an open system. A system that bases its action both on external orders and on the behavior of the load or quantity that it controls is a closed system.

a. Open Control System. Assume that an engineer is in charge of a large steam-driven engine which is the main driving engine of a ship. He is able to control the speed of this engine by adjusting a throttle that limits the amount of steam reaching the engine. Assume, further, that the engineer is unable to read the speed of the engine directly. He, therefore, makes a table of throttle settings, based on experience, that probably will give any particular engine speed. If the engineer receives a speed order calling for the engine to be operated at 90 revolutions per minute, he consults his table and makes the appropriate throttle setting. The throttle itself is an open control system, since the amount of steam it passes is governed by the setting and is not affected by the engine speed. The combination of throttle and engineer is also an open control system, since the amount of steam passed to the engine is governed by the throttle setting, and this is determined by the speed order that the engineer receives. The amount of steam will not be increased if the engine runs too slowly, nor will it be decreased if the engine runs too fast.

b. Open Control System With Repeat-Back. Suppose, now, that a tachometer, an instrument that indicates engine speed, is added to the engine room equipment. It is called a repeat-back because it reports the actual engine speed to the engineer. The throttle alone is still an open system, and the combination of throttle and engineer is also an open system with repeat back if the engineer does not look at the tachometer. If, however, the engineer watches the tachometer and changes the throttle setting whenever the engine speed does not agree with the speed order, the system becomes closed. The amount of steam passed to the engine is governed by the speed order and by the engine speed, with the engine speed being the controlled quantity.

c. Closed Control System. Assume that automatic control is added to the control system. Thus, the throttle is adjusted automatically until the engine speed agrees with the speed order. This is always a closed system. It is worth noting that the complete engine control system may be converted from an open control to closed control, either by the engineer watching the tachometer and making adjustments in the throttle setting when the speed varies from the speed order, or by an automatic device.

Section IV. POSITIONING SERVO

7. INTRODUCTION

Certain basic principles governing the operation of any servo are presented in this chapter by considering two types of elementary servos, analyzing their behavior, and showing how their performance is improved by various modifications. The types of servos are the positioning servo and the rate servo. The positioning servo, discussed in this section, is representative of a large class of servos used in military applications. The 16-inch guns of a battleship, for example, are moved by positioning servos; and in contrast, the dials of the compass repeater also are set by a positioning servo. The rate servo controls the speed of a load and is discussed in section V. The components of the servos (motors, amplifiers, generators, etc.) are described in terms of their specific functions and detailed discussions of these various servo components are given in subsequent chapters.

8. POSITIONING SERVO ELEMENTS

The various elements shown in figure 5 are present in any positioning servo, although, in many cases, a single component serves as more than one element. A synchro control transformer, for example, is a combination data receiver, follow-up system, and sensing element. The actuator is assumed to be an electric motor. (The type of motor or whether a hydraulic device would be preferable is unimportant in analyzing the action of the servo as a whole).

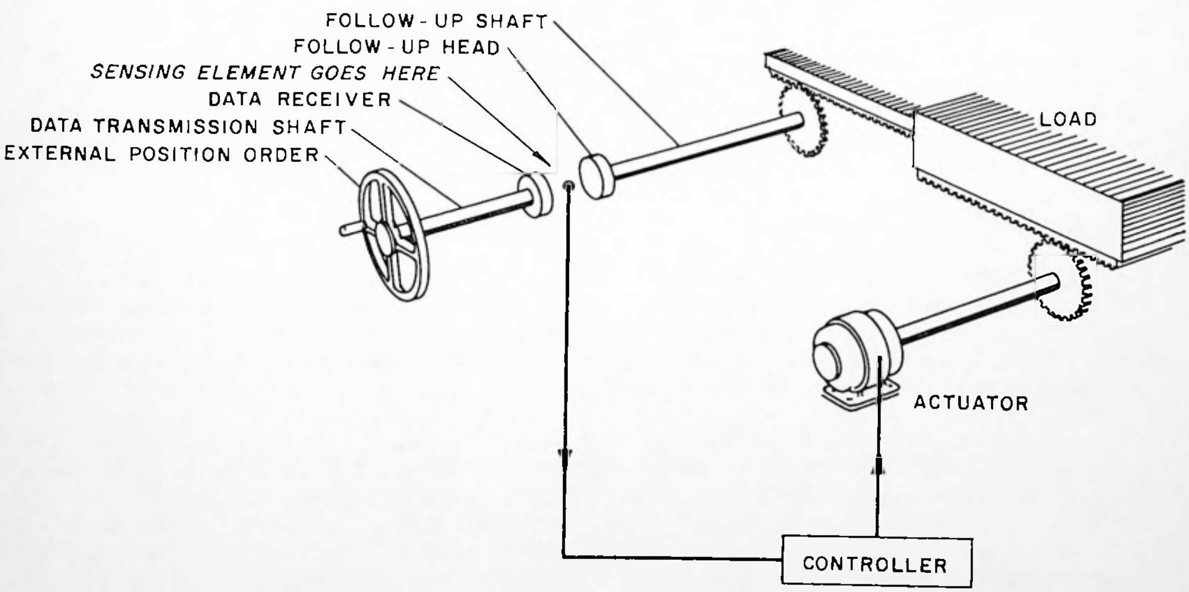


Figure 5. Positioning servo elements.

a. Load. The load is a mass that is positioned by the servo in response to an external order. (The operation of the servo is strongly affected by friction; however, for this discussion, the load is assumed to move without friction.)

b. Actuator. The actuator moves the load. In this discussion, it is assumed that the actuator is a motor. The type of motor is not important at this time, since it depends primarily on the weight of the load, and the speed with which it must be moved.

c. Controller. The controller acts as a torque amplifier and operates the actuator in response to error signals it receives from the sensing element.

d. Follow-up System. The function of the follow-up system is to repeat the actual position of the load to the sensing element. The system consists of a follow-up shaft and a follow-up head. The follow-up shaft is mechanically connected to the load. A small disc or follow-up head is connected to the opposite end of the follow-up shaft and turns with the load. The linkage between the sensing element and the follow-up head is determined by the type of sensing element used.

e. Data-Transmission System. The data-transmission system serves as the linkage between the external order and the sensing element. The external order is fed into the system by adjustment of a small hand wheel which is linked by a shift to the data receiver. The linkage between the data receiver and the sensing element also is determined by the type of sensing element used.

f. Sensing Element. The sensing element is not shown in figure 5, since a number of different sensing elements, including mechanical differentials, differential amplifiers, and synchros, are discussed later. The function of the sensing element is to receive the external position order from the data receiver and the actual load position from the follow-up head, compare them, and originate an error signal.

9. SENSING ELEMENT OUTPUT

The output from the sensing element, whether it be electrical, mechanical, or hydraulic, is the result of the difference between the actual position of the load and the position called for by an external order. This difference is called an error signal. In the servo system shown in figure 5, the error signal is an electrical signal that is produced by the relative positions of the data receiver and the follow-up head. In the automatic engine-speed control system described in paragraph 4b, the speed order and the speed information are in the form of voltages, and the error signal is a voltage which is the difference between the two.

10. CONTROL METHODS

The method of control, or the way the actuator is directed to respond to an error, depends on the sensing element and on various auxiliary devices that may be introduced ahead of the sensing element. There are three representative methods of control: on-off control, stepwise control, and proportional control. These terms are frequently used to describe servos; for example, an on-off servo is one that uses on-off control.

a. On-Off Control. In an on-off servo, the actuator moves the load at a constant speed either in one direction or the other. If the actuator is a motor, the motor is either off (when no error signal is present), or full on (in either the forward or reverse direction). In the on-off control mechanism shown in figure 6, a contact-type sensing element is used to provide the error signal for the controller (the two relays). Two contact springs are mounted on the data-receiver head, and are connected to the windings of the controller relays. A contact arm is mounted on the follow-up head and is connected through a power source (battery) to the opposite end of each of the windings of the controller relays. In the absence of an external order, the contact arm lies midway between the two contact springs, and neither relay is energized. When an external order is received, the data-receiver head turns in either one direction or the other, causing one of the springs to make contact with the contact arm. This action results in one of the controller relays being energized, and causes the actuator motor (not shown) to move the load in the desired direction. When the load is positioned properly, the follow-up head will have turned so that the contact arm is once again midway between the two contact springs, and no further error signal is developed. If the current-carrying capacity of the contacts exceeds the maximum motor current, the controller relays may be omitted. In this case the actuator motor is connected directly (through a power source) to the contacts on the data-receiver and follow-up heads.

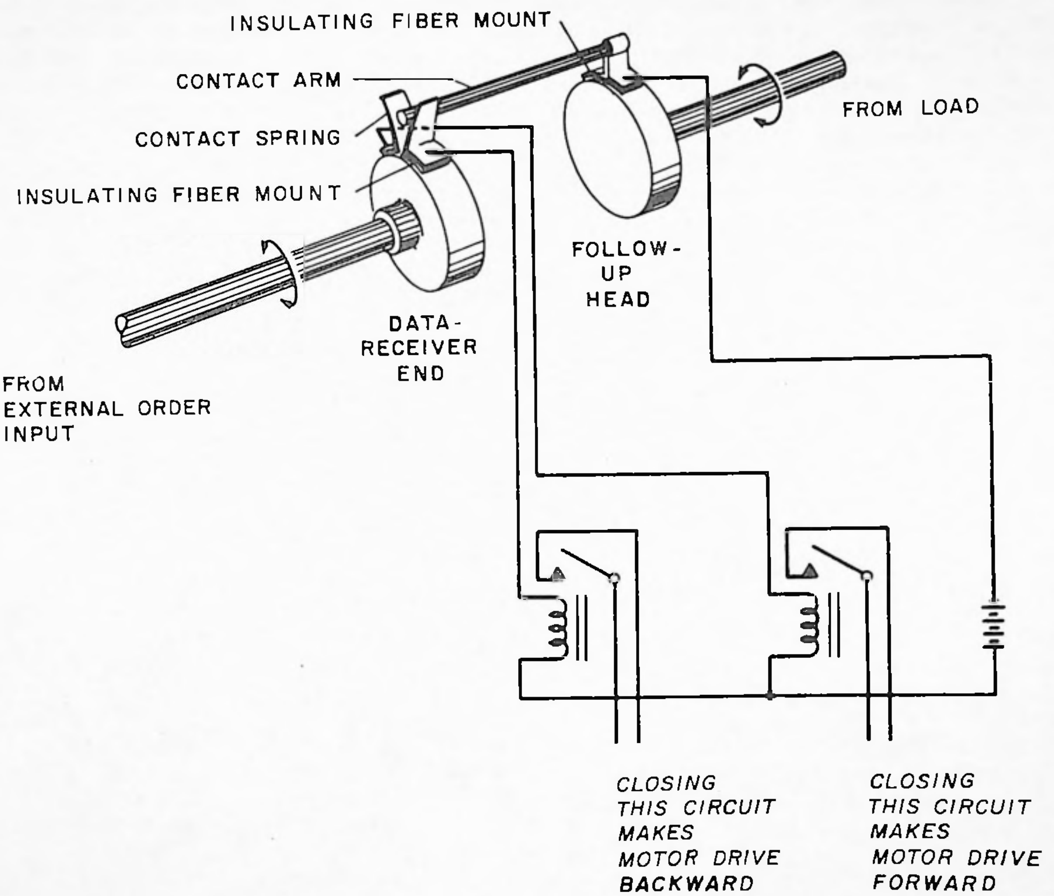


Figure 6. On-off control mechanism.

b. Stepwise Control. In a stepwise servo, any error is corrected in a series of steps, with the amount of correction in each step proportional to the error that exists at the start of the step. During the first part of each step, a sensing device notes the error; during the second part, the actuator makes a correction proportional to the error. A mechanism that provides stepwise control is shown in figure 7. This mechanism is added to the servo system before the sensing element and between the follow-up shaft and the follow-up head. In this case, the sensing element is assumed to be the simple on-off element described previously. The follow-up head is connected to the follow-up shaft by two driving systems. The main drive is connected directly by means of a flexible shaft and the auxiliary drive is connected through gearing, rigid shafts, and a clutch. The main drive, since it is a direct connection, attempts to make the follow-up head move with the follow-up shaft. While the clutch is disengaged, the auxiliary drive does nothing; however, when the clutch is engaged, it turns the follow-up head in the same direction as the follow-up shaft but, because of the gearing, turns it faster. With a gear ratio of 2:1, the follow-up head will be turned 10 degrees by the auxiliary drive (when the clutch is engaged) when the follow-up shaft has turned 5 degrees. During the first part of the step, the controller is disabled and the clutch in the auxiliary drive is disengaged. The follow-up head, therefore, assumes a position that matches that of the follow-up shaft, and the contacts of the sensing element see the actual error. During the second part of the step, the clutch is engaged and the controller is allowed to operate. The actuator then moves the load in the direction that reduces the error. Because of the auxiliary drive, the follow-up head is turned toward zero error position faster than the load moves to its proper position. At some point short of complete correction, the sensing element sees a zero error and turns the actuator off. At the same time, an extra circuit, controlled by the contacts of the sensing element, disables the controller and disengages the clutch in the auxiliary drive, thus starting the first part of the stepping cycle again. After a short interval, during which the flexible shaft of the main drive untwists itself and brings the follow-up head back to coincidence with the follow-up shaft, the controller is energized once more and the clutch is engaged again. The error thus is corrected in a stepwise way. If the gear ratio in the auxiliary drive is 2:1, the error will be halved in each step. Other mechanisms may be devised which will control the step length by altering the duration of the step instead of directly controlling its length, or by changing the speed at which the actuator moves the load. All, however, result in the stepwise correction from which the method receives its name.

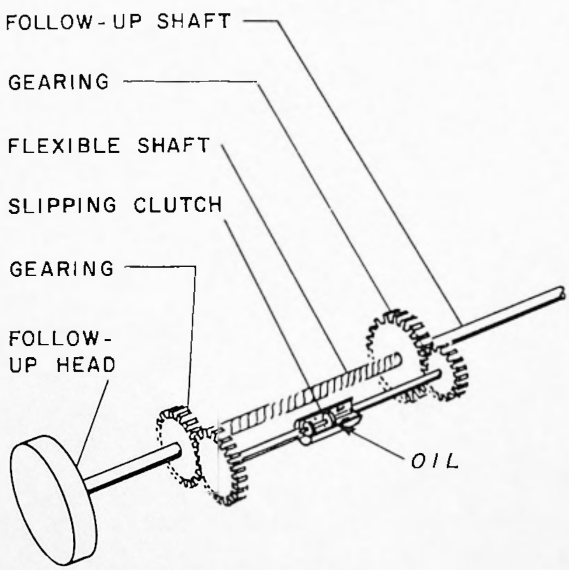


Figure 7. Stepwise-control mechanism.

c. Proportional Control. The proportional control system is the one most generally used. The simplest way of achieving proportional control is to replace the contact-type sensing element with a potentiometer (fig. 8). The body of the potentiometer is carried on the data-receiver head, and the potentiometer arm is driven by the follow-up head (although the positions may be reversed). The potentiometer is excited by a balanced input; voltages of opposite polarity are applied to the two ends if it is in a dc system, or of opposite phase in the case of an ac system. When the potentiometer arm is at the center of its range, it delivers an output of 0 volt. The potentiometer and potentiometer arm are so mounted on the two heads that this output is 0 volt when the load is at its proper position. When an error exists, the potentiometer arm is displaced from the center of its range by an amount that is proportional to the error. The error signal is, therefore, a voltage proportional to the error, and with the usual controllers and actuators, the force (for small errors) exerted by the actuator is proportional to the error. Although the controller can be omitted or replaced with a pair of relays in the on-off and stepwise methods, it is impossible here unless the potentiometer is to carry the full motor current. The usual method is to use the potentiometer output as the input signal for an amplifier of some sort, and let this provide the power for the motor.

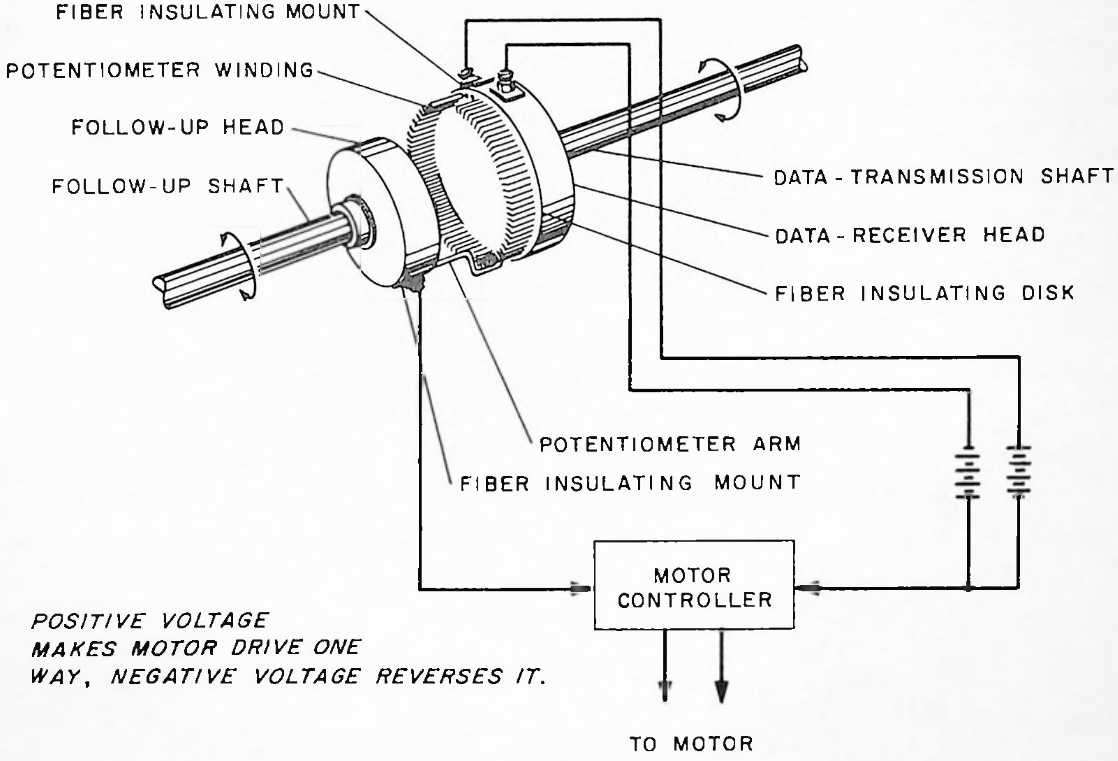


Figure 8. Proportional control sensing element.

11. RATE SERVO OPERATION

A rate servo is one that controls the rate, or speed, of a load instead of controlling the load position. It varies the rate at which the load moves in response to an external rate order. A typical example of rate servo is found in radar antenna systems where a rheostat is used to vary the field voltage, which decreases or increases the speed of the motor. Thus, the antenna is turned at a faster or slower rate.

12. RATE SERVO ELEMENTS

In the rate servo illustrated in figure 9, the load is a flywheel which turns at a controlled rate. The actuator is an electric motor, and the controller is an amplifier. The follow-up is a tachometer generator developing an output proportional to its speed. The data-transmission link is a wire over which the speed order is sent in the form of a voltage. There is no separate data receiver, and the sensing element is a simple voltage-subtraction circuit where the speed order and the tachometer output are compared.

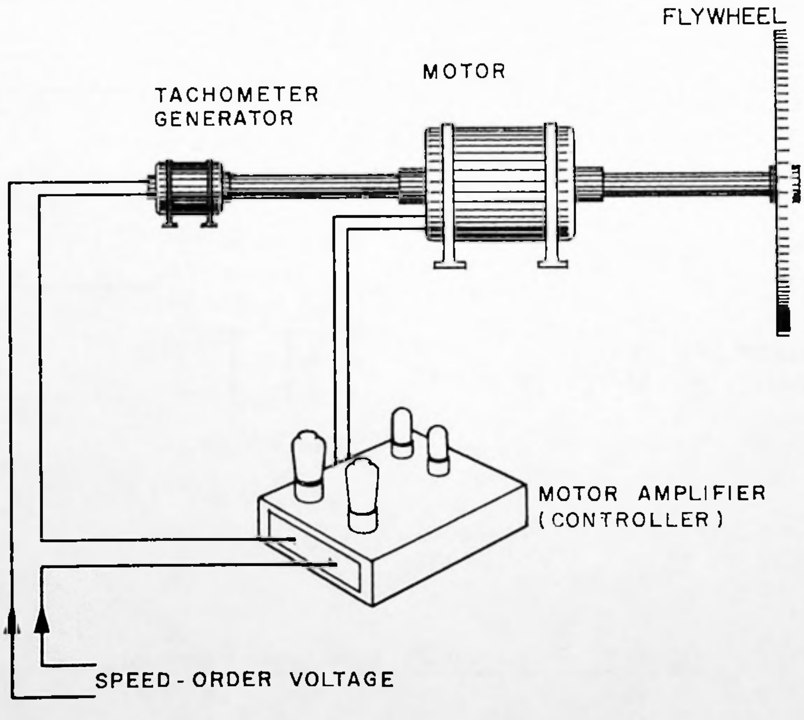


Figure 9. Rate servo.

13. SIGNAL FROM SENSING ELEMENT

The signal from the sensing element is the voltage difference between the speed order and the tachometer-output voltages. The signal is proportional to the speed error, and is sent to the controller, where it causes the actuator to increase or decrease the load speed.

14. CONTROL METHOD

On-off control can be accomplished by allowing the speed-error signal to close one relay when the speed is too high and another relay when the speed is too low. Because of the large dead space, the load speed will fluctuate between two values, one of which is higher than the speed order, and the other lower. Stepwise control is difficult to achieve except in cases where a stepwise servo is used to adjust the speed of the motor driving the flywheel. The use of an auxiliary servo for this purpose is similar to the use of an auxiliary throttle adjuster in the engine speed-control system described in paragraph 4. In practice, the rate servo usually is operated with proportional control. It runs at a speed slightly below the control speed order, the resulting error being just sufficient to develop an error signal that will cause the motor output to balance the frictional forces in the system.

Section VI. REPRESENTATIVE MILITARY APPLICATIONS OF SERVOS

15. POSITIONING LOADS

Servos are used to position guns, searchlights, radar antennas, compass repeaters, control surfaces of aircraft, and rudders of ships. In general, they are used when the load is so located that a direct mechanical connection to the operating station is undesirable or impossible, or when the signal originates in another equipment and automatic operation is desirable.

16. AUTOMATIC TRACKING

Servos used for automatic tracking in radar operate in response to signals provided by the radar itself. Tracking is the process of following a moving target with some device that indicates the target direction. In optical tracking, a telescope is directed at a moving target by an operator (or sometimes by two operators who operate a pair of telescopes that are mechanically connected) by holding the target in the center of the field of view. In radar tracking, the radar can be directed at a moving target by operators who observe the radar output, or by automatic tracking using servo systems. In automatic tracking, the reflected radar signals indicate any difference (error) between the actual position of the radar antenna and the desired position. An automatic tracking system is fast and precise. It generally is more accurate than a manual tracking system, except in the presence of jamming. The enemy may jam a tracking radar to interfere with its tracking, which will spoil the accuracy of any gunfire based on information from the radar. Jamming is accomplished by sending strong signals at the operating frequency of the radar which are detected by the radar receiver, and cause it to deliver output signals that have nothing to do with the tracking error. If the jamming signals are strong enough, they may mask the tracking-error signals almost completely and make the radar inoperative. With jamming, the servo tracking system fails, because servos are not designed to exercise judgment and, consequently, are unable to distinguish between the real and false error signals. Special servos can be built, however, that are useful in combatting certain types of jamming, and these perform better than human operators under the conditions for which they are designed. Chapter 9 describes in detail several examples of servo systems and component applications used in actual military equipment.

Section VII. SUMMARY AND REVIEW QUESTIONS

17. SUMMARY

a. A servo may be briefly described as a simplified control system in which the controlling action is dependent upon the external demands of the system and the behavior of the quantity controlled. The difference between these two actions is referrred to as the servo error. The successful operation of a servo is completed when this servo error is zero.

b. Control systems, generally, are used to accomplish certain tasks more easily, more rapidly, or more precisely than human operators. They may be divided into two types: open and closed. An open system operates only in response to external orders; a closed system bases its action both on external orders and on the behavior of the load it controls.

c. The positioning servo is representative of a large class of servos used in military applications. All positioning servos consist of the following elements: load, actuator, controller, follow-up, a data receiver, and a sensing element.

d. There are three representative methods of servo controls: on-off, stepwise, and proportional.

e. A rate servo is one that controls the rate (speed) of positioning a load, rather than its position. It usually is operated with proportional control and, when so operated, is inherently stable.

f. Servo systems have many applications, such as positioning guns and searchlights, automatically altering the pitch of aircraft propellors, and in positioning automatic-tracking radar.

18. REVIEW QUESTIONS

a. Give a basic description of the operation of a servo loop.

b. What is the difference between an open control system and a closed one?

c. Give four general functions of control systems.

d. Name the basic components of a positioning servo system and their basic functions.

e. What is the difference between a positioning servo and a rate servo?

f. Name three types of control methods used in a positioning servo.

g. Give a brief description of the operation of proportional control in a rate servo.

CHAPTER 2

STABILITY AND ERROR CONSIDERATIONS

Section I. STABILITY IN SERVO SYSTEMS

19. INTRODUCTION

Although a servo system can be defined rather broadly, mainly, it is used to transmit movement commands for the purpose of remote control. For example, to drive an antenna, a handwheel is turned in a servo system, and some distance away a large antenna rotates. If the handwheel were coupled mechanically to the antenna, the antenna would stop turning when the handwheel stopped. However, since the handwheel and the antenna are coupled to each other electrically, the antenna, due to its inertia, may rotate past the stopping point determined by the handwheel. This action is called overshooting. After the antenna passes the intended point (zero error), the sensing element detects an error opposite in polarity to the original error, causing the actuator to exert a force which slows the antenna and then returns it toward the desired stopping point. The distance the load travels past the stopping point before its motion is reversed is called the overshoot distance. Successive overshooting, alternately, in opposite directions is called oscillation, or hunting, and a servo that oscillates or hunts is called an unstable servo. This chapter discusses the various types of damping methods used to reduce instability, and characteristics and types of errors found in servo systems.

20. DAMPING

a. A discussion of damping can be introduced by considering the example of the steering of a ship. If the ship is off its proper heading, the steersman applies the rudder to correct the heading. If the rudder is centered when the proper heading is reached, the ship will swing past its correct orientation. Opposite rudder then is applied to return the ship on course. Now, if the steersman applies opposite rudder to check the swing of the ship before it reaches its proper position, he is essentially using a form of damping to stabilize the ship's heading. Servo systems are stabilized similarly by providing a damping force, either electrically or mechanically, that causes the actuator to apply a reverse force to the load before the stopping point is reached.

b. With little damping (all systems have some damping), a servo will oscillate, but the overshoots are successively smaller until the oscillation finally ceases. A servo in which the load comes to rest after one or more overshoots is called an underdamped servo. With increased damping, the load can be slowed so as to rest at the proper position without overshoot. The smallest amount of damping that prevents overshoot is called critical damping. A critically damped servo reduces the error to zero and the load reaches its rest position in the shortest possible time. A servo having more than critical damping is called an overdamped servo; it takes an unnecessarily long time for the load to reach its rest position since the load is slowed down more than is required to avoid overshoot.

c. Damping is produced in servo systems by either frictional mechanisms or electrical networks. The methods discussed in this section include both frictional and electrical damping. The frictional type of damping discussed is viscous-friction damping, while the electrical methods include error-rate damping and acceleration damping. Combined viscous-friction and error-rate damping, which is both frictional and electrical, is also included.

21. VISCOUS-FRICTION DAMPING

a. General. Viscosity is the characteristic of a fluid which produces a resistive force when there is relative motion between adjacent portions of the liquid or between a solid body and a liquid with which it is in contact. This resistive force is proportional to the relative velocity between the solid and the fluid, and is known as viscous friction. The viscous properties of fluids produce damping (viscous-friction damping) whenever relative motion occurs between a fluid and a solid body with which the fluid is in contact. Viscous-friction damping mechanisms often consist of two parallel discs or concentric cylinders which are separated by a small gap filled with a viscous fluid (oil), and which are capable of moving relative to one another. Viscous-friction damping also occurs when a viscous fluid flows into pipes or tubing.

b. Characteristics. Viscous-friction damping decreases oscillatory behavior of a servo system by introducing a frictional retarding force at the servo motor shaft. This normally is done by filling the clutch mechanism with oil. This damping method is used mainly in low-power servo systems. The advantage of viscous-friction damping is its reliability. It has, however, disadvantages, which are as follows:

(1) Power is wasted in unproductive work, and the size of the motor may be inadequate to furnish the additional torque required to overcome the viscous friction torque at high speeds.

(2) Increasing the frictional force leads to increased lags in velocity, acceleration, etc.

(3) In high-power servo systems, this damping method is impractical because of the problem of heat dissipation.

c. Viscous-Friction Damping Mechanism. Figure 10 illustrates a mechanism capable of producing a viscous-frictional force used in the damping of servos. This mechanism is added in the follow-up linkage between the follow-up shaft and the follow-up head. Although this mechanism can be used in on-off, stepwise, and proportional servos, this discussion describes the operation of the mechanism in the on-off servo only. The follow-up head has a main and auxiliary drive. The main drive uses a flexible shaft connected directly to the follow-up shaft; the auxiliary drive is through gears, rigid shafts, and a slipping clutch. The auxiliary drive moves the follow-up head faster than the follow-up shaft; the main drive attempts to turn the follow-up head at the same speed as the follow-up shaft. If the auxiliary drive should become disabled, the main drive will turn the follow-up head at the same speed as the follow-up shaft. However, due to the flexible coupling, the follow-up head will lag the follow-up shaft by an amount dependent on the degree of flexibility of the shaft and the size of the load presented by the follow-up head. The slipping clutch consists of two paddle wheels running in a housing filled with oil. One paddle wheel is connected to the driving shaft of the clutch, the other to the driven shaft. When one wheel is turned, it whirls the oil which moves the other wheel in the same direction. A frictional retarding force results from the viscous friction between the oil and the housing and paddle wheels. As a result of the viscous friction, the oil will heat and cause energy to be removed from the system. Assume that the load is at rest when an external order is applied to the system. The sensing element detects the error (difference between the actual load position and the desired position) and turns the actuator on. The main drive attempts to turn the follow-up head at a speed equal to that of the follow-up shaft. The auxiliary drive, however, turns the follow-up head at a faster rate until the resistance of the twisted shaft is sufficient to balance the force transmitted by the damped, slipping clutch. At this point, the follow-up head has been shifted ahead of the load. The load continues to move toward its proper position, while the follow-up head moves (ahead of the load) toward a position of zero error. Shortly before the load reaches its proper position, the follow-up head will have reached a position of zero error. The sensing element, therefore, sees a zero error and turns the actuator off. Due to its inertia, the load (and consequently the follow-up head) continues to move in the same direction (overshoot). As a result, an error signal of the opposite polarity is developed and thus turns the actuator on again, but in the reverse direction. This tends to slow the load, and if the system is adjusted correctly, the load will come to rest at the proper position. At the same time, since the follow-up shaft slows and finally stops, the shift in the position of the follow-up head is reduced to zero so that it reaches its normal position, and the sensing element sees a zero error as the load comes to rest. Viscous-friction damping, however, introduces velocity lag into the servo system, which results in delay in positioning of the load (see par. 27d).

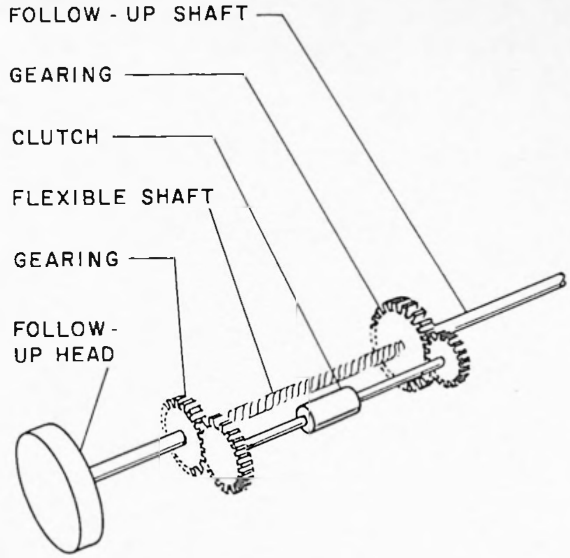


Figure 10. Viscous damping mechanism.

22. ERROR-RATE DAMPING

a. General Characteristics. Error-rate damping is accomplished by generating an error signal consisting of two parts: one part is proportional to the position error; the other is proportional to the velocity of the load. The combined signal is proportional to the rate of change of error of the load, hence the name error-rate damping. The complete signal is applied to the actuator to produce a retarding force. An advantage of error-rate damping over viscous-friction damping is that it will not introduce velocity lag into the system. It will not, however, eliminate other velocity lag resulting from the inherent friction of the system.

b. Theory. An error-rate damped servo system (fig. 11) uses the basic components of the servo systems described in previous paragraphs and introduces some components not yet discussed, but which are treated in subsequent chapters. The sensing element used in this system is a differential; the controller is a dc generator and a dc amplifier; and the actuator is a servo motor. The differential indicates the angular difference between the positions of the load and the external order (input-output error) by the angular position of its error shaft. Mechanically coupled to this shaft is the slider of a potentiometer P, the resistance element of which is connected across a battery B. Also driven by the differential error shaft is a dc generator G. One terminal of this generator is connected to the potentiometer slider. The other generator terminal and the center tap of the battery are connected to the input terminals of a dc amplifier, the output terminals of which are connected to the servo motor of the system. This servo motor, either directly or through a suitable gear, drives the output shaft and load. Under these conditions, a constant input-output error from the sensing element causes the error shaft of the differential device to be angularly displaced from its zero-error position, by an amount proportional to the position error. The potentiometer slider P, which is mechanically connected to the error shaft, is shifted by a corresponding amount, and the voltage V_1 across the potentiometer, therefore, indicates the magnitude and direction of the error.

If the error varies to some other value, the angular position of the error shaft and the position of the slider change accordingly. During the error variation, the error shaft at the same time rotates the armature of the generator G by a certain angle and causes the generator to develop a voltage V_2 that is proportional to the error speed. Thus, the voltage V_3 that is impressed on the input terminals of the amplifier feeding the servo motor is the algebraic sum of the voltages V_1 and V_2. The servo motor, in turn, either increases or decreases the movement of the load in accordance with the time rate change of the error.

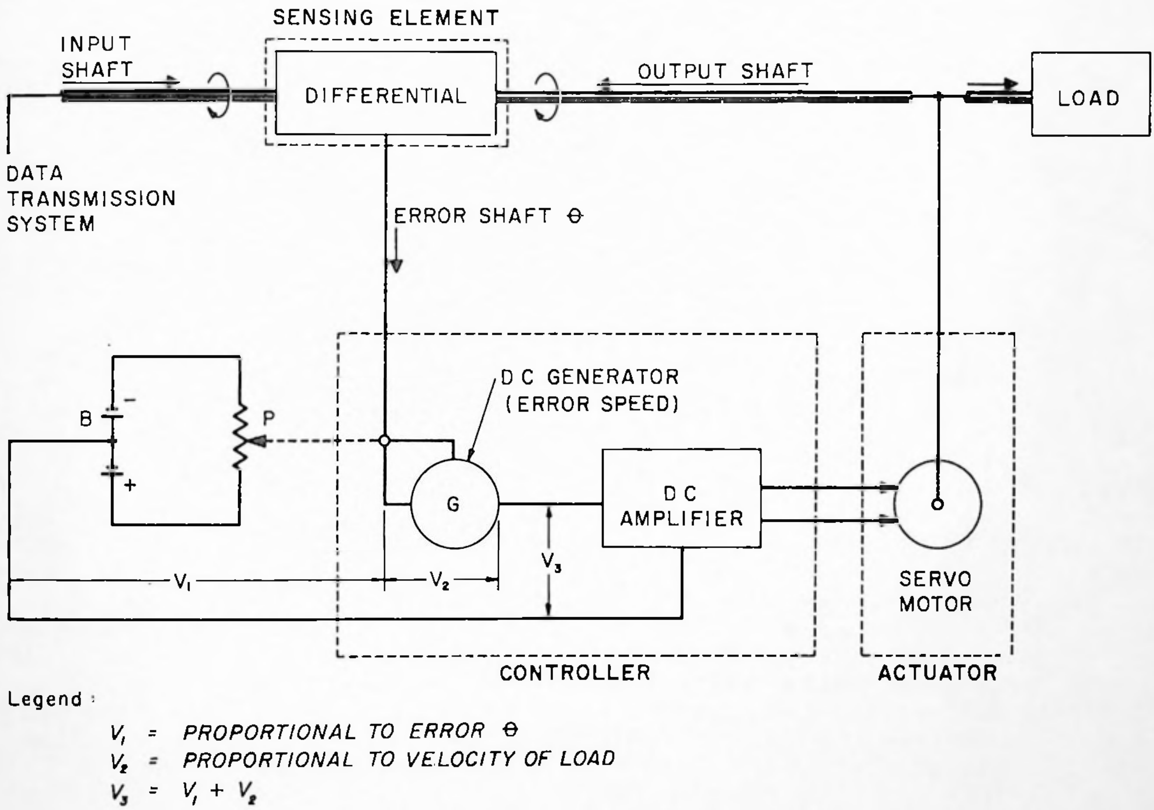


Figure 11. Error-rate damping servo system.

23. COMBINED VISCOUS AND ERROR-RATE DAMPING

Error-rate damping does not introduce additional velocity lag into the system. However, there is always a certain amount of unavoidable friction in the moving parts of the system's mechanism, and if the servo is an induction motor with a high resistance rotor, an additional retarding force is added to the system. Both these retarding forces affect the system as would viscous friction damping. It is necessary, therefore, to consider an operating positioning servo as having combined viscous-friction and error-rate damping. Such a servo is represented schematically in figure 12.

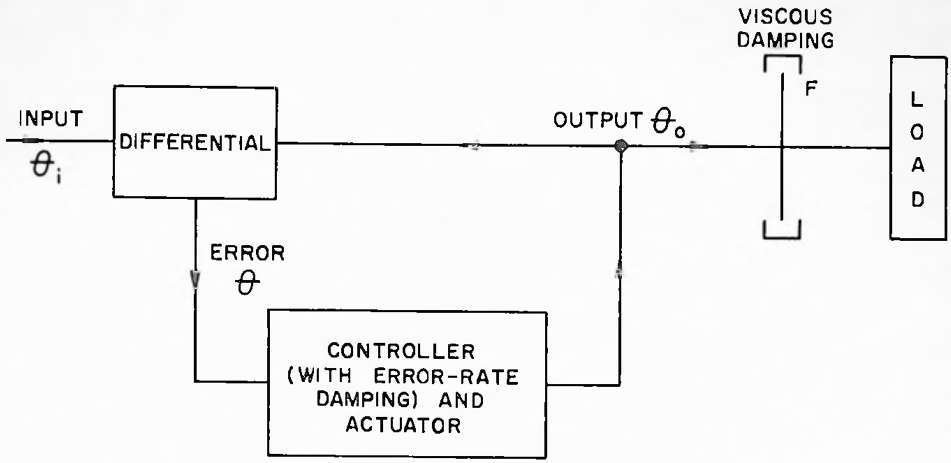


Figure 12. Servo system with combined viscous output and error-rate damping.

24. ACCELERATION DAMPING

In addition to the normal errors which are characteristics of on-off and stepwise servos, an additional error, known as acceleration lag, is present in servo systems using proportional control. If the load position orders change nonuniformly, the ordered position will change with a varying velocity, and the speed at which the load moves must do the same. Since additional force is required to alter the velocity of the load, the load will lag behind its ordered position when it is being accelerated and will run ahead of its ordered position when it is being decelerated. It is possible to compensate for this lag by means of acceleration damping. This type of damping is obtained from an electrical circuit which produces a signal proportional to the acceleration error which, in effect, behaves in the same way as the viscous-damping mechanism (par. 21). It exerts a slowing force on the load and applies it in advance so that the load comes to rest at the stopping point called for by the speed order. Acceleration damping generally is not used since the acceleration error of most systems is small compared with the other errors; however, it can be helpful when precise control of the load is desired.

25. GENERAL

Before discussing the error characteristics of servos, it is necessary to understand the terms, transient error and steady-state error. A transient error is an error with a changing magnitude. Since the magnitude of an error can only change when the servo is actuated (load is moving), transient errors only occur at this time. A steady-state error is an error with a constant magnitude. Steady-state errors can occur when the load is at rest and also when the servo is actuated. This section includes a discussion on the factors determining the transient and steady-state errors and their effects on the operation of viscous damping servos, error-rate damping servos, and combined viscous and error-rate damping servos.

26. TRANSIENT ERROR

Transient errors occur when the servo is in a transient condition; that is, when there is a change in acceleration or deceleration of the load or when the load is moving from a rest to a moving position. Oscillation is an example where transient errors occur. There is continual, changing acceleration and deceleration, and the magnitude of the error is constantly changing, both negatively and positively, until the load reaches a rest position. The factors determining the transient errors are too numerous and unpredictable for this discussion. In general, it can be stated that the characteristics of the servo components themselves are the determining factors of transient errors with each characteristic having a part in delaying the time in which the system reaches a steady-state. Therefore, these errors are treated by considering the overall response of the system in which it reacts to specific external orders.

27. STEADY-STATE ERROR

Steady-state error occurs when the servo is in a steady-state condition; that is, when the load is at a rest position, when the load is moving at a constant velocity, or when the load is moving at a constant acceleration or deceleration. The factors determining the steady-state errors of a servo are the dead space error, effect of noise on dead space, mechanical error, velocity lag, and acceleration lag.

a. Dead Space Error. When a load controlled by a servo is at rest in a position other than the one called for by the external position order, the sensing element normally recognizes the existence of an error, and the resulting error signal that it originates causes the actuator to move the load toward its proper position. However, the servo will not act unless the error exceeds some minimum value. If, for example, the load can be displaced 0.02 inch in either direction before the servo acts, the servo is said to have a dead space of 0.04 inch. This dead space results in inaccurate positioning of the load.

b. Effect of Noise on Dead Space. If the electrical noise of the system is sufficient to mask the error signal (in cases of small errors), the actuator would be prevented from correcting the error. Thus, noise increases the dead space error of the system.

c. Mechanical Error. The mechanical errors inherent to servos are the errors caused by the limited precision with which the mechanical parts of the system can be made. These normally are found in the follow-up head, the data receiver, and the sensing element. In a positioning servo, the position order is set into the system by rotating the data receiver, and the load position is repeated to the sensing element by rotating the follow-up head. The precision to which the follow-up head and data receiver can be manufactured determines the amount of mechanical error introduced into the system.

d. Velocity Lag. Suppose that the position order sent to a servo is changing uniformly. The load must move at a constant speed in order to remain in the position called for by the external order. Under this condition, viscous damping (par. 21) produces an error called velocity lag. The effect of a viscous damping device is to displace the follow-up head so that it runs ahead of the load when the load is moving. The load, therefore, in lagging behind the follow-up head and the data receiver, also lags behind the position order. The amount of the lag is proportional to the velocity with which the load moves. Friction, as previously discussed, increases velocity lag. Velocity lag caused by damping could be eliminated by removing the damping mechanism, but this would make the system unstable, which is more undesirable than the velocity lag error.

e. Acceleration Lag. Suppose the position order changes nonuniformly. The load then will move with a constant acceleration or deceleration. A force is required, however, to accelerate or decelerate the load. The actuator is unable to exert such a force unless the sensing element sees an error, and consequently the load lags behind its ordered position when it is being accelerated and runs ahead of its ordered position when it is being decelerated.

28. ERROR CHARACTERISTICS IN VISCOUS DAMPING

a. Steady-State Error. Velocity lag is the steady-state error commonly associated with a viscous-damped servo. This error is proportional to the difference between the input speed and the output speed of the load. This velocity lag exists only when the load is moving. In a practical servo with viscous damping, there are other factors affecting the steady-state error, such as static friction, moving friction, noise, and mechanical errors. Static friction, noise, and mechanical errors are responsible for the dead-space error, which exists when the load is stationary. The load does not move until the static friction is overcome, so that a small position error is introduced until the output torque of the controller and actuator become strong enough to overcome the static friction torque. In a practical servo with viscous damping that uses proportional control, the dead-space error is considerably smaller than the velocity lag. The effect of the moving friction is to increase the steady-state error when the load is moving by a fixed amount, independent of the speed of the load.

b. Transient Errors. Transient errors occur during a changing condition (transient response) of the servo system. The following several different types of transient response are possible: undamped response, critically damped response, underdamped response, and overdamped response.

(1) Undamped response. If there is neither friction nor damping in a servo system, the output shaft will oscillate continuously after receipt of a position order, and the transient error will be maximum. The frequency of the oscillation is called the natural frequency of the servo. The oscillation of the error is shown graphically in curve A of figure 13. The error is expressed in units of V_1/V_n as a function of time in units of $1/V_n$. V_1 is the input velocity in radians per second (where radians per second equals degrees per second times $\pi/180$ and V_n is the natural frequency in radians per second. Figure 14 shows the relationship between the input and output. At zero time units the input to the system is suddenly set into motion at a constant angular velocity V_1, so that the input angular position increases linearly with time. The output load being originally at rest, this input order produces an error between the positions of the input and output. At first, this error increases with time, as shown in the OM portion of curve A, figure 13. This error causes the controller and actuator to develop a force that is proportional to the error which sets the load in motion. The output load accelerates until its position, which has lagged behind that of the input, overtakes the latter and reduces the error to zero (point N, figure 13A). When the error is reduced to zero, the force, which is developed by the controller and actuator, is also reduced to zero, but the output inertia (load, motor, gears, etc.) of the system causes the output to overshoot this position. The output load then advances ahead of the input, producing a negative error (point P, fig. 13A); and the actuator, therefore, develops a negative, or retarding torque. This tends to decelerate the output load and again reduces the error to zero.

The output load, once more, overshoots the coincidence position, and the oscillation process or hunting, repeats itself indefinitely.

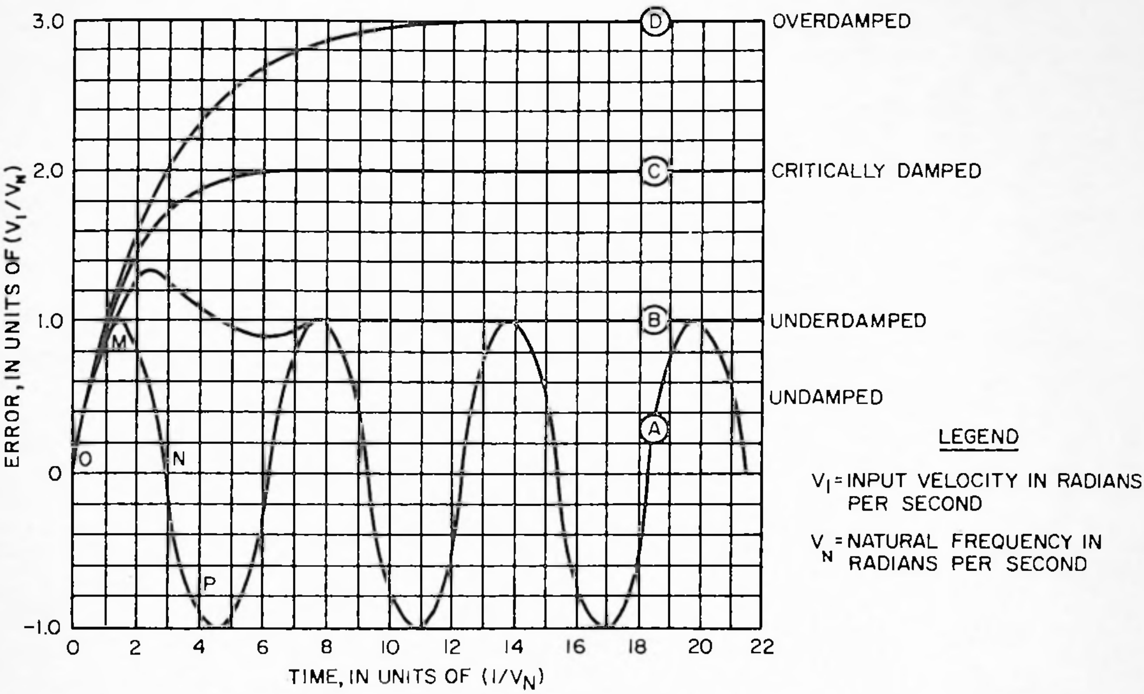


Figure 13. Response characteristics of viscous-damped servo.

(2) Critically damped response. If the viscous-friction damping is increased until it equals the critical value, the error approaches a constant steady-state value, as shown in curve C, figure 13. From zero to six time units the error is transient, after which the error is steady state. However, the steady-state error is twice the maximum amplitude of the error obtained with no damping. The input-output position relationship of the critically damped servo is shown in figure 14C.

(3) Underdamped response. For practical applications, the undamped and critically damped servos described previously represent limited cases. An undamped system has the advantage of having an average error equal to zero, but possesses the disadvantage of steady oscillation, or hunting. On the other hand, a critically damped system is free from oscillation, but has the drawback of causing a larger steady-state error than can be tolerated in applications where accuracy is required. A compromise between these conditions is generally desirable, where a tolerably small error is obtained at the cost of a temporary or transient oscillation occurring whenever the input speed is suddenly changed. This compromise is represented by the underdamped system in which the damping in the system is less than that of the critical value. The degree of underdamping is indicated by the ratio of the damping in the system to the critical value. Curve B, figure 13, and curve D, figure 14, indicate the error response and position, respectively, as a function of time for an underdamped positioning servo with a damping ratio of 0.5. It can be seen that while the transient error occurs for

eight time units, the magnitude of steady-state error is less. As the amount of viscous damping is increased from zero towards the critical value, the steady-state error is increased while the transient error is decreased.

(4) Overdamped response. This type of response is generally not encountered in practical servo systems. The response of the load to the input order is a single surge without oscillation, but the steady-state error is so great (see fig. 13D) as to make the system impractical. It will not be discussed further in this chapter.

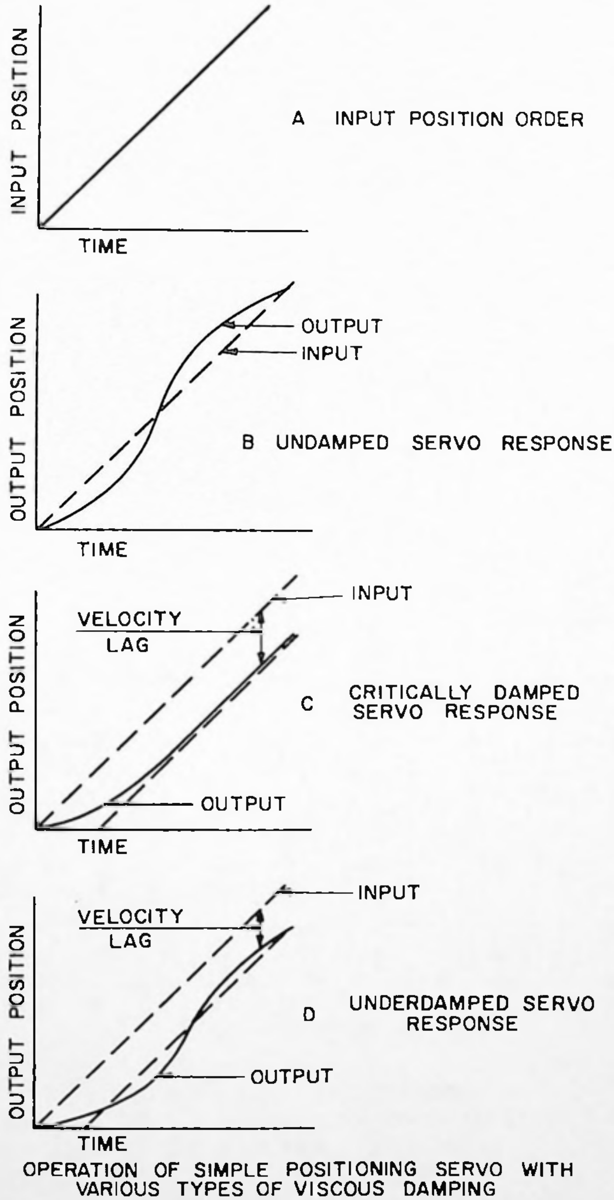


Figure 14. Graph of viscous-damped servo (output vs. input).

29. ERROR CHARACTERISTICS IN ERROR-RATE DAMPING SERVOS

a. Steady-State Error. The steady-state error of an ideal error-rate damped servo (assumed to be frictionless), to which a velocity-step input has been applied, is zero. No steady-state error exists in this type of servo, because, after the output load has been accelerated to the input speed, there is no output retarding force acting on the servo. No controller-actuator force is then necessary to maintain the output load moving at the input speed, and, consequently, this steady-state speed can be maintained without any error signal being fed into the controller. This contrasts sharply with the case of the viscous-damped servo, where a retarding force prevents the output load from maintaining its speed in the absence of a signal from the controller. In a practical error-rate servo, however, friction is always present. Therefore, a steady-state error is produced by the moving and static friction, noise, and mechanical inaccuracies, although it is not as great as in a viscous-friction damped servo.

b. Transient Error. An error-rate damped servo also can have an undamped response, underdamped response, or critically damped response, depending upon the intensity of the error-rate signal. If the error-rate signal is zero (assuming no friction), the response is as indicated in curve A of figure 15. This is the same response obtained for a viscous-damped servo (see previous discussion), and logically so, since the retarding forces are the same (zero). Curve B of figure 15 indicates the response of an underdamped error-rate servo system with a damping ratio of 0.5. Comparing it to figure 13B, it can be seen that the transient error for the error-rate servo is less than that of the viscous-damped servo. This also is

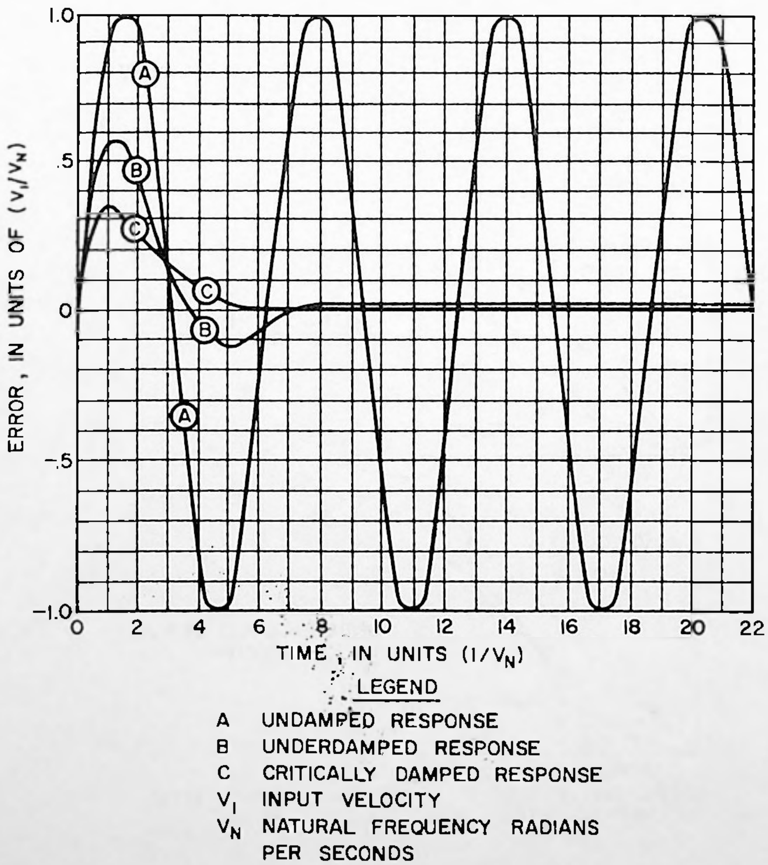


Figure 15. Response characteristics of error-rate servo.

true for the critically damped error-rate and viscous-damped servo systems (fig. 15C and 13C). From the curves shown in figure 15, it is apparent that a critically damped system is most desirable for an error-rate damped servo system, since the transient error is less and the steady-state error is not a factor. However, since some viscous damping exists in every servo system, some compromise is necessary and the system is somewhat less than critically damped (underdamped).

30. ERROR CHARACTERISTICS IN COMBINED VISCOUS AND ERROR-RATE DAMPING SERVOS

Every servo contains the equivalent of some viscous damping resulting from moving and static friction. A discussion, then, of error-rate damping is fine theoretically to show the advantages and disadvantages of the system, but practically, error-rate damped servos must be considered as combined viscous and error-rate damped servos.

a. Steady-State Error. The steady-state error of a positioning servo with combined damping, to which a velocity-step input has been applied, is constant and equal to the same value as in the servo with viscous damping alone, since no steady-state error results from error-rate damping (fig. 15). Figure 16 shows the steady-state error in a typical servo system with combined viscous and error-rate damping. Curve A shows the transient response that would result if the error-rate damping were removed. However, since the viscous damping remains in the system, the transient response gradually decays. Also, it does not decay about the zero axis, but about the value of the steady-state error in the system, which is the same for the underdamped, critically damped, and overdamped cases (curves B, C, and D of fig. 16). Since it is assumed that the viscous damping in the system remains constant, the steady-state error also remains constant.

b. Transient Error. The transient responses illustrated in figure 16 show the various degrees of error-rate damping combined with an irreducible amount of viscous damping. When these curves are compared with those for a viscous-damped servo shown in figure 13, it can be seen that the waveforms are similar, but as the viscous damping is increased, the steady-state error is increased considerably. Consequently, a minimum of viscous damping combined with a maximum of error-rate damping is the ideal for which to strive. A minimum of viscous damping is obtained by proper mechanical design. There is no limit to the amount of error-rate damping that can be designed into the system; the limitations are determined by the system response that is desired. But with a minimum of viscous damping in the system, the combined damping can approach that of the critical value.

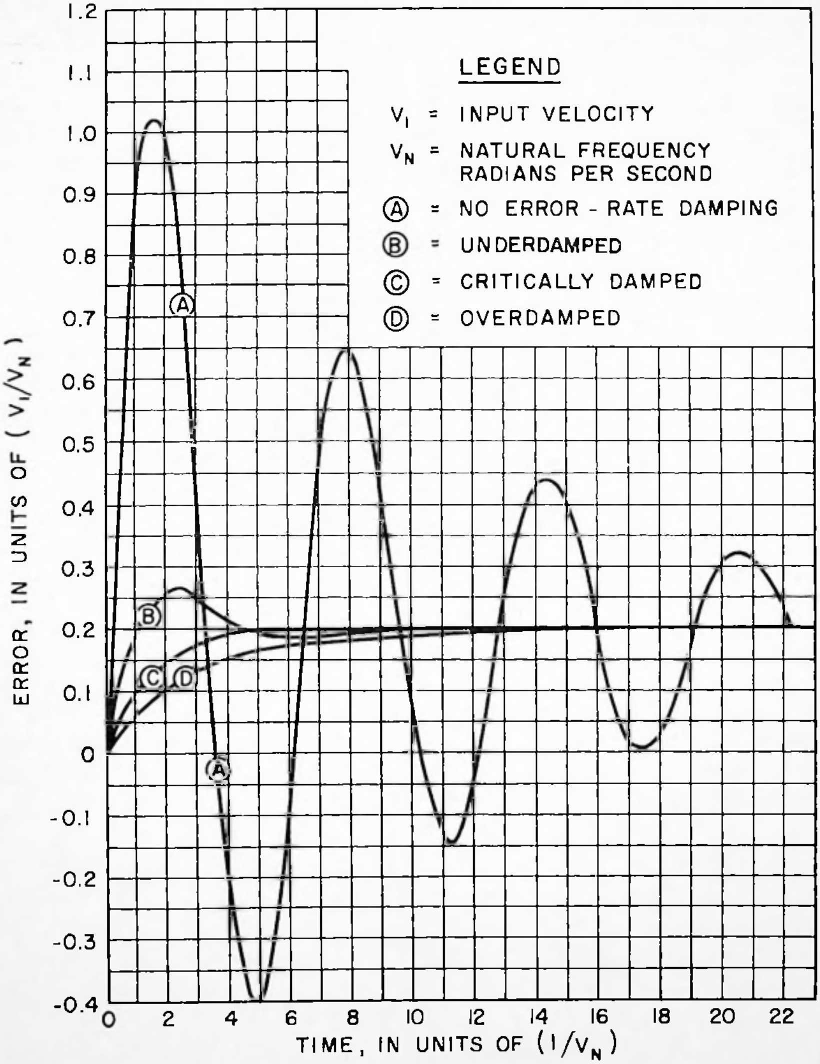


Figure 16. Response characteristics of combined viscous- and error-rate damped servo.

Section III. INTEGRAL CONTROL

31. INTRODUCTION

Viscous damping, error-rate damping, or a combination of both, stabilizes the transient response of a servo at the cost of producing a steady-state error (in the case of viscous output damping), or of requiring an amplifier and additional controller gain (in the case of error-rate damping). Error-rate damping is particularly effective in servos having a large inertia load. A large inertia load is defined as a load having tendency to remain at rest if at rest, or, if moving to keep moving in the same direction. However, these stabilization methods do not prevent the input-output error from increasing when the amount of power drawn from the system by the driven load is increased. In such cases, methods of integral control are generally used in addition to the aforementioned stabilization methods to reduce the error of the servo without raising the damping in the system to an amount that would create undesirable response characteristics. Integral control, therefore, is particularly valuable in cases of heavy, external load demands, such as are encountered in numerous industrial and military applications.

32. GENERAL METHOD OF INTEGRAL CONTROL

This paragraph does not present a detailed analysis of integral control, but rather a basic concept of its operation. The integral of a quantity over a definite time interval is equal to the average value of the quantity, during that time interval, multiplied by the length of the time interval. The integral of a large error which lasts a short time may be equal to the integral of a small error which lasts a long time. It frequently is desirable to ensure an average error of a certain set value, and for this purpose a signal proportional to the integral of the error may be added to the control signal. If, for example, oil is delivered to a tank through a valve whose opening is controlled by a servo, the addition of integral control will insure that, if the valve is not open wide enough for a certain period of time there will be another period during which it will be open more than necessary. As a result the average valve opening will be correct. Unfortunately, the addition of integral control makes the servo load try to coast past its ordered position in an attempt to compensate for the error which was present while it was approaching the position. This results in unstable operation, and the addition of error-rate control to damp the servo and make it stable once more will merely cancel the integral control effect. Fortunately, in applications where integral control is desirable, the existence of velocity lag is not normally objectionable. The servo, therefore, may be stabilized by viscous damping, which will not impair the integral control feature.

Section IV. SUMMARY AND REVIEW QUESTIONS

33. SUMMARY

a. Various types of damping methods are used in servo operation to prevent instability resulting from excessive hunting or oscillations. The common methods used are: viscous-friction output damping, error-rate damping, combined viscous-friction and error-rate damping, acceleration damping, and integral control.

b. Viscous-friction output damping introduces a retarding frictional force in the system for ensuring the stoppage of the load at its proper position.

c. Error-rate damping networks generate an error signal proportional to the positioning error and the velocity of the load.

d. All errors inherent in servo systems can generally be classified into two distinct types, namely, steady-state error and transient error.

e. Transient error is defined as that error whose magnitude is changing, and which must occur necessarily when the servo is actuated. Steady-state error is defined as that error whose magnitude is a constant amount, and can occur when the load is moving or at rest.

f. Integral control is used in servo systems to prevent the input-output error from increasing when the system is used to drive heavy loads. In integral control, a signal is generated that is proportional to the integral of the error which, in effect, reduces the average error of the system to zero.

34. REVIEW QUESTIONS

a. What are the three common types of damping methods used in servo systems? How do they differ from each other?

b. Name an advantage of viscous-friction output damping.

c. What are three disadvantages of viscous-friction output damping?

d. Describe briefly the operation of a servo system using error-rate damping.

e. What is the main advantage of combining viscous-friction output damping and error-rate damping in a servo system?

f. Distinguish between a steady-state error and a transient error.

CHAPTER 3

SYNCHROS AND SENSING ELEMENTS

Section I. INTRODUCTION

35. GENERAL

The sensing element of a servo system is the error-detecting device that senses or measures the difference between the input and output quantities. For example, the sensing element receives the external position order from the data receiver, and the actual load position from the follow-up head; it compares these, and originates an error signal. This error signal is electrical and indicates the difference between the external order and the actual position of the load. A variety of sensing elements have been developed. No attempt is made here, however, to list or discuss all of them. This chapter discusses the basic types of sensing elements including synchros, mechanical differentials, and differential amplifiers. Since synchros can be used as both sensing elements and combination of sensing element, follow-up head, and data receiver, this chapter also includes a discussion on the construction, operation and alignment of synchro transmitters and receivers, synchro control transformers, and synchro differential transmitters and receivers.

Section II. SYNCHROS

36. GENERAL

a. Synchros, as identified by the Armed Forces, are electromagnetic devices used primarily for the transfer of angular-position data. Physically, synchros resemble small electric motors; electrically, they are transformers whose primary-to-secondary coupling can be varied by physically rotating one winding inside the other. Synchro systems consist of two or more interconnected synchros. Systems that provide a low-power mechanical output sufficient to position indicating devices, actuate switches, or move light loads are known as torque systems. Systems that provide an electrical output are called control systems, and are used as sensing elements and follow-up links in many servo systems. Individual synchro units are designed for use in either torque or control systems. Some torque units may be used as control units, but control units cannot be used to replace torque units.

b. This discussion on synchros includes the construction, operation and alignment of the following: synchro transmitters and receivers, synchro control transformers, and synchro differential transmitters and receivers.

37. SYNCHRO CONSTRUCTION AND CHARACTERISTICS

To obtain a better understanding of synchro operation, a knowledge of its construction and characteristics is essential. Synchros are, in effect, transformers whose primary to secondary coupling may be varied by physically changing the relative orientation of the two windings so that one winding is free to rotate inside the other. The inner, movable, winding is called the rotor, and the outer, usually stationary winding, is called the stator. Figure 17 illustrates a typical synchro receiver unit. A synchro transmitter unit is similar to a receiver except that a damper is not used.

a. Rotor Construction. The rotor consists of either one or three coils wound on sheet steel laminations. The laminations of the rotor core are stacked together and rigidly mounted on a shaft. Slip rings terminate the end of the coil or coils and are mounted on, but insulated from the shaft. During rotation of the rotor, brushes ride on the slip rings to provide electrical continuity, and low friction ball bearings permit the shaft to turn easily. These ball bearings must permit rotation of the rotor shaft from very low speeds to speeds as high as 1200 revolutions per minute (rpm).

b. Stator Construction. The stator of a synchro is a cylindrical structure of slotted laminations on which three Y-connected coils are wound with their axis 120 degrees apart. Stators in differential and control transformers function as the primary windings; and in transmitters and receivers as the secondary windings. Normally, stators are not connected directly to an ac source; their excitation is supplied by the magnetic field set up by the rotation of the rotor.

c. Unit Housing. A cylindrical frame houses the synchro components so that the rotor is mounted within the stator and is free to rotate. Standard synchros have an insulated terminal block secured to one end of the housing. The internal connections of the stator and rotor terminate at this block where the external connections are made. Some special type synchros do not have a terminal block; the stator and rotor leads are brought out of the housing.

38. SYNCHRO TRANSMITTER

a. A synchro transmitter is a unit which electrically transmits angular information according to the physical position of its rotor with respect to its stator. The physical position of its rotor is determined mechanically or manually by the information to be transmitted; the end result is the transformation of angular data into corresponding electrical values. Synchro transmitters are normally connected to synchro receivers, synchro differential receivers, or synchro differential transmitters.

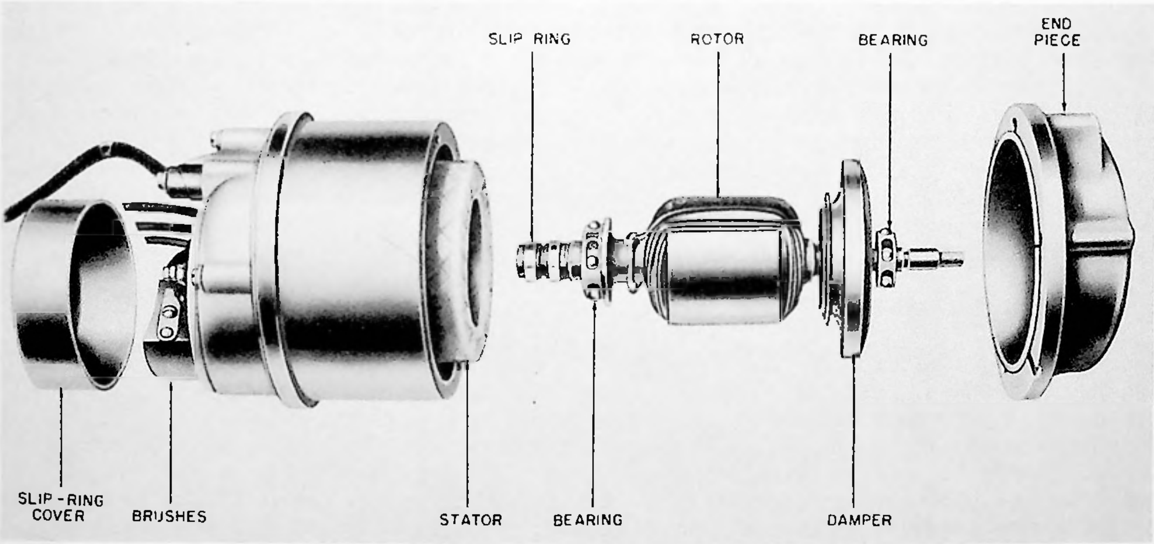


Figure 17. Synchro receiver unit.

b. When an ac excitation voltage is applied to the rotor, the current develops a magnetic field around the rotor winding. The rotor becomes an electromagnet with the poles continuously changing in proportion to the polarity of the ac current. The physical position of the rotor is determined by the synchro data to be transmitted. The transformer action between rotor and stator induces voltage in the stator. The effective voltage induced in each stator is dependent upon the angular position of the stator's axis relative to the rotor axis. Figure 18 illustrates the effective or rms values of voltage induced in one stator winding for one complete revolution of the rotor. The ac excitation voltage of the rotor is 115 volts with the maximum induced voltage at 52 volts.

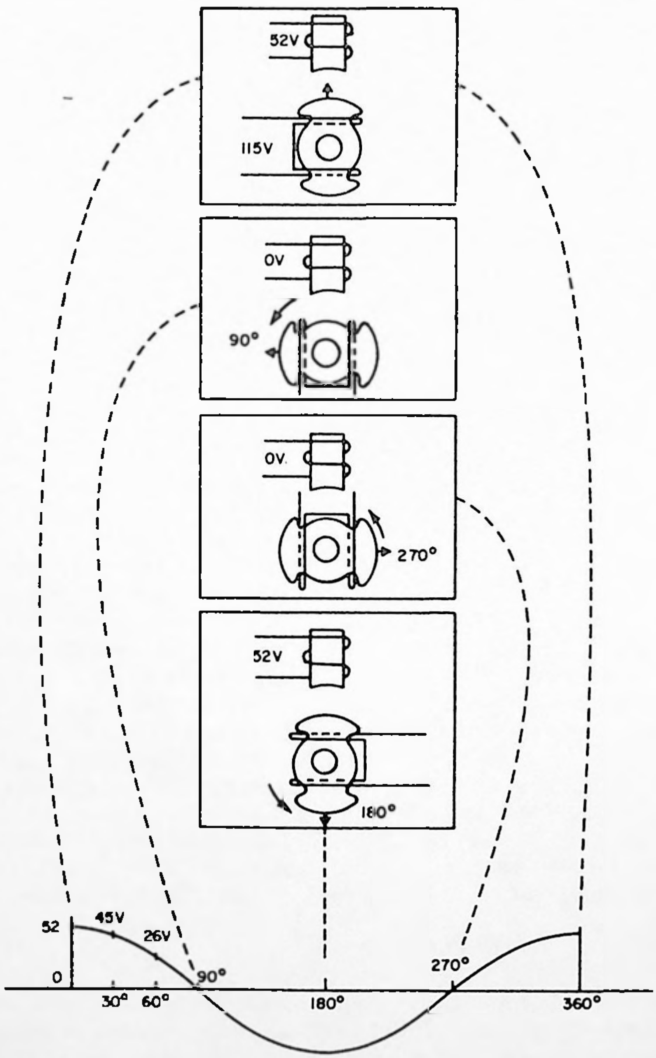


Figure 18. Stator voltage vs. rotor position.

c. There are two rotor positions, 0 degrees and 180 degrees, where the position of the rotor is parallel with the stator windings. In either of these two positions, all the magnetic field developed by the rotor current passes through the stator winding, and maximum voltage is induced in the stator. In one of the two positions, the stator voltage is in phase with the rotor voltage; in the other, the two voltages have a phase difference of 180 degrees. The position of the rotor when the two voltages are in phase is called the zero or reference position. The induced voltage for two stator positions is zero, as shown in figure 18. In one of these positions, the rotor is at 90 degrees, and in the other, the rotor is at 270 degrees.

39. STATOR VOLTAGES IN A SYNCHRO TRANSMITTER

In a synchro unit, the actual induced stator voltages cannot be measured because the common connection between the stator windings is inaccessible. Therefore, when measuring the induced voltages of a synchro, the terminal-to-terminal voltages must be considered. When the maximum terminal-to-terminal voltage is known, the terminal-to-terminal voltage for any angular displacement can be determined. Figure 19 shows the effective or rms variations in the induced voltage showing the amplitude and phase as a function of the rotor position for synchro units using 115 volts and 26 volts for rotor excitation. For example, if a rotor using an ac excitation of 115 volts is turned 60 degrees from the reference position in a counterclockwise direction, the S3-S1 voltage is approximately 78 volts and is in phase with the R1-R2 voltage; the S1-S2 voltage is approximately 78 volts and is 180 degrees out of phase with the R1-R2 volts; and the S2-S3 voltage is zero volts.

40. SYNCHRO RECEIVER

a. A synchro receiver is electrically identical to a synchro transmitter and is used to receive the transmitter synchro data. Physically, it differs by having a mechanical damper on its shaft (fig. 17) and low friction bearings. The damper is free to rotate on the synchro shaft, but is partially restrained by friction disks which are rigidly connected to the shaft, thus preventing overshoot, which may cause motor action at the synchro receiver. Figure 19B shows the voltages which must be applied to the stator to turn the rotor to a desired position determined by the transmitter synchro. It should be remembered that a transmitter synchro is a unit whose shaft is turned; the receiver synchro is the unit whose shaft follows.

b. A synchro receiver is connected to a synchro transmitter, as shown in figure 20. In this figure, the rotors of both synchros are at 0 degrees and are connected to the same ac power source. A maximum voltage, 52 volts, is induced in the S2 winding of the transmitter synchro by the alternating magnetic field of the rotor coil because the coupling between these coils is maximum at 0 degrees. The S1 and S3 coils are so wound that at 0 degrees the induced voltage is 26 volts, in phase with the S2 voltage. Since the receiver synchro is electrically identical to the transmitter synchro and the two rotors are connected in parallel, the voltage induced in each receiver stator is equal to that of the corresponding transmitter stator. However, in each case, the voltage developed in the receiver stators opposes the voltage in the transmitter stators. Therefore, in each complete electrical stator circuit of the system the sum of the voltages is zero. No current flows in the stator coils to establish a magnetic field and no force is exerted on the rotors. Similar static conditions result from any angular rotor position providing that the position is the same for both transmitting and receiving rotors.

41. SYNCHRO CONTROL TRANSFORMER

a. A synchro control transformer receives electrical synchro data and has its shaft set mechanically by an external source. It develops an output voltage at its rotor terminals by the difference between the rotor shaft and the position called for by the synchro data. It thus combines the functions of a data receiver, follow-up, and sensing element. The synchro control transformer normally controls a positioning servo which sets its rotor shaft at the same time that it positions a load in accordance with the synchro data. The stator windings receive the synchro data from either another control transformer or a synchro transmitter. The magnetic field created by the stator currents represents the position of the rotor of the synchro supplying the excitation. By transformer action, voltage is induced in the rotor which is the difference between the rotor shaft position and the position called for by the synchro data.

b. The synchro control transformer is connected to the synchro transmitter in the same way as a synchro receiver, except the rotor of the control transmitter is not connected to the ac source (fig. 21). The currents in the stator windings are determined by the voltages applied by the synchro transmitter. The rotor itself is wound so that rotor position has little effect on the stator currents. Therefore, the rotor does not turn to any particular position when voltages are applied to the stator windings. When current flows in the stator windings of a control transformer, a resultant field is produced. The interaction between the rotor position and this resultant field develops an output in the rotor coils which is a voltage representation of the difference between the position called for by the synchro data from the synchro transmitter and

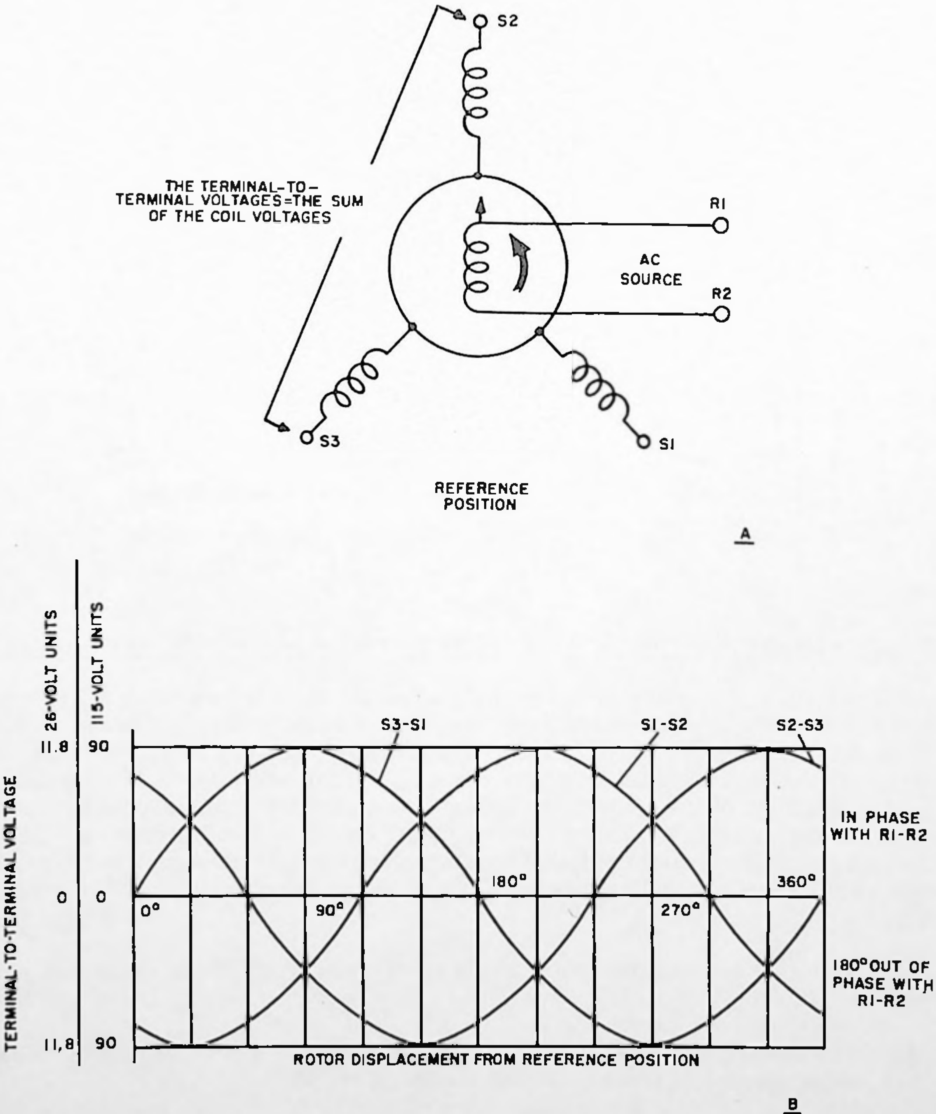


Figure 19. Terminal-to-terminal voltages.

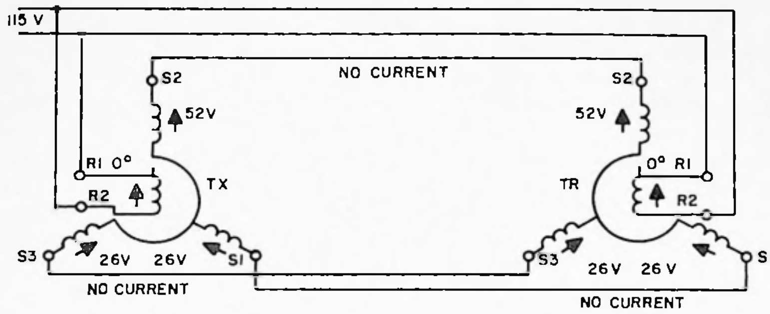


Figure 20. Connections of receiver synchro with transmitter synchro.

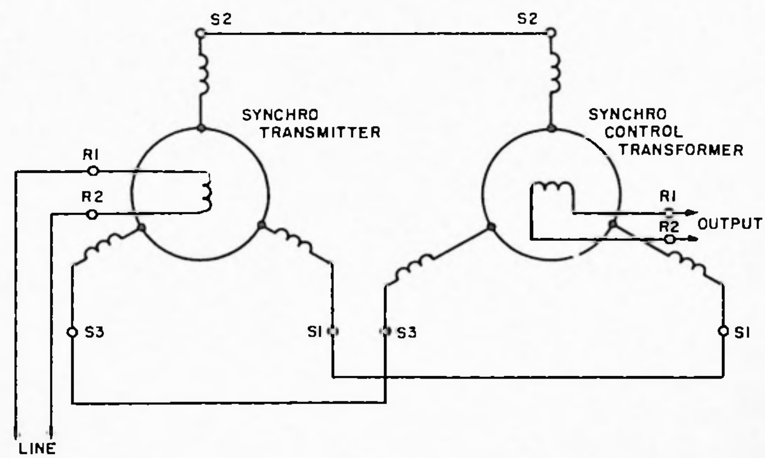


Figure 21. Synchro control transformer connected to a synchro transmitter.

the position of the rotor. For any position of the synchro transmitter rotor which produces the resultant field, there are two positions of the control transformer for which no voltage is induced. The servo, however, drives toward one of these positions and away from the other. The zero position of the control transformer rotor is one for which there is no induced voltage when the stator windings of the control transformer are connected to a synchro transmitter whose rotor is at zero position. There are two positions for which this is true. The zero position is the one for which a slight positive (counterclockwise) rotation of the control transformer rotor results in an output having the same phase as the excitation of the synchro transmitter rotor.

c. The following are the important points to remember about the operation of a control transformer:

(1) The electrical output of a control transformer is zero when its rotor is in the same electrical position as the transmitter rotor.

(2) When the displacement between the rotors of a control transformer and transmitter is less than 90 degrees, the magnitude of the output of the control transformer is proportional to the angular displacement between the two rotors.

(3) The phase of the control transformer's output indicates the direction of the angular displacement between the two rotors.

42. SYNCHRO DIFFERENTIAL UNITS

a. The demands on a synchro system are not always so simple as the positioning of an indicating device in response to the data received from one source. In some cases, it may be necessary to use a synchro system for a response to specific data from more than one source. For example, an error detector used in checking fire-control equipment employs a synchro system to determine the error in a gun turret's position with respect to the desired position determined by an external source. To do this, the synchro system must accept two signals, one containing the desired position order and the other giving the turret's actual position. The system must then compare the two and position an indicator to show the difference between them, which is the error. Therefore, to perform a function of this type, a different type of synchro is needed which can accept two-position data signals simultaneously, add or subtract the data, and furnish an output proportional to the sum or difference of the two inputs. This is accomplished by a synchro differential which can perform all three of these functions.

b. Synchro differentials can be used as either transmitters or receivers. When a differential unit is used as a transmitter, one electrical and one mechanical input produce one electrical output; when used as a receiver, two electrical inputs produce one mechanical output. In differential units, both rotor and stator windings consist of three Y-connected coils.

43. SYNCHRO DIFFERENTIAL TRANSMITTER

a. A synchro differential transmitter receives both electrical and mechanical inputs. Instead of developing an error voltage, however, its output is synchro data. Figure 22 shows a synchro differential transmitter connected to a synchro transmitter. If the incoming synchro data is equivalent to shaft angle A, and the mechanical shaft setting of the synchro differential transmitter is shaft angle B, the electrical output is synchro data equivalent to either shaft angle (A-B) or shaft angle (A+B).

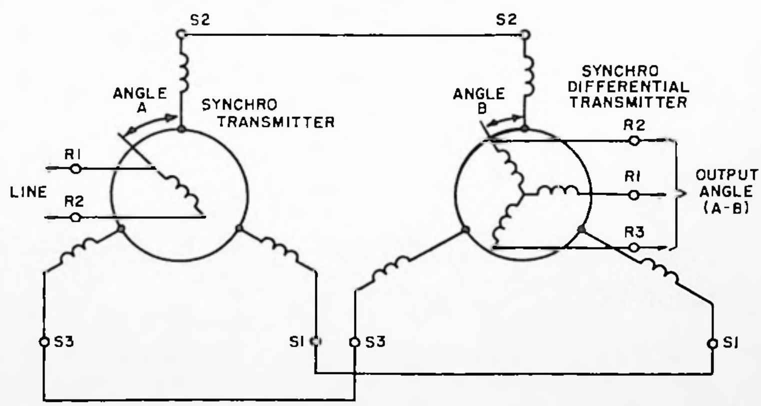


Figure 22. Synchro transmitter connected to a synchro differential transmitter.

b. The rotor field (resulting from angle A) of the synchro transmitter is reproduced in the stator winding of the differential transmitter. This induces voltages in the three windings of the differential rotor, exactly as the field of the transmitter rotor induces voltages in the windings of the transmitter stator. The resulting output voltages are treated in exactly the same way as those of an ordinary synchro transmitter. Thus, if the synchro differential rotor is set at zero, its output will be the same as that of the synchro transmitter which feeds it. If, however, the differential rotor is turned to a different rotor position, as angle B in figure 22, the effect on the output will be the same as that of turning the transmitter rotor in the opposite direction. This is because the differential stator reproduces the field of the transmitter rotor, and the differential rotor takes the place of a transmitter stator. Hence, the output of the differential synchro is synchro data, either angle (A+B) or angle (A-B), determined by the direction of rotation of the differential rotor.

44. SYNCHRO DIFFERENTIAL RECEIVER

a. A synchro differential receiver is connected to two synchro transmitters, either directly or through differential transmitters, and sets its rotor to the synchro data it receives. It develops low torque and is used as a remote indicator in the same way as the synchro receiver. The synchro differential receiver is electrically and physically similar to a synchro differential transmitter, with the exception that it has a mechanical damper like that of the synchro receiver.

b. A synchro differential receiver is connected as shown in figure 23. The stator windings reproduce the magnetic field of one transmitter rotor, and the rotor windings reproduce the field of the other. Thus, the differential shaft of the receiver is set in accordance with the combined input synchro data. In the case shown in figure 23 angle A is applied to the stator, and angle B is applied to the rotor. The differential shaft, therefore, is set to angle (A-B). Since the differential receiver has a field like a transmitter rotor, it behaves like a motor and lines up with the field. As before, the damper is required to avoid the effects of overshoot.

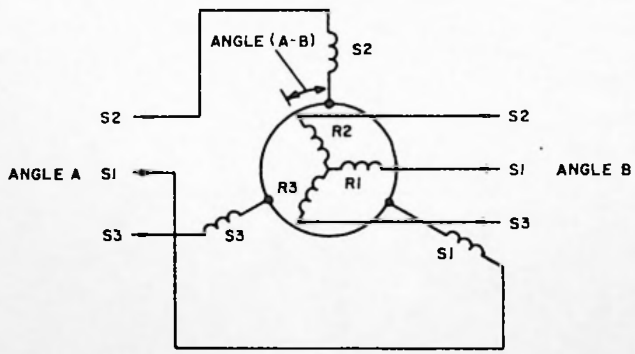


Figure 23. Synchro differential receiver connections.

45. ALIGNMENT OF SYNCHROS

All elements of a synchro data-transmission system must be synchronized to operate properly. That is, the synchro receivers must read correctly and the synchro control transformers must cause their associated servos to position loads properly. It is possible to set all of the input shafts and then rotate the receivers and control transformers in their mountings until proper results are obtained. The various components usually are so far apart, however, that this is inconvenient. Instead, each component is adjusted individually so that it operates correctly at zero or reference position. For example, the device which sets a synchro transmitter is set at its reference position. The synchro transmitter then is loosened in its mounting and its stator is rotated until its output corresponds to the zero shaft position. If this is done for all of the synchros in the system, the system will operate properly. The only equipment required for zeroing is a voltmeter. This meter should have a high range with an input of one and three-quarters or two times the synchro excitation voltage for full-scale deflection, and a low range with an input of about 1/20 of the excitation voltage for full-scale deflection. If no meter is available, a lamp, or two lamps in series, may be used when the high range is called for, and a pair of headphones for the low range. Dim lamps or low output from the headphones are the equivalent of a low meter reading. For zeroing 115-volt synchros, two 115-volt lamps, in series, must be used, since a single lamp will burn out if connected to a high-voltage source.

a. Zeroing a Synchro Transmitter. To zero a synchro transmitter, remove the stator leads and set the equipment to which the synchro is connected exactly on zero, loosen the clamps that hold the synchro housing in its mount, and follow the steps shown in A of figure 24. If there is no voltage between S1 and S3, the voltages induced in the stator windings to which they are connected must be equal. The synchro is, therefore, either at zero or at 180 degrees. The ambiguity is resolved by connecting S3 to one side of the line R2, and reading the voltage

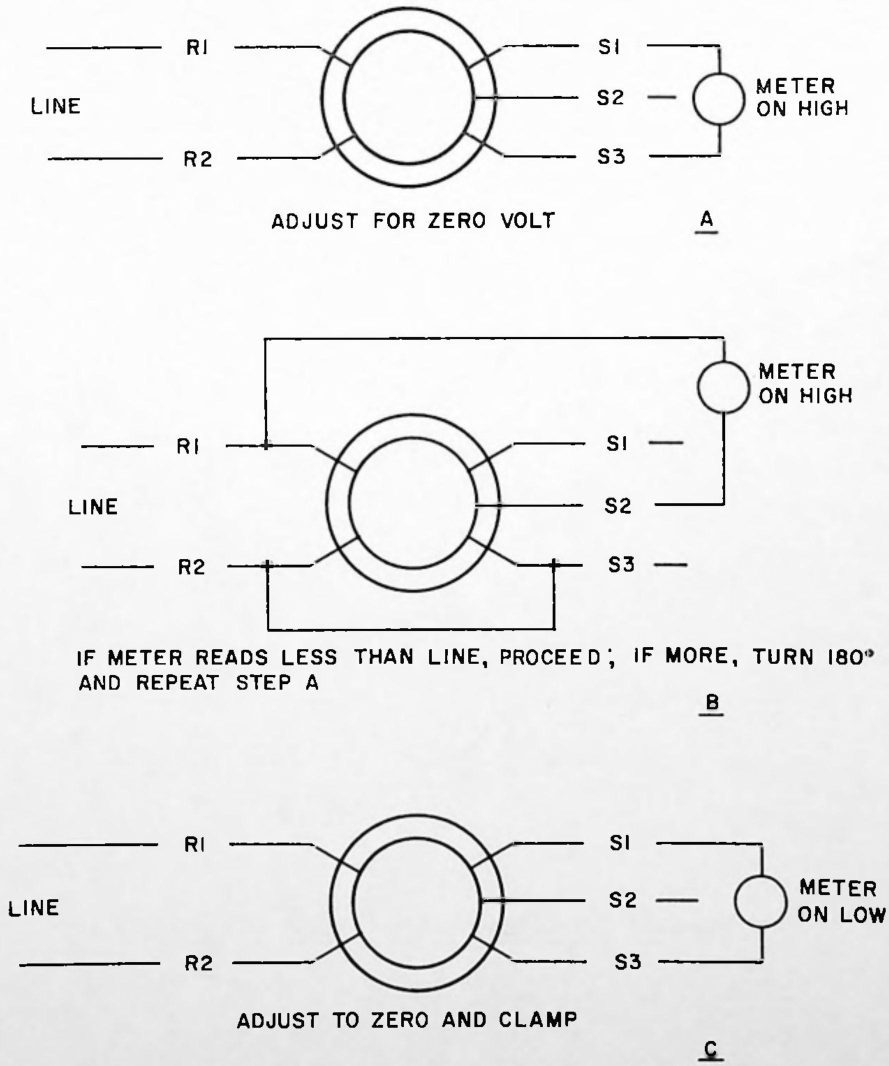
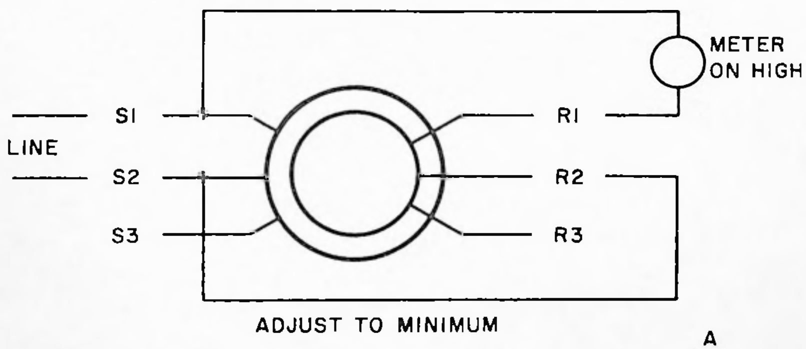


Figure 24. Zeroing a synchro transmitter.

between S2 and the other side of the line R1 (B of fig. 24). Since the voltage between S2 and S3 is in phase with the line voltage at zero degrees, and 180 degrees out of phase with it at 180 degrees, the meter will read lower at zero degrees than at 180 degrees. When the synchro is definitely near zero, a precise adjustment may be made using the low range of the voltmeter (C of fig. 24). Following this, clamp the housing securely in the mounting and reconnect the stator leads.

b. Zeroing a Synchro Differential Transmitter. Remove all leads from the synchro, set the equipment on zero, and loosen the clamps. Zero is determined approximately by connecting S1 and S2 to the line (A of fig. 25), and turning the stator in its mount until the voltage between R1 and S1 is minimum. At this point the voltage between R1 and R2 is in phase with the line. The setting of the differential then is approximately zero degrees, since the first condition for electrical zero requires that the phase at R2 be the same as the phase at S2. Precise adjustment is obtained by connecting the differential as shown in B of figure 25. The differential then is moved precisely to the point of zero voltage, as indicated by the voltmeter. This last step is to provide for the second condition of electrical zero; that is, there should be zero voltage between R1 and R3. When the adjustment has been completed, tighten the mounting clamp and reconnect the leads.



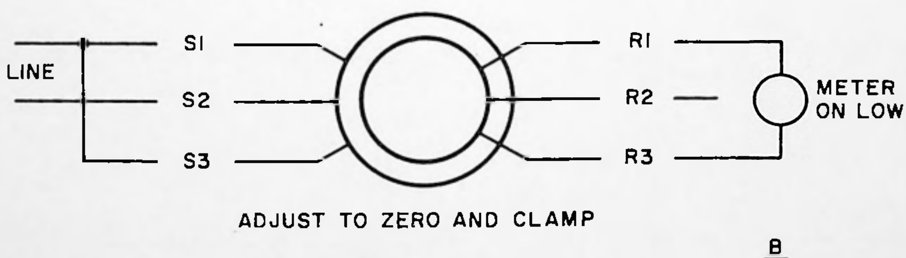


Figure 25. Zeroing a synchro differential transmitter.

c. Zeroing a Synchro Control Transformer. Remove all leads from the synchro, set the equipment on zero, and loosen the mounting clamps. Determine the approximate zero position by connecting the control transformer as shown in A of figure 26, and adjusting the unit for a minimum reading on the voltmeter. At this point the rotor voltage is in phase with the line (S1-S3) voltage. Next, connect the control transformer as shown in B of figure 26, and adjust the unit for a zero indication on the voltmeter. When this reading is obtained, the unit should be clamped and the leads reconnected. When no bias is used, the voltmeter reading obtained during the last step indicates the synchro output. However, in many cases, particularly with coarse synchros, bias is added to the synchro output. The combined signal, synchro output plug bias, must then be zero, and the meter must be connected as shown in B, so that it reads the sum of the two voltages. This may be omitted in the preliminary adjustment shown in A (although this step may also be made with the bias circuit connected), but the final adjustment always must be made on the basis of combined synchro output and bias.

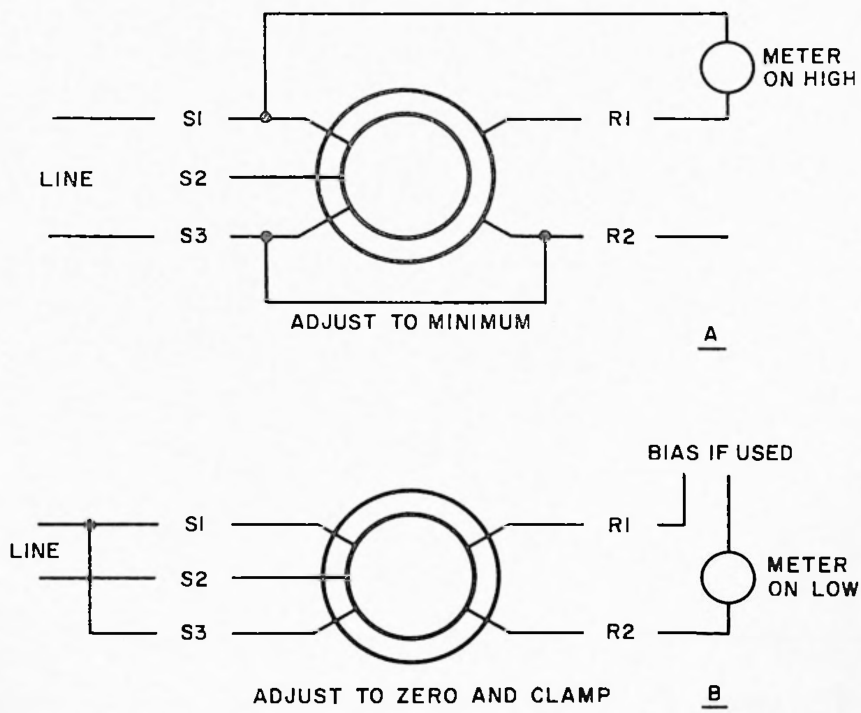


Figure 26. Zeroing a synchro control transformer.

d. Zeroing a Synchro Receiver. To zero a synchro receiver, remove the stator leads, loosen the clamps, and connect as shown in figure 27 to simulate a zero position input. The synchro receiver will set itself to electrical zero, and it may be rotated in its mount until a dial or pointer reading of zero is obtained. Tighten the clamps and reconnect the leads. Do not leave the synchro connected to the line longer than necessary.

e. Zeroing a Synchro Differential Receiver. Remove all leads from the synchro, loosen the clamps, and connect as shown in figure 28 to simulate a zero electrical input to both rotor and stator. Rotate the synchro in its mount until a zero dial or pointer reading is obtained, clamp, and reconnect the leads. Do not leave the synchro connected to the line longer than necessary.

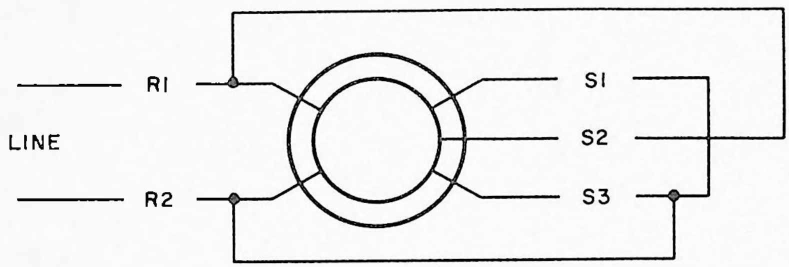


Figure 27. Zeroing a synchro receiver.

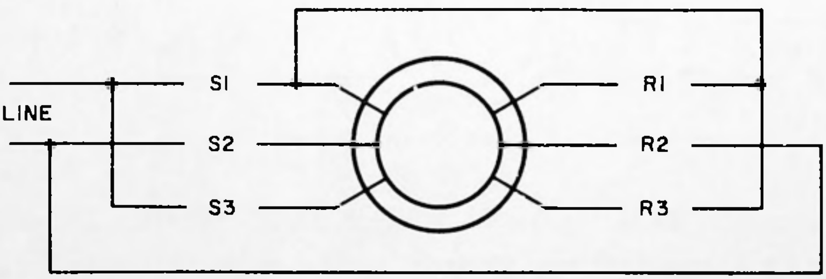
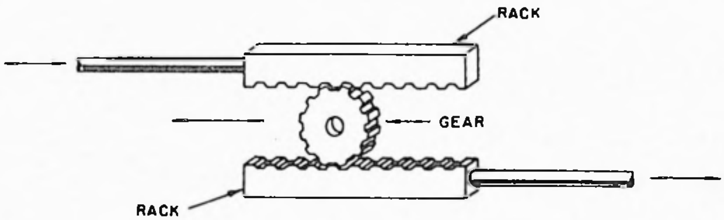


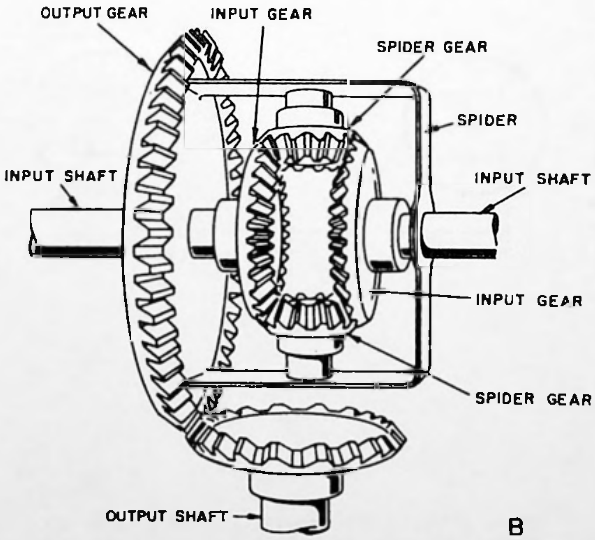
Figure 28. Zeroing a synchro differential receiver.

46. MECHANICAL DIFFERENTIAL

The mechanical differential is a basic sensing element used to compare two mechanical positions when they are in the form of shaft rotations. Its operation can be understood easily from A of figure 29, which shows two racks and a small gear which meshes with both of them. If the two racks move equal distances in the same direction, the small gear moves with them. If only one rack moves, the gear rolls between the racks and moves half as far as the moving rack. If the racks move equal distances but in opposite directions, the gear rolls between them but remains in the same place. In the mechanical differential, the two racks are folded around (B of fig. 29) and become a pair of bevel gears. The gear between the racks is replaced by a gear called the spider gear, which is carried on a mounting frame called the spider. In the usual differential there are two spider gears. In the mechanical differential shown in B of figure 29, it should be noted that the input shaft on the left is not connected to the output gear, and the input shaft on the right is not connected to the spider. If both of the input shafts turn through the same angle in the same direction, the spider rotates through the same angle as the input shafts. If only one input shaft turns, while the other remains stationary, the spider rotates through one-half the angle of that input shaft. If the input shafts are turned through equal



A



B

Figure 29. Mechanical differential.

angles but in opposite directions, the spider does not move. The behavior of the differential is summed up by the statement that the spider turns through an angle equal to one-half the sum of the angles through which the input shafts have been turned. It now can be seen that the mechanical differential may be used as a sensing element. Assume that one of the input shafts of the differential is turned by rotation of the data-input shaft. The other input shaft of the differential is turned by rotation of the follow-up shaft. If the data-input shaft and the follow-up shaft turn in opposite directions through equal angles, the spider does not rotate. This occurs when the load is positioned properly. The displacement of the spider from its zero position is thus a measure of the error in the load position. If the actuator is mechanical or hydraulic, the spider may act directly on the controller through additional gearing. If the actuator is electrical, the spider may turn a potentiometer which provides an electrical error signal.

47. DIFFERENTIAL AMPLIFIER

a. A differential amplifier circuit (fig. 30) functions as a sensing element when both the external input signal and the follow-up signal appear as voltages. These two voltages are compared in this circuit and a differential voltage is developed. The inputs may be two dc voltages, in which case, the output is a dc voltage, or they may be two ac voltages combining to form an ac voltage output.

b. For purposes of discussion, assume that the external input signal is applied to the control grid of V2, and the follow-up signal to the control grid of V1. The conduction of V1 varies according to the grid input signal, causing a variation in the voltage developed across the common cathode resistor of V1 and V2. This change in cathode voltage varies the conduction of V2, which, in turn, produces a change in V2 plate voltage. The output taken at the V2 plate is proportional to the difference between the external input voltage and the follow-up voltage, and is the error signal used in the servo system.

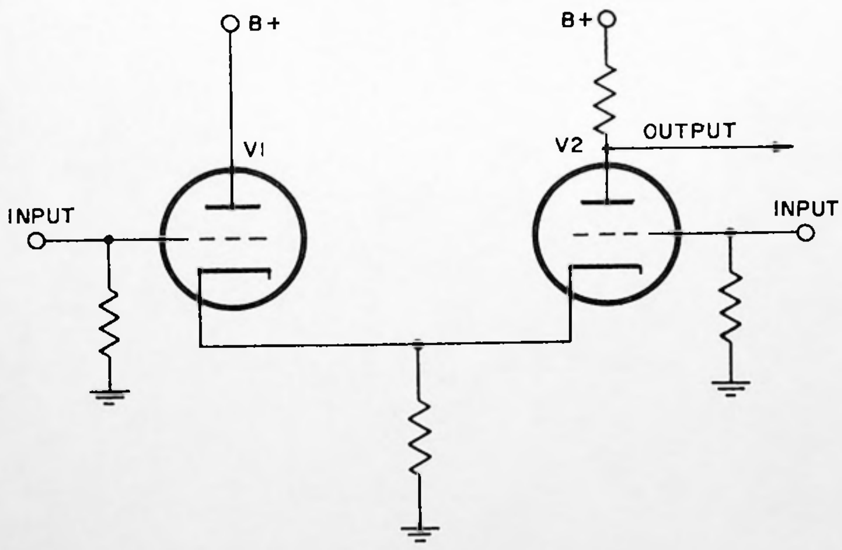


Figure 30. Differential amplifier circuit.

Section IV. POTENTIOMETERS

48. TYPES OF POTENTIOMETERS

A potentiometer is a tapped resistor, in which the position of the tap (sliding contact) can be varied by some sort of mechanical control. The electrical resistance between the sliding contact and either end point of the resistance element is a predetermined function of the distance of the sliding contact from the end point of the resistor. Therefore, a potentiometer converts the position of the sliding contact into electrical resistance. The standard high resistance potentiometer used in communication circuits employs a resistance element consisting of a thin film of carbon deposited on some insulating material. However, this type of potentiometer is not practical in servo applications because the resistance of such a carbon film changes with wear and variations in temperature and humidity. Since a more rugged type is required, the potentiometers used in servos generally use resistance elements consisting of a number of turns of wire (wire-wound potentiometers). The potentiometers discussed here are classified according to their electrical characteristics as follows: linear, helipot, sine-cosine, and induction.

a. Linear Potentiometer. A of figure 31 illustrates a linear type of potentiometer commonly used in servo applications. The resistance wire is wound on an insulating strip called a resistance card. The card is bent so that it forms an arc of nearly 360 degrees and is mounted so that the slider makes contact with the winding along one edge of the strip. The slider usually is able to rotate continuously, but it loses contact with the resistance over minute arc increments. The potentiometer is considered as a variable voltage source rather than as a variable resistor, in that an input voltage is applied to the resistance element, and a fraction of this voltage appears as an output between the slider arm and one end of the resistance element. Unfortunately, the output of a potentiometer does not change smoothly as the slider is moved. Instead, the output voltage changes in jumps, each jump being equal to the voltage difference existing between adjacent turns of wire. A potentiometer having 1000 turns of wire on the resistance element is said to have a resolution of 1 part in 1000 or a resolution of 0.1 percent. This means that the smallest change in output voltage is 1/1000 of the input voltage. Since a linear sensing element is required in most servo systems, linear potentiometers are the most common types used. Also, the required tolerance in most servo systems is so close that only precision potentiometers normally are used.

b. Helipot Potentiometers. To improve the resolution of a linear potentiometer, the resistance element is sometimes wound in a helix (spiral-shape) as shown in the helipot potentiometer in B of figure 31. The slider arm may make as many as 10 turns before covering the complete resistance range. This permits many more turns of wire for the resistance element, however, the slider cannot be rotated continuously. The chief advantage in this type of potentiometer is that with a greater number of turns, the voltage jumps are smaller, resulting in closer tolerance and smoother operation.

c. Sine-Cosine Potentiometer. Figure 32 shows a typical sine-cosine potentiometer, in which the output voltage is proportional to the sine or cosine of the angle through which the potentiometer shaft is turned. Where the card is narrow, the resistance between two adjacent points in the winding turns is low, and the voltage changes slowly with the rotation of the slider arm. Where the card is wide, the length of wire in each turn is longer, the resistance is high, and the voltage changes at a faster rate with slider rotation. Therefore, the rate of change of the voltage is dependent on the resistance of the windings and, therefore, produces a nonlinear output voltage. This type of a potentiometer provides an output voltage proportional to the cosine of the angle of the potentiometer shaft when the zero position of the shaft coincides with the point at which the positive excitation is applied. If at this point, the shaft has turned through 90 degrees, the output voltage is proportional to the sine of the shaft angle.

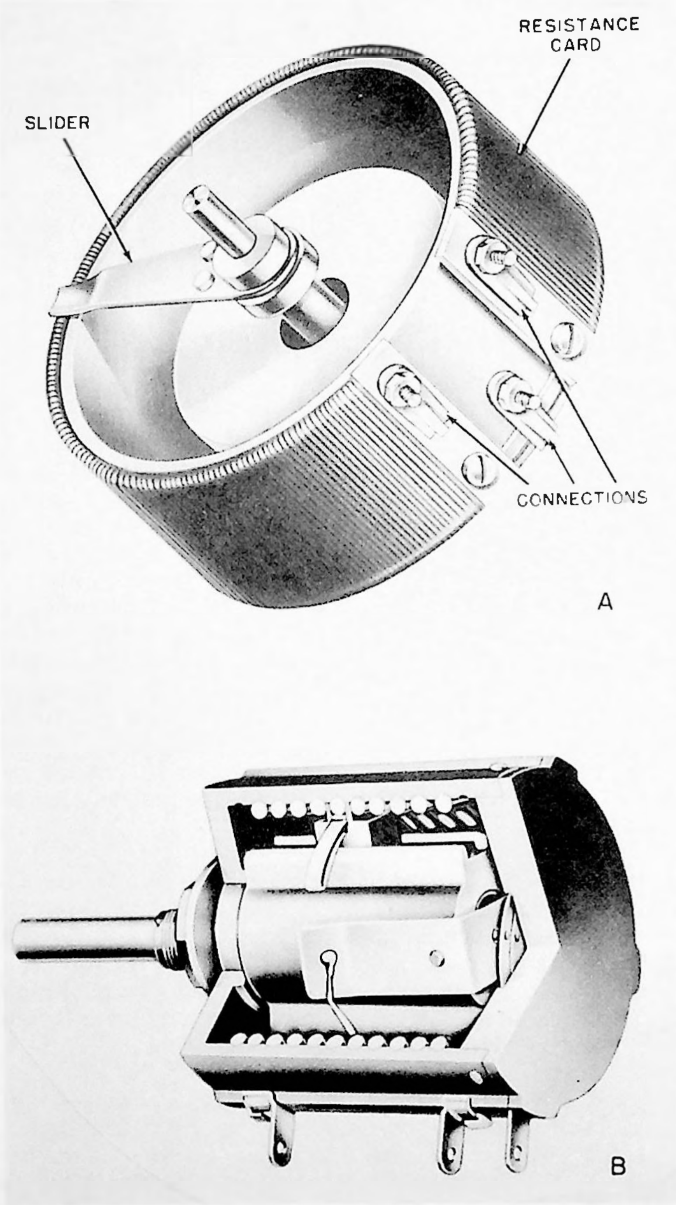


Figure 31. Linear potentiometer.

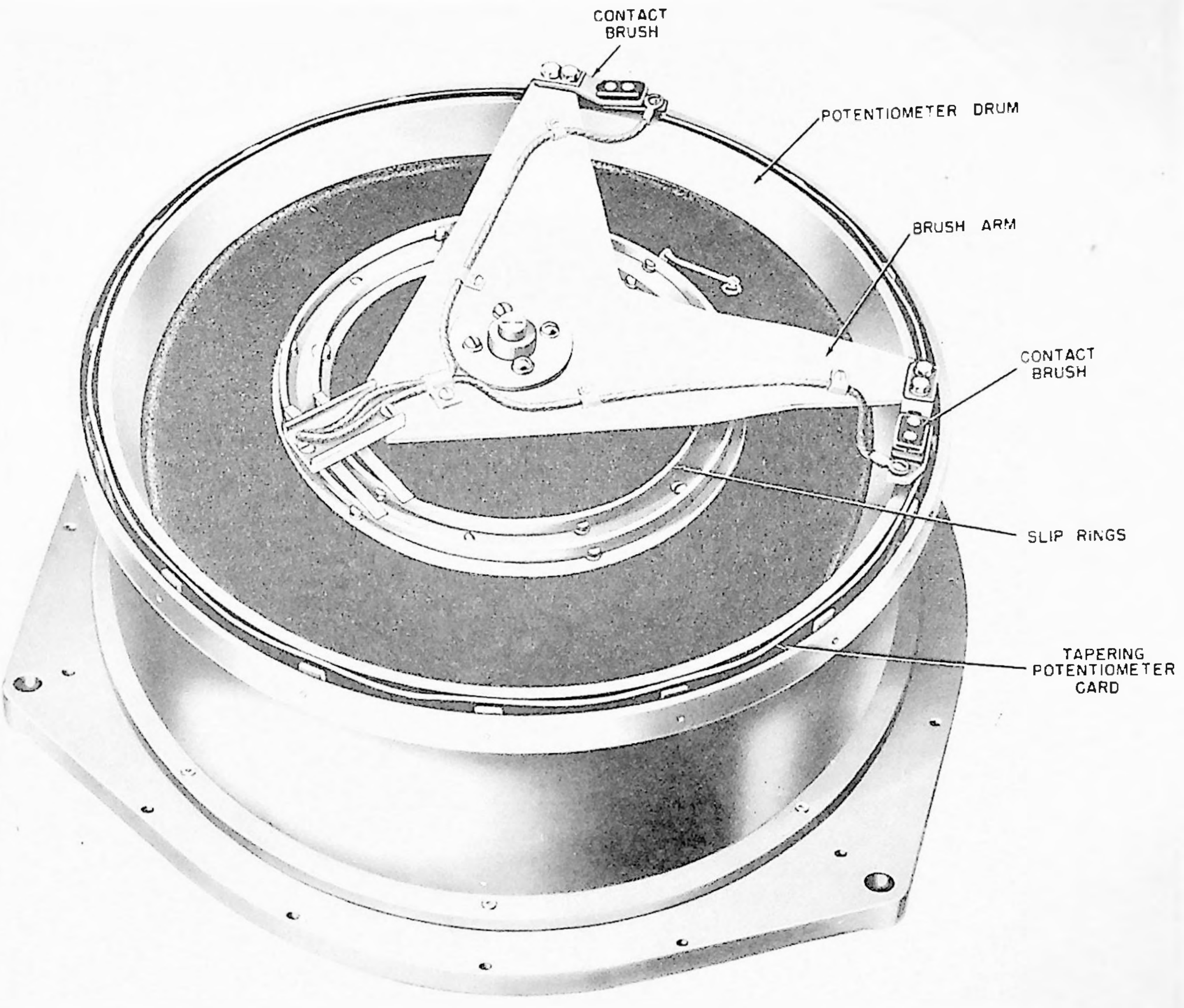


Figure 32. Sine-cosine potentiometer.

d. Induction Potentiometer. An induction potentiometer is a rotary transformer that generates an output voltage which is a linear function of the rotor angular displacement. As a result, these devices produce an output voltage proportional to the actual position of the rotor rather than the sine of the rotor's angular displacement, as in a synchro unit. Induction potentiometers are commonly used in place of conventional potentiometers to control positioning servos. In positioning servos, the position order is set on a potentiometer shaft and transmitted to the servo as an electrical voltage. A follow-up potentiometer at the servo develops an output voltage proportional to the actual servo position. The error voltage is the difference between the two potentiometer outputs. When conventional wire-wound potentiometers are used for this purpose, small errors cause the servo to hunt back and forth between positions corresponding to adjacent turns of the resistance element. This fault is minimized by the use of induction potentiometers which have a higher resolution than most wire-wound resistance potentiometers.

(1) Physically, an induction potentiometer is similar to a synchro unit except that it has only one stator (primary) winding and one rotor (secondary) winding. Both the stator and the rotor are cylindrical and are constructed from magnetic material. Induction potentiometers are designed for ac operation only.

(2) In comparison with wire-wound potentiometers, induction potentiometers have lower restraining torques and lower angular errors. Induction potentiometers also have isolated input and output circuits, low noise levels, and low null-voltage values. Their chief merit, however, lies in the fact that they have a higher resolution than most wire-wound potentiometers.

49. APPLICATION IN SERVO SYSTEMS

a. Since linear potentiometers are capable of developing an output voltage that is proportional to their shaft angle, they frequently are used as sensing elements in data-transmission systems. The rate servo discussed in paragraphs 11 through 14 operates by matching the output voltage of a tachometer against an external speed order in the form of a voltage. The speed order voltage may be obtained conveniently from a potentiometer by using a fixed excitation, and setting the shaft to an angle corresponding to the desired speed.

b. Potentiometers also can be used as sensing elements in positioning servos. The potentiometer used in this type of application (fig. 33) has a movable casing as well as a sliding contact. Connections are made to the two end points (A and B) of the resistance winding through slip-rings and brushes. A tap T, between two resistors R1 and R2, establishes a fixed potential with respect to terminal C. If the potential between the slider arm S of the potentiometer and terminal A is the same as between terminals T and C, then no difference of potential exists at the input to the amplifier, and there is no error voltage to actuate the motor. If the slider arm S is moved in either direction, a difference in potential immediately exists between

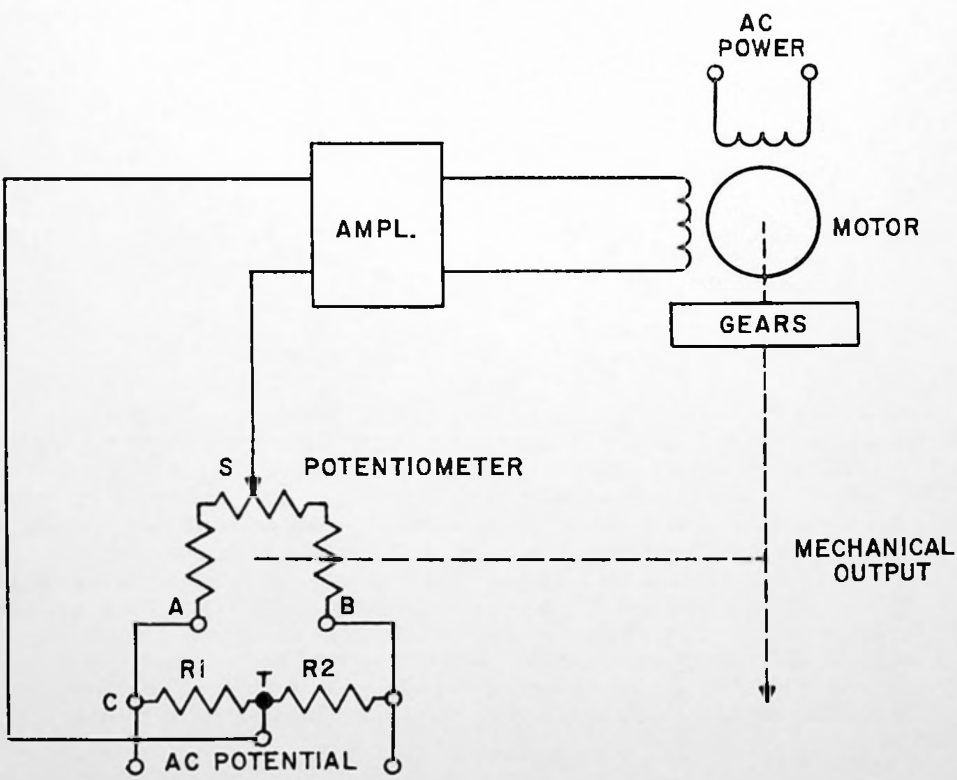


Figure 33. Operation of a potentiometer in a servo system.

S and A, and terminal C and T. This difference or error voltage is applied to the amplifier which, in turn, causes the motor to turn. The rotation of the motor causes displacement of the casing of the potentiometer through their mechanical linkage. When the casing has turned through the same angle that the slider arm was moved, the difference voltage is again zero, and the motor stops. Therefore, the motor turns only when there is an error voltage applied to the amplifier, and stops turning when the casing has turned through the same angular displacement as the slider arm S. As discussed in paragraph 48d, it also is possible to use two potentiometers (one as the sensing element and one as the follow-up device) to control a positioning servo system.

c. When ac power is not available, dc synchros (fig. 34) frequently are used in place of conventional synchro units as remote indicating systems. A circular sine-cosine potentiometer, with three sliding contacts spaced 120 degrees apart, is used as the sensing element. The three output voltages are similar to those of a conventional synchro transmitter, except that they are dc instead of ac voltages. The receiving element consists of three stator coils and a permanent magnet rotor. The three voltages cause current to flow in the windings, which sets up a magnetic field and positions the rotor.

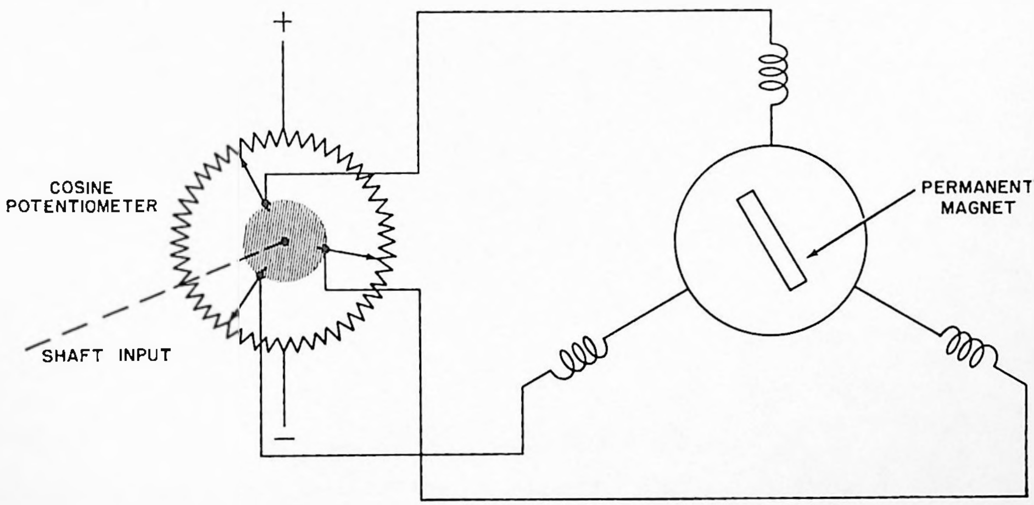


Figure 34. Dc synchro circuit.

50. MICROSENS

a. Microsens (fig. 35) are rotary transformers that operate similar to induction potentiometers (par. 48d). They consist of a four-pole stator and a special-shaped two-pole rotor. The rotor is mounted on ball bearings and, because it has no windings, requires no slip rings or brushes. The magnetic field of the input windings magnetizes the iron rotor, and the magnetic field of the iron rotor, in turn, induces a voltage that is proportional to the displacement of the rotor in the output windings.

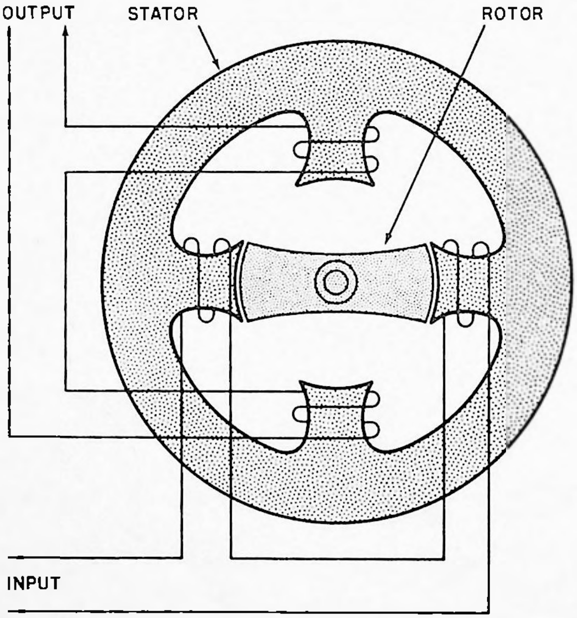


Figure 35. Microsen circuit.

b. The performance characteristics of a microsen unit depend upon several factors. The most important of these factors are the unit size, the excitation current, and the excitation frequency. Microsens have been manufactured in sizes ranging from 1.0 to 2.5 inches in diameter. Excitation currents may be selected with magnitudes up to 400 ma and with frequencies up to 1000 cps. However, the most commonly used values are 100 ma and 400 cps.

51. E-TRANSFORMER

The E-transformer (fig. 36) is used sometimes to control positioning servos. An ac voltage is applied to the input coil on the center leg of the core. When the armature is in its zero position, the magnetic field of the input coil is split evenly between the two outer legs, and the voltage induced in the two output coils are equal. The coils are connected so that the two voltages oppose each other, and the net output is zero. When the armature is displaced, more of the field passes through one of the outer legs than through the other. Therefore, the voltage induced in one output coil increases while the voltage in the other output coil decreases. As a result, the output is no longer zero. The output voltage is proportional to the displacement of the armature, being in phase with the input for displacements in one direction, and being 180 degrees out of phase with the input for displacements in the other direction. E-transformers are advantageous when used in a servo system that positions one mechanical part so that it follows the motion of another part. One part is connected to the armature, the other part is connected to the core, and the servo drives the follower part to a position for which the transformer output is zero.

52. LINEAR-CONTROL TRANSFORMER

A linear-control transformer is much the same as an E-transformer, except that the moving element is a short core which moves inside the three windings. With the core in the center position, the voltages induced in the two output windings are equal and the output is zero. As the core is moved, the voltage induced in one output winding increases while the voltage in the other output winding decreases. The output voltage is proportional to the displacement of the core.

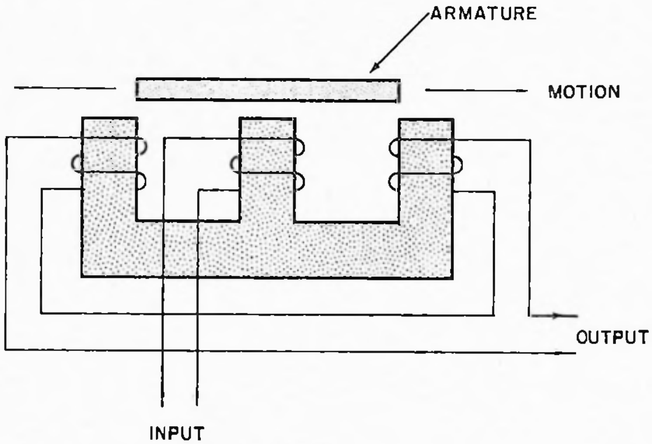


Figure 36. E-transformer circuit.

Section VI. SUMMARY AND REVIEW QUESTIONS

53. SUMMARY

a. Synchros function in servo applications as converters for mechanical shaft angles and electrical input signals. They can be used to convert the mechanical shaft angles into electrical signals, or, to convert electrical signals into mechanical shaft angles.

b. To differentiate between the functions of a synchro transmitter and a synchro receiver, remember that the shaft of the transmitter turns, whereas the shaft of the receiver follows.

c. A synchro control transformer develops an output voltage equivalent to the difference between its actual shaft position and that called for by the synchro data. It combines the functions of data receiver, follow-up, and sensing element.

d. A synchro differential transmitter develops synchro data equivalent to the sum or difference of its inputs, which are both mechanical and electrical. A synchro differential receiver is connected to two synchro transmitters, and sets its shaft to the difference between the transmitted angles. It is used normally as a remote indicator.

e. For normal operation of a synchro-data transmission system, each individual component should be set to a standard reference level of the complete system.

f. A mechanical differential is used as a sensing element in a servo system when two mechanical positions are compared. These positions are usually in the form of shaft rotations.

g. A differential amplifier circuit can function as a sensing element providing the input orders are both electrical.

h. A number of turns of wire is preferred over carbon as the resistance element of a potentiometer because the resistance of carbon changes with wear, which it would experience in normal servo operation.

i. In a servo system using a potentiometer as a sensing element, the induction potentiometer is preferred where a high degree of resolution is required.

54. REVIEW QUESTIONS

a. What is the basic difference between the construction of a synchro transmitter and receiver?

b. Give three advantages that a synchro system has over a mechanical system performing identical functions.

c. How is the rotor position in a synchro transmitter reproduced in a receiver synchro?

d. What determines the output voltage of a synchro control transformer?

e. Give three important points about the operation of a control transformer.

f. Give an example of the function of a differential synchro system.

g. Describe the procedure used in zeroing a synchro transmitter, synchro control transformer, and a synchro receiver.

h. Describe briefly how a mechanical differential operates.

i. What are three types of potentiometers used in servo applications?

CHAPTER 4

ACTUATORS

Section I. INTRODUCTION

55. GENERAL

In chapter 1, an actuator is defined as a device in a servo system that controls the movement of the load. The discussion here covers the types of actuators used in servo systems and how these types fulfill their functions. The following topics are discussed in this chapter: torque; characteristics and operation of series dc motors, shunt dc motors, and split-field dc motors; theory and characteristics of two-phase ac induction motors and split-phase ac induction motors; and characteristics of hydraulic actuators.

56. BASIC CONCEPT OF TORQUE

Before discussing the torque characteristics of motors, a basic understanding of what is meant by torque and how it is measured is necessary. Torque, by definition, is a force or combination of forces that produces or tends to produce a twisting or rotating motion. Torque is calculated by multiplying the applied force by the perpendicular distance between the line of action of the force and axis of rotation. For example, figure 37 illustrates a balance beam with equal torques. The two applied forces on this diagram are designated as A and B respectively. The axis of rotation is represented as X, with Y and Z designating the distances between the two lines of action of the forces and the axis of rotation. The torque of the 1-pound force is 3 foot-pounds in the clockwise direction. The torque of the 3-pound force is 3 foot-pounds in the counterclockwise direction. Since these two torque forces are equal and opposite in direction, the beam balance is not upset. Now suppose the force B in figure 37 is increased to 2 pounds. The torque produced by the 2-pound force is 6 foot-pounds. The beam balance then will upset in the clockwise direction. The same result could be obtained by increasing the distance of the 1-pound force from 3 feet to 6 feet.

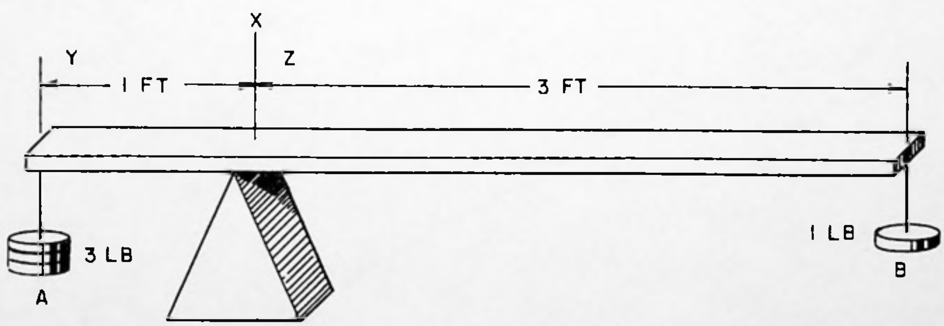


Figure 37. Equal torques balanced beam.

57. TORQUE CHARACTERISTICS OF MOTORS

a. From the torque discussion (par. 56) it is evident that the revolving of any body requires application of a twisting effort or driving torque. In the case of the beam balance, the driving torque when the beam is upset in the clockwise direction is 6 foot-pounds, whereas, the resisting torque is 3 foot-pounds. In an electric motor, the driving torque is produced by the magnetic action between the armature poles and the field poles; the resisting torque is produced by the load applied to its shaft. If the armature is 2 feet in diameter and the magnetic force applied at the armature surface is 30 pounds, then the torque that the shaft of the motor exerts is 30 foot-pounds. In order for the armature to be put into motion, it is essential that the driving torque be greater than the mechanical resisting torque of the load applied to its shaft. Once the armature is in motion it will accelerate until the driving torque and the resisting torque become equal; once this condition is established, the speed of the armature will become constant.

b. If the driving torque is assumed to be constant and the resisting torque increases, the motor speed will decrease steadily until it stops. If the resisting torque is less than the driving torque, the motor will continue to accelerate until the driving torque and the resisting torque become equal. If the operating conditions are such that the resisting torque can never equal the driving torque, the motor will accelerate to destruction. The design characteristics of an electric motor are such that it tends to be self regulating with regard to the adjustment of the driving torque to the resisting torque. Whenever the resisting torque resulting from the motor load changes, a change in the motor speed will occur, and this change in speed will be in a direction that will cause the driving torque and the resisting torque to become equal again.

c. Figure 38 shows a method of measuring the torque output of a motor. It is possible to discuss the force exerted by the motor, since this is the quantity read by the spring balance; the motor, however, runs at a fixed speed because the driving torque on the shaft is balanced exactly by the resisting or load torque applied by the brake shoe. If the radius of the brake shoe is increased -- equivalent to increasing the distance between the axis of rotation and the line of action -- the same torque would be applied by a lighter force, and the spring balance would have a lower reading. Therefore, it is desirable to discuss the torque output of a motor instead of the force output. The torque output depends on the power supplied to it, and on the speed at which it runs. The torque output of a motor that is not rotating is called the stall torque of the motor, and the speed of the motor at which the torque output drops to zero is called the no-load speed.

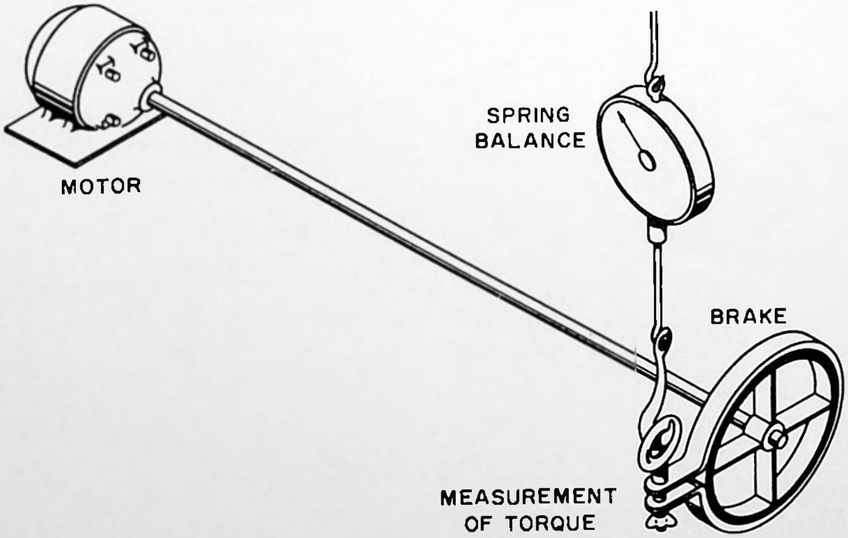


Figure 38. Torque measurement in a motor.

58. GENERAL

Dc motors develop higher stall torque than ac motors and, therefore, are used more often in servo applications driving heavy loads such as gun turrets and radar antennas. Figure 39 is a photograph of one type of dc motor. Dc motors are used also where large amounts of ac power are not readily available, as in aircraft installations.

59. BASIC THEORY

a. A dc motor is a device for converting electrical energy into mechanical energy. This mechanical energy is used to drive various loads by means of belts, gears, or direct shaft connections. Figure 40 illustrates a simplified dc motor consisting of a field structure and armature assembly. The field structure is a pair of pole pieces with coils wound around them connected to a field excitation source. A magnetic field is set up between the poles when current is passed through the coils. The armature assembly consists of a single-turn loop, commutator, and brushes. The brushes are connected to an armature current source.

b. When a dc voltage is applied to the brushes, a current flows around the loop, and the magnetic field produced by this flow of current interacts with the magnetic field produced by the field structure. This interaction between magnetic fields obeys the first law of magnetism which states that like poles repel and unlike poles attract. Current flowing through the field coils produces the field poles, and current through the armature coils develops armature poles. Attraction and repulsion between these two sets of poles produce rotation of the armature loop. In figure 40, the loop rotates counterclockwise due to the resultant magnetic fields. It can be noted that the force acting in one direction (on one side of the loop) and the force acting in the other direction (on the other side of the loop) combine to cause the coil to turn on its axis. The loop thus acts as if it were a lever with a turning force, or torque, at each end. It would appear that when the armature loop revolved to a position where the unlike poles of the field and armature were adjacent, that the armature would cease rotating. But this does not happen because of the action of the brushes and commutator. Referring to figure 40, when the armature rotates 180 degrees, the sliding action of the brushes on the commutator causes the polarities of the armature and field pole to be the same relative to each other, and the armature continues to rotate in the same direction.

c. The torque developed by a motor is directly proportional to the strength of the magnetic field set up by the field poles (field flux) and the amount of current flowing in the armature, or, $T = K\theta I$

where T is torque
K is a motor constant
θ is the field flux
I is the current

A motor capable of exerting a relatively high twisting effort per ampere of input applied to the armature when it is starting is said to have a relatively high starting torque; one that generates a low twisting effort per ampere of input when starting is said to have a relatively low starting torque. The torque per ampere of input that any given motor will develop depends upon the type of motor, series or shunt, and how well the machine is designed. In general, the starting torque per ampere is greatest for the series motor, somewhat less for the shunt motor.

60. BACK ELECTROMOTIVE FORCE

a. When the armature is turned by an external power source, a dc motor can be used as a dc generator. Voltages are induced in the armature windings as they cut the magnetic lines of force set up by the field structures. During motor operation, voltages also are induced

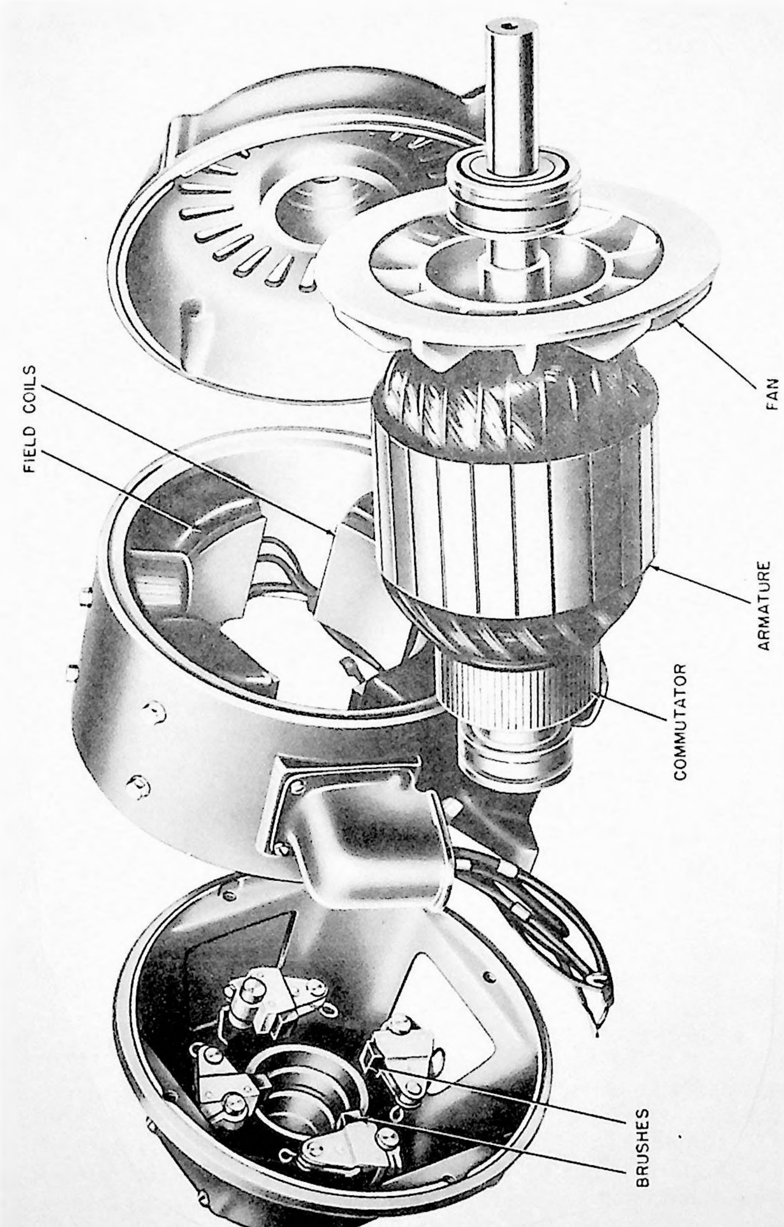


Figure 39. Typical dc motor.

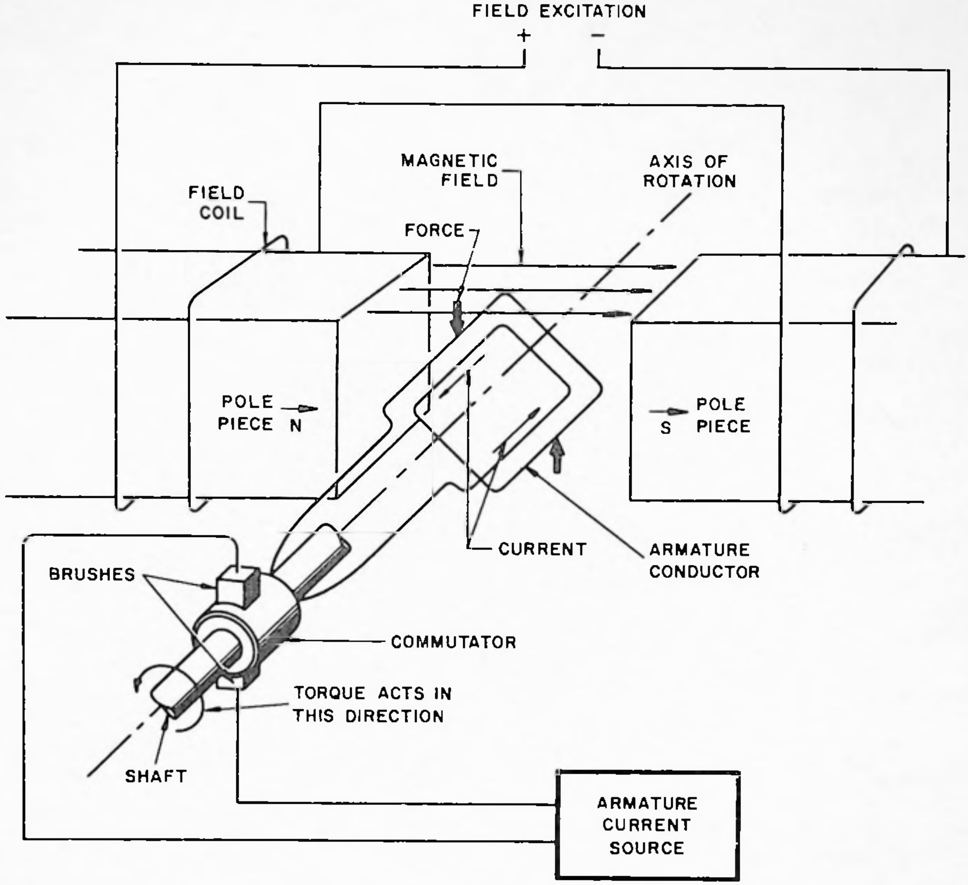


Figure 40. Torque produced in a dc motor.

into the armature winding when the armature turns similar to the action of a dc generator. This voltage, called back electromotive force, is in a direction opposing the armature driving voltage and is always present in a dc motor. For example, if 10 volts is applied to the armature of a dc motor, current flows and torque is developed. If the motor now is prevented from rotating, the torque output will be the stall torque of the motor for an input of 10 volts. If the motor is allowed to turn, a back electromotive force of perhaps 2 volts will be developed. Since this 2 volts of back electromotive force is in a direction opposing the 10 volts input to the armature, only 8 volts is available to cause current to flow through the armature. The torque output at this speed with 10 volts input is thus the same as the stall torque with 8 volts input. As the motor speed increases, the back electromotive force also increases; when the back electromotive force reaches 10 volts, there will be no torque output. The speed at which the back electromotive force and the armature current cancel each other is called the no-load speed and, in this case, is referred to as the no-load speed with 10 volts input.

Section III. TYPES OF DC MOTORS

61. SERIES DC MOTOR

In a series dc motor, the field is connected in series with the armature, as shown in figure 41, and the field carries the same current as the armature. Therefore, if the load changes the current through the armature, it also changes the current in the field. Up to the point of saturation of the field structure, the magnetic field set up by the poles is almost directly proportional to the armature current. Then, the torque of the motor can be obtained from the equation $T = K \theta I$, where K is a circuit constant, I is the current through the armature, and θ is the strength of the magnetic field. Since θ varies directly with I, I may be substituted for θ, and the equation becomes $T = KI^2$. Thus, in a series motor, the torque is proportional to the square of the current flowing through the armature. Doubling the armature current results in quadrupling the torque. For example, if the torque is 40 ft-lb at 25 amperes, at 50 amperes the torque would be 160 ft-lb. From this example, it is obvious that the torque rises very rapidly as the current increases. This characteristic of a series motor makes its use very desirable in starting heavy loads, since at the time of starting, before the motor has built up any back electomotive force, the current is high and the starting torque is high at the time it is most needed.

a. Speed Regulation. When the armature is not rotating, the armature current (and torque) is at a maximum because no back electromotive force (emf) is generated in the armature, and the current is limited by the applied voltage and the resistance of the armature and field coils. As the armature gains speed, the back emf increases, decreasing the torque output and the armature current. The speed regulation is poor because the speed of the motor is regulated by the applied load. When the load is light, a series motor operates at high speeds, and overspeeds if the load is entirely disconnected.

b. Speed Control. The speed of a series motor can be controlled by the use of a variable rheostat in series with the armature (fig. 41). Increasing the resistance reduces the applied voltage, thereby decreasing the current flow and torque which reduces the speed. This type of speed control is generally used when initially starting the motor. The rheostat is kept at maximum resistance and then decreased until the desired speed is obtained.

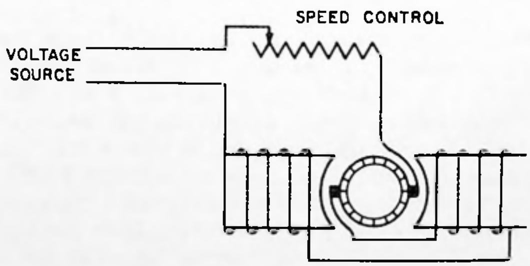


Figure 41. Series dc motor with speed control.

62. SHUNT DC MOTOR

The field coil winding of a shunt motor is connected directly across the source of voltage, in parallel with its armature (fig. 42). When the supply voltage remains constant, the current through the field coil remains constant. As a result, the magnetic field is also constant and the torque of the shunt motor varies only with the current through the armature. If the load increases, the armature current must increase in direct proportion with the load. When starting these motors, the torque is dependent on both the field strength and the current flowing through the armature, thus the starting torque is considered only fair and is not generally used in starting heavy loads. Shunt motors can carry their full-rated load but should not be overloaded, as their stalling torque is low. For example, if the motor is overloaded to the extent that the armature is stopped, no back electromotive force is generated. This results in the full current from the voltage source to flow through the low-resistance armature. Such high current would burn out the armature winding. Fuses or circuit breakers are generally used to open the voltage source line when the armature is stopped.

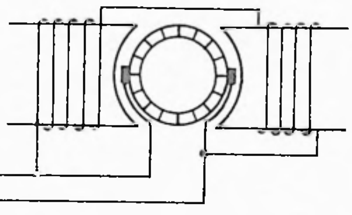


Figure 42. Shunt dc motor.

a. Speed Regulation. The speed regulation of a shunt dc motor is considered excellent because it changes speed very little between no load and full load. For example, assume that a shunt motor is rotating at a particular speed with no load connected. Now if a load is connected, the armature speed is slowed down resulting in a decrease in back emf. This decrease in back emf allows more current to flow through the armature, thereby increasing the torque and maintaining approximately the same speed.

b. Speed Control. The speed of a shunt motor driving a load can be controlled by changing either the magnetic strength of the field or the voltage applied to the armature. If a rheostat is inserted in series with the field windings, varying the resistance changes the strength of the field. If the field is weakened, the motor speed increases, because the back emf is reduced, allowing more current to flow through the armature. If the field is strengthened, the motor speed decreases, because this stronger field allows the back emf to be generated at lower speed. Varying the resistance of a rheostat, placed in series with the armature windings, changes the current flowing through the armature. The speed of the motor varies proportionately with the amount of current flowing in the armature.

63. SPLIT-FIELD DC MOTOR

a. A split-field dc motor has two sets of field coils wound in opposite directions. The direction of rotation, therefore, is determined by choosing the appropriate field winding and exciting it in series with the armature. A split-field motor of this type is shown in figure 43. In terms of physical dimensions required for a motor having a given torque output, this motor is not as efficient as a single-field motor of the same output. However, it is simple to control and is used frequently in servo applications.

b. A of figure 44 shows a typical schemetic representation of a split-field dc motor; B of figure 44 shows typical examples of its torque-speed curves in relation to the applied voltage. As in any dc motor, the stall torque is proportional to both the armature current and the strength of the magnetic field. Since the field strength is proportional to the field current, which is the same as the armature current, the torque is proportional to the square of the armature current ($T = KI^2$). At zero speed there is no back electromotive force, and the current is proportional to the applied voltage; consequently, the stall torque is proportional to the square of the applied voltage. Assume that the motor is running at some speed and developing

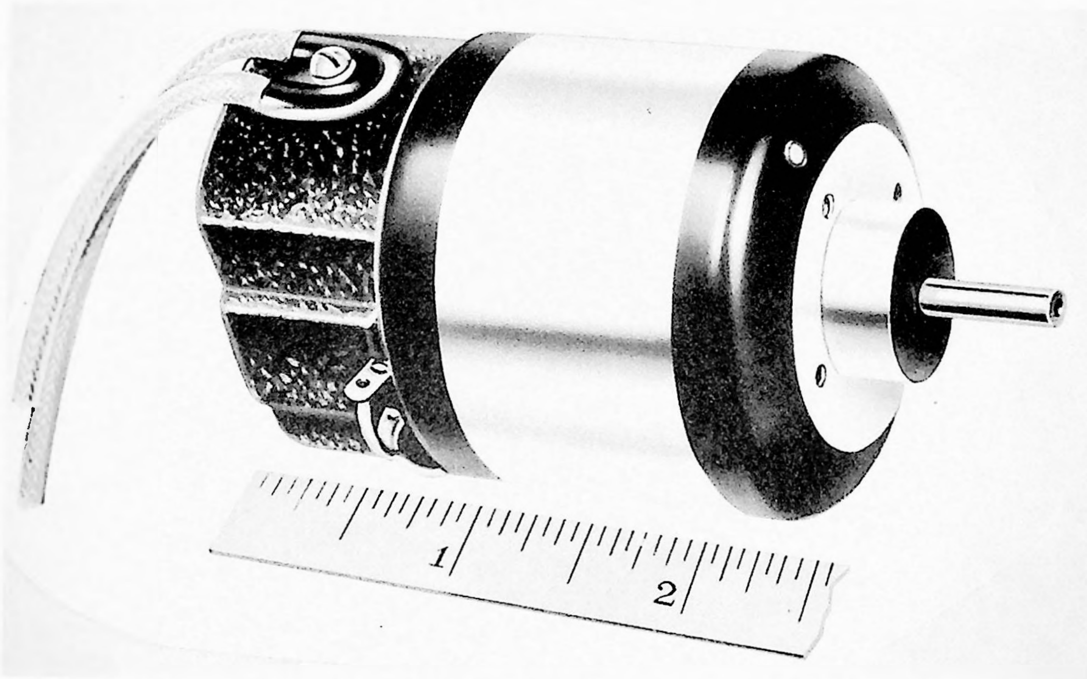


Figure 43. Split-field dc motor.

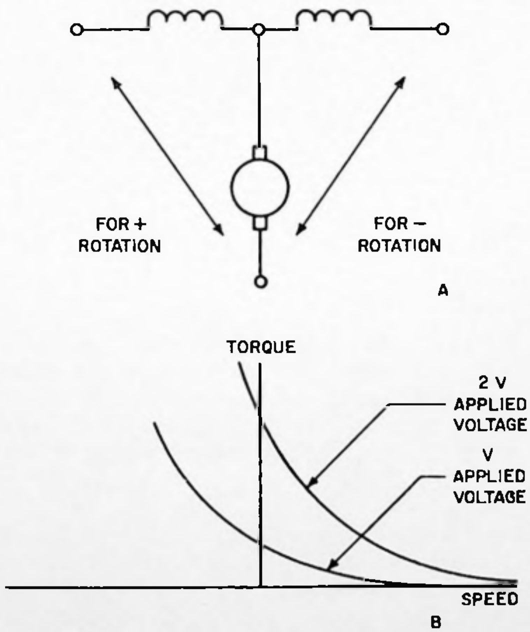


Figure 44. Split-field dc motor and typical torque speed curves.

an output torque. If its speed is increased slightly, the back electromotive force increases. The change in back electromotive force is proportional to the magnetic field, and, therefore, proportional to the current. Since the back electromotive force bucks the applied voltage, there is a drop in current as the speed is increased. This drop in current is proportional to the back electromotive force, and, therefore, proportional to the current flowing through the motor. For any applied voltage, V, the torque falls with increasing speed, but it falls off more slowly at high speeds than at low speeds (fig. 44). The 2V curve shows the same effect but with twice the amount of applied voltage as the V curve.

Section IV. AC MOTORS

64. GENERAL

The induction motor is the usual type of ac motor used in servo systems. Its design is simple and its construction rugged. The induction motor is suitable for driving loads at constant speeds and does not use a commutator, which eliminates a source of trouble found in dc motors. An induction motor consists of a stator and rotor. The stator construction is similar to the field structure of a dc motor in that it is made of iron core with a number of coils of wire wound around it. The rotor sometimes is wound on an iron core, but more frequently consists of a rotating cup illustrated in figure 45. An induction motor can be either a single-phase or polyphase machine. The operating principle is the same in either case, and depends on a revolving, or rotating magnetic field to produce torque. An understanding of a rotating magnetic field is essential to understand the operation of an induction motor. This section discusses the generation of a rotating field, the theory and characteristics of a two-phase ac induction motor, and a split-phase ac induction motor.

65. ROTATING MAGNETIC FIELD

a. A rotating magnetic field in an ac motor is the result of shifting the magnetic field of the stator. Figure 46 illustrates a vector analysis of the rotating field of a stator that has two sets of field windings excited by two separate ac voltage sources. One voltage source in this example is assumed to be 90 degrees out of phase with the other. One set of windings magnetizes poles 1 and 2, and the other set magnetizes poles 3 and 4. The field set up by poles 1 and 2 varies sinusoidally with the input voltage source. This field is directed from one of the poles toward the other with its direction changing with the input voltage. Poles 3 and 4 set up a similar field, but 90 degrees out of phase with poles 1 and 2. The two fields add to form a resultant field. The instantaneous direction and strength of this field is obtained by a method called vector addition. Figure 46B shows the rotation of the magnetic field for one-half cycle at various intervals. In this example, the resultant field begins at a reference point where the horizontal field of poles 3 and 4 is zero, and the vertical field is at a maximum. The resultant field of the next interval, one-twelfth of a cycle later, is obtained from the diagonal of a parallelogram with the sides formed by the vector arms representing the field strengths of the horizontal and vertical components. The resultant vector at any instant represents the rotation of the magnetic field turning at a uniform rate determined by the frequency of the inputs.

b. To find the speed of rotation of the magnetic field, it is necessary to consider the number of pairs of poles per phase and the frequency of the input. For example, if a machine has four poles per phase (representing 720 electrical degrees), it would require two cycles of input for the field to make one complete rotation. Thus, the number of revolutions per second for the magnetic field is equal to the frequency divided by the number of pairs of poles per phase, or $S = f \div P/2 = 2f/P$

where: S is the speed of rotation in rps
f is the frequency in cycles per second
P is the number of poles per phase

The speed of the rotating field is called the synchronous speed. To sum it up, the speed of the rotating field -- synchronous speed -- varies directly as the frequency of the applied voltage and inversely as the number of pairs of poles per phase in the motor.

66. TORQUE CHARACTERISTICS

As the rotating field in the stator of the motor travels around the stator, it cuts across the copper bars in the rotor. Thus, a voltage is induced in these bars and, since they are

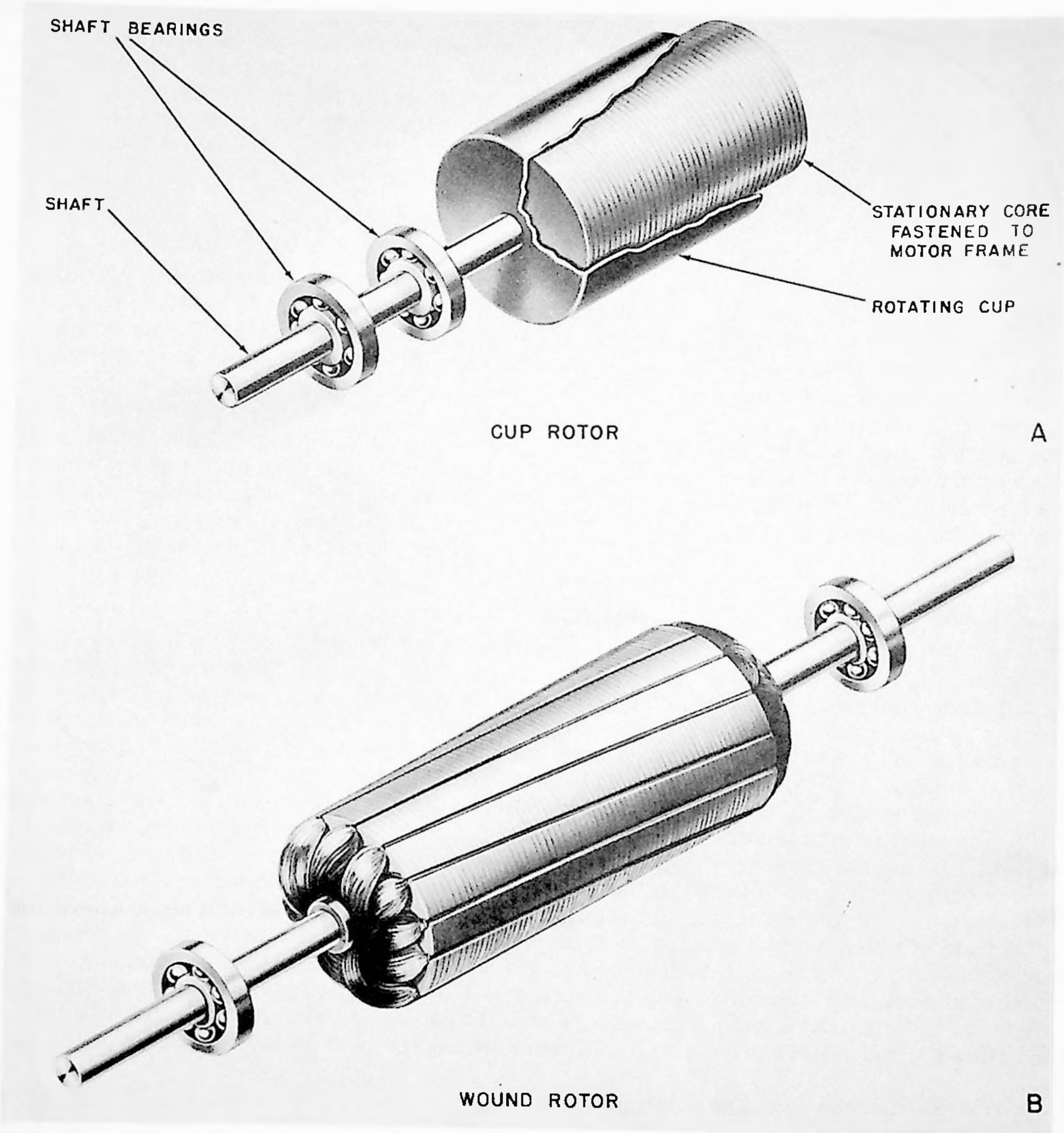


Figure 45. Types of rotors.

short-circuited, current flows in them. Therefore, just as in dc motors, you have current-carrying conductors in a magnetic field and a torque results. This torque is developed in the same direction as the rotating field, so the rotor of the motor begins to rotate in the same direction. In general, the torque delivered by an ac motor depends upon the field strength and the current flowing in the rotor. To reverse the rotor direction, reverse the field by interchanging two stator leads.

67. TWO-PHASE INDUCTION MOTOR

As the name implies, a two-phase induction motor is one which has two ac inputs with each input 90 degrees out of phase with the other. Basically, the motor operates as discussed in paragraph 64. Figure 46A shows the stator connection of a two-phase induction motor with the two excitation sources originating from two separate voltage sources. In servo

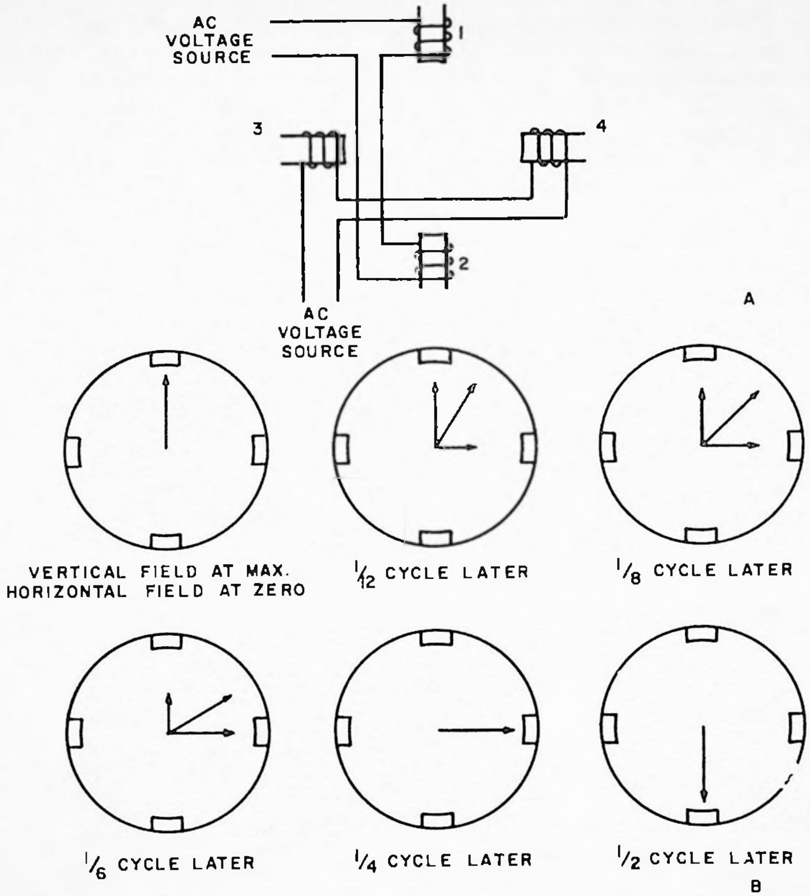


Figure 46. Rotating magnetic field.

applications, one input is connected to the output of a controller, whereas, the other is connected to an external ac voltage source. The two inputs are still out of phase with each other by 90 degrees, however, their voltages are unequal. To understand how the controller controls the operation of the motor, a discussion of the effects of unequal excitation is necessary.

a. Two-Phase Motor With Unequal Excitation. Unequal excitation on the stator windings of a two-phase motor results in the generation of two magnetic rotating fields, one forward, the other backward. These fields are explained best in the following manner. Assume that the stator windings in figure 46A are connected to unequal voltage sources. Each of the poles develop individual fields which are directed one way or the other along a line between the pole pairs developing the magnetic field. For example, the fields of poles one and two are directed between poles one and two, and the fields of poles three and four are directed between poles three and four. The strength of the field generated between pole pairs is proportional to the current flowing in the appropriate windings. A field of this sort, the strength of which varies sinusoidally, may be considered as the resultant of two separate fields, rotating in opposite directions and both having the same strength. The field from poles one and two is, therefore, the resultant of two fields, one rotating clockwise and the other counterclockwise, both having the same strength. The field from poles three and four can be considered in the same way. If the voltages applied to the two sets of stator windings are 90 degrees apart in phase, the rotating fields in one direction will have a resultant equal to the arithmetic sum of their magnitude, since both point in the same direction. The rotating fields in the other direction will have a resultant equal to the arithmetic difference, since they point in opposite directions. In servo applications, one set of windings, called the main field, is connected to an ac line. The other set, called the control field, is connected to the output of the controller. The resultant field when both sets of windings are energized is then the same as the resultant of two rotating fields, one having a strength proportional to the sum of main and field excitations, the other having a strength proportional to the difference between excitations. If the phase of the control field excitation is reversed, the strength of the two rotating fields are interchanged, and any torque produced by the fields has its direction reversed.

b. Voltages Induced in Rotor. From the preceding discussion, it was determined that both the forward and backward rotating magnetic fields induce voltages in the rotor (fig. 47). The voltage is proportional to the strength of the magnetic field and the speed of the rotor relative to the speed of the rotating fields. The strength of the field is shown as straight lines intersecting the voltage and speed axes with the lines designated as relative quantities of the magnetic density. For example, the +2 line indicates twice as much density as the +1 line. The speed of the rotating fields is shown as the horizontal axes indicating increasing speed in a positive direction for the forward rotating field, and in a negative direction for the backward rotating field. When the rotor turns at the same speed as the field (synchronous speed) no voltage is induced into the rotor. As the rotor speed falls below synchronous speed, the induced voltage increases uniformly.

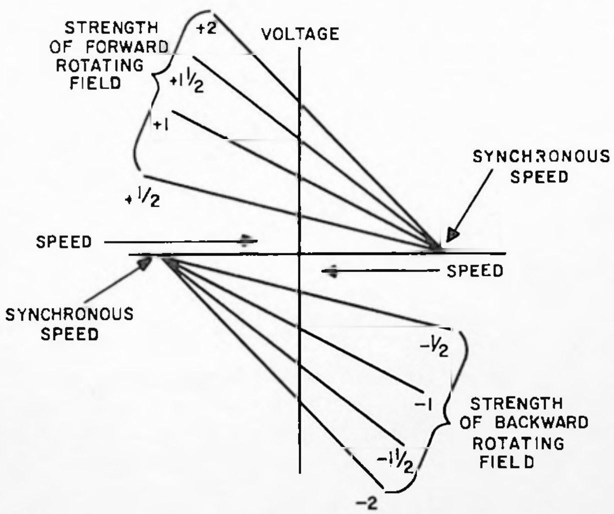


Figure 47. Induced voltage curves of an ac motor.

c. Torque Developed by Forward Rotating Field. The torque developed by the forward rotating field is the result of the interaction between the magnetic field and the two induced currents of the rotor. The positions on the rotor at which voltages are induced by the rotating field move around the rotor with the field. Thus, the current also moves in the same manner. Therefore, any rotor current induced by the backward field rotates in the direction of the backward field. The interaction between such a current and the forward magnetic field (which rotates in the opposite direction) develops an alternating torque with an average value of zero. The torque developed by the forward rotating field depends on the interaction of the forward rotating field and the rotor currents. A high-resistance rotor has the current in phase with the voltage, and the torque is proportional to the product of the current and the field strength. A low-resistance rotor has low stall torque and rarely is used in servo systems. The torque-speed curves for forward rotating fields are shown on figure 48.

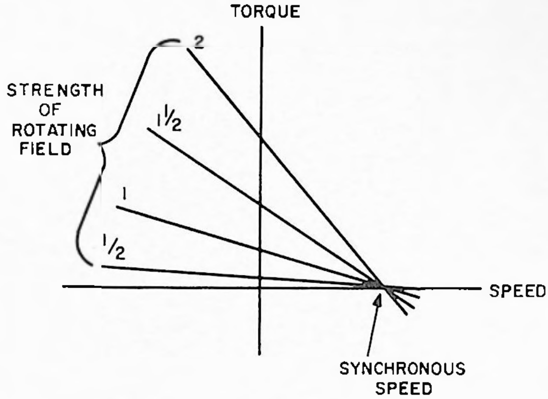


Figure 48. Torque-speed curves for forward rotating field.

d. Torque in Two-Phase Induction Motor. The torque-speed curves for a two-phase induction motor are obtained by adding the torques for the forward and backward rotating fields. Normally, the main field is connected to the ac voltage source. If a controller supplies full excitation of the control field, the forward rotating fields are added and result in the torque-speed curve in figure 49. The backward rotating fields cancel. If a controller supplies one-half excitation of the control field, the forward rotating fields are added, but, the backward rotating field reduces the torque-speed. The stall torque is proportional to the excitation of the control field which makes this type of a motor desirable in servo applications.

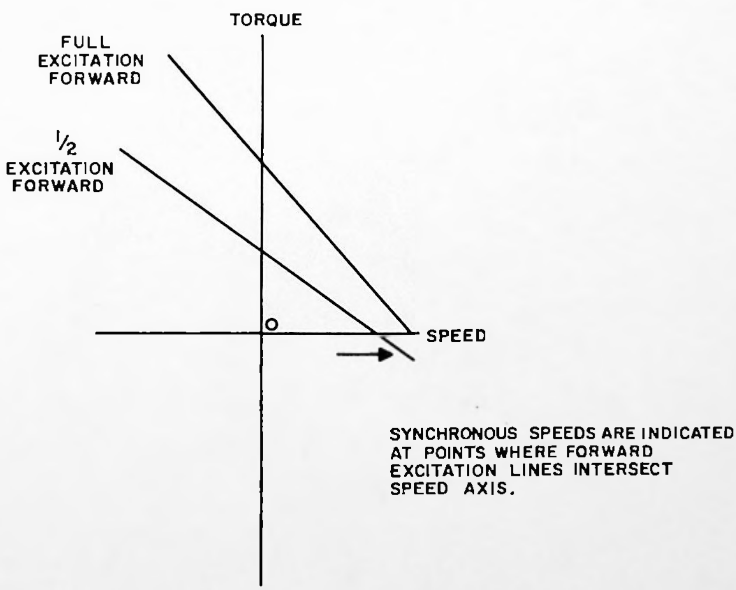


Figure 49. Torque-speed curves for two-phase induction motor.

68. SPLIT-PHASE MOTOR

A split-phase motor is a type of self-starting motor that uses only one phase of input voltage. It consists of a main winding and a starting winding. The main winding is wound on the stator and the starting winding is wound on top of it in such a manner that the centers of the poles of the two windings are displaced by 90 degrees. Both windings are connected in parallel to the same voltage source. The main winding has a low resistance and a high inductance. The starting winding has a high resistance and a lower inductance than the main winding. Therefore, when the same voltage is applied to both windings, the current in the main winding lags the voltage by a greater amount than does the current in the starting winding. For explanation purposes, assume that the current in the main winding lags the voltage by 40 degrees and the current in the starting winding lags the voltage by 30 degrees. The magnetic fields set up by the currents are 90 degrees apart, since the windings are displaced 90 degrees, and the two windings have a current phase difference of 10 degrees. This produces a weak rotating field which starts the motor. It is obvious that this field is not as strong as the rotating field produced by a regular two-phase current in which the phase difference is 90 degrees; however, it should be sufficient to start the motor. Since the starting winding has a high resistance, it will burn out if it is left connected in the circuit. Therefore, a centrifugal switch is used to disconnect the starting winding automatically after the rotor has attained approximately 25 percent of its rated speed.

Section V. HYDRAULIC ACTUATORS

69. GENERAL

Hydraulic actuators are used in servo systems when the system requires operation for short periods separated by long intervals. Under these conditions, it is possible to obtain an extremely large output from a small hydraulic actuator. For this reason, hydraulic actuators are frequently used in aircraft systems where weight and size are major factors. High pressure variable-displacement pumps or hydraulic accumulators normally are used to provide energy, in the form of high-pressure oil, to the hydraulic actuators or motors. Hydraulic accumulators (fig. 50) contain a bag filled with oil. Air pressure is built up in the accumulator forcing the oil out to the actuator at high pressure. The main disadvantage of hydraulic systems is that they cannot be used efficiently where continuous operation is required.

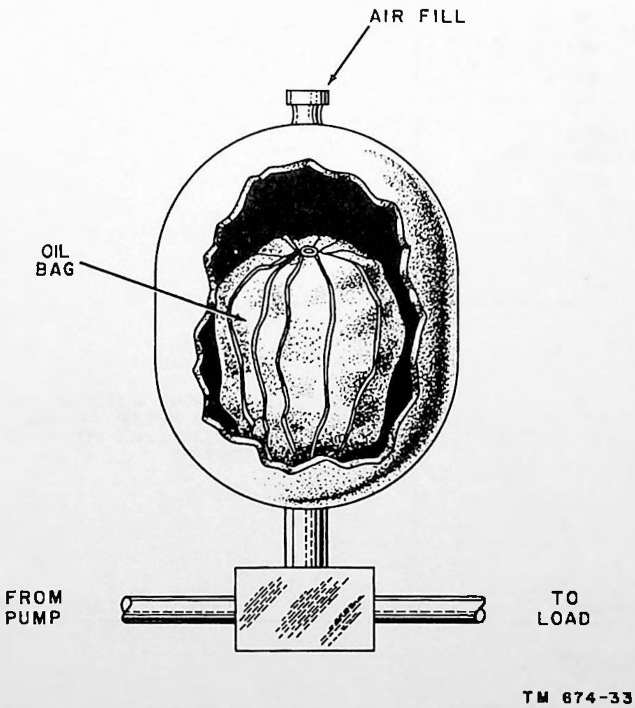


Figure 50. Hydraulic accumulator.

a. Swash-Plate Motor. A four-cylinder swash-plate motor is illustrated in figure 51. The body of the motor serves as a cylinder block, the output shaft is connected to the swash-plate against which the three pistons act. The other end of the output shaft is connected to a valve plate. This valve plate uncovers ports in the cylinders and alternately connects each cylinder to the input and output oil lines. Torque is developed when oil is admitted to one of the oil lines. The pistons in the cylinders connected to that oil line then push down on the swash-plate turning the output shaft. As this shaft turns, the other pistons rise, and the oil from these cylinders passes out through the other oil line. The direction of the torque is controlled by connecting the proper oil line to the hydraulic accumulator or other source of high pressure. The swash-plate motor operates like any other motor in servo applications. The torque-speed curves are all straight lines. The curves correspond to the different hydraulic valve settings which control the amount of oil pressure. These curves all pass through the approximate same torque point, and the no-load speed for each curve is proportional to the amount by which the valve has been opened. The major advantage of the swash-plate motor is that it can provide a large amount of torque for a short time by using the energy (oil pressure) stored in the power source.

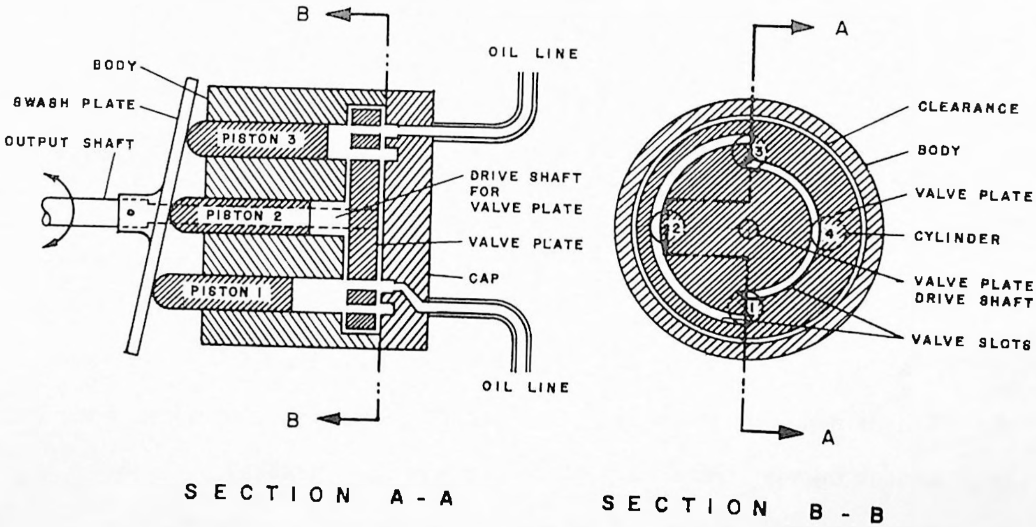


Figure 51. Four-cylinder swash plate motor.

b. Hydraulic Ram. The hydraulic ram is another type of a hydraulic actuator. It is especially useful where back-and-forth operation is required. It is operated by admitting oil under high pressure to one side of its piston. The cylinder on the other side is connected to a low-pressure oil line.

Section VI. SUMMARY AND REVIEW QUESTIONS

70. SUMMARY

a. Torque is defined as a force or a combination of forces that produces or tends to produce a twisting or rotating motion. It is calculated by multiplying the applied force by the perpendicular distance between the line of action of the force and the axis of rotation.

b. Dc motors are used commonly as actuators in servos driving heavy loads, since they develop higher stall torque than ac motors. Control by variation of the armature voltage normally is preferred to control by variation of field voltage. In low-power servos, split-field dc motors frequently are used.

c. Many servo systems have ac induction motors. Although wound iron-core rotors are sometimes used, cup rotors usually are preferred.

d. Hydraulic actuators frequently are used, particularly in aircraft systems. A hydraulic accumulator provides energy in the form of high-pressure oil for a swash-plate motor or hydraulic ram.

71. REVIEW QUESTIONS

a. Explain the torque concept and how torque is measured.

b. Why is a dc motor used in servo applications where the control of heavy loads is required?

c. Name the basic components of a dc motor.

d. What is the basic difference between a shunt dc motor and a series dc motor?

e. What two methods are used for controlling the operation of a dc motor?

f. What is meant by stall torque and no-load speed when referring to motors?

g. What is the major advantage of ac motors over dc motors?

h. How is power furnished for the operation of hydraulic actuators?

CHAPTER 5

CONTROLLERS

Section I. INTRODUCTION

72. GENERAL

Basically, a controller is an element of a servo system that controls the operation of the actuator in response to an error signal it receives from the sensing element. This error signal from the sensing element is usually very weak and, therefore, cannot by itself be used to drive the actuator. The function of the controller is to add sufficient power to the error signal for driving the various types of actuators used in servo systems. This chapter includes discussions on the following types of controllers or control systems used in servos: the Ward-Leonard drive and amplidyne systems, the vacuum-tube control and thyratron control systems, the magnetic control and saturable-reactor control systems, and hydraulic controllers.

Section II. WARD-LEONARD DRIVE

73. GENERAL

The Ward-Leonard drive is a control system used for driving high-powered dc motors. This system consists of a dc generator with an output which varies as the generator field excitation is changed. The error signal from the sensing element is used to excite the generator field, either directly or through an amplifier, and the generator output is used to drive the servo motor.

74. OPERATION OF THE WARD-LEONARD DRIVE

In the Ward-Leonard drive, the armature of the dc generator is turned by an ac or dc motor, which runs at approximately constant speed. The field winding of the dc generator is excited by the output of a dc amplifier (fig. 52). The rotation of the generator armature through the magnetic field causes voltages to be induced into the coils of the armature. Commutator brushes connect the output of the armature coils to a dc motor. The output voltage is proportional to the speed at which the generator is rotated and to the strength of the magnetic field. Since the speed of the motor turning the generator is more or less constant, the output voltage varies with the magnetic field and this, in turn, is proportional to the excitation current.

75. MODIFIED WARD-LEONARD SYSTEM FOR SERVO APPLICATIONS

When the Ward-Leonard system is used in servos, the field of the dc generator tends to remain magnetized when no excitation is applied. In servo applications, this is undesirable because of the small output applied to the servo motor when no error is detected by the sensing element, and the actuator (servo motor) continues to develop torque, which introduces additional errors in the system. One solution to the problem is to provide additional windings on the generator field. If these are excited by ac at a low level, the resulting magnetizing force, which will be alternating, will cause the average magnetization of the generator field to fall to zero when there is no excitation for the main field windings. The objection to this solution is the fact that ac current in the windings also causes the magnetic field to fluctuate slightly, thereby producing a small ac component in the generator output. For this reason, small permanent magnets sometimes are mounted on the armature. These revolve with the armature, producing an alternating magnetizing force for the generator field, and the dc output of the generator then falls to zero when there is no field excitation. The permanent magnets are fixed with relation to the armature coils in such a way that they cannot induce voltage in the coils. Therefore, the generator output is free from an ac component. The same effect can be obtained by so arranging the additional windings that the field they produce rotates at the same speed as the generator armature.

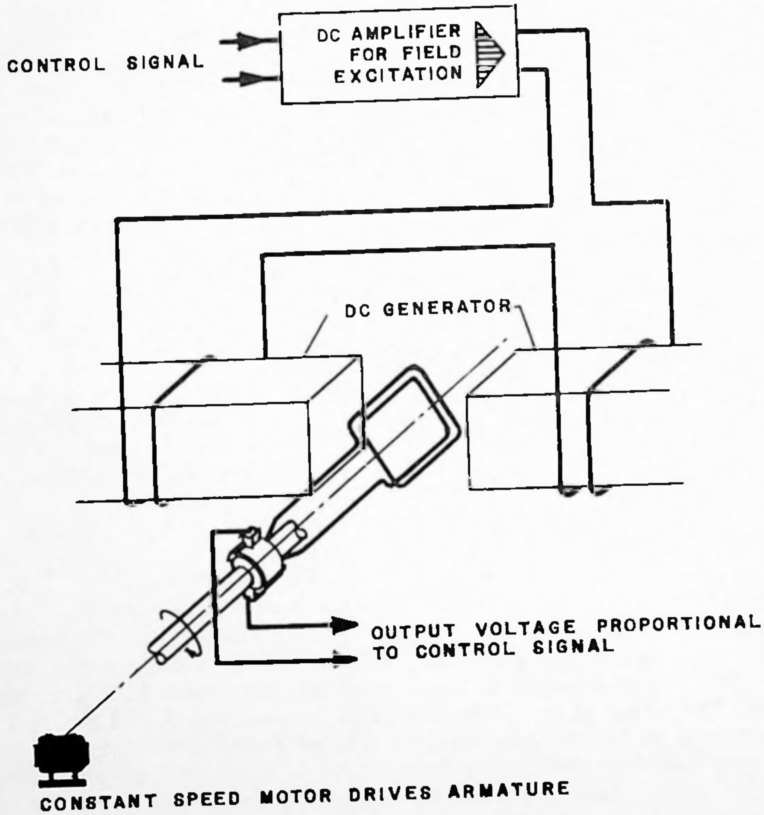


Figure 52. Ward-Leonard control system.

Section III. AMPLIDYNE DRIVE SYSTEM

76. GENERAL

The amplidyne drive system is similar to a Ward-Leonard system in that it is used for driving high-powered servo motors. An amplidyne is a dc generator with a number of modifications which provides a tremendous power gain. This power gain is in excess of 10,000. This means that with a small input signal, the amplidyne is capable of releasing many kilowatts of power.

77. THEORY OF THE AMPLIDYNE DRIVE

a. Since the amplidyne is a modified dc generator, review the generation of back electromotive force covered in paragraph 60 before proceeding with this discussion. Figure 53 shows a schematic of an amplidyne drive. The modifications consist of placing a short circuit across the armature by connecting the upper and lower brushes, and adding two more brushes 90 degrees from the short-circuited brushes (fig. 53).

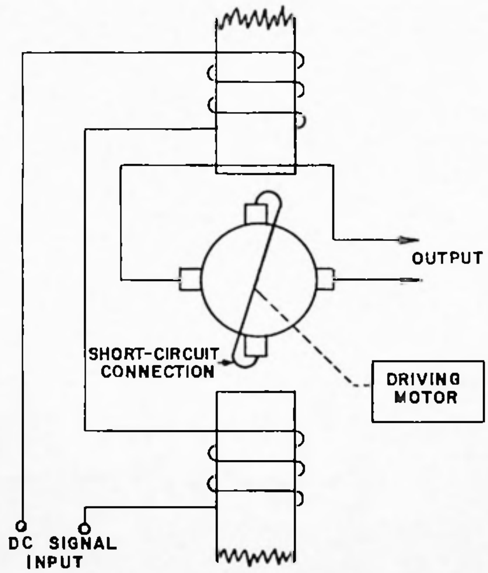


Figure 53. Amplidyne drive used in control systems.

b. A dc input signal from the sensing element is used to excite the field structures of the amplidyne. Since the armature is turned by a motor, the armature coils cut through the field set up by the field coils and a voltage is induced in the armature brushes. A flow of current results because the upper and lower brushes are short-circuited. This flow of current causes a second magnetic field to be developed at right angles to the one produced by the field coils. The armature coils cut through this additional magnetic field causing more current to flow between the short-circuited brushes, increasing the magnetic field, and causing more current to flow, etc. This process continues until a balance is reached in the system. The output is taken from the extra brushes 90 degrees from the short-circuited brushes (fig. 53). The output still is proportional to the dc input signal. It is obvious from the above discussion that tremendous amplification is possible with an amplidyne.

c. The undesirable characteristics of the Ward-Leonard drive also are applicable to the amplidyne system (refer to par. 75). The amplidyne system has an additional drawback in that it has poor regulation. Since the output voltage depends strongly upon the magnetic field caused by the current flowing between the brushes and this magnetic field bucks the main field, the system has poor regulation. It is possible to correct this poor regulation by adding auxiliary windings to the field. The magnetizing force produced by passing the output current through the auxiliary field can be made to balance that produced by the current flowing between the brushes.

d. The amplidyne drive uses a small ac magneto-type generator mounted on the amplidyne armature shaft to remove any residual magnetism in the field structure where there is no excitation of the field windings. This generator has a permanent magnet armature rotating between small field coils. The ac voltage induced in these coils is applied to a demagnetizing winding, wound in the same position as the control winding. If this residual magnetism is not removed, the amplidyne drive provides an output when no error is detected by the sensing element. This output results in undesirable oscillations in the servo system.

78. FUNCTION OF THE AMPLIDYNE DRIVE AS A CONTROLLER

Figure 54 illustrates the use of an amplidyne drive as a controller in a typical servo system. When an error signal is detected by the sensing element, this signal is amplified by a dc amplifier. The output of this amplifier is used to excite the control field of the amplidyne. The amplidyne then generates a large power output that is proportional to the input error signal. This power output is used for driving the dc servo motor either clockwise or counterclockwise. The direction of rotation is determined by the polarity of the input error signal, whereas, the speed of rotation is determined by the amplitude of the error signal.

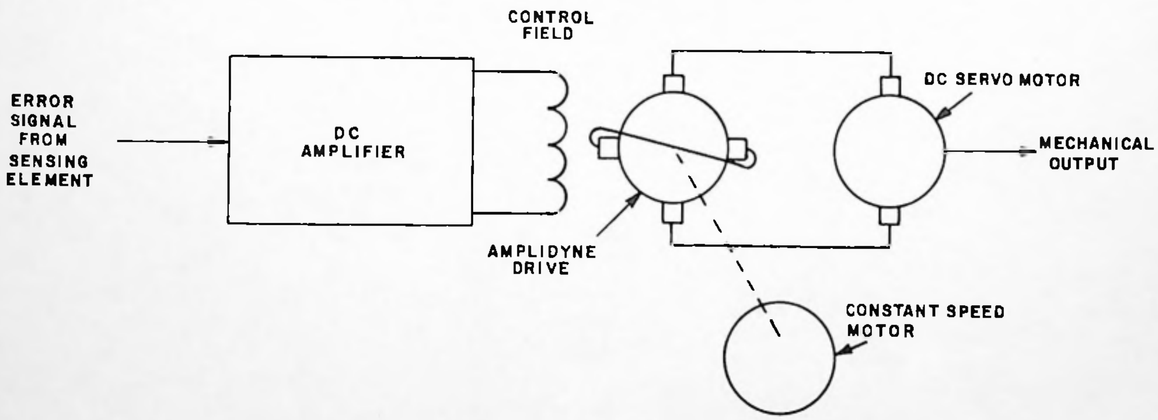


Figure 54. Amplidyne drive used in servo systems.

Section IV. VACUUM-TUBE CONTROL SYSTEM

79. INTRODUCTION

The vacuum-tube control system, another method of controlling the operation of a servo motor, also depends upon the error input signal detected by the sensing element. The use of the vacuum-tube control system, the Ward-Leonard system, or the amplidyne system is determined largely by the output power requirements. The Ward-Leonard and amplidyne systems are used in high-powered applications while vacuum-tube control systems control servos requiring low power. This discussion includes the operating characteristics of dc and ac vacuum-tube control systems. These systems usually are called servo amplifiers.

80. OPERATING CHARACTERISTICS OF A DC SERVO AMPLIFIER

a. The basic function of a dc servo amplifier is to control the operation of a dc servo motor by providing a dc voltage to the motor. The input error signal is an ac voltage, so a dc amplifier must be capable of converting the ac input signal into an amplified dc output. A dc servo amplifier also must be able to reverse the direction of the motor by reversing the polarity of the dc output with a shift in phase of the input signal.

b. The dc amplifier can also be used in conjunction with the Ward-Leonard and amplidyne systems where the dc amplifier amplifies the error signal to obtain greater field excitation of the dc generators. Generally, when servo amplifiers are used alone to drive servo motors, the power requirements of the system are low.

81. OPERATING CHARACTERISTICS OF AN AC SERVO AMPLIFIER

a. Figure 55 shows a typical application of an ac servo amplifier in controlling the operation of an ac motor. The stator B winding of the two-phase induction winding is called the reference winding. It is excited from the ac power source through phase-shift network which shifts the phase of the voltage applied to the stator B winding by 90 degrees, in reference to the ac power source. Since the same ac power source is used for the servo system, the error signal which is applied to the ac amplifier is either in phase, or 180 degrees out of phase with the power source. Therefore, the error signal is either leading or lagging the excitation voltage applied to the stator B winding by 90 degrees, providing no phase shifting takes place in the servo amplifier.

b. The function of the servo amplifier is to amplify the error signal detected by the sensing element. This amplified signal is then applied to the stator A winding of the induction motor. Since the magnetic fields in the stator windings are 90 degrees out of phase with each other, the motor rotates in a direction to correct the error in the system. If the phase of the error signal is shifted, the phase of the magnetic field in stator winding A is shifted. This results in an opposite direction of rotation for the ac motor. If the error signal is zero, there is no magnetic field in stator winding A. Thus, no torque is produced and the motor does not rotate. This system is used only to control low-power ac motors since the power is limited by the power output available from the vacuum tubes in the servo amplifier. For ac motors requiring up to 80 watts or so on the control field, the system is efficient and normally is used.

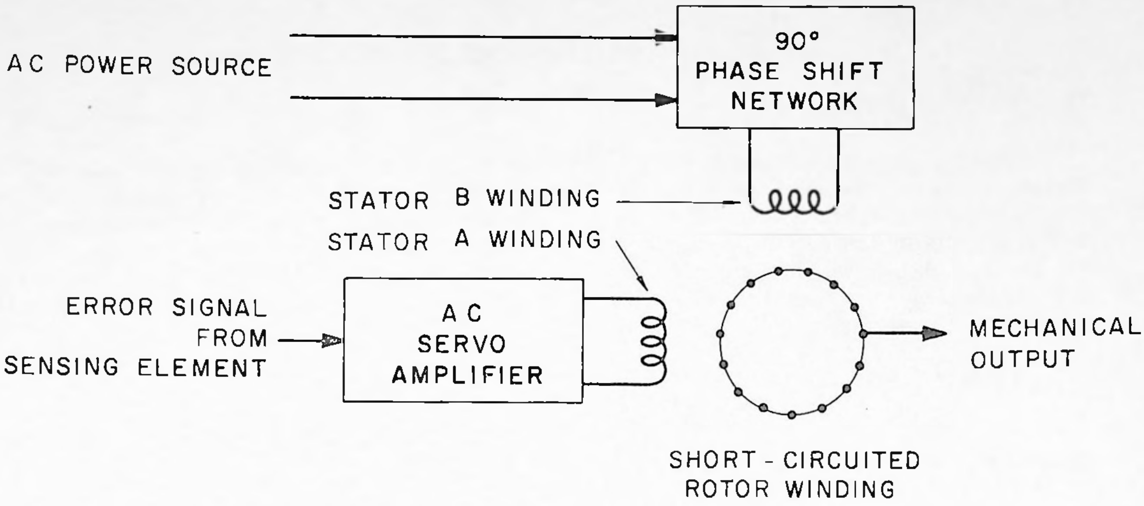


Figure 55. Ac servo amplifier driving an induction motor.

Section V. THYRATRON CONTROL SYSTEM

82. GENERAL

When load current requirements increase, servo vacuum tubes cannot meet large current demands because their high internal plate resistances limit the plate current flow for a given plate supply voltage. To decrease the plate resistance and increase the power output, thyratron tubes are used. The thyratron, although generally similar to a vacuum tube, differs from the vacuum tube in that it is filled with an easily ionized gas. If the grid of the thyratron is held at a sufficiently negative potential, the tube does not conduct even though the anode is positive. If the negative potential on the grid, however, is reduced to a point where the tube starts conducting, ionization of the gas molecules takes place and the grid no longer controls the tube current flow. The operation of the thyratron is then similar to that of a vacuum tube rectifier. Current can be cut off only by decreasing the anode voltage to a point where ionization stops. Although thyratron tubes can be used in both ac and dc servo applications, this discussion is limited to a thyratron control circuit for a dc motor.

83. OPERATION OF A DC THYRATRON CONTROL CIRCUIT

The operation of a thyratron control circuit is illustrated in the following example, where it is used to control the operation of a split-field dc motor. The direction of rotation of a split-field dc motor is determined by the excitation of one of the field windings. If voltage is applied through one end of the center-tapped field and the free end of the armature, the motor rotates in one direction. It runs in the opposite direction when voltage is applied through the other end of the center-tapped field and the free end of the armature. Figure 56 shows a schematic of a thyratron control circuit of this type. Assume that no error signal is detected. The thyratrons simply act as half-wave rectifiers. Since the plates of the thyratrons are connected to opposite ends of the transformer secondary, the plate voltages of the two tubes are 180 degrees out of phase. As a result, the thyratrons fire on alternate half cycles of the ac power source voltage. The motor, therefore, is energized first in one direction and then in the other, and its net torque output is zero, and the motor does not rotate. When an error is detected, the grid of one thyratron swings in the positive direction when the plate is positive and, therefore, the tube fires a little earlier than it would without an error. In the other thyratron, the grid swings in the negative direction when the plate swings positive and, as a result, the tube fires later than it does with no error. The result is that the torque output of the motor is proportional to the error signal, and the rotation of the motor is determined by the firing of the thyratron tubes. This system can operate more smoothly by adding a capacitor from each end of the split field to the free end of the armature. However, this capacitive action reduces the system response.

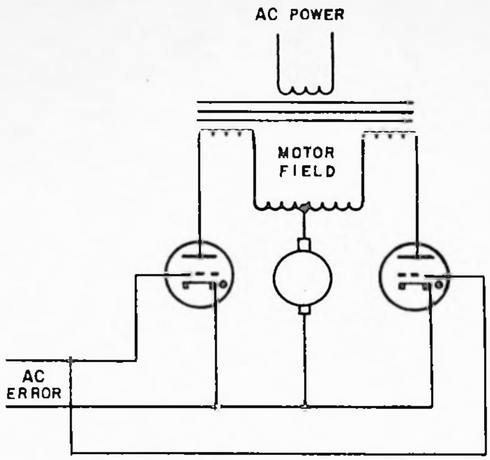


Figure 56. Thyratron control circuit for split-field dc motor.

Section VI. SATURABLE-REACTOR CONTROL SYSTEM

84. SATURABLE-REACTOR CONTROL

a. General. A saturable reactor is, in effect, an inductor whose inductance can be varied by means of a control current. A saturable reactor, properly connected, can be used as part of the control system for an ac motor. The control current is the error detected by the sensing element and is applied to the saturable reactor. The output then is applied to the actuator which drives the load in proportion to the error. The power-handling capability of a saturable-reactor system is far greater than that of a vacuum-tube amplifier and, therefore, saturable reactors often are used to control large ac motors.

b. Saturable-Reactor Theory. Refer to figure 57. When current flows through the windings of an iron-core inductor, a magnetizing force, H, is developed. This, in turn, sets up a magnetic field, G, in the core. When the current is changed, the accompanying change in H causes a change in G, and the change in G induces voltage in all of the windings that encircle the iron core. The induced voltage is proportional to the rate at which G changes, and if G is proportional to H, the induced voltage is proportional to the rate at which the current changes. In some types of core material, the relation between G and H is like that shown by the BC curve in A of figure 57. A winding on such a core will have induced voltage when ac is passed through it. If, now, dc is added in the same winding or in another, as shown in B of figure 57, the variations in H no longer take place about an average value of the ac. Instead, H oscillates about a value determined by the dc current. If this value is sufficiently far beyond the bend in the BC curve, there will be only a small change in G and a small induced voltage. The result is that an inductor made of such material can be designed to have a high inductance when no dc flows in the windings, and a much lower inductance when it does flow.

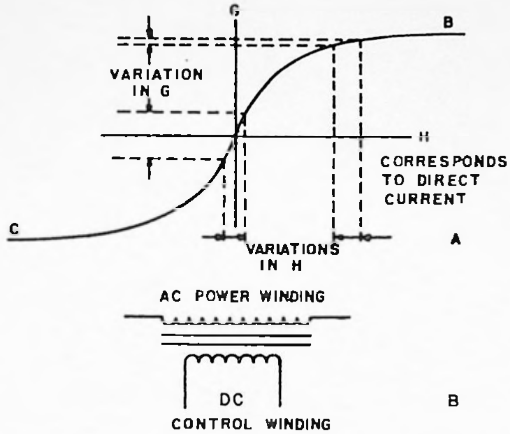


Figure 57. G-H curve for saturable reactor.

85. ANALYSIS OF A SATURABLE-REACTOR CONTROL SYSTEM

a. Figure 58 is a typical saturable-reactor control circuit for an ac motor. In this circuit, the main field of the induction motor is connected to the ac line. One end of the control field is connected to the center tap of a transformer whose primary is connected to the ac line; the other end is connected through a pair of saturable reactors to both ends of the transformer. The dc control windings of the saturable reactors are connected to a thyratron control circuit.

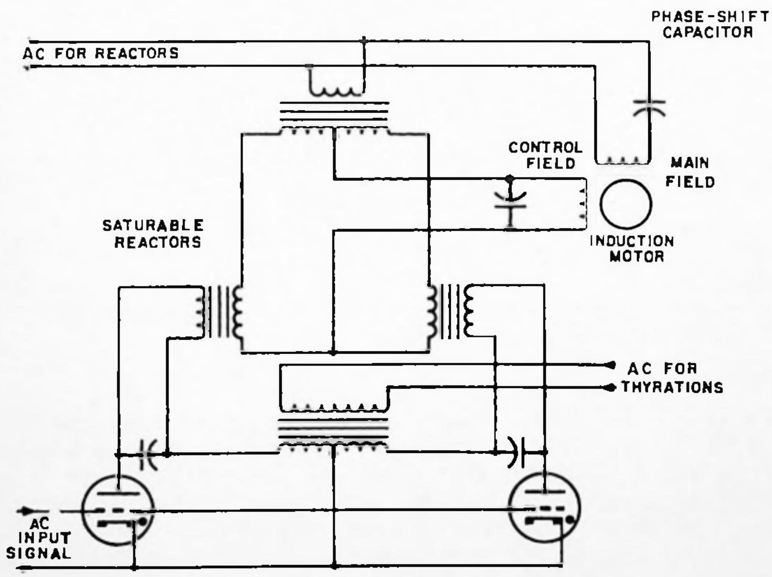


Figure 58. Saturable-reactor control circuit for ac motor.

b. When an ac error signal is detected, it is fed to the thyratron control circuit. This circuit operates in the same manner as described in paragraph 83. The outputs of the thyratrons are connected to the dc control windings of the saturable reactors. When dc flows through either reactor, its inductance is decreased. Therefore, the current path of the control field of the motor is through one end of the transformer which has a high impedance, and through one of the reactors which has a low impedance. The motor is then energized in one direction or the other, depending on which reactor has the dc control current, and forward or reverse torque is developed in proportion to the ac error signal. If the error signal is dc, it may be possible to eliminate the thyratron control circuit, and apply the error signal directly to the saturable reactors, or through a dc amplifier. A major disadvantage to this type of control is the slowness in response to a detected error in a servo system. This slowness is due mainly to the inductance in the control winding where it takes a perceptible time to establish the control current.

86. MAGNETIC AMPLIFIERS

a. A magnetic amplifier consists essentially of saturable reactors with extra windings carrying a direct current called bias current. It depends upon the nonlinear nature of the relationship between magnetic flux and magnetizing current as discussed in paragraph 84b. The major difference between the operation of a magnetic amplifier and a saturable reactor is the magnetic amplifier has extra windings between the ac power windings and dc control windings. These extra windings are supplied with a dc bias to keep the reactors operating near the saturation portions of their respective G-H curves.

b. A magnetic amplifier has advantages over a vacuum-tube amplifier in that it requires no heating elements, is far more shock-resistant, and can be hermetically sealed so as not to require attention for years. The disadvantage is mainly that of slowness in response. Since it is powered by ac which it modulates in accordance with the control signal, it cannot respond any faster than one ac cycle. This limits it to a response speed of 1/60 second when the power supply is 60 cps, and 1/400 second when the power supply is 400 cps.

87. ANALYSIS OF MAGNETIC CONTROL SYSTEM

a. The magnetic control system illustrated in figure 59 uses two saturable reactors with extra windings carrying a dc bias. The power windings of the saturable reactors are connected directly to the power transformer, and the dc control windings are connected in series and require a dc control signal. The direction in which the bias current flows is selected so that the magnetizing force developed by the bias current aids the force developed by the control current in one reactor, and bucks it in the other. The induction motor and power windings of the reactor are connected in the same manner as in figure 58, saturable reactor control system.

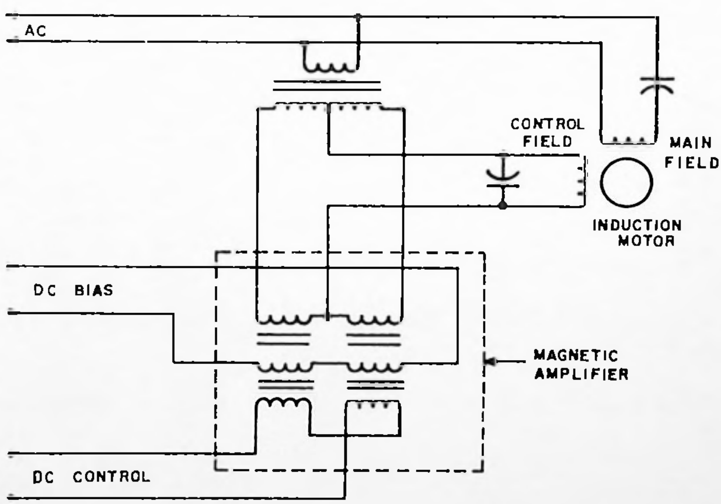


Figure 59. Magnetic-amplifier control circuit for ac motor.

b. When no dc control signal is detected, the currents in each reactor are the same and the control field of the motor is not energized. The dc bias in the extra windings keeps the saturable reactors partially saturated. When a dc control signal is detected, the dc current further saturates one reactor and reduces the saturation in the other reactor. The variations in saturation present a high and low impedance to the control field of the induction motor. The motor, therefore, is energized in one direction or the other in proportion to the dc control signal. As stated previously in paragraph 86, the response of this magnetic-amplifier control is dependent upon the frequency of the ac line. Both the magnetic amplifier and the saturable reactor suffer from the fact that, because of the control winding inductance, it takes a perceptible time to establish the control current. In applications where this time lag is not objectionable, a magnetic amplifier is desirable because it has neither moving parts nor tubes.

Section VIII. HYDRAULIC CONTROLLERS

88. GENERAL

Hydraulic servo systems employ a variety of valves, usually controlled electrically, and may either use a piston acting in a cylinder as the motive force, or a hydraulic pump and motor. In paragraph 69, the discussion on hydraulic actuators included the swash-plate motor and hydraulic ram. The general characteristics of hydraulic controllers are discussed in this section.

89. CHARACTERISTICS

a. The hydraulic controller usually consists of a valve, which may be operated by a solenoid or by a small motor. The opening and closing of the valve determines the connection from the actuator to the high pressure oil lines. The error signal detected by the sensing element controls the operation of the solenoid or motor which, in turn, opens or closes the valve in proportion to the error signal.

b. The advantages of servo systems using hydraulic controllers or combined hydraulic controllers and actuators are as follows:

(1) Compactness and light weight for a given horsepower.

(2) Ability to hold a load at a fixed position without the necessity of applying braking action.

(3) A high overload power, when needed, as much as twice the normal operating value.

(4) Efficiency of approximately 90 percent.

c. The disadvantages of hydraulic controllers or combined hydraulic controllers and actuators are as follows:

(1) Oil lines are bulkier and more expensive than electrical lines.

(2) Operation is for short intervals only because of the necessity for pressurizing the oil lines.

(3) Leakage of the oil lines is a constant source of trouble.

Section IX. SUMMARY AND REVIEW QUESTIONS

90. SUMMARY

a. The Ward-Leonard drive system is used in servo applications for furnishing large amounts of power to dc motors driving heavy loads. The operation of this system is compared to the operation of a power amplifier where both use a small amount of input power to generate a large amount of output power.

b. The amplidyne drive system is similar to the operation of a Ward-Leonard system in that both are used to drive high-powered dc motors. The amplidyne drive system uses a generator modified by shorting the two brush connections and adding two more brushes for the purpose of gaining more power output.

c. A vacuum-tube control system is used for driving low-powered dc motors in servo applications. To meet the requirements of servo systems, the vacuum-tube control system must be able to convert an ac error signal input into amplified dc output, and must be phase sensitive.

d. Thyratron control systems are used in place of vacuum-tube control systems in servo systems requiring increased current.

e. Saturable reactor and magnetic amplifier control systems are desirable in servo applications because they do not have moving parts or require vacuum tubes. A disadvantage of these systems is the slow response that is characterized by the use of ac power supplied to the ac power windings.

f. Hydraulic controllers are applied in servo systems where the power output is required for short intervals.

91. REVIEW QUESTIONS

a. What is the basic difference between the generator used in a Ward-Leonard system and those used in an amplidyne system?

b. How does an amplidyne control system provide high output power?

c. What are the basic requirements of a vacuum-tube control system?

d. How does a thyratron control system differ from a dc servo amplifier?

e. Give three advantages of a hydraulic system. Give two disadvantages.

CHAPTER 6

RESOLVERS

Section I. INTRODUCTION

92. GENERAL

In certain computing systems, voltages serve to represent numerical quantities, and the problem arises wherein position data must be changed from one form of coordinate system to another. For example, in a case where the position of a target is given in terms of slant-range and angle of elevation, it is necessary in many radar and fire control equipments to translate such information into voltages representing the horizontal range and height of the target for computation purposes. This means that a conversion must be made in order that these new quantities may be obtained. Such conversion from one coordinate system to another is known as resolving. There are a number of resolving devices available, but the most accurate one in present day use is the synchronous resolver. This chapter discusses the theory of operation for resolvers, as well as certain practical applications.

Section II. RESOLVER THEORY AND APPLICATIONS

93. BASIC RESOLVER THEORY

a. A synchronous resolver closely resembles a conventional synchro unit in appearance. Resolvers have rotor and stator windings and their operation is similar to that of synchro control transformers since they are used to produce voltages rather than rotation. Although resolvers vary in design depending upon their application, the most common type (fig. 60) has two stator windings wound inside a cylindrical form with the two coil axes at right angles to each other. The stator windings act as transformer primaries and are designated in figure 60 as P1-P3 and P2-P4. Two secondary windings, designated as S2-S4 and S1-S3, are also wound with their coil axes perpendicular and are carried on a cylindrical rotor. Some models have extra windings for feedback purposes, while others may have one primary or one secondary omitted.

b. The typical resolver of figure 60 is shown with the rotor in the zero position. It is evident that the magnetic coupling for the zero position is such that primary P1-P3 induces maximum voltage in secondary S1-S3, but no voltage in secondary S2-S4. Similarly, P2-P4 induces maximum voltage in S2-S4, and no voltage in S1-S3. In addition, the resolver secondary windings are designed so that the voltages induced in each (for the zero position) are <u>in phase</u> with their respective primary voltages, and the transformation ratio between primaries and secondaries is one-to-one.

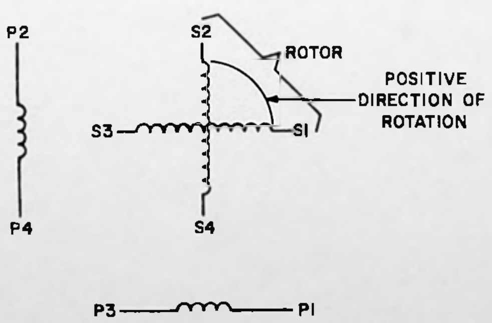


Figure 60. Schematic representation of a resolver.

c. The output voltage from a transformer with a secondary that rotates relative to its primary is proportional to the cosine of the angular displacement of the two windings. If we apply an input voltage of 1 volt to P2-P4, neglecting the P1-P3 winding, we can make a tabulation of the voltage input (E_{in}) against the voltage output (E_{out}) from the S2-S4 secondary winding. Starting in the zero position, with E_{in} equal to 1 volt, values of E_{out} for various displacement angles assuming a positive (counterclockwise) rotation are as follows:

$E_{out} = E_{in} \cos 0^\circ = 1.0$
$E_{out} = E_{in} \cos 30^\circ = .866$
$E_{out} = E_{in} \cos 45^\circ = .707$
$E_{out} = E_{in} \cos 60^\circ = .5$
$E_{out} = E_{in} \cos 90^\circ = 0.0$
$E_{out} = E_{in} \cos 120^\circ = -.5$
$E_{out} = E_{in} \cos 135^\circ = -.707$
$E_{out} = E_{in} \cos 150^\circ = -.866$
$E_{out} = E_{in} \cos 180^\circ = -1.0$
$E_{out} = E_{in} \cos 210^\circ = -.866$
$E_{out} = E_{in} \cos 225^\circ = -.707$
$E_{out} = E_{in} \cos 240^\circ = -.5$
$E_{out} = E_{in} \cos 270^\circ = 0.0$
$E_{out} = E_{in} \cos 300^\circ = .5$
$E_{out} = E_{in} \cos 315^\circ = .707$
$E_{out} = E_{in} \cos 330^\circ = .866$

The values above show how the voltage across the S2-S4 rotor winding varies according to the cosine of the angle it forms with its respective stator winding. However, we must realize that P2-P4 induces a voltage in the other rotor winding as well, since the S1-S3 is also cut by the P2-P4 flux, but at an angle displaced by 90 degrees from the angle at which the flux cuts the S2-S4 winding. The output voltage from S1-S3 will follow the same pattern as that of S2-S4, but will be displaced by 90 degrees and thus vary as the sine of the displacement angle. The preceding discussion also applies to winding P1-P3. When P1-P3 is energized, a voltage proportional to the cosine of the displacement angle is induced in S1-S3; while in S2-S4, the voltage induced is proportional to the sine of that angle.

d. Consider now a case where both primaries of a resolver are energized. In this case, a resultant magnetic field is produced which is the vector sum of the individual primary fields. The induced voltages in the secondaries will then be proportional to the components of the resultant field which lie parallel to each of the windings. In the example of figure 61, the resultant field shows a vector equivalent of approximately 4.4 volts. If the S1-S3 axis were parallel to the resultant field, its induced voltage would be maximum, or 4.4 volts, and, since the S2-S4 axis is displaced 90 degrees the induced voltage in that winding would be zero. If the secondaries are rotated to the position shown in figure 62A, a positive-going voltage will be induced in S1-S3 and a negative-going voltage induced in S2-S4 as shown in figure 62B. Thus, the instantaneous polarity relationship between the primary voltages determines the quadrant in which the resultant field will lie, while the instantaneous amplitude relationships between the primary voltages establishes the strength and position of the resultant field in the particular quadrant.

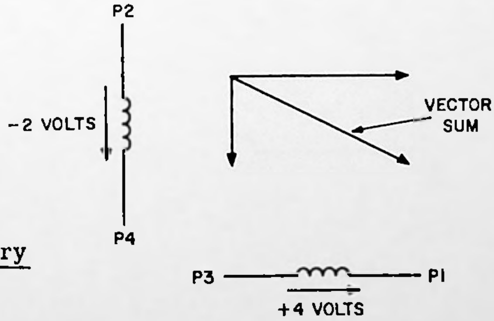


Figure 61. Field produced by resolver primary winding.

94. PLANE COORDINATES

Since plane coordinates are essential to any discussion of resolvers, a brief review of the two coordinate systems (Cartesian and polar coordinates) follows. If the location of any point in a plane is known, it is possible to locate the position of any other point in that plane. In the Cartesian coordinate (or x-y coordinate) system, two distances relative to the known point will locate another point. For example, you can describe the location of a point by stating it is 4 miles north and 3 miles east of a reference point. In the polar coordinate system, the location of a point in a plane is described by a distance from a reference point and an angle with respect to a reference direction. For example, you can describe the location of a point by stating it is 4 miles from the reference point and due north.

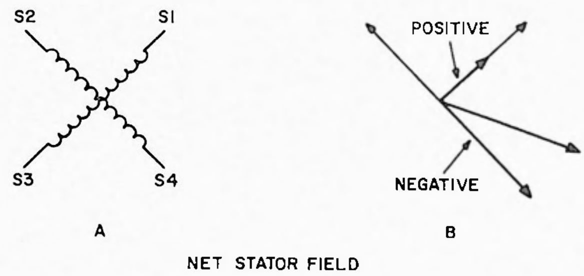


Figure 62. Voltages induced in resolver secondaries.

a. Plane Cartesian or X-Y Coordinates. With plane Cartesian coordinates, the position of a point is given in terms of two distances. The coordinate system uses two axes that are perpendicular to each other. The point of intersection of the axes is called the reference point. The two coordinate distances are then the vector components, parallel to the axes, of the distance between the reference point and the point in question. A, figure 63, shows a point with coordinates 3 and 2, and B shows a point with coordinates 2.5 and -1. The directions of the positive axes may be called north and east, in which case the second point lies one unit south of the origin, or forward and to the right, or any other pair of perpendicular directions.

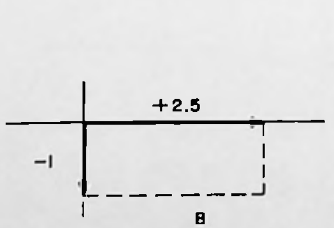


Figure 63. Plane Cartesian coordinates.

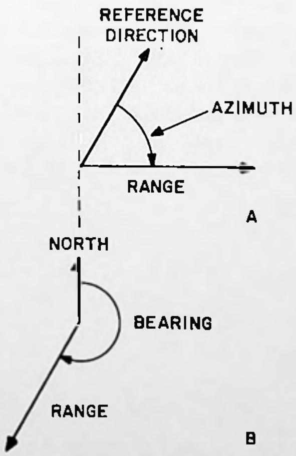


Figure 64. Polar coordinates.

b. Polar Coordinates. The coordinates of a point in a polar coordinate system are the distance and direction of the point from the origin. The distance customarily is called range and is always positive. The direction is measured from a reference direction; in most military applications it is measured in a clockwise direction. When the reference direction is north, the direction angle is called a bearing (B of fig. 64). When the reference direction, as in A, is other than north, the angle is called an azimuth angle, or simply azimuth. Bearing is primarily used in the Navy and the Air Force, since ships and aircraft are steered with reference to north. Azimuth is used more commonly in Army installations, since it is frequently more convenient to use reference directions other than north, such as a line between an emplacement and a distant, clearly visible landmark.

c. Coordinate Conversion. The method of converting from one coordinate system to the other is shown in figure 65. Plane Cartesian coordinates may be added by vector addition of the x and y quantities to find polar coordinates. Conversely, the plane Cartesian coordinates are the rectangular components of the polar coordinate vector. In a resolver, the primary voltages may be thought of as plane Cartesian coordinates. The primary windings then produce magnetic fields which are the Cartesian vector components of a combined field that can be expressed in polar form (field strength and direction). The voltages induced in the secondaries are the Cartesian vector components of the combined field for a different set of Cartesian axes.

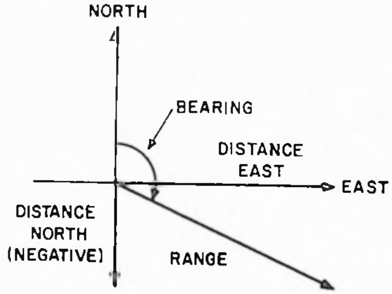


Figure 65. Conversion of coordinates.

d. Rotation of Axes. Figure 66 illustrates a basic example of rotation of Cartesian coordinates when it becomes necessary to change quadrants. In this example, consider the operation as taking place in the following three steps:

(1) Convert the desired point of the Cartesian coordinates to polar coordinates before rotation of the axes.

(2) The coordinates axes are then rotated through the desired angle.

(3) The new polar coordinates designated as relative bearing are converted to plane Cartesian coordinates.

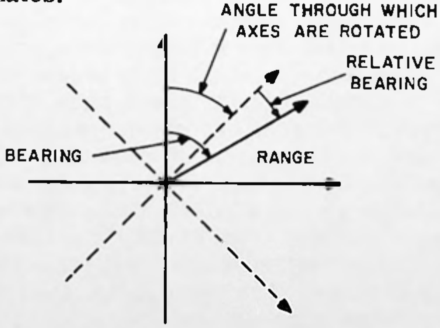


Figure 66. Rotation of Cartesian axes.

95. RESOLVER AS COMPUTING ELEMENT

In the following paragraphs the resolver is discussed, carrying out the three transformations discussed in paragraph 93; conversion from polar to plane Cartesian coordinates, rotation of Cartesian coordinate axes, and conversion from plane Cartesian to polar coordinates.

a. Conversion from Polar to Plane Cartesian Coordinates. Converting from polar to plane coordinates would be the equivalent of obtaining the distances north and east when the range and bearing of the target are known. If, in A of figure 67, a voltage proportional to the range is applied to P2-P4, and the rotor turned by an external device from the zero position in the positive direction through an angle equal to the bearing, the distance north appears as a voltage at S2-S4, and the distance east appears as a voltage at S1-S3. In vector diagram B, the vectors are aligned with the axes of the resolver coils in the schematic, but in C the vectors are tipped so that north is vertical, as is customary. A similar problem, which is handled in the same way, is the determination of the horizontal range and height of an airborne target when the slant range and elevation angle are known.

b. Rotation of Cartesian Coordinate Axes. On a ship bearing angles customarily are measured either from north or from the forward direction. Angles measured from north are called bearings; those measured from the forward direction are called relative bearings. Examination of A of figure 68 shows that the bearing of a target is the sum of the relative bearing and the course of the ship, since this course is the angle measured from north to the forward direction. Suppose then, that the position of a target is given in plane Cartesian coordinates as distance forward and distance to the right, and that it is necessary to convert these to distance north and distance east. Voltages proportional to the forward distance and distance to the right are applied, respectively, to P2-P4, and to P1-P3 (B of fig. 68). The resulting magnetic field then has a strength proportional to the range, and a direction relative to the stator, which is the same as the relative bearing. When the rotor is turned counterclockwise, as in C, through angle Y, equal to the course angle, the secondary voltages will be proportional to the distance north at S2-S4, and to the distance east at S1-S3.

c. Conversion from Plane Cartesian to Polar Coordinates. Conversion from the plane Cartesian coordinates of a target, distances north and east, to the polar coordinates, range and bearing, is another application for the resolver. Voltages proportional to distance north and distance east are applied, respectively, to P2-P4, and to P1-P3 (A of fig. 69). The resultant magnetic field vector has a strength proportional to the range, and a direction the same as the bearing. If, therefore, the rotor is turned in the negative direction (clockwise) through angle X, equal to the bearing in B, a positive voltage proportional to the range will be induced in S2-S4, and no voltage will be induced in S1-S3. In practice, a servo is used as the external device to turn the rotor until there is no output from S1-S3. The required bearing is then the negative of the rotor position angle, and the range appears as a voltage at S2-S4. The resolver, in this case, functions as a computing component and develops its own position order (in terms of the direction of the magnetic field) from the input voltages. It also serves as a follow-up and as a sensing element. The output from S1-S3 is proportional to the sine of the error angle and also proportional to the strength of the magnetic field. When the range is increased, the stronger magnetic field develops a larger error voltage for a given angular error and the servo motor develops a greater torque. This makes it extremely difficult to damp such a servo, since it will be underdamped for long ranges and overdamped for short ranges. The problem is eliminated by using a variable gain amplifier. The range voltage, from S2-S4, is used as a control voltage, and the error voltage, from S1-S3, is passed through the signal channel. With increasing range, the amplification is reduced so that the output of the variable gain amplifier is substantially independent of range. The servo motor then develops a torque, for a given angular error, that is independent of range, and the servo can be damped easily.

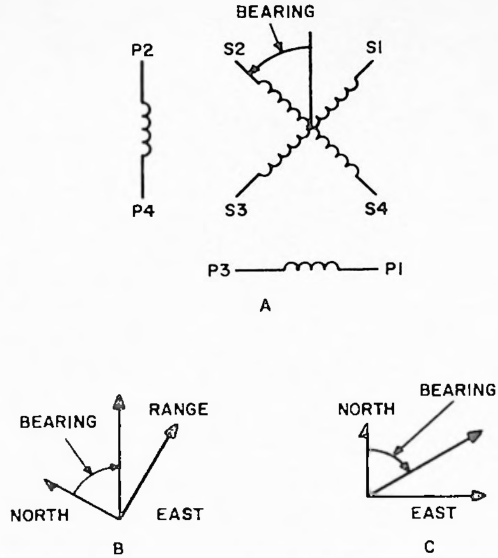


Figure 67. Conversion from polar to plane Cartesian coordinate axes in a resolver.

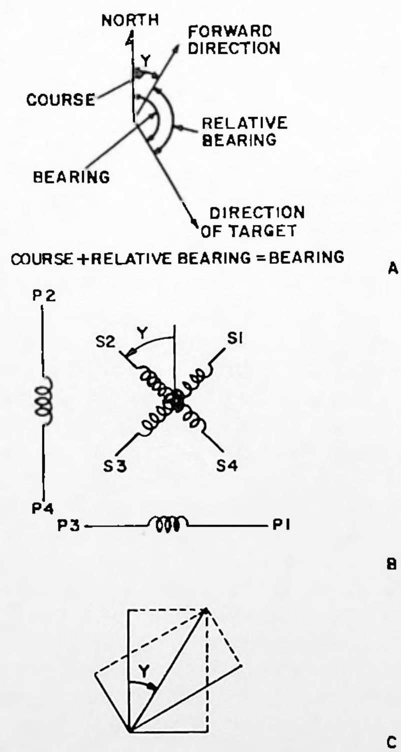


Figure 68. Rotation of plane Cartesian to polar coordinates in a resolver.

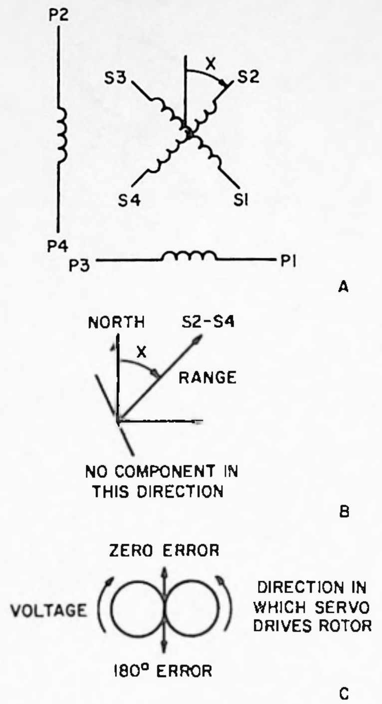


Figure 69. Conversion from plane Cartesian to polar coordinates in a resolver.

96. BOOSTER AMPLIFIERS

Resolvers sometimes are excited through booster amplifiers. That is, the input voltage is fed to a booster amplifier which drives the resolver primary. It is impossible to use a coarse-fine system in resolver computing (as is done in data transmission with synchros), so other means are necessary to minimize possible errors. The booster amplifier eliminates the worst errors, those which result from the winding resistance and leakage reactance in the primary and secondary.

a. Theory. Resolvers frequently are cascaded in chains of three or four. One of the input signals to the final resolver may pass through all of the preceding resolvers, whereas the other may pass only through one. In order to preserve the proper phases and levels, it is imperative that there be no change in level except as called for by the rotor position. Both of these results can be achieved if, first, the proper magnetic field is produced by each primary, and, second, if neither secondary draws more than a negligible amount of current. Both of these requirements can be met by using booster amplifiers between the cascaded resolvers. The output of a secondary is fed to the input of a booster amplifier (fig. 70), which has a high input impedance and draws almost no current, and the output of the booster drives the following primary. To ensure that the proper field is produced an auxiliary winding in the stator structure measures the field produced by the main winding, with the voltage induced in the auxiliary a measure of field strength. The voltage from the auxiliary winding then is fed back to the booster input in opposition to the external signal which normally comes from the preceding resolver secondary. The actual input seen by the first amplifier stage is then the difference between the external input and the follow-up input, a voltage which is proportional to the error in the strength of the field. The booster then acts like a servo and delivers the current required to produce the proper field. Two separate boosters are associated with each resolver, one to drive each primary. There are two auxiliary windings in the stator, one associated with each primary winding and its driving booster.

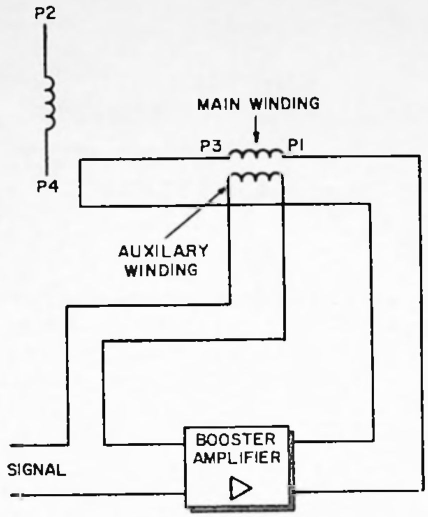


Figure 70. Connection to a booster amplifier.

b. Application. In some cases, all computing voltages may originate at the two secondaries of a resolver having an input on only one primary. In figure 70, however, the booster driving that primary may be omitted, since any phase shift and change in level will be the same at both secondaries. In almost all other cases, a booster is used with each resolver primary that is excited.

97. RESOLVERS FOR DATA TRANSMISSION

Resolvers normally are not used for data transmission. It is possible, however, to excite one primary of a resolver, use the two outputs to excite the primaries of a second resolver, and then drive the shaft of the second with a servo so that it repeats the shaft angle of the first. In terms of the transformation described previously, the first resolver is given a fixed range (constant primary excitation on one winding, no excitation on the other) and any desired bearing (as a shaft angle). The outputs are the corresponding plane Cartesian coordinates. These may be fed to a second resolver which develops its own position order by converting the data back to polar form. The range output of the second resolver may be disregarded, and the negative of the shaft angle will be the bearing, which is the shaft angle of the first. By appropriate reversal of the connections to one secondary, the second shaft can be made to repeat the position of the first directly. Nevertheless, synchros are preferred, since the normal coarse-fine synchro system used in most applications is more accurate than a single pair of resolvers.

Section III. SUMMARY AND REVIEW QUESTIONS

98. SUMMARY

a. Resolvers are, in effect, variable transformers that usually have two primary windings positioned at right angles to each other, and two secondary windings also positioned at right angles to each other. They are used primarily in electrical computations involving the interchange of rectangular and polar coordinates, and the rotation of coordinate axes.

b. The resolver is used in all radar and missile guidance systems because of its accuracy in providing output voltages proportional to the functions of angles.

c. Resolvers serve as coordinate converters in computers. To provide greater precision, booster amplifiers are used to reduce errors due to the winding resistance and leakage reactance in the primary and secondary windings.

99. REVIEW QUESTIONS

a. Describe briefly the operation of a resolver.

b. Name three computing functions of a resolver.

c. Explain how it is possible to use resolvers for data transmission.

CHAPTER 7
AUXILIARY SERVO ELEMENTS

Section I. GENERAL

100. INTRODUCTION

The auxiliary elements of a servo system are those elements used in conjunction with the primary elements (actuator, controller, etc.) for the improvement or compatibility of the system operating as a unit. No set rules can be given regarding the possible combinations of elements (both primary and auxiliary) in a servo system. In general, the selection is determined by power level, but it may be governed also by the availability of power sources, and by limitations on size and weight. The previous discussion acquainted you with some of the various types of servo systems and their respective characteristics, operation and considerations. This chapter deals with the auxiliary elements including the operation and characteristics of modulators, phase-sensitive devices, tachometer and ac eddy current (induction) generators, high- and low-power dc amplifiers, and transfer circuits.

Section II. MODULATORS

101. GENERAL

Modulators are used in servo systems for converting polarized dc signals to properly phased ac signals. These properly phased ac signals contain the dc error components that were originally detected by the sensing element. Thus, an ordinary ac amplifier, rather than a critical dc amplifier with its problems of bias and amplitude drifts, can be employed in the processing of the error signal. This discussion covers the theory and application of various types of modulators including the mechanical and vacuum-tube choppers, and the rectifier modulators.

102. THEORY OF MECHANICAL CHOPPERS

a. Figure 71 illustrates a typical mechanical chopper used in servo systems. Basically, this circuit is a synchronized switch with one contact connected to a dc input and the other connected to ground level. The center arm S is connected alternately to each contact by the ac line voltage that energizes the driving coil C. A dc current also is applied to another coil on the same core to prevent the center arm of the switch from vibrating more than once in one cycle of line voltage.

b. When the line voltage flows through the driving coil C in one direction, the magnetizing force is aided by that of the dc, and the center arm S is attracted to one of the contacts (C_1 or C_2). However, when the ac line voltage flows in the opposite direction, the magnetizing force of the coil C is reduced by the opposite directions of the dc and line voltage. Therefore, the center arm S vibrates at a frequency equal to that of the ac line voltage. The output is a square wave, having the level of dc input for one-half cycle and having zero level for the other. The power required for driving the synchronized switch is reduced by having the center arm tuned to the frequency of the line voltage. Blocking capacitors in the following amplifier remove the dc component, so that the signal becomes a square wave with an amplitude proportional to the dc signal level and a phase which shifts when the dc signal changes polarity. The following amplifier also discriminates against high-frequency signals, so that the square wave ultimately is converted to a sine wave at the frequency of the chopper switching.

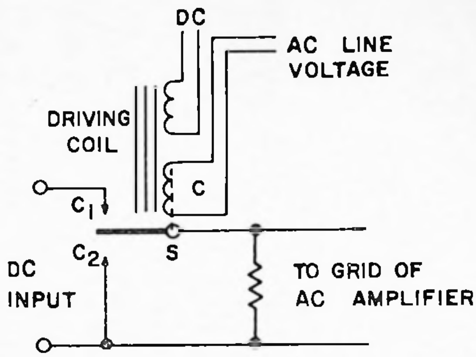


Figure 71. Mechanical-chopper circuit.

103. THEORY OF VACUUM-TUBE CHOPPER

a. The vacuum-tube chopper circuit shown in figure 72 basically consists of two tetrode tubes V1 and V2, a transformer T1, and a balance adjusting resistor R3. The error signal is a pulsating dc signal which is applied between the control grids of V1 and V2. The screen grids of these tubes are connected to the end terminals of a transformer T1 whose primary is connected to an ac reference voltage. The reference voltages applied to the screens of V1 and V2 are 180 degrees out of phase with each other due to the transformer coupling. The adjustable cathode resistor R3 is used for balancing the currents of V1 and V2 so that the output drops to zero when no error signal is detected.

b. When the tubes carry the same currents, the effect of raising the screen of V1 is exactly balanced by that of lowering the screen of V2; consequently, the total current flowing in the common load resistor is unchanged, and there is no ac output. In the presence of an error signal, this is no longer true; ac will appear across the load resistor with an amplitude proportional to the amplitude of the error signal and a phase which reverses when the polarity of the error signal is changed.

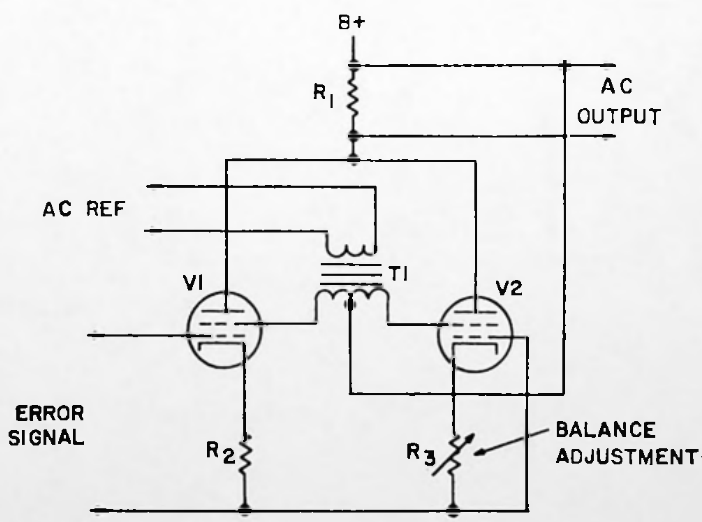


Figure 72. Vacuum-tube chopper circuit.

104. THEORY OF RECTIFIER MODULATORS

a. The rectifier-modulator circuit shown in figure 73 is another type of synchronous switch operation. This circuit consists basically of four diode tubes (D_1, D_2, D_3, and D_4) connected in a standard bridge-rectifier arrangement. The ac reference voltage is connected to the primary of transformer T2 whose secondary is connected to points A and B of the diode arrangement. The center tap of the secondary is connected through isolation transformer T1 to a voltage dividing resistor where the dc input is applied. The output of this circuit is taken across the secondary of the isolation transformer.

b. Since points A and B are connected directly to the secondary of the reference transformer, each pair of diodes (D1 and D2, and D3 and D4) conducts on alternate half-cycles of the ac reference voltage, when no dc input signal is present. The input signal, which is a pulsating dc voltage, is applied across center-tapped resistor R1. One end of this resistor is connected to point E, which is the midpoint of a voltage divider (consisting of D1 and D2) across the secondary of transformer T2. The other end of R1 is connected to point F, which is also the midpoint of a voltage divider (D3 and D4) across the secondary of T2. The output voltage is equal to the voltage between the center tap of R1 and point E for one half-cycle of the ac reference voltage, and is equal to the voltage between the center tap of R1 and point F during the other half-cycle of the ac reference voltage. The output voltage, therefore, is alternately positive and negative with respect to the center tap of resistor R1. When no input voltage is present, the output is zero. When a dc input voltage is applied, however, the output is an ac voltage having a frequency equal to that of the ac reference voltage, and a peak-to-peak amplitude equal to the value of the dc input voltage. Since one side of the input resistor usually is grounded, it is necessary to take the output through the isolating transformer in order to remove the dc component.

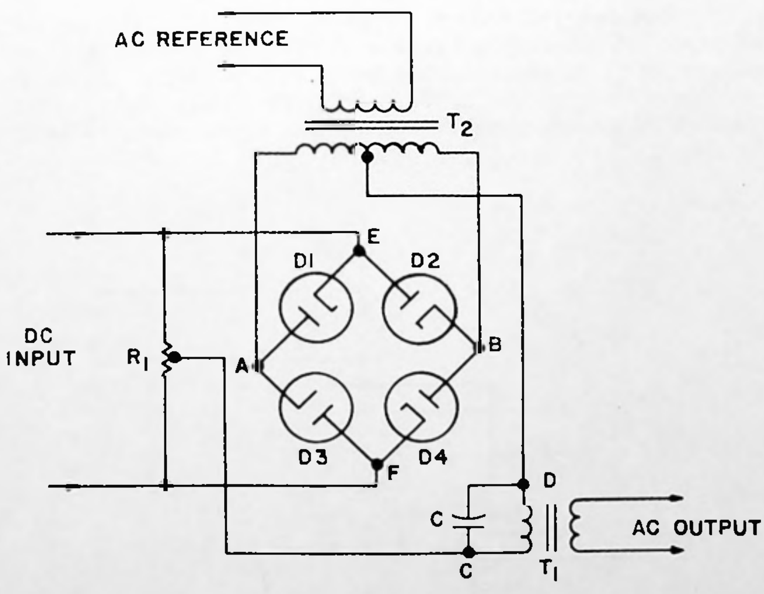


Figure 73. Rectifier-modulator circuit.

Section III. PHASE-SENSITIVE DEVICES

105. GENERAL

The function of a phase-sensitive device in a servo system is to convert an ac error signal into a dc signal containing the error characteristics of the original error signal. The dc signal developed is either positive or negative depending on the phase of the ac signal. The types of phase sensitive devices discussed in this section are the synchronous mechanical switch and the vacuum-tube commutator.

106. SYNCHRONOUS MECHANICAL SWITCH

The synchronous mechanical switch circuit shown in figure 74 is similar to the mechanical chopper circuit (par. 102) in that the operation of the vibrating arm is controlled by an ac reference voltage and a dc bias. Assume that the ac input voltage causes contact C_1 to be positive during the half-cycle that the center arm S is in the up position. During the next half-cycle, when the arm is down, contact C_2 is positive. The resulting output (fig. 74B) is similar to that of a full-wave rectifier and, after filtering, has a positive dc component proportional to the peak-to-peak amplitude of the ac input voltage. If the ac input causes the contacts C_1 and C_2 to be negative when they are in contact with the center arm, the resulting output will be negative (fig. 74C). Thus, the output of this circuit is a converted dc signal that is proportional to the error characteristics of the ac input.

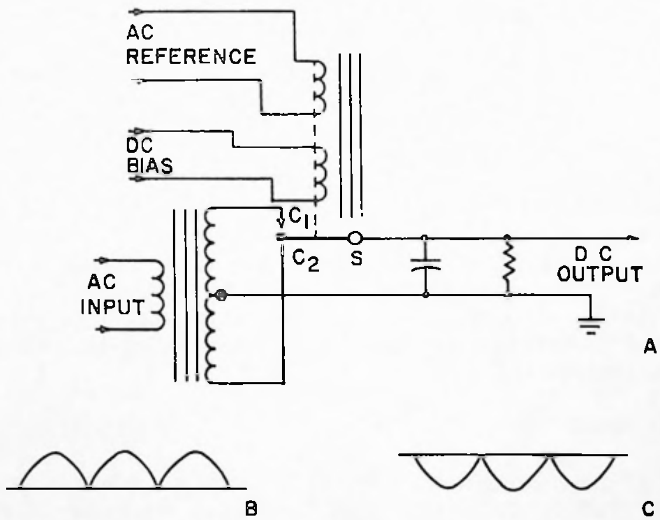


Figure 74. Synchronous switch circuit and waveforms.

107. VACUUM-TUBE COMMUTATOR

A number of vacuum-tube commutator circuits are capable of converting an ac error signal into a dc signal, and still retaining the original signal characteristics. One such circuit is shown in figure 75. The dc bias on the control grids is sufficient to hold both tubes at cutoff. Assume that the phase relationship between the ac input signal and the ac reference voltage causes the grid voltages to change in a positive direction at the same time as the screen of V1. During the positive half-cycle of current flow, therefore, the polarity of the ac reference voltage ensures that the screen of V1 is more positive than the screen of V2. As a result, the screen current of V1 is greater than the screen current of V2. The cathode of V1, therefore, is more positive than the cathode of V2, and the plate of V1 is more negative (less positive) than the plate of V2. The output is the difference between the two plate voltages. A phase reversal of the grid signal causes V2 to draw more current than V1, and reverses the polarity of both the cathode-to-cathode and the plate-to-plate signals. As a result, the output voltage is opposite in polarity. A circuit of this sort is useful where a dc output need not be developed in respect to ground as, for example, in controlling the field current of a Ward-Leonard or amplidyne drive system.

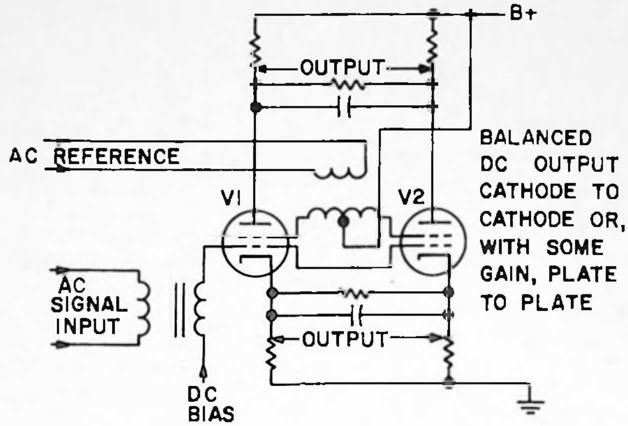


Figure 75. Vacuum-tube commutator circuit.

Section IV. TACHOMETER AND INDUCTION GENERATORS

108. GENERAL

A small generator, called a tachometer generator, was discussed in paragraph 12 where it was used as the follow-up element in a rate servo. In addition to this function, it can be used for developing a damping voltage rather than using a cumbersome viscous damping mechanism. In either case, the output voltage is proportional to the speed of shaft rotation. It can be used in dc and ac servo applications. When used in dc servo applications, it usually is called a dc tachometer generator and uses a permanent magnet field to provide a dc output proportional to its speed of rotation. When used in ac servo applications, it is called an induction generator and provides an ac output proportional to its speed of rotation. This section covers the operation of an induction generator only since a dc tachometer generator is not practical for high-accuracy servo applications.

109. INDUCTION GENERATOR

a. The usual ac generator, or alternator, delivers an output in which both the amplitude and the frequency are proportional to shaft speed. This is obviously not suitable for use in an ac servo, since it is not permissible to use anything but the normal operating frequency of the servo. The induction generator, however, delivers an output proportional to its shaft speed, which has a fixed frequency, and which reverses its phase when the direction of rotation is reversed.

b. A schematic of an induction generator, shown in figure 76, has two fixed windings located at right angles and a rotor. The main winding or reference winding ER is excited from an ac source of a fixed frequency. No voltage is induced in the ES winding because the axis of the ER winding is at a right angle to the axis of the ES winding. When the rotor rotates, voltage is induced in the rotor and current flows. The voltage and current are proportional to the speed of the rotor and also the magnetic field. Since the magnetic field alternates, the rotor voltage and current alternate as well. The magnetic field of the rotor induces voltage in the ES winding of the same frequency as the exciting source and an amplitude that is essentially proportional to the angular velocity of the rotor.

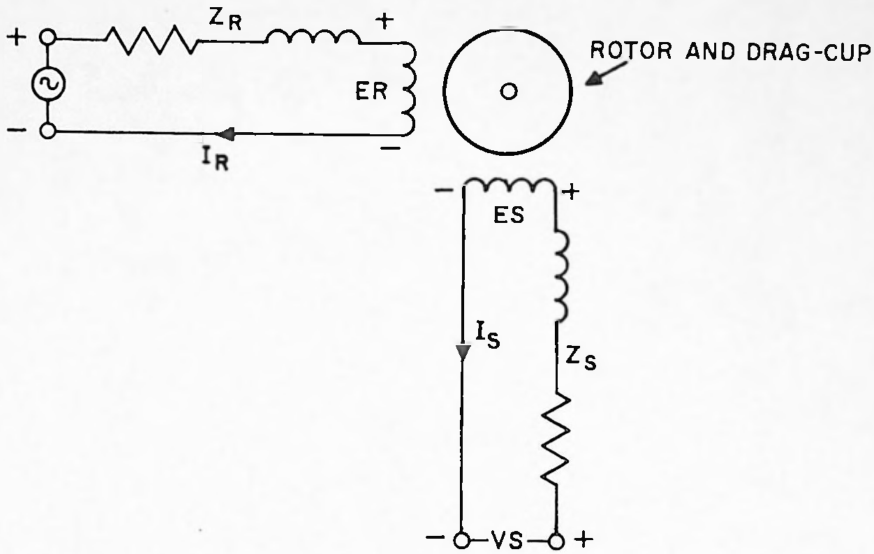


Figure 76. Schematic of an induction generator.

Section V. DIRECT-COUPLED AMPLIFIERS

110. INTRODUCTION

A direct-coupled amplifier is one that can amplify dc and low-frequency voltages and currents. Its distinguishing feature is that the plate of one stage is coupled directly to the grid of the following stage without the use of a capacitor or a transformer. A conventional amplifier (for example, one using capacitor coupling between the plate of one stage to the grid of the following stage) functions satisfactorily for sine-wave signals over a wide frequency range. However, if the frequency of the input signal becomes low enough, the capacitor reactance will increase causing a decrease in the amount of signal reaching the grid of the succeeding stage. In servo applications, the frequency is low enough to cause such a loss in signal thus reducing whatever gain that can be obtained through the use of an amplifier. A direct-coupled amplifier is used to lift this low frequency limit by eliminating the capacitance reactance and make amplification possible at the low frequency range used in servo applications. This section discusses the theory of basic direct-coupled amplifiers and its operation in the antenna-positioning system of radar set AN/MPQ-10.

111. BASIC DIRECT-COUPLED AMPLIFIERS

a. Figure 77 illustrates a typical direct-coupled amplifier using triodes. In this type of a circuit, voltage distribution must be such that the plate of V1 must have a positive voltage with respect to its cathode, the grid of V2 must have a negative voltage with respect to its cathode, and the two cathodes can not operate at the same potential. This voltage distribution is obtained by a voltage divider, R_d. The B-plus supply voltage is impressed across R_d which is tapped at various points. Capacitor C_d is used to bypass any ac variations of voltage that may appear across R_d. The input voltage, e_{in}, is amplified by V1 and V2 and appears as e_{out} at the plate of V2. The plate-load resistor of V1, R_{L1}, also acts as the grid resistor of V2, since the voltage developed across it appears at the grid of V2. R_{L2} is the plate-load resistor of V2.

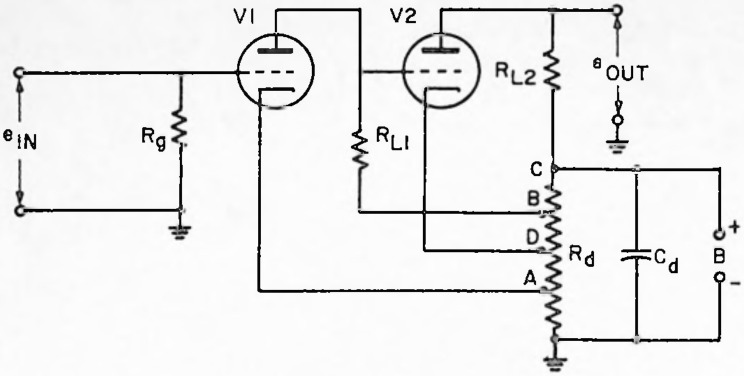


Figure 77. Basic dc amplifier.

b. The cathode of V1 is connected to point A and the plate is connected to point B on the voltage divider. Point B is positive with relation to point A, making the plate positive with relation to its cathode. This permits V1 to conduct. The voltage developed from point A to ground is the bias voltage for V1.

c. The plate of V2 must be positive relative to its cathode for conduction to occur. In addition, the grid voltage of V2 must not be positive relative to its cathode. The plate current of V1 which flows through R_{L1} produces a considerable dc voltage drop across this resistor. As a result, the voltage at the plate of V1 and at the grid of V2 is less positive than is point B on the voltage divider. Tap D is so located on resistor R_d that the magnitude of the positive voltage on the grid of V2 is lower than the magnitude of the positive voltage on the cathode of V2. Therefore, the grid of V2 is actually less positive relative to the cathode of V2, and the tube operates normally. The voltage that appears from point C to point D is the plate voltage of V2.

112. CIRCUIT OPERATION OF DC AMPLIFIERS USED IN AN/MPQ-10

a. The dc amplifiers shown in figure 78 consist of V1505, V1506, V1507, and V1508. The function of these amplifiers is to amplify the dc output from the phase detector, producing dc signals of sufficient amplitude to excite the azimuth servo generator. The amplifiers also combine the rate generator (tachometer) and the servo generator current feedback voltages with the phase detector output.

b. The dc error voltage from the phase detector is applied to V1505 grid (pin 1) (fig. 78). Common cathode resistor R1525 provides cathode-coupling and phase inversion of the error signal to dc amplifier V1506. The time constants of the resistance-capacitance circuits connected to the grid circuits of V1505 and V1506 depend on the mode of operation of the radar set (either AUTO or MANUAL). Except for the change of resistance in the V1505 grid circuit, the circuit is identical for automatic or manual operation.

c. The dc error signal from the phase detector is impressed across resistor R1518 and thyrite resistor CR1501. During manual operation, the CR1501 bilateral resistance forms the V1505 grid-to-ground resistance. During automatic tracking, the V1505 grid-to-ground resistance is increased by the addition of R1518 and R1519. Because these resistors are in series with CR1501, its effect is not as pronounced during automatic tracking as during manual operation.

d. CR1501 has a nonlinear current-voltage characteristic which is expressed as follows:

$$I = k\,E^n$$

where n is a number between 2 and 7. Because of this, the resistance changes so that a constant voltage across its terminals is maintained. A hundredfold increase of current through CR1501 produces only a twofold voltage increase. This stabilizing effect prevents excessive voltages, which occur during manual operation or sector scan, from damaging the equipment. This type of stabilization is not required during automatic tracking because sudden acceleration usually is not encountered.

e. Dc balance potentiometer R1524 is adjusted so that, in the absence of any signal on the V1505 grid (pin 1), current flow through common cathode resistor R1525 divides equally between V1505 and V1506. The voltages at the V1505 and V1506 plates (pin 5) are equal. This condition produces no servo generator field input, hence there is no armature current in the azimuth servo generator and no movements of the azimuth servo motor. As a result, there is no rate generator voltage and no armature current feedback to the dc amplifiers.

f. Assume that there is a positive signal on the V1505 grid (pin 1) and no signal on the V1506 grid (pin 1). The positive V1505 signal drives the plate voltage in a negative direction. This negative signal appears at the grid (pin 5) of dc power amplifier V1507 (fig. 78). At the same time, the voltage at the R1524 arm rises because of the increased current flow through R1525. This results in the following effects:

(1) The V1506 cathode voltage (pin 7) increases because of the increased current flow through R1525. The V1506 grid (pin 1) remains at ground potential while the cathode (pins 2 and 7) becomes positive. This is equivalent to a negative signal on the grid, which raises the V1506 plate potential and sends a positive signal to the grid (pin 5) of dc power amplifier V1508 (fig. 78).

(2) As a result of these two equal and opposite signals on the V1507 and V1508 control grids (pin 5), the plate current through one-half of the azimuth servo generator field coil decreases, while the current through the other half increases. Because the currents through the two halves of the field coil set up opposing lines of force, the direction of the resultant flux is determined by the polarity of the larger current. The resultant field strength is equal to the difference between intensities of the two fields.

g. If the signal on the grid (pin 1) of V1505 is negative, the current through V1505 decreases, making the cathode more negative. This is equivalent to a positive signal on the V1506 grid (pin 1). Polarities on the V1507 and V1508 grids are now reversed. The resultant generator field flux is of opposite polarity, producing rotation of the servo motor in the opposite direction.

h. If a signal is fed to the V1506 grid (pin 1) in the absence of a signal on V1505, the amplifier operates in a similar manner. A positive signal on the V1506 grid produces a motor rotation opposite in direction to that obtained when a positive signal is impressed on the grid (pin 1) of V1505. This is used as one means of stabilization for the dc servo amplifier.

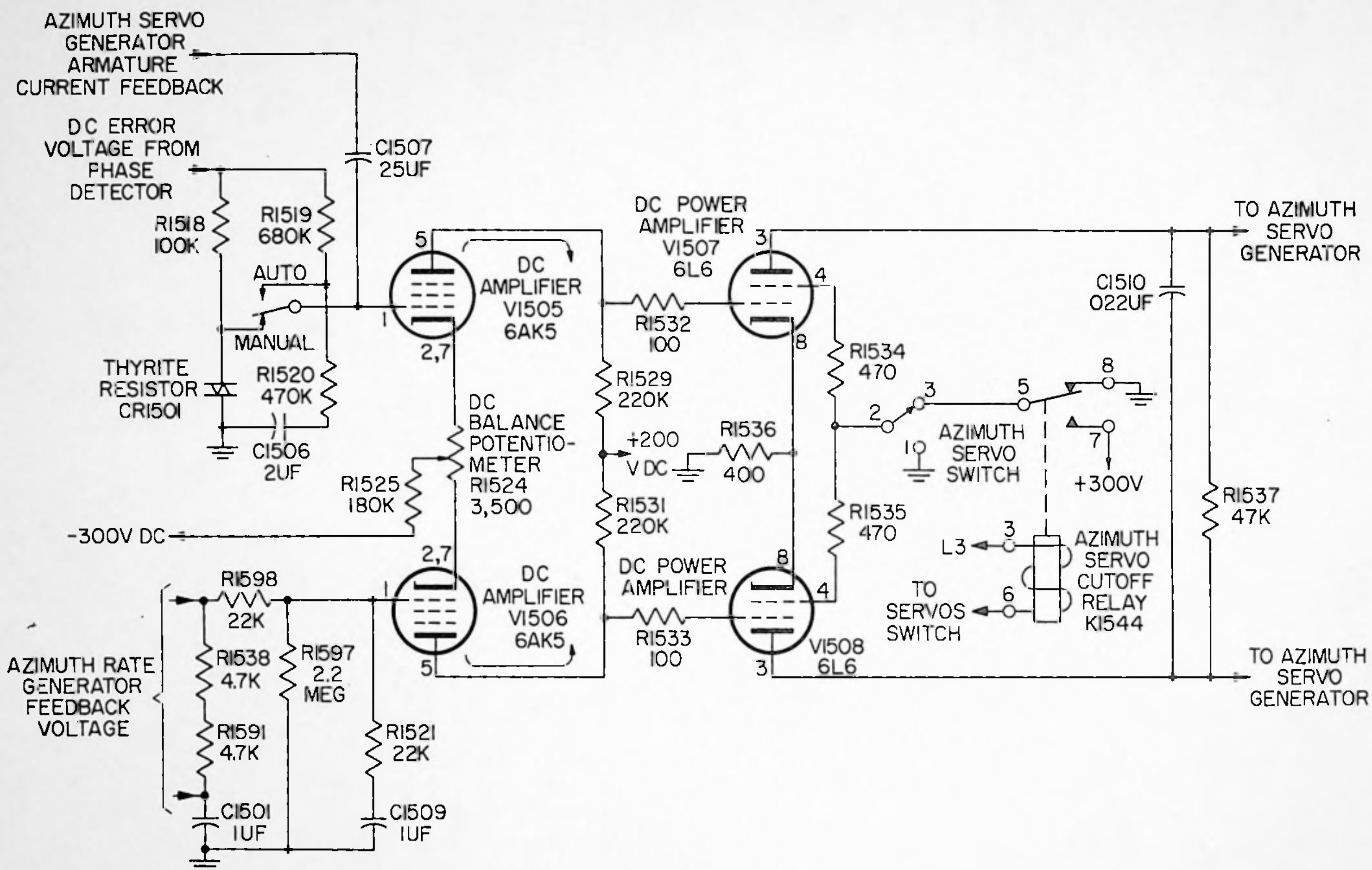


Figure 78. Dc amplifiers in the antenna positioning system of Radar Set AN/MPQ-10.

Section VI. TRANSFER CIRCUITS

113. GENERAL

In some instances of servo applications it is necessary to use two separate data input channels preceding the controller. These dual inputs are known as a coarse-fine control system. The coarse section of the system consists of a coarse sensing element and follow-ups; the fine section consists of a fine sensing element and follow-ups. The switching process from fine to coarse control, or, from coarse to fine control, is made possible by the use of transfer circuits. A transfer circuit is used with a coarse-fine system in order to retain the precision of the fine system and the greater range of the coarse system. For example, the load is positioned roughly by allowing the actuator to be controlled by the output of the coarse sensing element. When the coarse sensing element sees only a small error, control of the actuator is transferred to the fine sensing element and the load is positioned precisely. The transfer circuit is operated by the error signal from the coarse sensing element. When this error is large, the circuit is activated and control of the system is handed to the coarse sensing element for approximate position. After the coarse error signal has been reduced to some lower level, the circuit allows control to revert to the fine sensing element. The various types of transfer circuits discussed in this section are the relay transfer circuit, vacuum-tube transfer circuit, and rectifier transfer circuit.

114. RELAY TRANSFER CIRCUIT

The relay transfer circuit shown in figure 79 is the simplest of the transfer circuits used in a coarse-fine control system. It consists of a relay which is energized by the coarse error signal. When this signal is large, the relay is energized closing the contact from fine control to coarse control. When the coarse signal is small, the relay is deenergized transferring the coarse control to fine control. The major disadvantage of the relay transfer circuit is that it may not transfer rapidly enough for a high-performance servo. For this reason, the relay transfer circuit is not used as frequently as the vacuum-tube and rectifier transfer circuits.

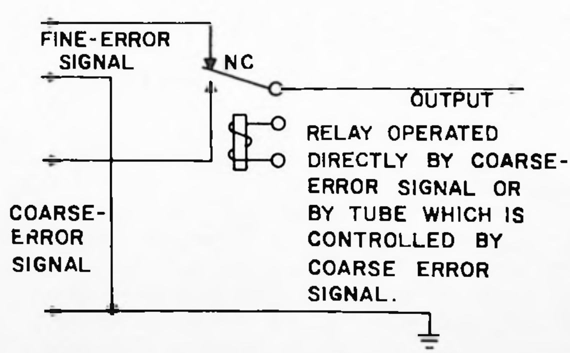


Figure 79. Relay transfer circuit.

115. VACUUM-TUBE TRANSFER CIRCUIT

In the vacuum-tube transfer circuit (fig. 80), the bias for tubes V1 and V2 is produced by the cathode resistors and the plate-bleeder resistors. The circuit is designed so that the cathode and plate resistors produce a bias voltage that allows V1 to pass the fine error signal, but prevents V2 from conducting. The coarse error signal is applied to rectifiers V3 and V4 which develop negative and positive dc outputs, respectively. The positive voltage from V4 is applied to the grid of V2 allowing it to pass the coarse error signal. The negative voltage cuts off V3 and it does not pass the fine error signal. Therefore, the vacuum-tube transfer circuit normally is operated with fine error control until the coarse error becomes large enough to transfer the control from fine to coarse.

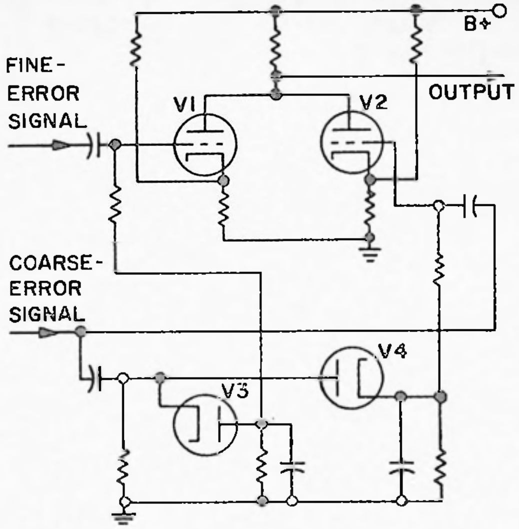


Figure 80. Vacuum-tube transfer circuit.

116. RECTIFIER TRANSFER CIRCUIT

The rectifier transfer circuit (fig. 81), depends on the nonlinear operation of the rectifiers. Each rectifier appears as an open circuit in the nonconducting direction. In the conducting direction, each rectifier, because of its nonlinear operation, has a high resistance for small signals and a low resistance for large signals. The fine error signal is developed across the voltage divider consisting of R2, CR3 and CR4 (in parallel), and R1. The coarse error signal is developed across the voltage divider consisting of R1 and the parallel combination of CR1 and CR2. The output voltage is developed across parallel diodes CR3 and CR4 and series resistor R1. Since the combination of CR1 and CR2 acts as a high resistance for small coarse error signals, only a small portion of these signals are developed across R1. Small fine error signals, however, are developed across the high resistance of CR3 and CR4 and, therefore, appear as the output voltage. When the coarse error signal becomes large enough to pass easily through the rectifier network (CR1 and CR2), it is developed across resistor R1 and overrides the fine error signal, which is limited by series resistor R2. The coarse error signal then appears at the output. The fine signal appears at the output until it is overridden by the coarse signal. The overall result of the operation of the circuit, after both the fine and coarse signals are added at the output, is that the output follows the fine signal only when it is small, and the coarse signal only when it is large. The operating levels of the circuit are designed so that the coarse signal, when it is large, will always override the fine signal. Rectifier transfer circuits, because they contain no filaments, consume less power than do vacuum tube circuits.

117. BIAS REQUIREMENT WITH TRANSFER CIRCUITS

a. In most systems where the follow-up head and data-transmission head make more than one revolution, there are two positions of the sensing element for which it delivers a zero output. This will be true, for example, with the contact sensing element described in paragraph

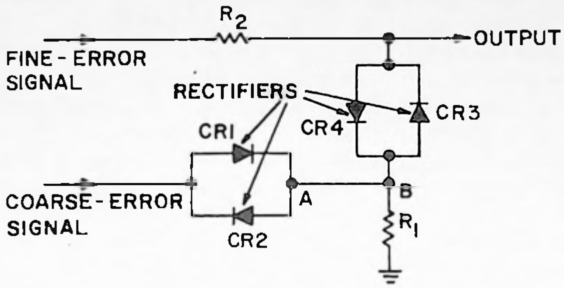


Figure 81. Rectifier transfer circuit.

10a if the two fixed arms are replaced by segments so that a complete revolution is possible. Although there is no error voltage at either of these positions (which are called nulls), only one of them is stable, since the servo will drive toward one and away from the other (A of fig. 82). Note that positive sloping error voltage indicates a stable null whereas a negative sloping error voltage denotes an unstable null.

b. The two nulls are usually 180 degrees apart, and this raises a difficulty in the case of a coarse-fine system having an even ratio. Assume, for example, that the fine system makes 36 revolutions for one revolution of the coarse system. The proper load position is one for which both fine and coarse sensing elements are at stable nulls. For other positions nearby, the fine sensing element will provide the error signal that causes the servo to drive the load in the proper direction; for positions more distant from the load position, the coarse sensing element will provide such a signal. Suppose, however, that the load is displaced just far enough to shift the coarse follow-up head by 180 degrees. The coarse sensing element then will be at a null and will relinquish control to the fine sensing element. With a coarse-fine ratio of 36, a half-revolution of the coarse system is accompanied by 18 turns of the fine system, and the fine sensing element will be a stable null (B of fig. 82). The servo now will hold the load at this ambiguous position unless, through some circumstances, the error increases enough to transfer control to the coarse sensing element. If this happens, the load will be driven to the proper position. However, if the servo positions the load with accuracy, the error may never increase that much.

c. The ambiguity inherent in the coarse-fine servos with an even ratio may be eliminated by using a coarse-fine servo with an odd ratio. For example, if the ratio is 27, the fine sensing element then will have turned through 13-1/2 revolutions, the point in question being an unstable null for both coarse and fine systems.

d. If it is not feasible to use an odd coarse-fine ratio, the ambiguity may be eliminated by displacing the unstable null of the coarse sensing element so that it coincides with an unstable null of the fine sensing element (C of fig. 82). With a coarse-fine ratio of 36, the unstable null of the coarse element may be shifted by 5 degrees from 180 degrees to 175 degrees or to 185 degrees, so that moving the coarse element from one null to the other will turn the fine sensing element through 17-1/2 or 18-1/2 turns, respectively.

e. If a synchro is used for a sensing element, the error signal it develops is proportional to the sine of the error angle. The two nulls of a synchro thus are always 180 degrees apart, and it is not desirable to modify the synchro. The solution is to add a small bias voltage to the error output of the coarse synchro and then to use the sum of these two voltages as the coarse error signal, as in C of figure 82. In C of figure 82, the bias voltage added to the output of the coarse synchro is equal to the output of the synchro for a positive error of 2.5 degrees. The resulting error signal will disappear when the actual error is minus 2.5 degrees, or plus 182.5 degrees. If the synchros are then offset or displaced by 2.5 degrees (with respect to the load), the new error axes will be as shown in C of figure 82. The biased coarse error signal will be zero at 0 degrees and 185 degrees, and the fine synchro will turn through 18-1/2 turns as the coarse synchro error travels from one null to the other. At the new zero position, there will be a stable null for both the 36:1 and the 1:1 synchros. The coarse, or 1:1, synchro error output corresponding to an error angle of minus 2.5 degrees will be equal and opposite to the bias voltage, so that the resulting error signal is zero. At the new ambiguous position, there will be an unstable null for both the 36:1 and the 1:1 synchros. Because of the offset, the coarse synchro sees an error of 182.5 degrees when the actual error is 185 degrees. At this point, also, its output balances the bias voltage to give a zero error signal. The combination of the offset and the bias causes the unstable null of the coarse synchro to be shifted by 5 degrees from 180 degrees to 185 degrees, where it coincides with an unstable null of the fine synchro.

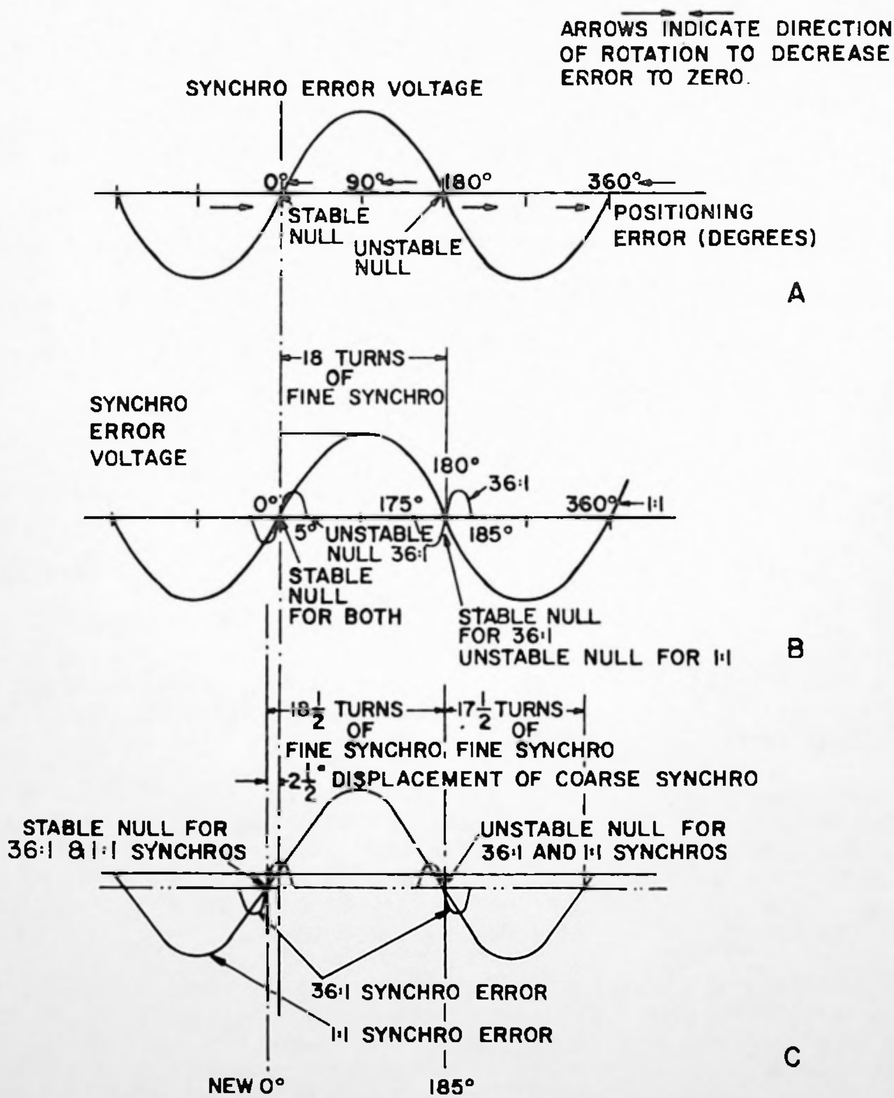


Figure 82. Phase-error positioning.

Section VII. SUMMARY AND REVIEW QUESTIONS

118. SUMMARY

a. Modulators in servo systems are used for converting error signals from dc to ac. This conversion can be accomplished by means of a mechanical chopper, vacuum tube, or rectifier-modulator.

b. Phase-sensitive devices are used for converting error signals from ac to dc. This conversion can be accomplished by means of a synchronous mechanical switch, or by vacuum tube commutators.

c. A tachometer generator is used in ac or dc servo applications for generating a damping voltage that is proportional to the angular velocity of its shaft. The frequency of this voltage is the same as the frequency of the fixed excitation source.

d. Dc amplifiers are used in servo applications for amplifying dc inputs from phase detectors so that the output fed to the servo generator is of a sufficient amplitude for effective excitation.

e. Transfer circuits function as a controlling device for determining whether coarse or fine error signals are used in coarse-fine servo systems. This can be accomplished by means of relay, vacuum-tube or rectifier circuits. Relay circuits are not used frequently for control because of the time lapse involved in the actual transfer.

f. When a synchro is used for a sensing element, it is necessary to provide a small bias voltage to the output of the coarse synchro. This, in effect, is used for displacing the nulls of the system.

119. REVIEW QUESTIONS

a. How is the dc input converted to an ac output in a mechanical chopper?

b. Describe briefly the operation of a vacuum tube chopper.

c. Describe briefly the basic operation of a drag-cup tachometer generator.

d. What function does a dc amplifier serve in a servo system?

e. What is the main disadvantage of a relay transfer circuit?

f. How are the nulls displaced when using a synchro as a sensing element?

CHAPTER 8

TYPICAL SERVO SYSTEMS

Section I. INTRODUCTION

120. GENERAL

This chapter contains a discussion of long-distance data transmission and the practical applications of typical servo systems, including a functional analysis of the components and circuits operating as a system. Specifically, the discussion includes the requirements and basic problems encountered in long-distance data transmission, synchro data transmission, an analysis of the operation of the SCR-584 antenna-positioning system, and an analysis of the operation of the AN/MPQ-10 antenna-positioning system.

Section II. LONG-DISTANCE DATA TRANSMISSION

121. USE OF LONG-DISTANCE DATA TRANSMISSION

In the discussion on servo elements in chapter 1, data transmission was discussed in reference to the method used to transmit the external order to the sensing element. Now, consider the case where it is necessary to transmit the external order between two locations separated by a much longer distance, such as occurs in a radar network. In a radar network that consists basically of an information center and early-warning radars, the connecting link between the information center and each radar is the long-distance data transmission system. A long-distance data transmission system presents target position data in a form that can be used by the tracking radar in locating the target in the fastest possible time, thus, increasing the efficiency of the system to either identify or destroy the target, whichever may be the case.

a. Designation of Target for Tracking Radar. In general, a tracking radar operates as follows. Information as to position of a target is fed to the tracking radar. It then searches for the target and when the target is found, begins to track. As soon as the radar starts tracking, a predictor begins calculating the anticipated position of the target on the arrival of a shell, and in a short time, gun orders are available. As target speeds increase, however, the interval between the time the target is detected and when gun orders are available must become less. One way of reducing this interval is to shorten the time required to find the target by sending more precise data to the radar, so that the antenna is pointing in almost the right direction when the target comes in view. Because the radar is already tracking as a result of the data fed into it, the predictor will have an approximate solution when the target comes in view, and precise gun orders are available after a fairly short tracking period. Early-warning radar is used to obtain this advance data, and to be effective the data must be transmitted over relatively long distances.

b. Data Transmission from Early-Warning Radar to Information Center. Information from an early-warning radar may be sent to an information center by voice using either telephone or radio communication. Because time is a critical factor, it is desirable to transmit the radar data automatically. Such an automatic data transmission system is presently being used in the Missile Master (AN/FSG-1) and Missile Monitor (AN/MSG-4) systems. In these systems, the ranges and bearings of targets observed at several early-warning radar stations are converted to some convenient form and automatically transmitted to a common information center.

c. Utilization of Data from Remote Tracking Radar. Data concerning the operation of long-range missiles used to intercept enemy aircraft must be transmitted from the tracking radar to the missile-launching site so that proper missile-launching orders can be computed.

122. PROBLEMS ENCOUNTERED IN LONG-DISTANCE DATA TRANSMISSION

The transmission of servo data normally involves transmitting the position of a shaft to some remote point. This usually is done with the aid of synchros, the synchro data being transmitted from one point to the other on transmission lines. However, transmitting synchro data over long transmission lines presents problems.

a. Nature of Synchro Signals. Synchro signals consist of alternating current, usually 60 cps, of varying amplitudes. As a synchro turns through a complete revolution, the signal on each of its output leads passes through a complete amplitude cycle. It falls to zero, rises to a maximum amplitude with reversed phase, falls again to zero, and then returns to its original phase. At some point during this cycle the signal passes through a maximum in its original phase. Thus, data transmission is reduced to the problem of transmitting 60-cps signals and the sidebands produced by these amplitude variations.

b. Effect of Long Transmission Lines on Synchro Data. Long transmission lines, whether wire lines or a series of telephone or radio links, affect signals in several ways. The signals are mixed because of cross-talk between lines; second, the signals pick up noise; third, the amplitude relationship between signals at the receiving end are not the same as those at the sending end; and fourth, the 60-cps signals by themselves cannot be transmitted through the radio links without a carrier of some sort. Any of these effects can spoil the accuracy of data transmitted over long distances.

123. SYNCHRO DATA TRANSMISSION OVER VOICE CHANNELS

a. Subcarrier Transmission. The simplest way to send synchro signals over a long distance without tying up a separate channel for each signal is to use subcarrier transmission over one or more voice channels. A number of distinct audio frequencies are selected as subcarriers. Each of these is modulated by a single synchro signal, either by amplitude or frequency modulation. The several modulated signals are added and the sum is sent as a voice signal over a wire line, or used to modulate a voice channel in a radio communications link. At the receiving end, the several subcarriers are separated by filters and detected either by frequency-modulation discriminators or amplitude-modulation detectors to recover the original signal. These methods result in the balanced treatment of the several signals and also reduce crosstalk (the effect of one signal on another). It has unfavorable aspects from the standpoint of signals contamination by noise, lack of bandwidth, and the availability of channels.

b. Effects of Noise. Since synchro data depends on the relative amplitudes of the three outputs of each synchro winding, any noise added to the signals reduces the accuracy with which the signal amplitudes can be identified. Furthermore, since the synchros at the receiving end are normally control transformers feeding repeater servos, noise reduces the precision with which the servos set the repeater shafts.

c. Effects of Bandwidth. A narrow bandwidth is desirable for each of the channels in the synchro transmission system, both to reduce contamination of the signals by noise and to reduce the total space required in the available frequency spectrum for transmission of a given number of synchro signals. Narrowing the bandwidth of a transmission system, however, produces a number of undesirable effects. If a bandpass filter is added at the output of the control transformer at the receiving end, it becomes a part of the servo loop of the repeater servo, and although such a filter will reduce the noise level in the servo system, it also will introduce a certain amount of integral control which is antidamping. If the bandpass filters are introduced in the transmission channels where they operate directly on the synchro output signals, they will produce lag in the transmission (in much the same way that a resonant circuit tends to ring) so that the repeater shaft will follow with a velocity lag. At first glance, it appears that improved accuracy can be obtained by using a higher gear ratio for the fine synchro, so that a given synchro error produces a smaller error in the position of the repeater shaft. Unfortunately, this improvement is obtained at the expense of an increased bandwidth requirement for the fine synchro signals, since the 60-cps output of the synchro changes more rapidly with changing shaft position when its gear ratio is increased. In general, improving the system accuracy, whether by reducing the noise with filters or by increasing the gear ratio of the fine synchros, introduces velocity lag. There is, therefore, a choice between obtaining good static accuracy accompanied by the undesirable velocity lag when using a narrow bandwidth, or obtaining poor static accuracy and somewhat less velocity lag when using a wide bandwidth. The effect is seen most clearly when the bandpass filter is added at the output of the receiving control transformer. The reduction of noise improves the static accuracy. The bandpass filter is, however, antidamping and, if additional viscous damping is added to restore stability, introduces velocity lag. It is not possible to use error-rate damping without getting velocity lag because the error-rate damping network is essentially a band-stop filter and precisely cancels the noise-reduction effect of the bandpass filter.

Section III. SCR-584 ANTENNA-POSITIONING SYSTEM

124. GENERAL

The purpose of the SCR-584 antenna-positioning system is to control the movement of the antenna in both azimuth and elevation. To accomplish this control function, the system consists of the following components: automatic tracking unit, azimuth and elevation tracking unit, antenna position control unit, and a servo system. This system is capable of automatically or manually controlling the antenna position. In automatic tracking, the error voltage is combined with the reference voltages, thus generating the desired control voltages for the drive motors positioning the antenna. When positioning the antenna manually, simulated error signals, generated by moving the azimuth and elevation handwheels, are combined with a reference voltage to produce the same result. This section covers the operation of the azimuth channel and includes a functional analysis of the components of the antenna-positioning system.

125. OPERATION OF AZIMUTH CHANNEL

A simplified block diagram of the azimuth channel is shown in figure 83. The elevation and azimuth channels are identical in operation differing only in the movement of the antenna. Since there are two possible modes of operation, automatic and manual, the operation of both modes is discussed in this section.

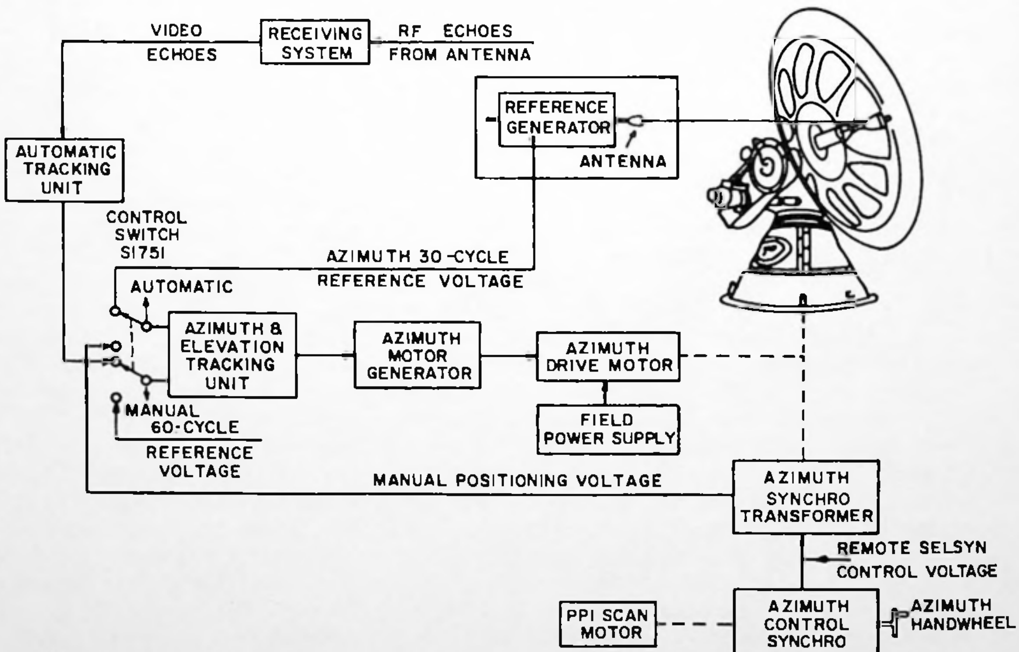


Figure 83. Azimuth channel of the antenna positioning system used in SCR-584.

a. Automatic Operation. With S1751 in the AUTOMATIC position, the signals from the automatic tracking unit and the reference generator are connected to the azimuth control channel in the azimuth and elevation tracking unit. The video input to the automatic tracking unit is the 30-cycle error voltage which results from the conical scanning of the radar beam about the tracking target. This error voltage is detected and fed through S1751 to the azimuth and elevation tracking unit. The control voltage output from the azimuth and elevation tracking unit is a push-pull dc voltage which is fed to the azimuth motor generator. The motor generator output is used to control the direction and amount that the azimuth drive motor moves the antenna. The antenna turns until the error voltage is not present. The field power furnishes the constant dc power for the drive motor fields.

b. Manual Operation. The manual positions include manual, PPI scan, and remote operation. In these types of operation, the controlling voltages are produced by azimuth and elevation synchros in the antenna position control unit and are controlled by the azimuth motor generator. With S1751 in MANUAL or PPI SCAN position, any movement of the azimuth control synchro caused by either the azimuth handwheel or the PPI scan motor, induces a voltage in the azimuth synchro transformer. The magnitude of the induced voltage depends on the relative positions of the azimuth transformer and azimuth control synchros. This induced voltage is zero if the two synchros are in line, and maximum if there is 180 degrees difference between the positions of the synchros. The output of the synchro transformer is the manual positioning error voltage. From the point where the error voltage is detected and fed through S1751, the circuit is exactly the same as for automatic operation.

126. FUNCTIONAL ANALYSIS OF THE COMPONENTS OF THE SCR-584 ANTENNA-POSITIONING SYSTEM

The complete block diagram of the antenna-positioning system of the SCR-584 is shown in figure 84. This diagram provides you with the overall operation of the system performing as an integral unit. The specific function of each individual component is discussed in subsequent paragraphs.

a. Automatic Tracking Unit. This unit produces an error voltage which indicates the direction and displacement the antenna is off target when the radar set is tracking automatically.

(1) Error signal detector. The video signals from the receiver servo channel are amplitude modulated by a 30-cycle sine wave. The percentage of modulation is determined by the position of the antenna in relation to the target being tracked. Error signal detector V502 detects the modulation of the video signals and applies the 30-cycle sine-wave output to error signal amplifier V503.

(2) Error signal amplifier. Error signal amplifier V503 functions as an amplifier and avc circuit. Its bias, supplied by the average dc level of the input signal, regulates the gain so that the output is proportional to the percentage of the input signal modulation and not to the amplitude. The output of V503 is fed to balanced amplifier V504 through center-tapped transformer T501.

(3) Balanced amplifier. Balanced amplifier V504 is a double-triode tube. The two input signals are obtained from T501, which has its secondary winding grounded at the center tap. The center tap causes the two input signals of V504 to be 180 degrees out of phase with each other. The output signals from V504 are amplified 30-cycle sine waves which are fed to the commutator tubes in the azimuth and elevation tracking unit.

(4) Power supply. The power supply furnishes 105 volts regulated, 300 volts unregulated, and filament voltages. The 105-volt power is furnished for screen voltage; the 300-volt power is used for plate voltage in the automatic tracking unit and in the azimuth and elevation tracking unit.

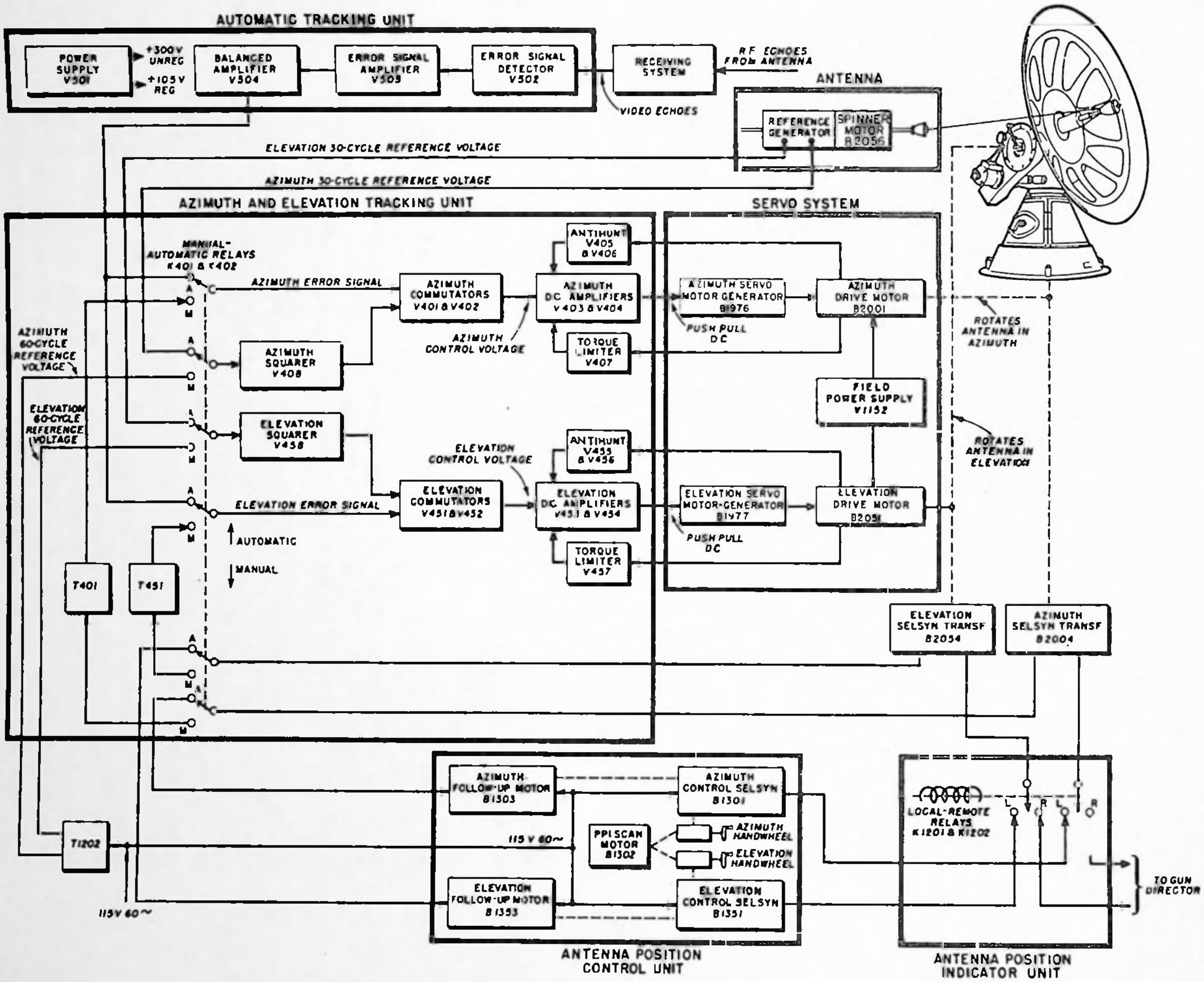


Figure 84. Antenna positioning system, complete block diagram.

b. Antenna Position Control Unit. The antenna may be positioned manually by means of the handwheels of the antenna position control unit or the PPI scan motor. Since the azimuth and elevation circuits of the control unit are identical, only the azimuth circuit is discussed. The PPI (Plan Position Indicator) scan motor causes the rotors of the azimuth and elevation control synchros to rotate when the operation of the system is in PPI scan. The rotor of the elevation synchro turns only enough to tilt the antenna upward through a 356-mil sector. After the upper limit is reached, the antenna and the rotor return to the starting position and the cycle is repeated. The lower limit of the 356-mil sector is set by turning the elevation handwheel. The rotor of the azimuth synchro turns continuously during PPI scan operation.

(1) Control synchros. The two control synchros transmit error signals to the synchro transformers in the pedestal. The rotors of the synchros may be rotated manually by the azimuth and elevation handwheels. During PPI scan operation, the rotors are turned by the PPI scan motor.

(2) Follow-up motors. The follow-up motors keep the control synchros aligned with the synchro transformers when the radar set is tracking automatically. In automatic operation, the control synchros are not used. Therefore, if the synchros are not kept in alignment with the antenna, the antenna slews violently when S1751 is moved from AUTOMATIC to any other position. The follow-up motors react to the signals produced by the synchro transformers and turn the control synchro rotors in order to reduce the error signal to zero.

c. Spinner Motor and Reference Generator. The spinner motor spins the reference generator and the dipole at 1800 rpm. The reference generator produces two 30-cycle voltages, 90 degrees out of phase, which are used for automatic tracking.

d. Azimuth and Elevation Tracking Unit. This unit receives the error signals and reference voltages. When tracking automatically, the error signals are produced by the automatic tracking unit and the reference voltages are supplied by the reference generator. If the radar set is tracking in one of the manual positions, the reference voltages are supplied by the 60-cycle ac line; the error signals are produced by the synchro transformers. The output of the azimuth and elevation tracking unit is a direct current which is proportional to the error voltage.

(1) Squarer circuits. When the set is tracking automatically, the contacts of manual-automatic relays, K401 and K402, are in the automatic position, and the two 30-cycle reference voltages from the reference generator are fed to the grids of V408 and V458. During operation in any of the manual positions, the contacts of K401 and K402 are in the manual position and the 60-cycle reference voltage is fed to the grids of V408 and V458. In all types of operation, the outputs are square waves 180 degrees out of phase.

(2) Commutator circuits. These circuits receive two input voltages: the plate voltage, which is a square wave from the squarer circuits; and the error voltages, which are fed to the grids from either the automatic tracking unit or the synchro transformers. The outputs of the commutator circuits are two dc voltages taken from the cathodes. As long as the antenna is on target, the cathode voltages remain at 76 volts. As the antenna varies about the target, the cathode voltage varies above and below 76 volts, depending upon the direction and magnitude of the error.

(3) Dc amplifiers. The output cathode voltages of the commutator tubes are fed directly to the grids of the dc amplifiers through a filter circuit. As long as the input voltage remains at 76 volts, a constant plate current flows through the dc amplifiers. When the input voltage to the amplifier changes, the plate current changes a proportional amount. The plate load for the dc amplifiers is the field winding of one of the motor generators in the servo system.

(4) Antihunt circuits. These circuits prevent the antenna from hunting or oscillating about the point where the error voltage is zero. As the antenna reaches this point, its inertia causes it to pass the point and an error voltage is produced of opposite polarity. The antenna then reverses and overshoots in the opposite direction. Thus, the antenna oscillates or hunts about the point of zero error voltage. To dampen these oscillations, a signal is fed back to the screen grids of the tubes in the antihunt circuits from the drive motors of the servo system. This feedback opposes any change in armature current, and the antenna comes quickly to rest.

(5) Torque-limiting circuits. These circuits reduce the grid voltage of the dc amplifiers if the error signal becomes great enough to move the antenna at an excessive rate. The plates of the torque-limiter tubes are connected to the grids of the dc amplifiers. When the current to the drive motor becomes excessive, the torque limiter tubes conduct and the drop in plate voltage is applied to the grids of the dc amplifiers.

e. Servo System. The servo system contains the drive motors that cause the antenna to rotate in azimuth and to tilt in elevation. The system also contains the motor generators which produce power for the drive motors.

(1) Motor generators. The motor generators, which consist of an ac motor and a dc generator, amplify the error signals and apply them to the armature of the drive motors.

(2) Drive motors. The azimuth and elevation drive motors supply the mechanical power to turn the antenna. The motor fields are supplied with a constant voltage from the field power supply. The outputs of the motor generators are applied to the drive motor armature to produce rotation in the desired direction and at the desired rate.

(3) Field power supply. This supply furnishes power to the fields of the drive motors. Its output is 260 volts direct current, at 225 ma.

f. Antenna Position Indicator Unit. This unit contains the local-remote relays, K1201 and K1202. These relays switch the input of the synchro transformers from either the control synchros in the radar set or the control synchros in a gun director.

Section IV. AN/MPQ-10 ANTENNA-POSITIONING SYSTEM

127. GENERAL

The AN/MPQ-10 antenna-positioning system is a servo system which controls the movement of the antenna in azimuth and elevation during manual or automatic operation, and provides antenna azimuth and elevation information to the data-transmitting system. The antenna-positioning system consists of the following units: antenna servo amplifier, elevation servo motor and rate generator, azimuth servo motor and rate generator, three-phase induction motor and generator assembly, servo control unit, secant potentiometer R1302 geared to the elevation servo motor, and the ELEVATION and AZIMUTH handwheels on the control panel.

a. Manual Operation. During manual operation, the antenna positioning system drives the antenna so that the azimuth and elevation angles correspond to the AZIMUTH and ELEVATION handwheel settings. This is accomplished as follows: Control transformers, geared to the handwheels, are supplied with actual antenna position data from synchro transmitters geared to the antenna drives. If the antenna position in azimuth or elevation differs from the handwheel position, the corresponding control transformer produces an ac error signal. This ac error signal is amplified and converted to a dc error voltage, the polarity and magnitude of which are proportional to the direction and magnitude of the angular difference. The dc error voltage is applied to the field winding of a servo generator, continuously driven by a 3-phase motor. The generator output, a dc voltage proportional to the dc error voltage, energizes a servo motor, which drives the antenna and the synchro transmitters so that the ac error voltage is reduced to zero.

b. Automatic Operation. During automatic tracking, the antenna-positioning system drives the antenna so that antenna azimuth and elevation angles remain equal to actual target azimuth and elevation angles with respect to the radar set. This is accomplished in the following manner. The spinner motor rotates the spinner and causes the antenna beam to describe a cone in space. When the target does not lie on the cone axis, video signals caused by target echoes undergo a 60-cps amplitude modulation, the phase and magnitude of which are proportional to the angle between the target and the cone axis. In the synchronizing system, the spin modulation detector separates the 60-cps modulation from the video signals, forming a 60-cps error voltage. This ac spin modulation error signal actuates the antenna-positioning system in the same manner that the synchro error voltage does during manual operation, causing the antenna to rotate in the direction that minimizes the ac spin modulation error signal.

128. OVERALL OPERATION OF SYSTEM

a. The block diagrams in figures 85 and 86 present an overall functional analysis of the complete antenna-positioning system used in the AN/MPQ-10 radar set. The antenna servo amplifier (fig. 86) contains two similar channels, each consisting of an ac amplifier, phase detector, and push-pull dc amplifier. During automatic tracking, the antenna servo amplifier is actuated by the output of the spin modulation detector in synchronizer unit 3. The reference generator in the spinner motor provides reference voltages which separate the azimuth and elevation error signals in the phase detectors. During manual operation, the inputs to the antenna servo amplifier are the voltages developed in the control transformers attached to the AZIMUTH and ELEVATION handwheels, and a constant-amplitude, 60-cps alternating current taken from the power line as a reference voltage.

b. The antenna servo amplifier provides high-amplitude dc error voltages which excite the fields of the azimuth and elevation servo generators, which are driven by the 3-phase induction motor (fig. 85). Relays in the servo control unit serve as on-off switches for the servo motors. The servo generators provide power amplification of the dc error voltages. The servo generator armature outputs are fed to the armature windings of the azimuth and elevation servo motors. The servo motors rotate in a direction determined by the armature voltage polarity; they drive gear trains that position the antenna in azimuth and elevation, and

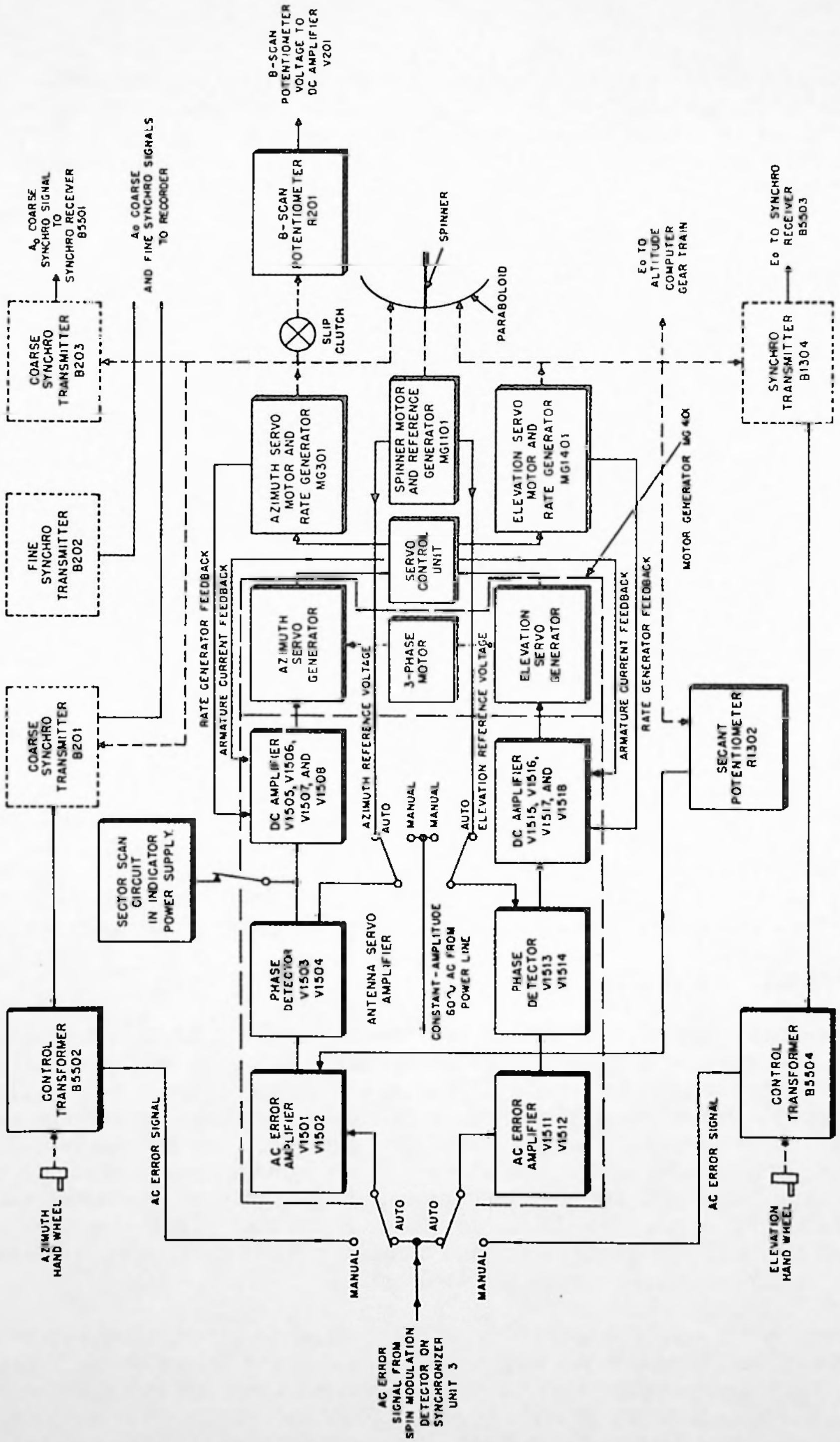


Figure 85. Antenna positioning system of AN/MPQ-10.

actuate data synchro transmitters that form azimuth and elevation signals.

c. Each servo amplifier channel contains two internal feed-back loops for increasing the system's response and preventing limiting or overshoot. One is a current feedback from the servo generator armature winding; the other is a voltage feedback from the rate generator. The rate generators (tachometers), part of the servo motors, provide dc feedback voltages that are proportional to the rotational velocity of the servo motors.

d. The azimuth channel (fig. 86) differs from the elevation channel as follows:

(1) The gain of the azimuth channel is a function of the elevation angle and is controlled by secant potentiometer R1302.

(2) The azimuth channel contains a sector scan circuit. This circuit permits the antenna to scan continuously an area of up to 800 mils in azimuth.

(3) The azimuth channel provides continuous 6400 mil coverage; the elevation channel has upper and lower limits of +1,540 and -125 mils, respectively.

e. The operation of the elevation channel is similar to that of the azimuth channel with the exception that there is no secant potentiometer in the elevation circuit.

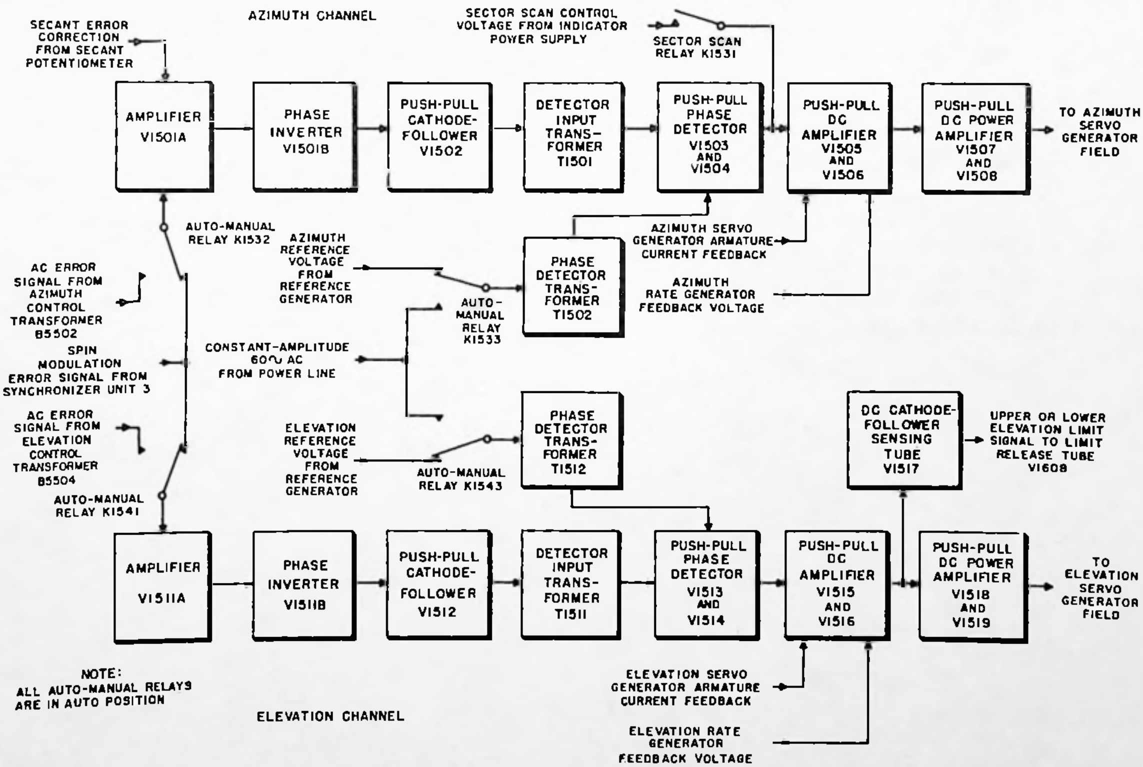


Figure 86. Antenna servo amplifier, block diagram.

Section V. SUMMARY AND REVIEW QUESTIONS

129. SUMMARY

a. Synchros generally are preferred in the transmission of data over transmission lines in servo application.

b. Subcarrier transmission is the simplest way of transmitting synchro data without using a separate channel for each synchro signal. Bandwidth and noise must be considered when conveying this data over transmission lines.

c. The antenna-positioning system used in the SCR-584 is capable of both automatic and manual tracking operation. The operation of the azimuth channel in this system is identical with the operation of the elevation channel.

d. The error voltage used in the SCR-584 is supplied by the conical scanning of the radar beam about the tracking target. The frequency of this error signal is 30-cps.

e. The purpose of the antenna-positioning system used in the AN/MPQ-10 radar set is to position the antenna in azimuth and elevation on the basis of data supplied by the error voltages.

130. REVIEW QUESTIONS

a. List the requirements for data transmission.

b. When using synchros for transmitting data, what frequency generally is used?

c. What are the effects of bandwidth in data transmission systems?

d. Describe briefly the operation of the azimuth channel in the SCR-584 antenna-positioning system.

e. Describe briefly the overall operation of the antenna-positioning system used in the AN/MPQ-10 radar set.