CHAPTER 2

SERVOS

LEARNING OBJECTIVES

Upon completion of this chapter you will be able to:

1. Define the term "servo system" and the terms associated with servo systems, including open-loop and closed-loop control systems.
2. Identify from schematics and block diagrams the various servo circuits; give short explanations of the components and their characteristics; and of each circuit and its characteristics.
3. Trace the flow of data through the components of typical servo systems from input(s) to outputs(s) (cause to effect).

SERVOS

Servo mechanisms, also called SERVO SYSTEMS or SERVOS for short, have countless applications in the operation of electrical and electronic equipment. In working with radar and antennas, directors, computing devices, ship's communications, aircraft control, and many other equipments, it is often necessary to operate a mechanical load that is remote from its source of control. To obtain smooth, continuous, and accurate operation, these loads are normally best controlled by synchros. As you already know, the big problem here is that synchros are not powerful enough to do any great amount of work. This is where servos come into use.

A servo system uses a weak control signal to move large loads to a desired position with great accuracy. The key words in this definition are move and great accuracy. Servos may be found in such varied applications as moving the rudder and elevators of a model airplane in radio-controlled flight, to controlling the diving planes and rudders of nuclear submarines.

Servos are powerful. They can move heavy loads and be remotely controlled with great precision by synchro devices.

They take many forms. Servo systems are either electromechanical, electrohydraulic, hydraulic, or pneumatic.

Whatever the form, a relatively weak signal that represents a desired movement of the load is generated, controlled, amplified, and fed to a servo motor that does the work of moving the heavy load.

Q-1. What is a servo?

CATEGORIES OF CONTROL SYSTEMS

A control system is a group of components that are linked together to perform a specific purpose. Generally, a control system has a large power gain between input and output. The components used in the system and the complexity of the system are directly related to the requirements of the system's application.

Control systems are broadly classified as either CLOSED-LOOP or OPEN-LOOP.

Closed-loop control systems are the type most commonly used in the Navy because they respond and move the loads they are controlling quicker and with greater accuracy than open-loop systems.

The reason for quicker response and greater accuracy is that an automatic feedback system informs the input that the desired movement has taken place. Upon receipt of this feedback information, the system stops the motor, and motion of the load ceases until another movement is ordered by the input. This is similar to the system that controls heat in many homes. The thermostat (input) calls for heat. The furnace (output) produces heat and distributes it. Some of the heat is "fed back" to the thermostat. When this "feedback" raises the temperature of the room to that of the thermostat setting, the thermostat responds by shutting the system down until heat is again required. In such a system, the feedback path, input to output and back to input, forms what is called a "closed loop." This is a term you will hear and use often in discussions of control systems. Because closed-loop control systems are automatic in nature, they are further classified by the function they serve (e.g., controlling the position, the velocity, or the acceleration of the load being driven).

An open-loop control system is controlled directly, and only, by an input signal, without the benefit of feedback. The basic units of this system are an amplifier and a motor. The amplifier receives a low-level input signal and amplifies it enough to drive the motor to perform the desired job. Open-loop control systems are not as commonly used as closed-loop control systems because they are less accurate.

OPEN-LOOP CONTROL SYSTEM

As we stated previously, an open-loop control system is controlled directly, and only, by an input signal. The basic units of this type consist only of an amplifier and a motor. The amplifier receives a low-level input signal and amplifies it enough to drive the motor to perform the desired job.

The open-loop control system is shown in basic block diagram form in figure 2-1. With this system, the input is a signal that is fed to the amplifier. The output of the amplifier is proportional to the amplitude of the input signal. The phase (ac system) and polarity (dc system) of the input signal determines the direction that the motor shaft will turn. After amplification, the input signal is fed to the motor, which moves the output shaft (load) in the direction that corresponds with the input signal. The motor will not stop driving the output shaft until the input signal is reduced to zero or removed. This system usually requires an operator who controls speed and direction of movement of the output by varying the input. The operator could be controlling the input by either a mechanical or an electrical linkage.

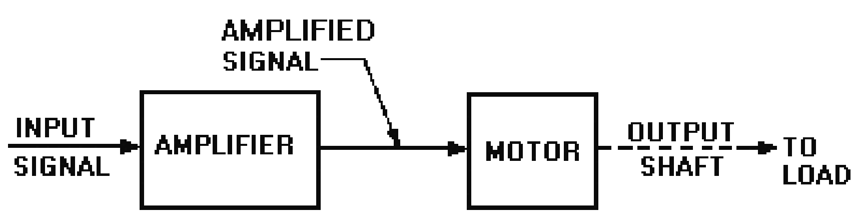


Figure 2-1.—Open-loop control system basic block diagram.

THE CLOSED-LOOP CONTROL SYSTEM

A closed-loop control system is another name for a servo system. To be classified as a servo, a control system must be capable of the following:

1. Accepting an order that defines the desired result
2. Determining the present conditions by some method of feedback
3. Comparing the desired result with the present conditions and obtaining a difference or an error signal
4. Issuing a correcting order (the error signal) that will properly change the existing conditions to the desired result
5. Obeying the correcting order

We have discussed the open- and closed-loop control systems and defined a servo system as a closed-loop control system. Although not technically accurate by definition, open-loop control systems are also often referred to in the Navy and many publications as servo systems even though they lack one of the five basic requirements, that of feedback.

Q-2. In an open-loop control system, what action reduces the input to zero so the load is stopped at the desired position?

Q-3. What basic requirement of a closed-loop system (not present in open-loops) enables present load position to be sensed?

OPERATION OF A BASIC SERVO SYSTEM

For the following discussion of a servo system, refer to figure 2-2, view (A), view (B), view (C) and view (D).This closed-loop servo system is the most common type in the Navy today. It is normally made up of electromechanical parts and consists basically of a synchro-control system, servo amplifier, servo motor, and some form of feedback (response).

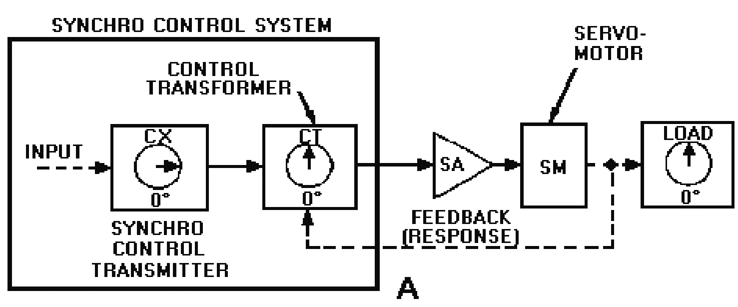


Figure 2-2A.—A basic servo system (closed-loop).

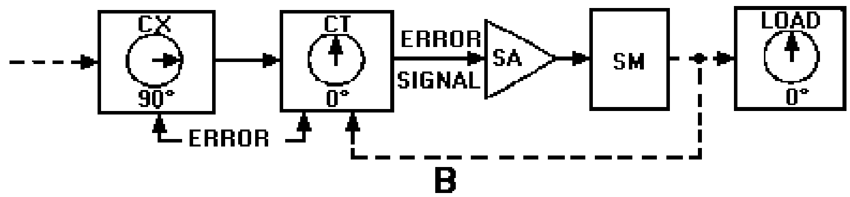


Figure 2-2B.—A basic servo system (closed-loop).

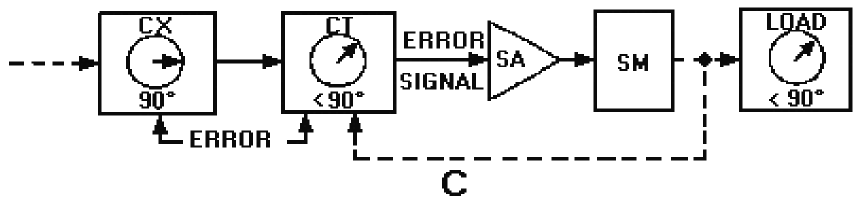


Figure 2-2C.—A basic servo system (closed-loop).

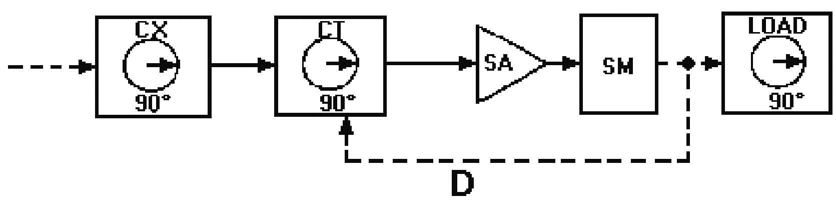


Figure 2-2D.—A basic servo system (closed-loop).

The synchro-control system provides a means of controlling the movement of the load, which may be located in a remote space. The servo amplifier and servo motor are the parts of the system in which power is actually developed (to move the load).

As you remember, the controlling signal from a CT is relatively weak, too weak to drive an electric motor directly. In views A through D of figure 2-2, assume that the control signal will be initiated by a handcrank input connected to the synchro transmitter (CX). The dials located on the CX and the CT indicate the positions of the synchro's rotors, while the dial on the load indicates the position of the load.

In view A, the dials of both the CX and the load indicate that the load is in the desired position. Because the load is where it should be, there will be no error signal present at the servo amplifier and no power to the servo motor.

In view B, the rotor of the CX has been moved by the handcrank to 90º. (This indicates that it is ordered to move the load by 90º.) Notice that the rotor of the CT is still at 0º. The CT now develops a signal, called the ERROR SIGNAL, which is proportional in amplitude to the amount the CT rotor is out of correspondence with the CX rotor. The phase of the error signal indicates the direction the CT rotor must move to reduce the error signal to zero or to "null out." The error signal is sent to the servo amplifier. In view C, the error signal has been amplified by the servo amplifier and sent on to the servo motor. The motor starts to drive in the direction that will reduce the error signal and bring the CT rotor back to the point of correspondence. In this case the motor is turning clockwise.

The mechanical linkage attached to the servo motor also moves the rotor of the CT. This feedback causes the amplitude of the error signal to decrease, slowing the speed at which the load is moving.

In view D, the servo motor has driven both the load and the rotor of the CT, so that the CT is now in correspondence with the CX rotor. As a result, the error signal is reduced to zero (nulled). The load stops at its new position. Note that in this servo system, we moved a heavy load to a predetermined position through the simple turning of a handcrank. In responding to the handcrank, the servo system performed a basic positioning function.

Two key points for you to remember, thus far, about the operation of the closed-loop servo system are:

1. The original error (movement of the CX rotor) was "detected" by the CT. For this reason the CT is called an ERROR DETECTOR.

2. The servo motor, in addition to moving the load, also provides mechanical feedback to the CT to reduce the error signal. For this reason the servo motor is also called an ERROR REDUCER.

Q-4. An error signal is the difference between what two quantities fed to the CT (error detector)?

Q-5. What are the two functions of the servo motor in the system shown in figure 2-2?

FUNCTIONAL SERVO LOOPS

Servo systems are also classified according to their functions: POSITION, VELOCITY, and ACCELERATION. We will cover the most common, POSITION and VELOCITY, in detail.

The Position Servo Loop

The primary purpose of the POSITION SERVO is to control the position of the load it is driving. It can be used to position a great number of devices (for example, valves, control surfaces, weapons, etc.). The basic servo loop we just explained using the block diagram in figure 2-2 is that of an ac position servo system. In the ac position servo system, the amplitude and phase of the ac error signal determine the amount and direction the load will be driven.

In a dc position servo system, the amplitude and polarity of a dc error signal respectively are used to determine the amount and direction the load will be driven.

Figure 2-3, view A, is a block diagram of a closed-loop de position servo. Note the Greek letter Sigma (Σ), meaning summation, surrounded by a circle.

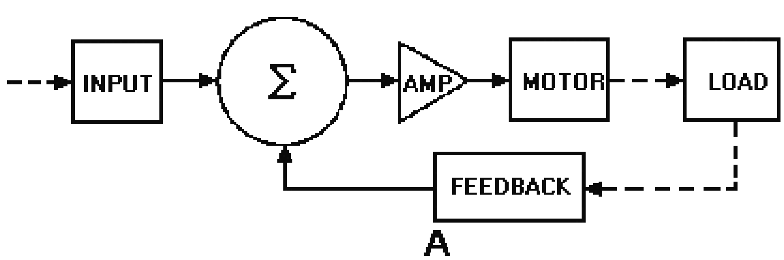


Figure 2-3A.—Block diagram of a position servo.

This is the summation, or "sum point" where the input signal, and the response signal (feedback) are summed to produce the error signal.

View B shows a more in-depth illustration of view A. With the wiper arms of R_1 and R_4 at the midpoint of travel, the voltage from the wiper arm to ground is zero volts. Therefore, zero volts would also be measured at the connection point between R_2 and R_3 (the summation point). This means that the error signal is zero. With no input signal, the amplifier output is zero; therefore, the motor shaft remains stationary.

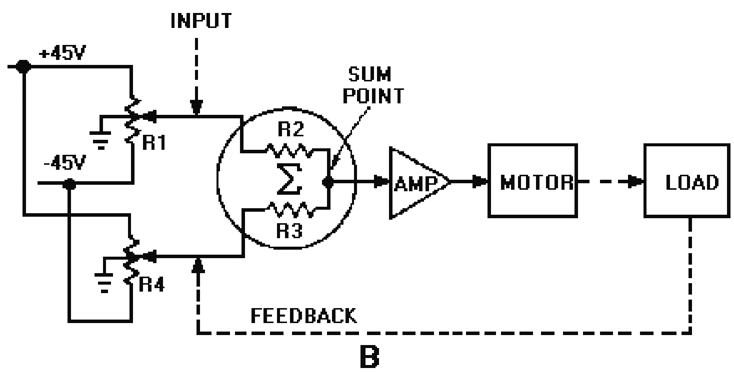


Figure 2-3B.—Block diagram of a position servo.

For the purpose of explanation, imagine that the R_1 wiper arm is mechanically moved upward to a new position where a voltage between the wiper arm and ground measures +10 volts. Further measurement shows zero volts between the wiper arm of $R_4$and ground. Since R_2 and R_3 are of equal values, +5 volts is measured between the sum point and ground because 5 volts is dropped across each resistor. The +5 volts at the sum point is the "error" signal.

As shown in figure 2-4, (view A, view B, and view C),when no error is present, the voltage at the sum point is zero. This is because the network composed of R_1, R_2, R_3, and R_4 is balanced. When the wiper of R_1 is moved toward +45 volts, the network becomes unbalanced as shown in view B. The left-hand side of R_2 becomes positive. This causes current to flow from +45 volts through R_3 and R_2 to the +10 volts at the left side of R_2. Because R_2 and R_3 are of equal value, the voltage drops then will be equal; therefore, the voltage at the sum point will equal +5 volts.

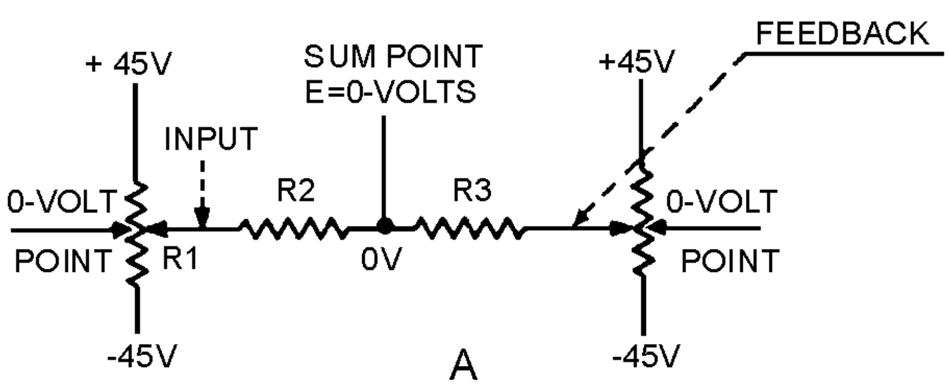


Figure 2-4A.—Development of the error signal.

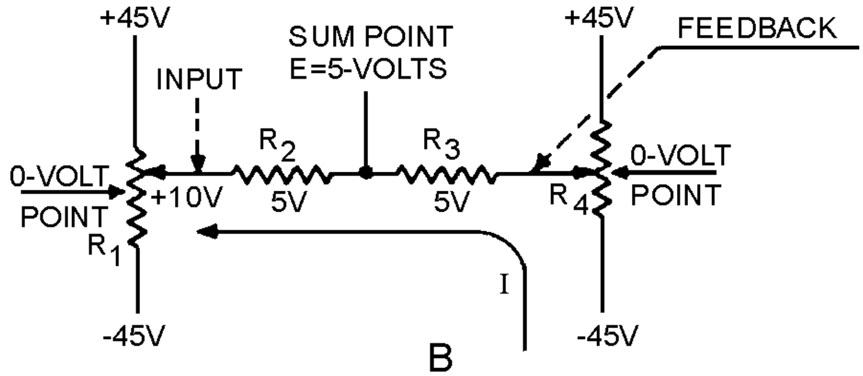


Figure 2-4B.—Development of the error signal.

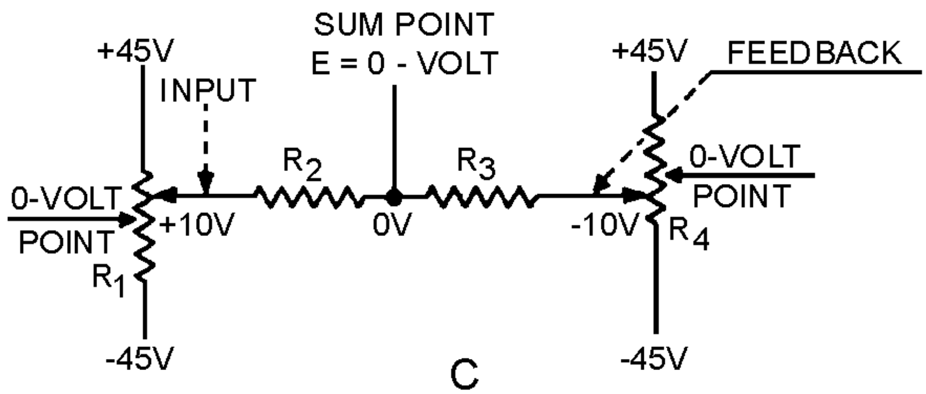


Figure 2-4C.—Development of the error signal.

The +5 volt error signal is fed into the amplifier. The amplified output starts driving the motor. The mechanical feedback from the motor drives the R_4 wiper arm down when the R_1 wiper is moved up, as shown in view C. This causes the right-hand side of R_3 to go negative. When the R_4 wiper travels far enough toward negative, it causes the right-hand side of R_3 to equal the voltage, but of opposite polarity, of the left-hand side of R_2. Simply stated, the voltage at the sum point will be zero again, and the motor will stop. This is true because R_2 and R_3 are of equal ohmic value, and when the left-hand side equals +10 volts, the right-hand side equals -10 volts. The point between the two resistors becomes zero volts at this time. At the instant that this occurs, the output shaft will have positioned the load to the new position.

Figure 2-5 shows the basic operation of a typical position servo having wide application in Navy equipment. Remember that in a position servo, an input order indicates a position in which a load is to be placed. The load in figure 2-5 is a gun turret. The purpose of the system is to position the gun by means of an order from a remote handcrank. The load is mechanically coupled through a gear train to the rotor of a CT so that the turret's position is always accurately represented by the position of the CT's rotor. An order signaling the desired position of the gun turret is fed into the servo by positioning the rotor of the CX with the handcrank. A corresponding signal immediately appears across the CT stator. This signal differs from the actual position of the gun turret, causing an error voltage to be developed across the CT rotor. The error voltage is fed from the CT rotor to the servo amplifier. At this point it is converted into power with a polarity or phase relationship that drives the motor in the direction necessary to bring the load into the desired position. As the turret moves, mechanical feedback turns the CT rotor toward agreement with the CX rotor. As the load approaches the proper position, less and less power is supplied to the motor because of the decreasing error voltage developed in the CT. When the electrical position of the CT rotor agrees with the position of the CX rotor, the error voltage reaches zero and power is removed from the motor. The turret is now in the desired position.

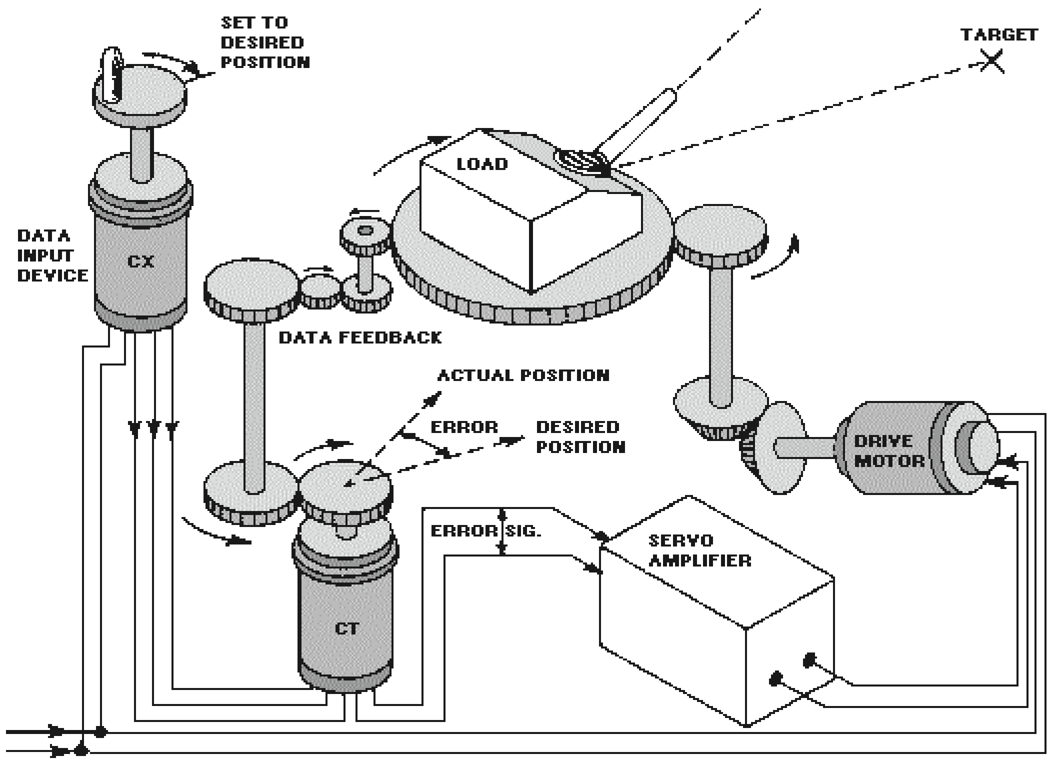


Figure 2-5.—Typical position servo.

In the actual system, the heavy gun turret's momentum tends to carry it past the desired position. This overshoot causes the rotor of the CT to move out of correspondence with the CX rotor. This, in turn, develops a new error signal that is opposite in polarity to the original input signal. The new error signal causes the turret to drive back toward the desired position — but the turret's momentum once again causes an overshoot, making the system drive in the opposite direction again. If this oscillation of the load around the desired position is allowed to go unchecked, a condition known as HUNTING results. Figure 2-6 shows graphically the result of a series of overtravels of the correspondence point (hunting). In most servos an electronic network known as an ANTIHUNT or DAMPING system is used to minimize this undesirable effect. We will cover antihunt and damping systems in depth later in this chapter.

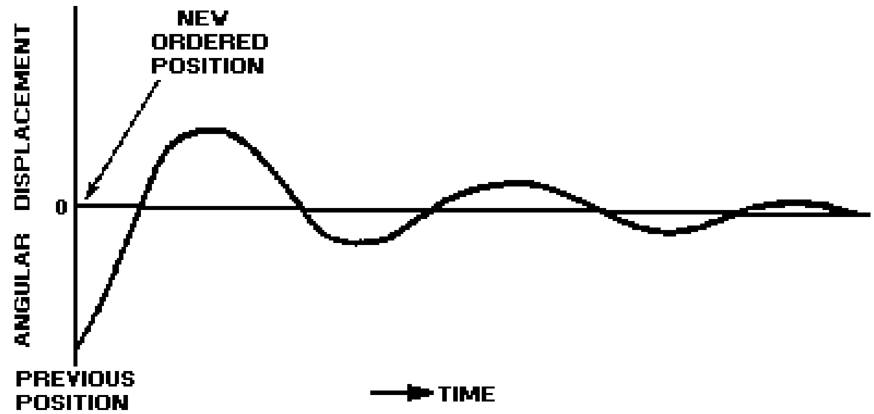


Figure 2-6.—Overtravels of the correspondence point (hunting).

Q-6. What are the three relatively common classifications of servo systems by function?

Q-7. The output of the sum point must contain information that controls what two factors of load movement in a position servo?

Q-8. What term is used for a series of overshoots in a servo system?

Velocity Servo Loop

The VELOCITY SERVO is based on the same principle of error-signal generation as the position servo, but there are some operational differences. Two major differences are as follows:

1. In this loop the VELOCITY of the output is sensed rather than the position of the load.
2. When the velocity loop is at correspondence or null position, an error signal is still present and the load is moving.

This type of servo is used in applications where the load is required to be driven at a constant speed. This speed is governed by the level of the error signal present. Radar antennas, star-tracking telescopes, machine cutting tools, and other devices requiring variable speed regulation are all examples of the types of load this servo may be used to drive.

Figure 2-7 is a block diagram of a velocity servo. It is similar to the block diagram of the position servo loop except that the velocity servo loop contains a TACHOMETER in the feedback line. The tachometer (tach) is a small generator that generates a voltage proportional to its shaft speed.

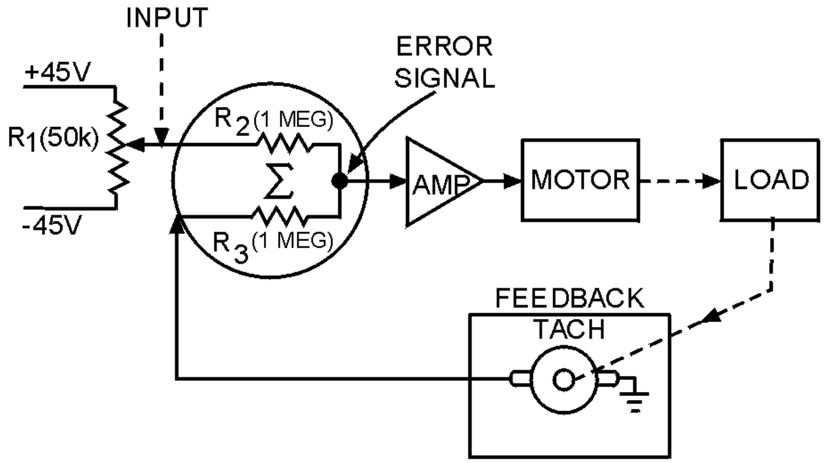


Figure 2-7.—Block diagram of a velocity servo.

In this application, the tach is used as a feedback device and is designed to produce 1 volt of feedback for each 10 rpm.

Let's assume that the motor is designed to turn 10 rpm for each volt of error signal. Figure 2-7 shows the tach mechanically connected to the load. With this arrangement, the shaft of the tach rotates as the load rotates, and the tach can be said to "sense" the speed of rotation of the load. For purposes of explanation, we win assume that the load is an antenna that we want to rotate at 30 rpm.

Initially, the wiper arm of R_1 is set at the 0-volt point (mid-position). This applies 0 volts to the left side of R_2. Since the motor is not turning, the load is not being driven, and the tach output is 0 volts. This applies 0 volts to the left side of R_3. Under these conditions, 0 volts is felt at the sum point and the motor is not driven. The voltage at the sum point is the error signal. When the wiper arm of R_1 is moved to the –9 volt point, an error signal appears at the sum point. At the first instant, the error signal (at the sum point) is –4.5 volts. This is because, at the first instant, the load and tach have not started to move. With the tach output at 0 volts, and the wiper of R_1 at –9 volts, –4.5 volts is present at the sum point. This voltage will cause the motor to start to rotate the load.

After a period of time, the load (and tach) are rotating at 10 rpm. This causes the tach to have an output of +1 volt. With +1 volt from the tach applied to the bottom of R_3, and –9 volts (from R_1 wiper) applied to the top of R_2, the voltage at the sum point (error signal) is –4 volts. Since the motor will turn 10 rpm for each volt of error signal, the motor continues to speed up. When the load reaches 30 rpm, the tach output is +3 volts. With this +3 volts at the bottom of R_3 and the –9 volts at the top of R_2, the error signal at the sum point is –3 volts. This –3 volts is the voltage required to drive the motor at 30 rpm, and places the system in balance. This satisfies the two conditions of the velocity servo. (1) The velocity of the output is sensed (by the tach), and (2) an error signal (–3 volts) is still present and the load continues to move when the velocity loop is at correspondence (30 rpm).

You may ask why the velocity loop and feedback are necessary. If this motor turns 10 rpm for each 1 volt error signal, why not simply feed –3 volts into this amplifier from the wiper of R_1 and not have a tach or summing network?

The answer is that the velocity loop will regulate the speed of the load for changing conditions. If the load in figure 2-7 were a rotating antenna on a ship, the antenna would tend to slow down as the wind opposed its movement and speed up as the wind aided its movement. Whenever the antenna slowed down, the output of the tach would decrease (since the tach is connected to the load). If the tach output decreased, the error signal would increase in amplitude and cause the motor to speed up. In the same way, if the antenna were to speed up, the tach output would increase, decreasing the error signal and the motor would slow down. Without the velocity loop to compensate for changing conditions, the load could not respond in the desired manner.

The system shown in figure 2-7 is a simplified version of a velocity loop. In practice, the reaction of the motor to error voltage and the output of the tach would not be equal (10 rpm per volt and 1 volt per 10 rpm). This would be compensated for by gearing between the motor and load and between the load and tach, or by using a summation network in which the resistors (R_2 and R_3) are riot equal. This use of unequal resistors is called a SCALING FACTOR and compensates for tach outputs and required motor inputs. This is just another way of saying that the individual components of the velocity loop must be made to work together so that each can respond in a manner that produces the desired system result.

Q-9. What are two major differences between velocity servos and position servos?

Q-10. In a typical velocity servo block diagram what device is placed in the feedback loop that is not present in the position servo?

Q-11. What is the advantage of using a closed-servo loop to control load velocity?

The Acceleration Servo

The acceleration servo is similar to the two loops we just discussed except that the acceleration of the load is sensed, rather than the position or velocity. In this loop, the tachometer of the velocity loop is replaced by an accelerometer (a device that generates a signal in response to an acceleration) as the feedback device.

We have not provided an illustration of the acceleration servo because of the complexity of its applications as well as its components. This type of servo is widely used in the rocket and missile fields, and is used whenever acceleration control is required.

SERVO CHARACTERISTICS

Servo characteristics vary primarily with the job the servo is designed to do. There are almost as many types of servos as there are jobs for servos. All servos usually have the common purpose of controlling output in a way ordered by the input. Ideally, motion and output shaft position should duplicate the track of the input shaft. However, this ideal performance is never achieved. We will discuss the major reasons for this, and show some methods used in the attempt to approach the ideal.

Because a servo compares an input signal with a feedback response, there will always be a TIME LAG between the input signal and the actual movement of the load. Also, the weight of the load may introduce an additional time lag. The time lag of the servo can be decreased by increasing the gain of the servo amplifier. If the gain is set too high, however, the servo output will tend to oscillate and be unstable. From this you can see that the gain of a servo is limited by stability considerations. Servo sensitivity must be considered along with stability to reach a "happy medium."

TIME LAG

To reduce time lag, the gain of the servo amplifier could be increased. Increasing the gain of the servo amplifier will decrease the lag time and cause the load to move faster. However, there is a serious drawback because the load is moving faster, its inertia will likely cause it to go past the desired position (overshoot). When the load attempts to drive back to the desired position, the high gain of the amplifier may cause it to overshoot in the opposite direction. Therefore, the system must be stabilized to minimize or eliminate the problem of overshoot. This is done through DAMPING. Damping can be done by either introducing a voltage in opposition to the signal voltage or placing a physical restraint on the servo output. The actual function of this antihunting is to reduce the amplitude and duration of the oscillations that may exist in the system. Every system has one or more natural oscillating frequencies that depend on the weight of the load, designed speed, and other characteristics.

The degree of damping is determined by the purpose and the use of the system. If the system is OVERDAMPED, it will not be bothered by oscillations. However, the large amount of restraint placed on the servo presents an additional problem. This is an excessive time requirement for the system to reach synchronization. Figure 2-8 is a graphic representation showing the time relationship with regard to degree of damping.

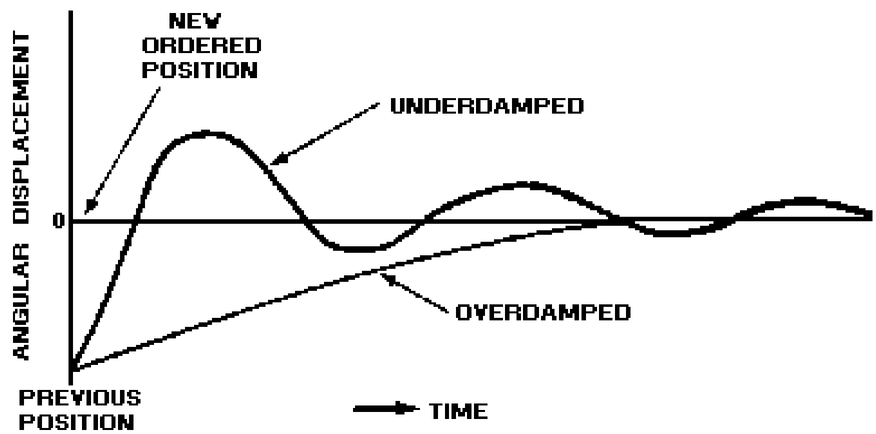


Figure 2-8.—Degree of damping.

An UNDERDAMPED servo system has other traits. The favorable one is its instantaneous response to an error signal. The unfavorable trait is an erratic operation around the point of synchronization because of the low amount of restraining force placed on the servo. Somewhere between overdamped and underdamped, there is a combination of desirable accuracy, smoothness, and moderately short synchronizing time.

The simplest form of damping is FRICTION damping. Friction damping is the application of friction to the output shaft or load that is proportional to the output velocity. The amount of friction applied to the system is critical, and will materially affect the results of the system. Friction absorbs power from the motor and converts that power to heat.

A pure friction damper would absorb an excessive amount of power from the system. However, two available systems have some of the characteristics of a friction damper, but with somewhat less power loss. These are the *friction clutch* and the *magnetic clutch*.

Q-12. If a position servo system tends to oscillate whenever a new position is selected, is the system overdamped or underdamped?

Q-13. If a position servo system does not respond to small changes of the input, is the system overdamped or underdamped?

Friction Clutch Damping

The friction clutch damper uses a friction clutch to couple a weighted flywheel to the output drive shaft of the servo motor. As the servo motor rotates, the clutch couples some of this motion to the flywheel. As the flywheel overcomes inertia and gains speed, it approaches the motor speed. The flywheel, in turning, absorbs energy (power) from the servo motor. The amount of energy stored in the flywheel is determined by its speed (velocity). Because of inertia, the flywheel resists any attempt to change its velocity.

As the correspondence point of the system is approached, the error signal is reduced and the motor begins to slow down. In an attempt to keep the output shaft turning at the same speed, the flywheel releases some of its energy into the shaft. This causes the first overshoot to be large. When the servo system drives past the point of correspondence, a new error signal is developed. The new error signal is of opposite polarity and causes the servo system motor to drive in the opposite direction. Once again the flywheel resists the motor movement and absorbs energy from the system. This causes a large reduction in the second overshoot and all subsequent overshoots of the system. The overall effect is to dampen the oscillations about the point of correspondence and reduce the synchronizing time.

The motor rotation is transmitted to the flywheel through the friction clutch. The inertia of the flywheel acts as an additional load on the motor. The friction clutch is designed to slip with a rapid change of direction or speed. This slipping effectively disconnects the flywheel instantaneously, and thus governs the amount of power the flywheel draws from the motor.

Magnetic Clutch

Another type of damper is the MAGNETIC CLUTCH. This type is similar in function to the friction-clutch damper. The main difference between the two is the method used to couple the flywheel to the shaft of the servo motor. There are two distinct types of magnetic clutch dampers. The first uses a magnetic field to draw two friction clutch plates together to produce damping. The action is similar to the friction clutch we just described.

The second version of the magnetic clutch uses the action of a magnetic field generated by two sets of coils, or one set of coils and the induced eddy currents, which result from rotation of the single set of coils near a conducting surface (the flywheel).

Coupling in this type of clutch is made by the interaction of two magnetic fields without a physical contact between the two. The two-coil or eddy-current type of magnetic clutch offers smoother operation than a pure friction clutch and has no problem of wear because of friction.

In summary, a smooth, efficient operating servo system can only be achieved by a system of compromises. As you recall, earlier we increased the gain of the amplifier to reduce time lag. This had the drawback of increasing hunting or oscillations about the point of correspondence. We overcame this difficulty through friction damping. This solved the problem of hunting and smoothed out servo operation but acted as part of the servo load. It caused a large first overshoot and increased the time lag. Some form of damping that can be used with high amplification to obtain smooth servo operation and minimum time lag is needed. The answer lies with the use of ERROR-RATE damping.

Q-14. Why is damping needed in a practical servo system?

Error-Rate Damping

Error-rate damping is a method of damping that "anticipates" the amount of overshoot. This form of damping corrects the overshoot by introducing a voltage in the error detector that is proportional to the rate of change of the error signal.

This "correction" voltage is combined with the error signal in the proper ratio to obtain the desired servo operation with reduced overshooting and minimum time lag.

The advantages of error-rate damping are as follows:

1. Maximum damping occurs when a maximum rate of change of error signal is present. This normally would occur as the servo load reverses direction.

2. Since a CHANGE in the signal causes damping, there is a minimum amount of damping when no signal, or a signal of constant strength, is present.

Error-rate voltages are generated by either electromechanical devices or electrical networks in the equipment. One electromechanical device widely used to generate an error-rate voltage is the tachometer generator. As you learned previously, its output voltage is proportional to the output velocity of the servo. Hence, the output voltage of the tachometer can be used to anticipate sudden movement changes of the load.

The compensating electrical network used for error-rate damping consists of a combination of resistors and capacitors forming an RC, differentiating or integrating network. You should recall that a differentiating circuit produces an output voltage that is proportional to the rate of change of the input voltage and that an integrating circuit produces an output proportional to the integral of the input signal.

Figure 2-9 shows a basic RC INTEGRATOR. It can be recognized by the output voltage being taken across the capacitor. R_1 is added in this circuit to develop the transient error signal (small variation in the signal from the error detector). The RC integrator is sometimes referred to as an INTEGRAL CONTROL CIRCUIT and will be used to explain electrical error-rate damping.

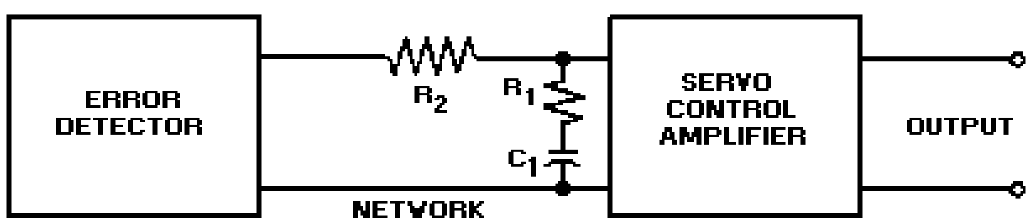


Figure 2-9.—Error rate stabilization network using an RC integrator.

The network consists of a capacitor and two resistors connected in series with the servo amplifier. The components of this circuit are designed to work with a constant or very slowly changing error signal.

Initially, all of the error voltage is divided between R_1 and R_2. But the longer the error voltage is applied, the more C_1 charges, and the greater the voltage at the input of the amplifier. Because of the RC time of the circuit, it takes time for the capacitor to charge to the value of the error input signal. Because of the long charge time of C_1, the circuit can not respond instantaneously to a rapid change in error signal.

What this means is that all error signals will be integrated (or smoothed out). The load will not respond as quickly. The inertia of the load will be reduced, and the system will be damped.

The capacitor, by not responding instantaneously to the error signal, causes the damping action. This action is used to stabilize the servo system at the new velocity. By tailoring the stabilization network (through the proper selection of the RC components) to the system's performance requirements and the type of load to be driven, undesirable load or performance characteristics can be minimized.

The various compensating networks that you will encounter will depend on the design of the individual servo system and will be covered in the associated system's technical manual.

In summary, the key to understanding compensating networks is to realize that components are chosen so the capacitor does not have time to charge and discharge in response to large, rapid fluctuations.

Q-15. Error-rate damping is effective because the circuitry has the capability of ______________ the amount of overshoot before it happens.

FREQUENCY RESPONSE

The frequency response of a servo is the range of frequencies to which the system is able to respond in moving the load. It is a characteristic of the system, chosen by the designers so the system will be able to respond to whatever frequencies are expected to be present in the input signal for the particular application.

Oscillating Input Signal

At first, we considered the input order to a servo as being suddenly put at a fixed desired value. Later, we studied the case where the order slowly increased to the desired value. Actually, the input order to a servo in a given application may accelerate, start, stop, or oscillate about a fixed point. We will now consider the actions of a servo while the order oscillates. When the order is constant, oscillations of the load are undesirable. When the order oscillates, the load must oscillate in a similar manner.

Let's assume that an oscillating input signal (order) is applied to a servo. The load may behave in several ways. Ideally, it would respond in perfect sync with the order. Actually, the amplitude and phase of the load are different from those of the order, figure 2-10. As we noted above, the frequency response of the system is normally designed so the load is able to respond to the order.

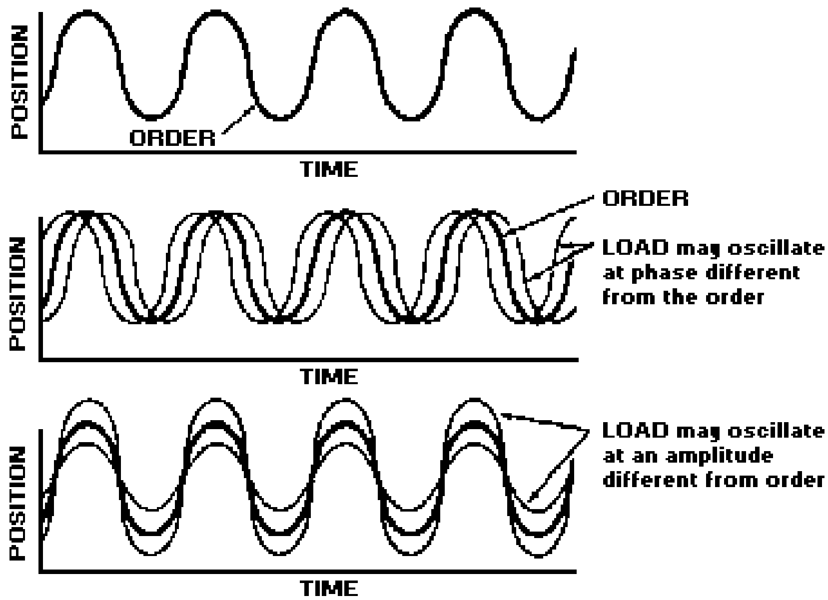


Figure 2-10.—Frequency response.

A servo may follow the order in amplitude and differ in phase; it may follow the order in phase, and differ in amplitude; or it may differ in both phase and amplitude.

Bandpass Frequencies in a Servo system

Servos are plagued by noise signals that ride through the system on desired electrical signals. These noise signals cause roughness in the servo system and must be eliminated to obtain smooth servo operation.

By examining the different signals in a servo system, we can determine which frequencies are related to the movement of the load and which ones are from noise sources, such as static, motors, harmonics, and mechanical resonances.

Filters in the signal circuit can be used to shunt some of the unwanted frequencies away from the amplifier, and allow only those frequencies that represent load movement to enter the amplifier. This can also be accomplished by designing the BANDWIDTH of the servo amplifier to accept only the range of frequencies that represents valid servo signals and to reject all others. This smooths servo response, but has the drawback of reducing amplifier gain. Reduced amplifier bandwidth is another compromise in achieving optimum servo operation.

Q-16. In a properly designed servo system that has an oscillating input (order), what should be the response of the load?

Q-17. What is the advantage of designing a limited bandwidth into a servo amplifier?

SERVO COMPONENTS AND CIRCUITS

In this section we will discuss the circuits and components that make up a typical servo system. We cannot cover all possible servo applications here because of the vast number of servo system configurations. The circuits and components discussed in the following pages are the most commonly used and represent a broad view of the systems used in the Navy today. We have not attempted to put the units into any rigid classification system. We will mention some of the more common terms used by manufacturers and the Navy to classify the devices to familiarize you with the wide variety of nomenclatures.

We will be covering much of the electronic application without discussing the theory of the units. You may want to review some of the applicable NEETS modules or other sources before or during this discussion. You will find that much of the material necessary to understand these subjects is contained in the basic theory of electricity and electronics.

POSITION SENSORS

A position sensor is a device that changes a mechanical position into a voltage that represents that position. The output of a position sensor can be either ac or dc voltage. There are many different kinds of position sensors. In the last chapter you learned about the CX, a synchro device that represents the position of its rotor by a voltage on its stators. You saw a CX used as a position sensor in a servo system earlier in this chapter. Other devices can be used as position sensors. The potentiometer is one of these devices.

Potentiometers

Potentiometer position sensors are generally used only where the input and output of the servo mechanism have limited motion They are characterized by high accuracy and small size, and may have either a dc or an ac output voltage. Their disadvantages include limited motion and a life problem resulting from the wear of the brush on the potentiometer wire. Also the voltage output of the potentiometer changes in discrete steps as the brush moves from wire to wire. A further disadvantage of some potentiometers is the high drive torque required to rotate the wiper contact.

A potentiometer is one of the simplest means of converting mechanical positional information to a proportional voltage. A schematic representation of a potentiometer is shown in figure 2-11.

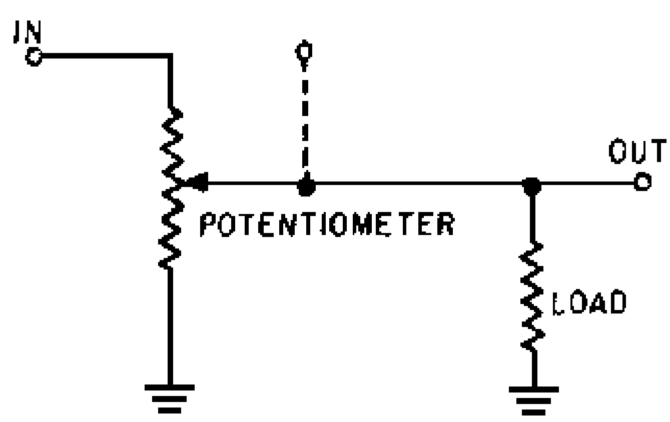


Figure 2-11.—A potentiometer.

A potentiometer is a variable voltage divider, with an output voltage that is a percentage of the input voltage. The amount of output voltage is proportional to the position of the wiper relative to the grounded end. For example, if the resistance from ground to the wiper is 50% of the total, the output voltage sensed by the load will be 50% of the total voltage across the potentiometer.

A basic, closed-loop servo system using a balanced potentiometer as a position sensor is shown in figure 2-12.

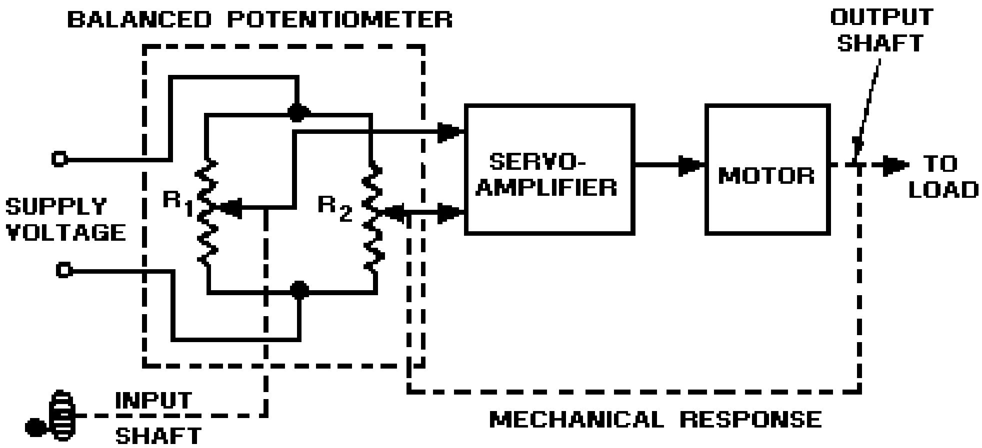


Figure 2-12.—Balanced potentiometer used In position sensing.

The command input shaft is mechanically linked to R_1, and the load is mechanically linked to R_2. A supply voltage is applied across both potentiometers.

The system is designed so that when the input and output shafts are in the same angular position, the voltages from the two potentiometers are equal and no error voltage is felt at the amplifier input. If the input shaft is rotated, moving the wiper contact of R_1, an error voltage is applied to the servo amplifier. This error voltage is the difference between the voltages at the wiper contents of R_1 and R_2. The output of the amplifier causes the motor to rotate the load and the wiper contact of R_2. This continues until both voltages are again equal. When the voltages are equal, the motor stops. In effect, the position of the output shaft has been sensed by the balanced potentiometer.

Q-18. When the input and output wipers of a balanced potentiometer are in the same angular position, what is the value of the error voltage?

ERROR DETECTORS

Electrical error detectors may be either ac or dc devices, depending upon the requirements of the servo system. An ac device used as an error detector must compare the two signals and produce an error signal in which the phase and amplitude will indicate the direction and amount of control, respectively, that are necessary for correspondence. A dc device differs in that the polarity of the output error signal determines the direction of the necessary correction. We will discuss in the following paragraphs various devices that are commonly used in servo systems.

Summing Networks

Summing networks, as we mentioned earlier, are used as error detectors in servo applications where the servo output must be proportional to the algebraic sum of two or more inputs. A typical circuit is shown in figure 2-13.

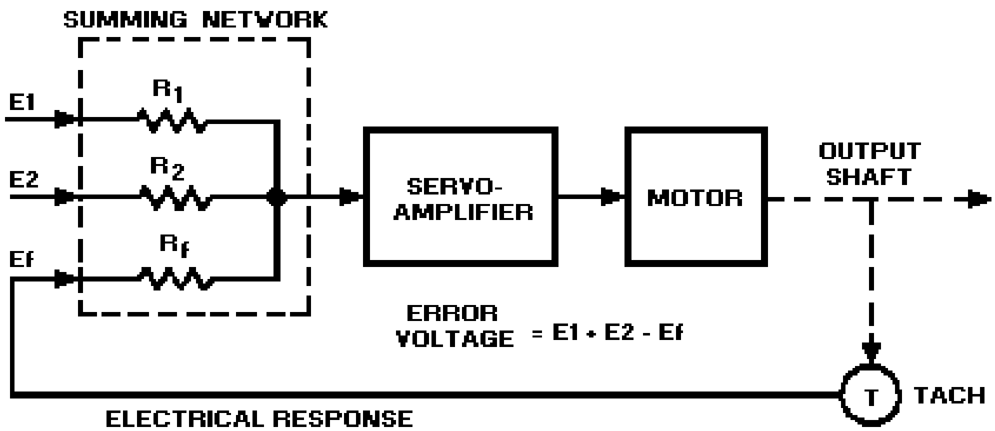


Figure 2-13.—Summing network as an error detector.

As in the case of potentiometers, the networks may use either ac or dc voltage, with the phase or polarity of the input voltage determining whether the signals are additive or subtractive. Refer to figure 2-13. If two input signals E_1 and E_2 are applied to the network, the network will provide an error voltage output that is proportional to the algebraic sum of the two signals. The servo motor drives the load and also a tachometer that supplies feedback voltage to resistor R_f. Resistor Rf nulls the error signal.

In some installations, the servo motor may position the wiper arm of a potentiometer instead of driving a tachometer to supply the feedback voltage.

E-Transformers

The E-transformer is a type of magnetic unit that is used as an error detector in systems in which the load is not required to move through large angles.

In the basic E-transformer shown in figure 2-14, an ac voltage is applied to the primary coil (2) located on the center leg of the laminated, E-shaped core. Two secondary coils (1 and 3) are wound series-opposing on the outer poles of the core. The magnetic coupling between the primary (coil 2) and the two secondaries varies with the position of the armature. The armature can be physically moved left or right in the magnetic circuit by mechanical linkage to the load. This changes the reluctance between either pole and the armature.

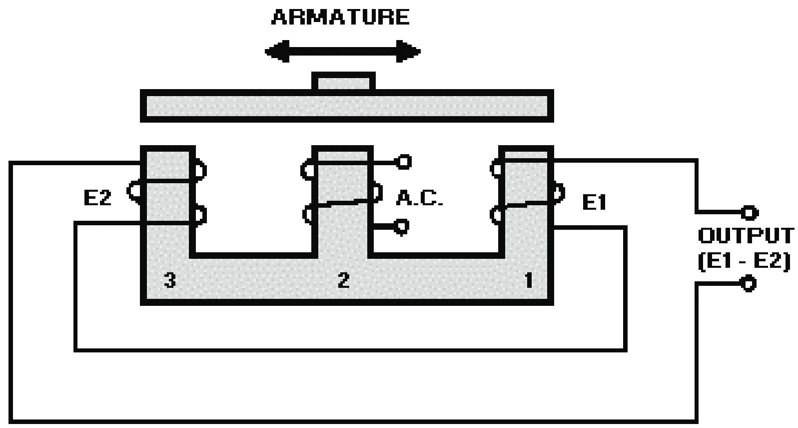


Figure 2-14.—Basic-E transformer.

When the armature is located in the center of the E-shaped core, as shown in the figure, equal and opposite voltages are induced in the secondary coils. The difference between them is zero. Thus, the voltage at the output terminals is also zero.

But, if the armature is moved, say to the tight, the voltage induced in coil 1 increases, while the voltage induced in coil 3 decreases. The two voltages are then unequal, so that the difference is no longer zero. A net voltage results at the output terminals. The amplitude of this voltage is directly proportional to the distance the armature has been moved from its center position. The phase of this output voltage, relative to the ac on the primary, controls the direction the load moves in correcting the error.

The basic E-transformer will detect movement of the armature in one axis only (either the horizontal or vertical depending upon the way the unit is mounted). To detect movement in both the horizontal and vertical axes, a CROSSED-E-TRANSFORMER is used.

If you place two E-transformers at right angles to each other and replace the bar armature with a dome-shaped one (fig. 2-15), you have the basic configuration of what is known as the crossed-E transformer, or pickoff. In most applications the dome-shaped armature is attached to a gyro, and the core assembly is fixed to a gimbal, which is the servo load.

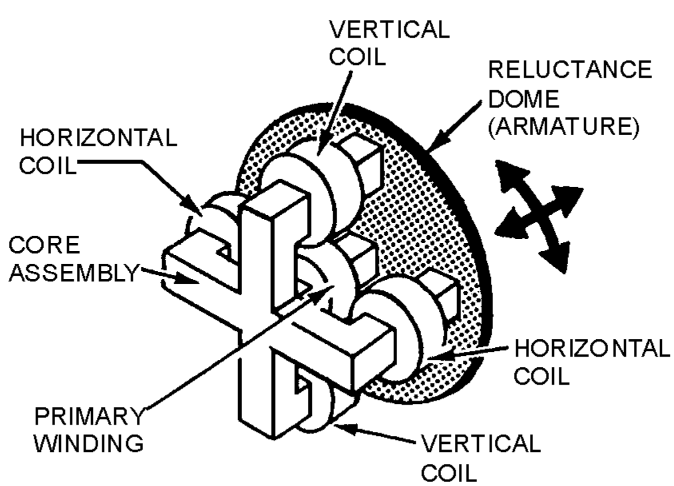


Figure 2-15.—Crossed-E transformer.

The crossed-E transformer assembly consists of five legs (poles). Each leg is encased by a coil. The coil around the center leg is the primary, which is excited by an alternating voltage. The remaining four coils are the secondaries. From this view, you can see how it gets the name, crossed-E.

When the reluctance dome (armature) is moved to the left of center, more flux links the left leg with the primary coil, and the voltage induced in the left secondary increases. The right leg has fewer flux linkages with the center coil; therefore, the voltage induced in the right coil will be less than that in the left coil. Thus there will now be a net voltage out of the pickoff. The phase of the output will be that of the larger voltage. If the dome were moved to the right, the opposite condition would exist. From this brief description, you can see that the crossed-E transformer works on the same fundamental principle as the basic type described earlier. The major difference between the two is in shape and the number of secondaries, and in the fact that the armature has universal movement.

Control Transformers

A commonly used magnetic error detector is the synchro-control transformer, which is used as a control device in servo systems. Recall that we covered the CTs operation in depth in chapter 1 of this module, and discussed its application to the servo system earlier in this chapter.

As an error detector, the CT compares the input signal impressed upon its stator with the angular position of its rotor, which is the actual position of the load. The output is an electrical (error) signal taken from the rotor, which is the difference between the ordered position and the actual position of the load.

A primary advantage of the CT over other types of error detectors is its unlimited rotation angle; that is, both the input and the output to the synchro control transformer may rotate through unlimited angles. A disadvantage is that the output supplied to the servo amplifier is always an ac error signal, and must be demodulated if it is to be used in a dc servo system.

Q-19. In the output of an ac error detector, what indicates the (a) direction and (b) amount of control necessary for correspondence?

Q-20. What two basic types of magnetic devices are used as error detectors?

RATE GENERATOR (TACHOMETER)

As we mentioned earlier, the tachometer in the velocity servo system is the heart of the feedback loop. It is used to sense the speed (velocity) of the load. The tachometer is sometimes referred to as a RATE GENERATOR. Whatever the name, it is a small ac or dc generator that develops an output voltage (proportional to its rpm) whose phase or polarity depends on the rotor's direction of rotation. The dc rate generator usually has permanent magnetic field excitation. The ac rate generator field is excited by a constant ac supply. In either case, the rotor of the tachometer is mechanically connected, directly or indirectly, to the load.

The AC Rate Generator

One type of ac rate generator used widely in the past is the drag-cup type.

The tachometer generator shown in figure 2-16 has two stator windings 90º apart, and an aluminum or copper cup rotor. The rotor rotates around a stationary, soft-iron, magnetic core. One stator winding is energized by a reference ac source. The other stator winding is the generator output, or secondary winding the voltage applied to the primary winding produces a magnetic field at right angles to the secondary winding when the rotor is stationary, as shown in view A. When the rotor is turned by mechanical linkage from the load, it distorts the magnetic field so that it is no longer 90 electrical degrees from the secondary winding. Flux lines cut the secondary winding, and a voltage is induced in the output winding as shown in views B and C. The amount of magnetic field that will be distorted is determined by the speed of the rotor. Therefore, the magnitude of the voltage induced in the secondary winding is proportional to the rotor's velocity (speed).

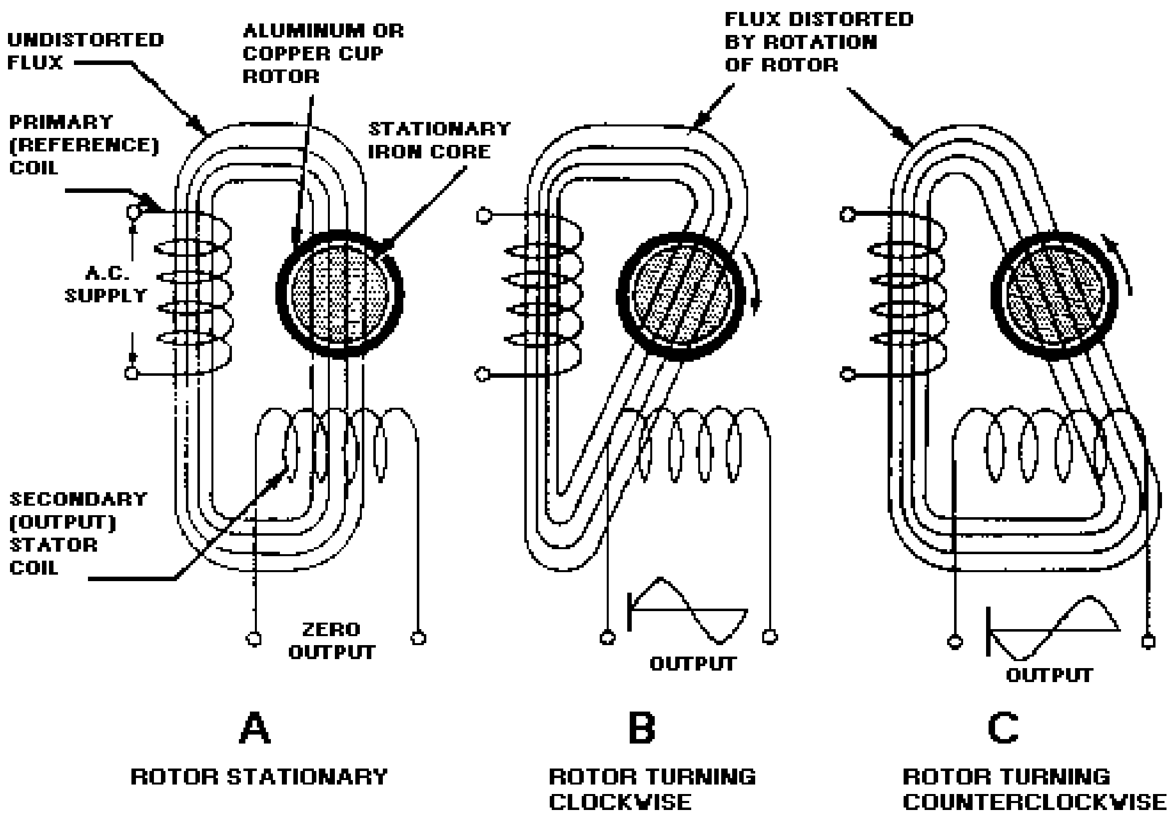


Figure 2-16.—Ac drag-cup rate generator.

The direction of the magnetic field's distortion is determined by the direction of the rotor's motion. If the rotor is turned in one direction, the lines of flux will cut the secondary winding in one direction. If the motion of the rotor is reversed, the lines of flux will cut the secondary winding in the opposite direction. Therefore, the phase of the voltage induced in the secondary winding, measured with respect to the phase of the supply voltage, is determined by the direction of the rotor's motion. The phase relationship is shown in views B and C at the output winding.

The frequency of the tachometer generator output voltage is the same as the frequency of the reference voltage. The output voltage is generated by the primary alternating flux field cutting the secondary winding; therefore, the output voltage must have the same frequency as the supply voltage.

Other types of ac tachometer generators have a squirrel-cage rotor. Otherwise their construction and principles of operation are identical to the drag-cup type.

The DC Rate Generator

The dc rate generator uses the same principles of magnetic coupling as the ac rate generator. The dc rate generator, however, has a steady (nonfluctuating) primary magnetic field. This magnetic field is usually supplied by permanent magnets. The amount of voltage induced in the rotor winding is proportional to the number of magnetic flux lines cut. The polarity of the output voltage is determined by the direction in which the rotor cuts the lines of magnetic flux.

The physical makeup and theory of operation of the dc rate generator (tach) is very similar to the dc generator (NEETS, Module 5, *Introduction to Generators and Motors*). The only major differences are size and the prime mover. The tach is much smaller and is linked mechanically to the servo motor or load instead of to a prime mover.

Tachometer generators are used in servo systems to supply velocity or damping signals and are sometimes mounted on or in the same housing as the servo motor.

Q-21. What is the basic difference between the primaries of ac and dc rate generators?

MODULATORS IN THE SERVO SYSTEM

Because of problems associated with dc amplifiers, such as drift (where the output varies with no variation of the input signal), the ac amplifier is more widely used in servo applications. This creates a need for a device to convert a dc error signal into an ac input for the servo amplifier. Such a device is referred to as a MODULATOR.

Modulator and modulating techniques vary with different types of electronic equipment. The modulator in the servo system performs a completely different function than its counterparts in radar or communications systems.

The servo modulator converts a dc error signal into an ac error signal. The modulator uses two inputs to produce the ac error signal. One input is the dc error signal (for example from an input potentiometer); the other input is an ac reference voltage from some other source, such as the swp's ac supply system. The ac output error signal must contain the same control information that is contained in the original dc error signal. This is done in the following manner:

1. The phase between the ac output and the ac reference signal is determined by the polarity of the dc input signal. The phase of the ac output indicates the direction of error (direction of the load movement).

2. The amplitude of the ac output is proportional to the amplitude of the dc input signal and indicates the amount of error signal (speed or angular displacement of the load).

These relationships of phase and amplitude must be maintained to ensure that the load will move the desired amount, or the proper speed, and in the right direction.

A typical modulator that you will see in a servo system is the CRYSTAL DIODE MODULATOR. The following paragraphs provide a brief explanation of how this modulator works.

Crystal Diode Modulators

The crystal diode modulator (fig. 2-17) consists of a diode bridge and a transformer network. When the ac reference voltage is applied to transformer T_1, diodes CR_2 and CR_3 conduct during the negative half-cycle. Conversely, diodes CR_1 and CR_4 conduct on the positive half-cycle. The diodes will conduct under these conditions because of the 180º phase reversal across T_1. Current flow during the positive and negative half-cycles is represented by dotted arrows and solid arrows, respectively. Suppose a positive, dc error signal is applied during the negative-going ac input half-cycle at the primary of T_1. Current will flow from ground, through the upper half of the primary winding of transformer T_2, through diode CR_2, and through the upper half of the secondary winding of transformer T_1 to the dc source. This produces a positive-going voltage (error signal) across the secondary of T_2 (the first half-cycle of the output signal).

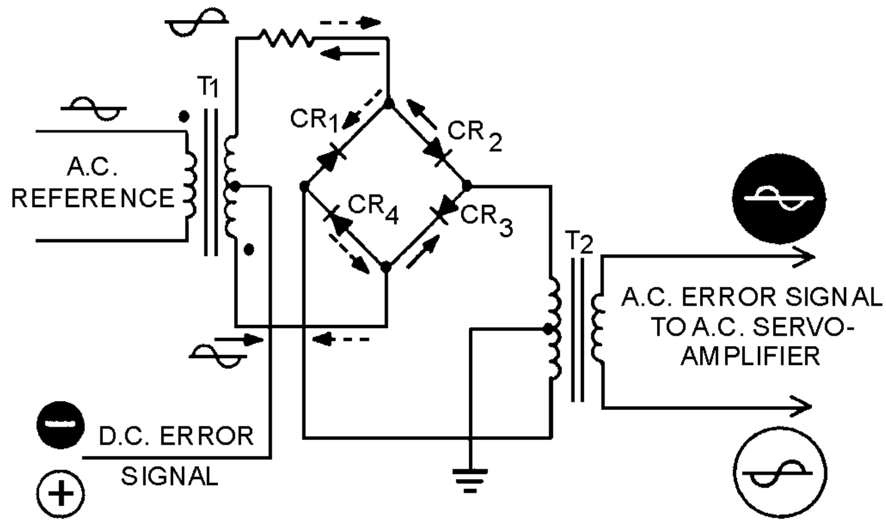


Figure 2-17.—Crystal diode modulator.

On the positive-going ac input reference voltage half-cycle, current will flow from ground, through the lower half of the primary of transformer T_2, through diode CR_4, and through transformer T_1 to the dc error signal source. This produces a negative-going voltage (error signal) across the secondary of T_2 (completing the cycle of the ac input reference). Notice that the error signal is 180º out of phase with the reference signal.

If a negative dc error signal is applied to the modulator, under the same conditions of ac reference signal, current flow through the circuit will be reversed. Keep in mind that this occurs, for example, when the load approaches the desired position from an opposite direction. This circuit will work with either a positive or a negative dc input signal, but only one condition will exist at any given time.

With a negative dc error applied, current will flow from the dc error signal source through diodes CR_3 and CR_1 (on different half-cycles of the ac reference) to ground. This causes an ac voltage to be produced across the secondary of T_2 in the same manner as previously described with the positive dc error signal input.

The only difference is that current will flow through the upper and lower halves of T_2 in a different direction (toward ground) and cause the output to be in phase with the ac reference signal.

In summary, the modulator produced an ac output, either in phase or 180º out of phase with the ac reference signal, depending upon the polarity of the dc input signal. The amplitude of the output will be proportional to the dc input signal amplitude and at the frequency of the ac reference voltage.

Q-22. What is the purpose of a modulator in a servo system?

DEMODULATORS IN THE SERVO SYSTEM

As you know, servo systems use both ac and dc servo motors depending upon the requirements of the system. Systems that are required to move light loads at constant speed use ac motors. Systems that are required to move heavy loads with a wide speed range use dc motors. When the requirements of the system call for a dc motor or other dc devices, the ac error signal within the servo system must be converted to a dc error signal before being fed to the dc servo amplifier. The conversion is made by the circuit known as a DEMODULATOR.

As with the modulator, the demodulator maintains the same relationships between its input and output signals. Just like the modulator, the demodulator's output amplitude is proportional to its input signal and its output polarity is determined by the phase of the input signal. These relationships, as in the modulator you just studied, are necessary so the "new" error signal will control the servo motor in the desired manner.

Diode Demodulator

One example of a servo demodulator is the DIODE DEMODULATOR, sometimes called a phase detector, shown in figure 2-18. This circuit is used in servo systems because it not only converts ac to dc, but it is also able to distinguish the phase of the ac signal by comparing it to a reference voltage. Do not confuse this circuit with other phase detector circuits, such as those used in radar or communications systems. This demodulator (phase detector) distinguishes signals that are either in phase or 180º out of phase. For this reason this circuit is useful in servo systems where the ac output from the error detector (CT) is either in phase with the reference signal or 180º out of phase. Whatever type of error detector is used in the servo system, the reference voltage to the error detector and to the demodulator must be IN PHASE with each other for the demodulator to do its job.

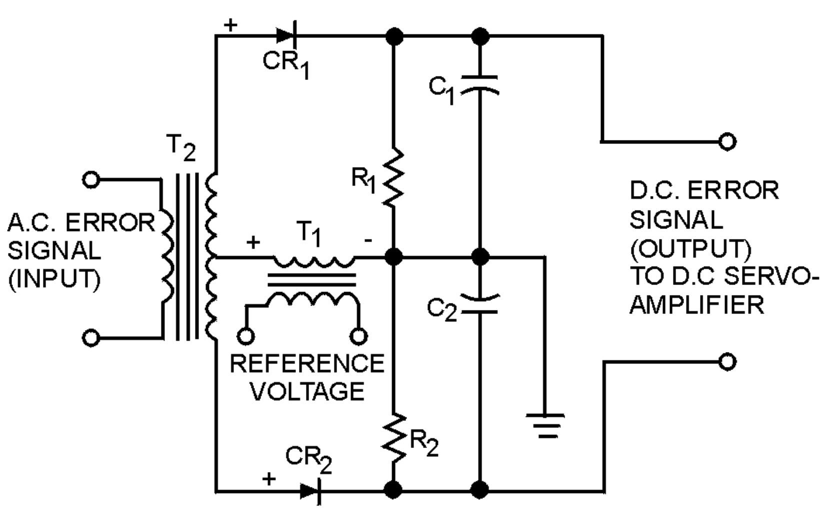


Figure 2-18.—Diode demodulator.

As shown in figure 2-18, the anodes of the two diodes are supplied with the same reference voltage.

With no ac error input signal applied to T_2 (quiescent state), both diodes will conduct equally on the positive half-cycle of the reference voltage. The voltage drops across $R_1$1 and R_2 are equal. This results in the two output terminals being at the same potential; therefore, the output voltage is zero for the positive half-cycle. During the negative half-cycle, a negative voltage is felt on the anodes of both diodes, both diodes are cut off, and zero potential is felt across the output terminals. The circuit will remain in this condition until an ac error signal is applied. As we make this circuit work, you will notice that CR_1 will conduct when the input signal is in phase with the reference voltage and then only on the positive half-cycle. CR_2 will remain in cutoff unless the phase relationship between the ac error signal and the reference voltage changes by 180º. At this time CR_1 will cut off. This change could be brought about by the error detector in the servo system sensing a change in the direction of the load. Effectively, we have a one-diode circuit for one direction of rotation.

Assume that an ac error signal is applied to T_2, making the anode of CR_1 positive and the anode of CR_2 negative. At the same time, the reference voltage on the anodes of CR_1 and CR_2 is on its positive half-cycle. Under these conditions, CR_1 will conduct and CR_2 will be cut off. A positive voltage will be developed across Ri and felt on the output terminals. During the negative half-cycle, a negative voltage will be felt on the anodes of CR_1, and CR_2 and will cut them off. The output of the circuit for one complete cycle of the reference signal will be a filtered, pulsating, dc voltage. As long as the input and reference signals are in phase, the circuit acts as a half-wave rectifier and a filter network.

As we mentioned earlier, this circuit will also respond to a 180º phase reversal between the input and reference signals. For instance, when the error signal applied to T_2 is 180º out of phase with the reference signal, CR_2 conducts and CR_1 cuts off, causing the output voltage to change polarity. You may encounter variations of the diode phase detector; however, they all depend on the same basic principle of operation.

To quickly summarize, the demodulator converted the ac input signal to a dc error signal. The polarity of the dc error signal was determined by the phase relationship between the ac error input signal and the reference signal. The amplitude of the dc error signal was directly proportional to the magnitude of the ac input signal.

Q-23. What is the purpose of a demodulator in a servo system?

SERVO AMPLIFIERS

The servo amplifiers previously discussed were used in servo systems to amplify either the ac or dc error signal to a sufficient amplitude to drive the servo motor. These amplifiers are the same amplifiers in principle as covered in NEETS Module 8, *Introduction to Amplifiers*. The basic amplifier chosen for use in the servo system must have the following characteristics:

1. Flat gain versus frequency response over the broad band of frequencies of interest.
2. Minimum phase shift with a change in input signal (zero phase shift is desired, but a small amount of phase-shift is acceptable, if constant).
3. A low output impedance.
4. A low noise level.

Up to this point in our discussion of servos, the amplifiers have been directly connected to the motor that drove the load. Servo amplifiers are also used within the system itself to amplify the error signal. For example, the signal from the demodulator or filter network may require additional amplification to maintain signal strength. In cases where the amplifier is used to feed large drive motors, to move large loads, the basic electronic amplifier that was presented earlier in this training series is not adequate to do the job. This type of work is done by large power amplifying devices such as the amplidyne generator (NEETS, Module 5, *Introduction to Generators and Motors*) and the MAGNETIC AMPLIFIER, which we will discuss later in this chapter.

AC SERVO MOTORS

Large ac motors are too inefficient for servo use. To move large loads, the ac motor draws excessive amounts of power, and is difficult to cool. Hence, ac servo motors are used primarily to move light loads. Most of the ac servo motors are of the two-phase or split-phase induction type. Fundamentally, these motors are constant-speed devices, although their speeds can be varied within limits by varying the amplitude of the voltage to one of the motors stator windings. When the load becomes heavy, the workhorse dc servo motor is used.

DC SERVO MOTORS

The control characteristics of dc servo motors are superior to those of ac servo motors. The dc servo motor can control heavy loads at variable speeds. Most dc servo motors are either the permanent magnet type, which are used for light loads, or the shunt field type, which are used for heavy loads. The direction and speed of the dc motor's rotation is determined by the armature current. An increase in armature current will increase the motor's speed. A reversal of the motor's armature current will change the motor's direction of rotation More thorough explanations of ac and dc motors are given in NEETS Module 5, *Introduction to Generators and Motors.*

SYNCHRONIZING CIRCUITS

As we explained in chapter 1, the use of a multi-speed synchro transmission system increases the accuracy of data transmission. The accuracy of the servo system depends in part upon the accuracy of the input fed from the synchro system. For example, a dual-speed synchro system operating in conjunction with a servo system uses two CTs (one coarse and one fine) to define a quantity accurately. This is done by feeding the output of the COARSE CT to the servo amplifier when the system is far out of correspondence and then shifting to the output of the FINE CT when the system is within 2 or 3 degrees of synchronization. A circuit that will perform this job is known as a SYNCHRONIZING NETWORK.

A synchronizing network (also called a crossover or switching network) senses how far the servo load is from the ordered position and then switches either the coarse signal or the fine signal into control. The signal selected by the circuit is the input to the amplifier. The selection is based on the size of the error signals the circuit receives. The coarse signal is the predominant factor in the selection, since it is a measure of the servo's output position throughout its limit of motion. The coarse signal drives the system into approximate synchronization, and then the fine signal is shifted into control.

Semiconductor-Diode Synchronizing Network

The SEMICONDUCTOR-DIODE SYNCHRONIZING NETWORK is fairly common and typical of the type used in servo systems. Let's take a look at a circuit that uses this technique. Figure 2-19 is an illustration of the circuit. In the following explanation, we will assume that the system is far out of correspondence (more than 3º). At this time, the coarse signal is large in amplitute. With this condition, CR_3 and CR_4, or CR_5 and CR_6, will be forward-biased, depending upon the polarity of the input signal. This will cause current to flow through R_1. The voltage developed across R_1 is felt on one leg of the summing newtork. A large amplitude fine signal CANNOT be present in the summing network, because CR_1 and CR_2 are designed to limit the fine amplitude to a small value. With this condition present at the summing network, the coarse signal maintains control and drives the load toward correspondence.

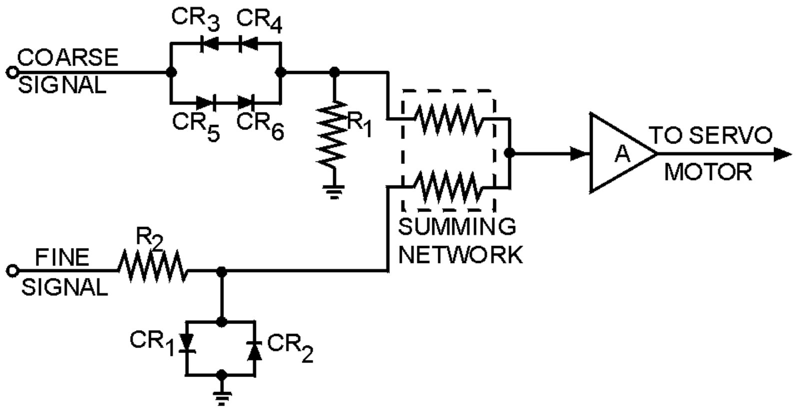


Figure 2-19.—Semiconductor diode synchronizing network.

When the load is within 3º of correspondence, the coarse signal is no longer large enough to forward bias the coarse diode network. The effect of this is to cause a large impedance across the diode network, which then drops most of the coarse signal. Practically no coarse signal voltage is felt across R_1 and one leg of the summing network. On the other hand, the fine signal is also small at this time, since the load is close to correspondence. Small fine signals are unaffected by CR_1 and CR_2. Therefore, the small fine signal is impressed across the summing network. With the fine signal being the only signal felt at the summing network, it takes control and drives the load to the exact point of correspondence. There are various types of synchronizing circuits used in servo systems. Some applications call for electron tubes, relays, and different types of semiconductor diodes. The theory of the specific type you will encounter in servo equipments will be explained in detail in the equipment's technical manual.

Q-24. What is the purpose of a synchronizing network in a servo system?

MAGNETIC AMPLIFIERS

As we stated earlier in this chapter, various types of servo amplifiers are used to drive servo motors. When the amplifier is required to produce a large amount of power, the conventional electronic amplifier becomes less efficient than some other types. The following is a brief discussion of a typical magnetic amplifier used in a servo system where large amounts of power are required to move a heavy load. If you need to refresh your memory on the theory of the magnetic amplifier, refer to Module 8 of this training series, *Introduction to Amplifiers*.

Magnetic Amplifiers in a Servo

Figure 2-20 illustrates a magnetic amplifier being used as the output stage of a servo amplifier.

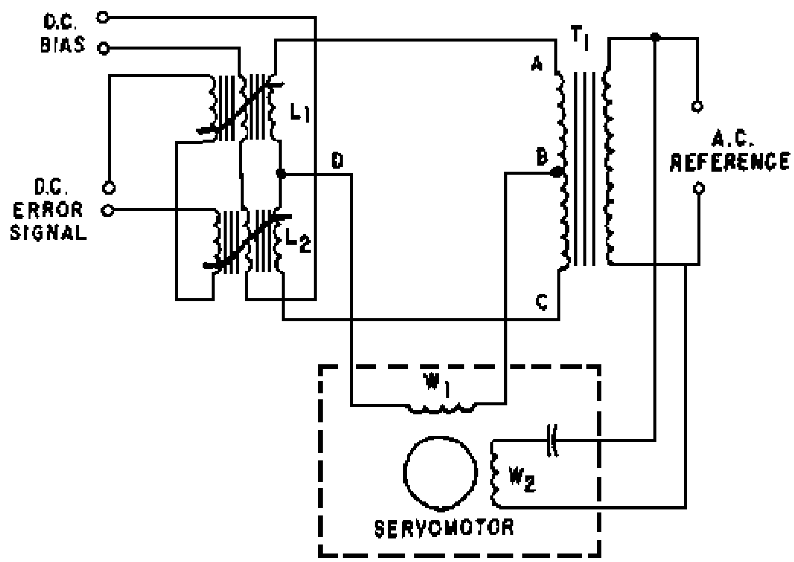


Figure 2-20.—Magnetic amplifier used to drive a servo motor.

The output of the servo amplifier is connected to one of the motor windings (controlled winding W_1). The other winding (uncontrolled winding W_2) is connected across the ac source, in series with a capacitor. The capacitor provides the required 90º phase shift necessary to cause motor rotation. The phase relationship of the current through the two windings determines the direction of rotation of the servo motor.

The magnetic amplifier consists of a transformer (T_1), and two saturable reactors (L_1 and L_2), each having three windings. The key point to the operation of this circuit lies in the fact that the error signal windings are connected in series-opposing while the bias windings are series-aiding.

With the circuit in the quiescent state (no input), the dc bias voltage causes the dc bias current to equally and partially saturate both reactors (L_1 and L_2). The reactances of L_1 and L_2 now being equal result in canceling currents through the W_1 windings of the servo motor. With only one input to the motor, it remains at rest.

Now, let's apply an error signal to the error signal windings. L_2 saturates and L_1 is driven further out of partial saturation, because the error windings are in series-opposition. This results in the error signal aiding the bias current in reactor L_2 and tending to cancel the bias current in reactor L_1. The reactance of L_2 is reduced, causing an increased current through the L_2 circuitry. In the other circuit (L_1), the reverse is true; its current decreases. This imbalance in the L_1 and L_2 circuitry results in current flow through W_1, say from left to right, and causes the motor to turn

Reversing the polarity of the error signal causes the direction of motor rotation to change. This is done by saturating reactor L_1 instead of reactor L_2 and causing current to reverse directions through W_1.

In the previous discussion, an ac motor was driven by the output of the magnetic amplifier. If a dc motor is required in the servo to move a heavy load, the ac output from the magnetic amplifier must be rectified.

NOTE: All of the components that have been described as units within a servo system are, in general, the same components used in many other electronic and electrical applications. The theory of these components has been discussed here and in other modules of the Navy Electricity and Electronics Training Series. If you have the desire or a need for an in-depth study of these components, the following are excellent references:

- Electronics Installation and Maintenance Books, NAVSEA 0967-LP-000-0130, for synchro and servo subjects.
- Electronics Installation and Maintenance Books, NAVSEA 0967-LP-000-0120, for the basic components of the servo system.

These references should be available in the technical library of your ship or station.

Q-25. What the three basic components make up the typical magnetic amplifier?

MULTI-LOOP SERVO SYSTEMS

Now that we have gone through the various servo loops and their components, let's continue our discussion with a realistic application of a servo system.

Very seldom will we find applications where one type of servo loop is used by itself. Usually several loops are combined through the use of various types of relays and switches. The many components of a complex system are caused to work together by switching them in and out as necessary.

Figure 2-21 illustrates a practical application of a multi-loop servo system. You should be able to recognize by now the different loops and components that make up this system. Nothing is really new in the system; we discussed all the loops and components earlier in this chapter.

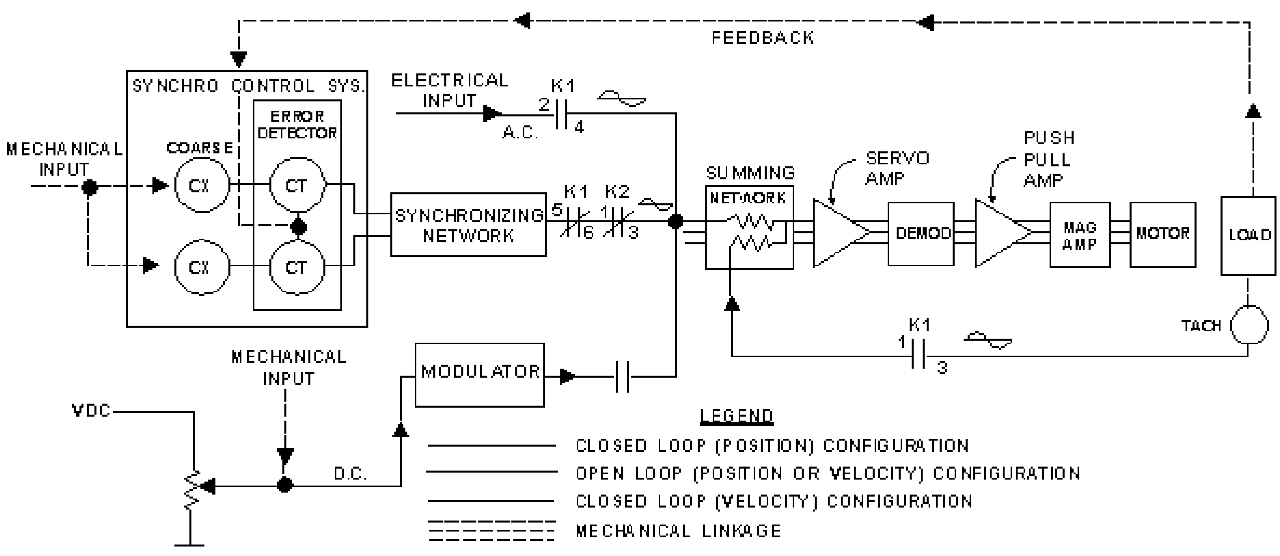


Figure 2-21.—Multi-loop servo system.

As shown by the relay conditions, the system is configured, in its normal state, as a closed-loop position servo. This is indicated by the heavy dark lines in the figure. An alternate configuration positions the load in this system by using the potentiometer. This is done by energizing relay K_2, and switching the system to an open-loop configuration. At the same time, the deenergized contacts of K_2 (1-3) open, thereby breaking the closed loop. The open loop is shown by the medium density lines in the figure. This loop is not as accurate as the closed loop, because the operator must intervene by turning the shaft of the potentiometer back to the zero voltage position to stop the load at the desired position. This type of circuit could be used by maintenance personnel to position the load for easy access to equipments, such as on an antenna or gun mount. The open loop can also function as a basic velocity loop by simply not returning the potentiometer to the zero position. This results in a constant error signal being present at the wiper arm of the potentiometer. With this condition, the load will continue to drive at some speed (rate) determined by the components in the loop.

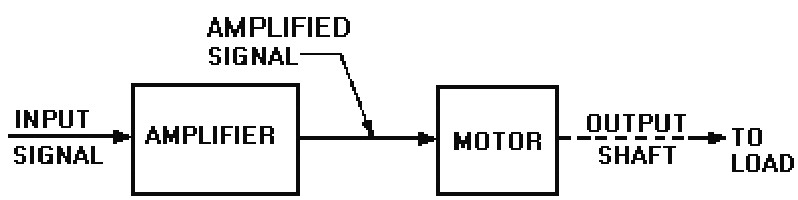
The last loop we will consider is the closed-loop velocity servo, indicated by the fine density lines.

This loop is switched into operation by energizing K_1. Notice that there are two inputs to the summing network with K_1 energized, the electrical input through contacts 2-4 and the feedback from the tach through contacts 1-3. The two signals are compared in the summing network, and their difference is used as the error signal to drive the load. When a state of equilibrium is reached in the circuit, the load will be moving at the desired velocity.

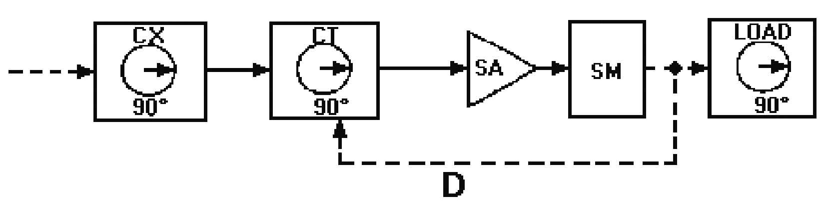
SUMMARY

This chapter has provided information basic to understanding servo systems and their components. The following is a summary of specific points in the chapter.

The **OPEN-LOOP CONTROL SYSTEM** is controlled directly, and only by an input signal. It has no feedback and is therefore less accurate than the closed-loop control system. The open-loop system usually requires an operator to control the speed and direction of movement of the output.



The **CLOSED-LOOP CONTROL SYSTEM** is the most common type used in the Navy. It can respond and move loads quickly and with greater accuracy than the open-loop system. The closed-loop system has an automatic feedback system that informs the input that the desired movement has taken place.



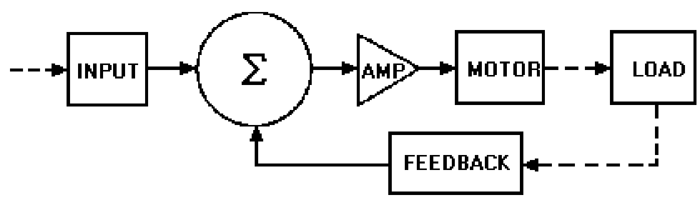
The **SERVO SYSTEM** is classified as a closed- loop system when it is capable of:

1. Accepting an order and defining the desired result,
2. Evaluating present conditions,
3. Comparing the desired result with present conditions and obtaining a difference or an error signal,
4. Issuing a correcting order, and changing the existing conditions to the desired result, and
5. Obeying the correcting order.

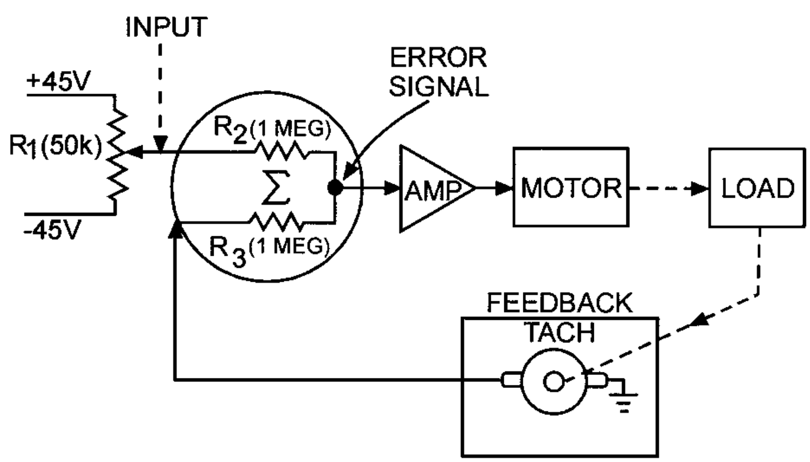
The **BASIC SERVO SYSTEM** is normally made up of electromechanical parts, and consists of a synchro-control system, servo amplifier, servo motor, and some form of feedback.

The **POSITION SERVO** has the goal of controlling the position of the load. In the ac position servo system, the amplitude and phase of the ac error signal determine the amount and direction the load will be driven.

In the dc position servo system, the amplitude and polarity of the dc error signal are used to determine the amount and direction the load will be driven.



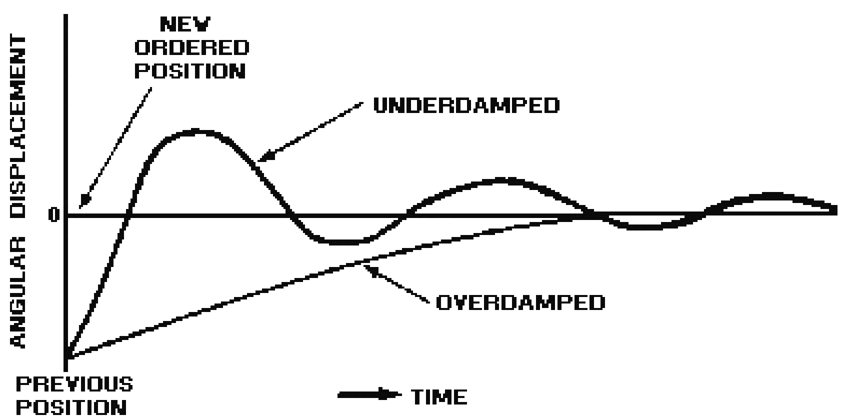
The **VELOCITY SERVO** is based on the same principle of error-signal generation as the position servo, except that the VELOCITY of the output is sensed rather than position of the load. When the velocity loop is at correspondence, an error signal is still present, and the load is moving at the desired velocity.



The **ACCELERATION SERVO** is similar to the velocity and position servos except that the acceleration of the load is being sensed rather than the position or velocity. In this loop, the tachometer of the velocity loop is replaced with an accelerometer.

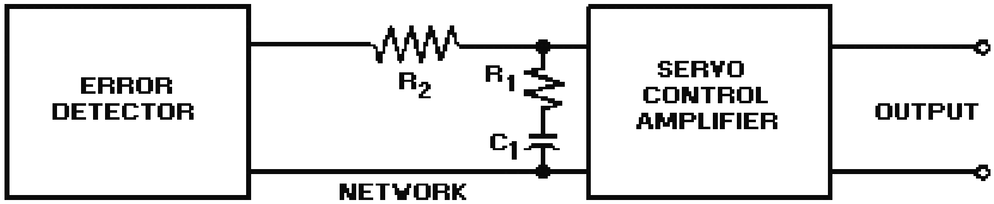
TIME LAG is a servo characteristic defined as the time between the input of the signal and the actual movement of the load. Time lag is undesirable and is reduced through the use of high-gain amplifiers. Damping systems are then added to attain smooth, efficient operation.

An **OVERDAMPED** system will not be subject to oscillations but takes an excessive amount of time to reach synchronization. An UNDERDAMPED system provides instant response to an error signal but results in the load oscillating about the point of synchronism. Somewhere between overdamped and underdamped, designers achieve adequate accuracy, smoothness, and a moderately short synchronizing time.

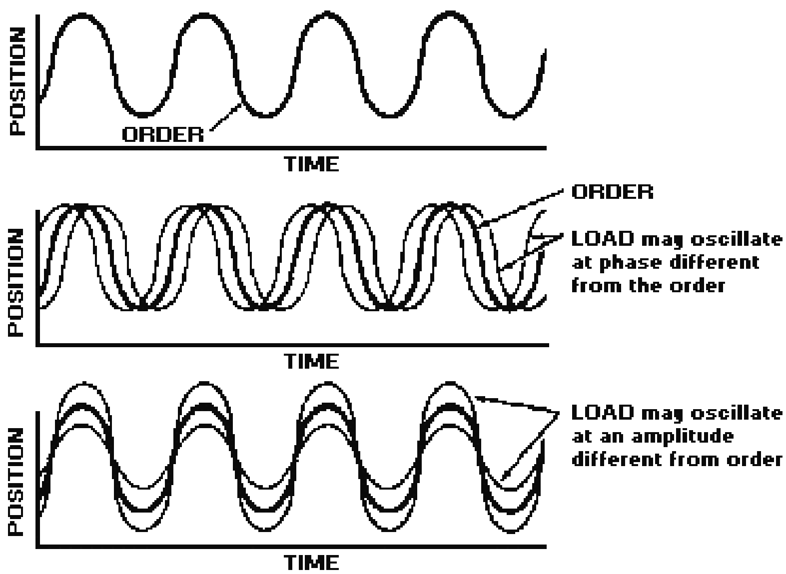


DAMPING is used to stabilize a system-to minimize or eliminate the problem of overshoot. The simplest form of damping is FRICTION CLUTCH damping. MAGNETIC CLUTCH damping is similar to friction clutch damping. The difference is in how the flywheel is coupled to the shaft of the servo motor. Magnetic coupling uses a magnetic field to draw two friction plates together to produce damping. Another method uses the magnetic field set up by a pair of coils or one coil in conjunction with a conducting surface (flywheel) to produce damping.

ERROR-RATE DAMPING is defined as a method of damping that "anticipates" the amount of overshoot. This form of damping corrects the overshoot by introducing a voltage in the error detector that is proportional to the rate of change of the error signal. The stabilization network used for error-rate damping consists of either an RC differentiating network or an integrating network. The components of the RC network are chosen to tailor the stabilization network to the requirements of the servo system.



FREQUENCY RESPONSE of a servo is the range of frequencies to which the system is able to respond in moving the load. The ideal system can respond to whatever frequencies are present in the input signal. Frequency response is a good way of judging servo performance. In a given servo system, good frequency response provides maximum stability and minimum time lag.

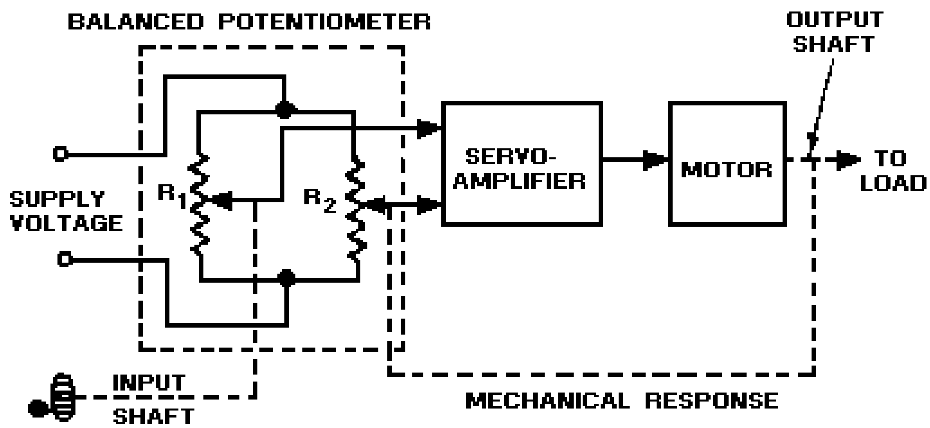


The **BANDWIDTH** of a servo amplifier, ideally, must be able to accept only the range of frequencies that represent valid servo signals.

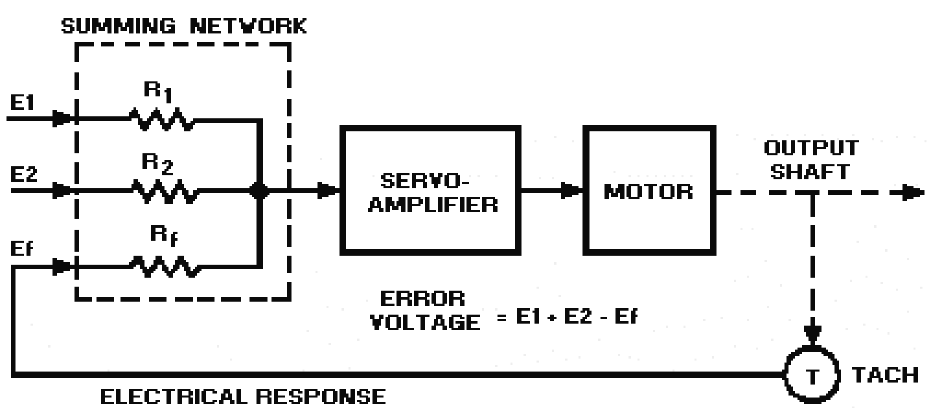
Amplifier bandwidth is another compromise in achieving optimum servo operation.

A **POTENTIOMETER** is one of the simplest position sensor devices and is generally used because of its small size, high accuracy, and output, which can be either ac or dc. Its primary disadvantages are limited motion, limited life due to wear, and high torque required to rotate the wiper contact.

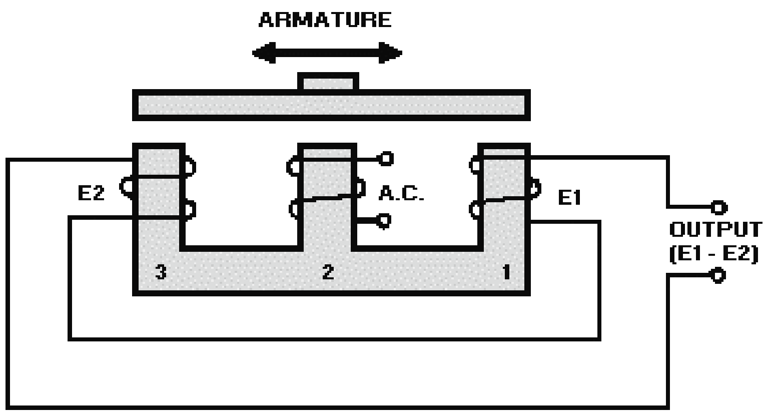
A **BALANCED POTENTIOMETER** in a closed-loop servo system is a voltage divider that functions as a position sensor and produces the error voltage that is fed to the servo amplifier.



SUMMING NETWORKS can be used as error detectors in servo systems to add algebraically two or more inputs and a feedback error voltage.



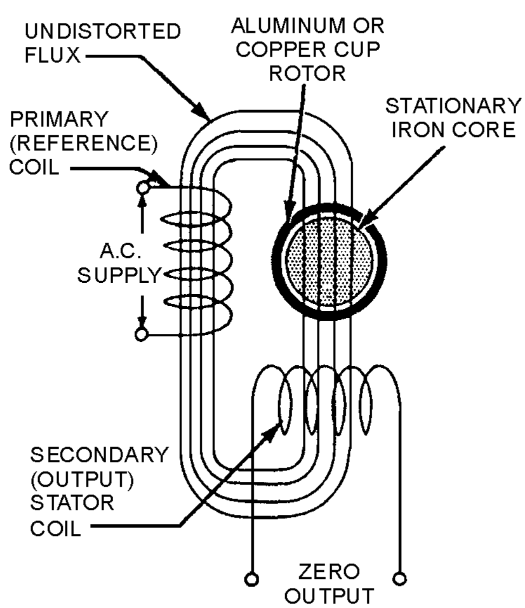
The **E-TRANSFORMER** is a magnetic error detector that can be used in systems limited by large angular movements. Output signals are either in phase, 180º out of phase, or zero, depending on the direction of the E-transformer's armature motion. The amplitude of the signal is determined by the amount of armature motion. The basic E-transformer can only detect motion in one axis.



A **CROSSED-E TRANSFORMER** (or pickoff) is two E-transformers placed at right angles to each other. This type of error detector is capable of detecting error in both horizontal and vertical directions.

A **CONTROL TRANSFORMER (CT)**, when used as a magnetic error detector, can rotate through unlimited angles. The output of this type of CT is always an ac servo error signal that must be demodulated if it is used with a dc servo motor.

A **RATE GENERATOR** (tachometer), when used in the velocity servo loop, is the heart of the feedback loop. The tach senses velocity (speed) of the load. A tachometer can be either an ac or dc rate generator. The output frequency of the ac tach is the same as the reference frequency, varying only in phase depending on the direction of rotation.



MODULATORS are used to change a dc error signal into an ac input error signal for servo amplifiers. This device is required when ac servo amplifiers are used instead of dc amplifiers.

DEMODULATORS convert ac error signals to dc error signals. The dc signal is required to drive a dc servo amplifier.

A **SERVO AMPLIFIER** used in an ac or dc servo system must have a flat gain, minimum phase shift, low output impedance, and low noise level.

AC SERVO MOTORS are used in servo systems that move light loads. Large ac motors are too inefficient for servo use when large loads are to be moved.

DC SERVO MOTORS can control heavy loads, and are widely used in servo systems. The speed and direction of the dc servo motor can be varied easily by varying the armature current.

MAGNETIC AMPLIFIERS are used when power from a conventional servo amplifier is too small to drive large servo motors (either ac or dc).

The **MULTI-LOOP SERVO SYSTEM** combines several closed and/or open servo loops together to control a common load.

ANSWERS TO QUESTIONS Q1. THROUGH Q25.

A-1. A system in which the precise movement of a large load is controlled by a relatively weak control signal.

A-2. Usually the operator senses the desired load movement and reduces the input to stop the motor.

A-3. Feedback.

A-4. Input signal and feedback.

A-5. To move the load and provide feedback data to the error detector.

A-6. Classifications in accordance with position, velocity, and acceleration functions.

A-7. Amount and direction of rotation.

A-8. Hunting.

A-9. Velocity loop senses velocity rather than position. When velocity loop is nulled, an error signal is still present and the load continues to move.

A-10. Tachometer.

A-11. The closed-servo loop can regulate load speed under changing conditions.

A-12. Underdamped.

A-13. Overdamped.

A-14. To minimize overshoot and/or oscillations.

A-15. Anticipating.

A-16. It should oscillate.

A-17. Unwanted noise-generated frequencies are rejected.

A-18. Zero.

A-19. (a) Phase. (b) Amplitude.

A-20. E-transformer and control transformers.

A-21. The method of primary excitation (ac and permanent magnet).

A-22. To convert a dc error signal into an ac error signal.

A-23. To convert an ac error signal into a dc error signal.

A-24. To switch control of the amplifier between either the coarse signal and the fine error signal.

A-25. Two saturable reactors and a transformer.