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CHAPTER 1

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REMOTE INDICATION AND CONTROL

Introduction

1. It is often necessary to note or record the value or any change in value of physical quantities (e.g., angular position, speed, temperature, etc.) at a point remote from the physical quantity itself.

There are many instances in radio engineering where angular movement of an input shaft must be reproduced accurately by motion of a second shaft, often at some considerable distance from the first. For example, in an aircraft, the loop aerial used for direction finding is placed at a suitable point in the aircraft and is often not readily accessible to the operator. A bearing indicator, if mounted at the base of the aerial shaft, would be inconvenient. This difficulty is overcome by ensuring that the movement of the loop aerial shaft is reproduced accurately by the motion of a second shaft in a *remote* indicator, placed at some convenient point in the aircraft.

A direct mechanical linkage, such as a flexible drive, between the two shafts is possible, but because of their separation distance there are practical difficulties of installation: in addition, there are inherent inaccuracies, and the efficiency of the system is poor. Much more satisfactory results are obtained by using electrical remote indication systems.

Electrical remote indication systems are sometimes referred to as '*data transmission systems*'. This term, however, is nowadays normally taken to have a much wider meaning: it is used, for example, to describe the method by which information is fed to a computer. Because of this, in order to avoid confusion, the term 'data transmission' is not used in this Chapter.

2. In electrical remote indication systems, the movements of the input shaft are translated into suitable electrical signals by a device known as a *transducer* or *transmitter unit*. A transducer (not to be confused with the transductor in a magnetic amplifier) measures the physical movement in terms of some electrical quantity whose magnitude is a strict measure of the movement. The electrical signals from this transmitter unit are then transmitted through wire links (and in certain cases, radio links) to appropriate receiver units located at any desired position: the received signals are used to turn a shaft which gives the remote indication or the required movement.

In the simple system outlined above, no torque amplification is provided: the torque developed in the output shaft is therefore less than that developed in the input shaft and the power required is provided by the input. Thus only moderate torques can be developed—in many cases only sufficient to move a light pointer over a graduated scale. For remote *indication* of such things as D/F bearings, or the position of a radar scanner, this system is normally adequate.

There are many occasions, however, when accurate remote control of the *position* of

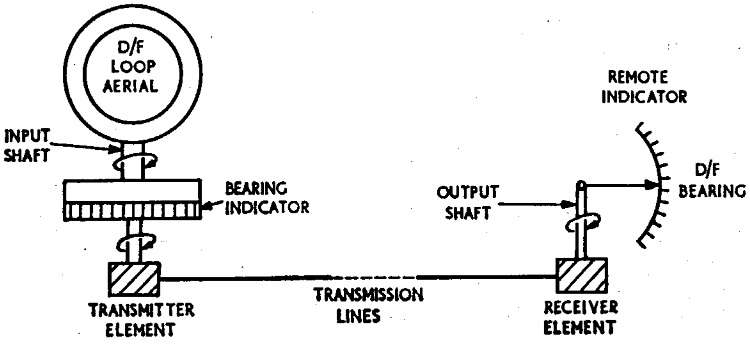


Fig. 1. ELECTRICAL REMOTE INDICATION

a heavy load is required (e.g. remote rotation of a radar scanner). Torque amplification is now necessary and to provide the required torque, use is made of hydraulic or electric amplifiers.

Many different devices are used to give remote indication of angular position or to control the movement of heavy loads from a distance. Some are operated from a d.c. supply; others from an a.c. supply. Some of the methods used in the Service are considered in the following paragraphs.

D.C. SYSTEMS

Desynn

3. **Introduction.** The Desynn system of transmission is a simple system which, because of its low torque characteristic, is useful only for remote *indication* of angular position. It is ideal where a simple pointer and scale indicator is adequate. Aircraft applications include remote indication of flap, rudder and elevator positions, and of D/F loop and compass readings. It is also used in ground installations to repeat the reading of an instrument at a remote point. The accuracy of the system is of the order of ± 2°, and this is sufficient for the applications mentioned.

4. **Circuit.** As in all electrical remote indication systems, the input shaft is connected to a transmitter element, and the output shaft, which operates the remote indicator, is driven by a receiver element: the transmitter and receiver are connected by electrical lines.

In the Desynn system (Fig. 2) the transmitter is a continuous resistance ring or toroidal potentiometer, which has three fixed tappings A, B, C spaced 120° apart and connected to the receiver. A rotating spring-loaded mechanism mounted on the input shaft, carries two sliding contacts or wipers that are at diammetrically opposite points on the toroid. The wipers are fed, via slip rings and brushes, from the positive and negative lines of the d.c. supply.

The receiver has three high resistance coils with axes at 120° in space (like the star-connected stator winding of an a.c. induction motor): within them is a permanent magnet rotor which is capable of rotation and which carries a pointer over a calibrated scale. The three coils in the receiver are connected to the tapping points A, B, C on the transmitter by the three lines as shown in Fig. 2.

5. **Operation.** When a d.c. supply is connected to the transmitter wipers, the voltages at the tapping points A, B, C cause currents to flow through the three stator coils in the receiver, and a resultant magnetic field is produced. The rotor magnet aligns itself with this field. The magnitude and polarity of the voltage at each tapping point in the transmitter vary according to the position of the wipers. Thus, if the input shaft is rotated, the variation of voltage at A, B, C produces changes in the currents flowing in the stator coils and a magnetic field rotating in sympathy with the input shaft is produced. The rotor magnet remains aligned with this field at all times and so rotates in synchronism with the input shaft.

6. This action is illustrated in Fig. 3, where the wipers of the transmitter are connected to opposite poles of a 24V d.c. supply. With the input shaft in the position shown in Fig. 3(a), the voltage distribution round the toroid is such that point A is 24 volts positive with respect to supply negative, while B and C are both 8 volts

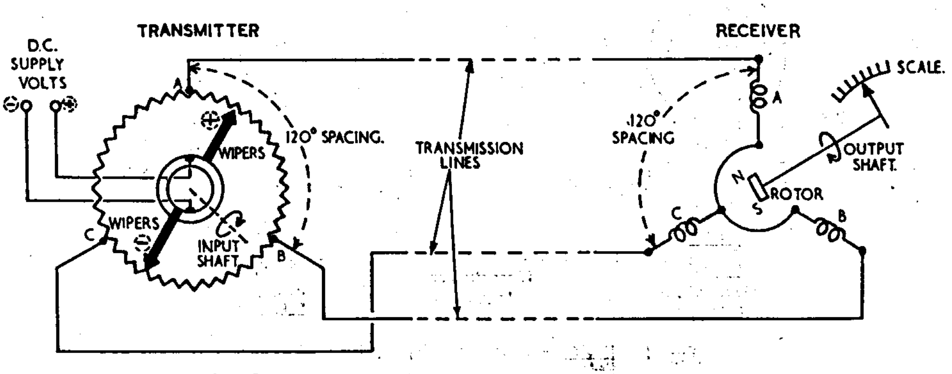


Fig. 2. DESYNN SYSTEM OF REMOTE INDICATION

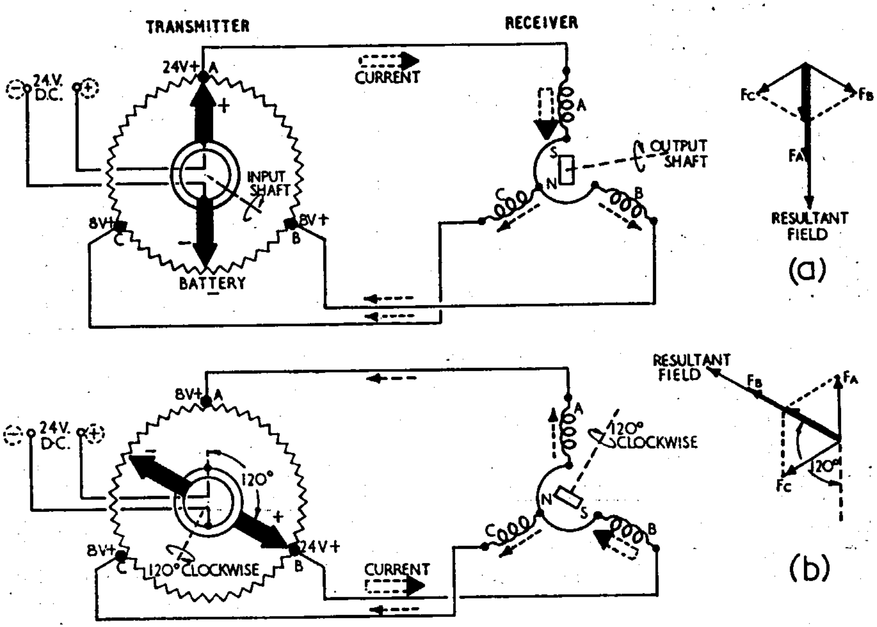


Fig. 3. OPERATION OF DESYNN

positive with respect to supply negative. With A positive by the same amount to both B and C, current flows from A through coil A in the receiver; it then divides equally at the star point and half the total current flows through coil B and half through coil C back to the transmitter. The individual and resultant magnetic fields produced by these currents are indicated by vectors, and with the input shaft in the position shown in Fig. 3(a), the axis of the resultant field lies vertically: the rotor magnet aligns itself with this axis.

If the input shaft is rotated 120° clockwise from its initial position, as shown in Fig. 3(b), the voltage distribution round the toroid is such that current flows from B through coil B in the receiver; it then divides equally and flows through coils A and C back to the transmitter. The vectors show that the resultant magnetic field has also rotated through 120° clockwise from its initial position and the rotor magnet aligns itself along this new axis.

7. **Summary.** Enough has been said to show that if the wipers in the transmitter are placed in any position by the input shaft, the resultant field at the receiver and hence the rotor magnet take up corresponding positions. Thus as the input shaft rotates through 360°, the rotor follows this movement *in the same direction;* if a pointer, moving over a calibrated scale, is attached to the rotor, remote indication of the position of the input shaft is immediately available. A typical example of the use of the Desynn is remote indication of bearing from the D/F loop—the loop shaft acting as the 'input' shaft.

M-type Transmission System

8. **Introduction.** Many practical indicators take the form of light geared mechanisms which are required to rotate fairly substantial drum-type indicators or comparable devices. For example, it may be required to rotate the deflection coils in a magnetic c.r.t. in synchronism with a radar aerial to produce the necessary trace on the screen. This requires a larger torque than is available with the Desynn system: in such circumstances, an M-type or 'step-by-step' transmission system can provide the moderate torque required.

9. **Circuit.** A toroidal potentiometer type of transmitter cannot control large currents to the receiver (i.e. allow the receiver to

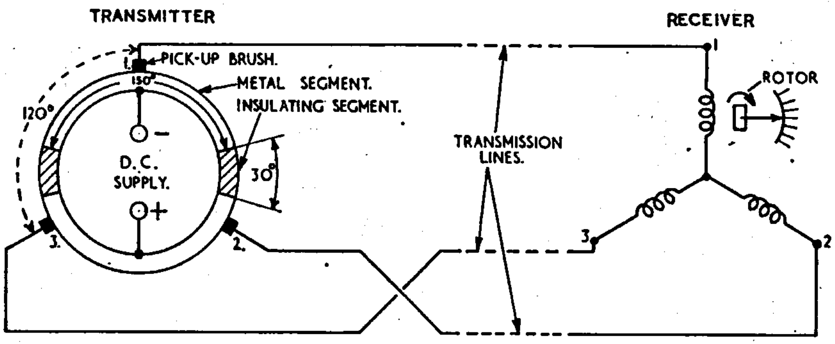


Fig. 4. M-TYPE TRANSMISSION

develop much torque) because a low-resistance transmitter would be needed and this would overheat and tend to burn out. In the M-type transmission system, therefore, the transmitter unit is modified considerably from that in the Desynn system: the receiver, however, operates on the same principle.

The essential features of a simple M-type transmission system are shown in Fig. 4. The transmitter is basically a drum-type switch, the metal drum of which consists of two segments each spanning an arc of 150°, separated by two sections of insulating material each extending over 30°. The two metal segments are connected to opposite poles of a suitable d.c. supply, and three 'pick-up' brushes are disposed round the drum at intervals of 120°.

The receiver unit (more than one unit may be operated from a single transmitter to give multiple indication) is similar to that in the Desynn system, although the rotor may be either a permanent magnet or a laminated soft-iron core. The outer end of each coil in the receiver is connected, via a transmission line, to one of the three pick-up brushes in the transmitter.

10. **Operation.** The action of the M-type transmission system is illustrated in Fig. 5.

In position 1, the input shaft driving the

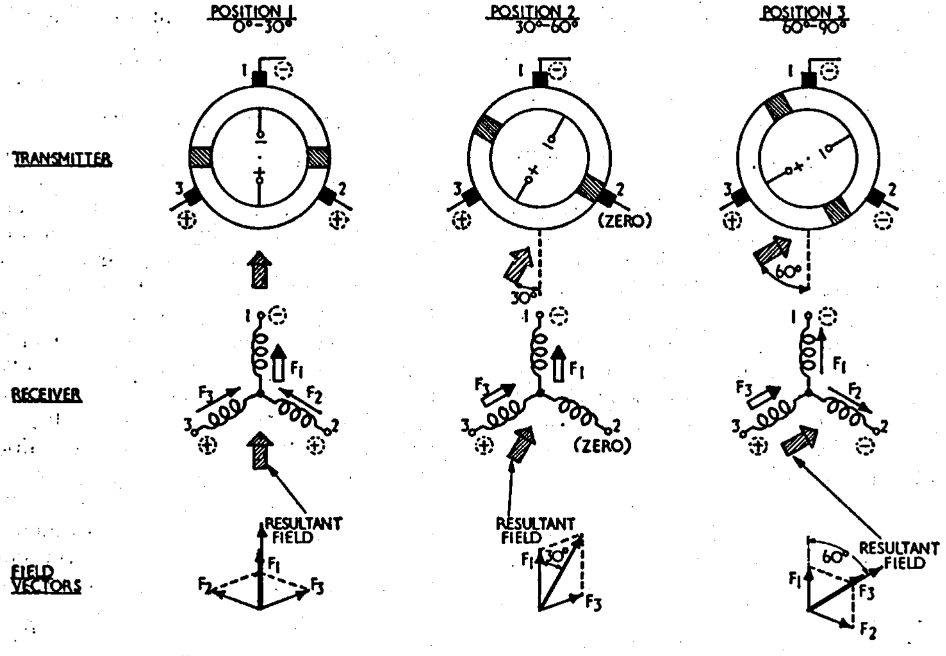


Fig. 5. OPERATION OF M-TYPE TRANSMISSION SYSTEM

transmitter drum is in such a position that brush 1 is connected to − of supply and brushes 2 and 3 to +. These polarities are applied to the three coils in the receiver, with the result that the current divides through coils 2 and 3, *all* the current flowing through coil 1. Magnetic fields F_1, F_2, F_3 are produced and resolving these three fields by vector gives a resultant in the direction shown.

If now the input shaft rotates through 30° clockwise (position 2), brush 1 is −, brush 2 is disconnected by the insulating segment and brush 3 is +. At the receiver, equal currents flow through coils 1 and 3, while coil 2 carries no current. By resolving the magnetic fields F_1 and F_3 produced by these currents, the resultant field is seen to have rotated through 30° in a clockwise direction in sympathy with the input shaft.

The condition after a further 30° rotation of the input shaft is shown at position 3. The resultant field at the receiver has now rotated through 60° clockwise from its initial position, thus following the input shaft.

In each case, the receiver rotor aligns itself with the axis of the resultant field and therefore follows the angular movement of the input shaft, *but only in discrete steps of* 30°.

11. With the arrangement shown, there is a change of pick-up brush polarity at one or other of the brushes each time the input shaft is turned through 30°. The complete pattern showing how in turn, the brushes are connected to +, −, 0 when the drum is rotated through 360° is given in Table 1. There are, of course, 12 steps in a complete rotation: the first 3 steps correspond to positions 1, 2 and 3 in Fig. 5.

For certain purposes, the 30° step is too large, and in such cases a modified transmission system giving 24 steps of 15° each may be used. The principle remains the same, but accuracy is improved.

The maximum operating rate of the M-type transmission system is dependent on the inductive time constant of the receiver coils. The system in general use is designed to give practical operating speeds of up to 180 steps per second.

12. **Drum transmitter.** The basic principle of the M-type transmission system has been described in a previous paragraph. A practical example of the transmitter unit used in this description is illustrated in Fig. 6. It is so constructed that the d.c. supply brushes are in contact at all times with opposite metal segments, whilst the pick-up brushes are in contact with either of the metal segments or with the insulated segment, depending on the position of the input shaft (i.e., connected to +, −, or 0 as previously explained).

Transmitter Position	Pick-up Brush Polarity		
	1	2	3
0° – 30°	−	+	+
30° – 60°	−	0	+
60° – 90°	−	−	+
90° – 120°	0	−	+
120° – 150°	+	−	+
150° – 180°	+	−	0
180° – 210°	+	−	−
210° – 240°	+	0	−
240° – 270°	+	+	−
270° – 300°	0	+	−
300° – 330°	−	+	−
330° – 360°	−	+	0

TABLE I.
POLARITY CHANGES DURING
360° ROTATION OF TRANSMITTER

13. **Commutator transmitter.** A schematic diagram of a commutator transmitter designed to give 24 step (15°) M-type sequence is shown in Fig. 7. It is similar to the drum type but much more compact. It consists of a thin commutator face plate rotating against five fixed brushes that are held in a support plate. The commutator is made up of three concentric rings of metal, separated by rings of insulating material. The outer and inner rings are both electrically con-

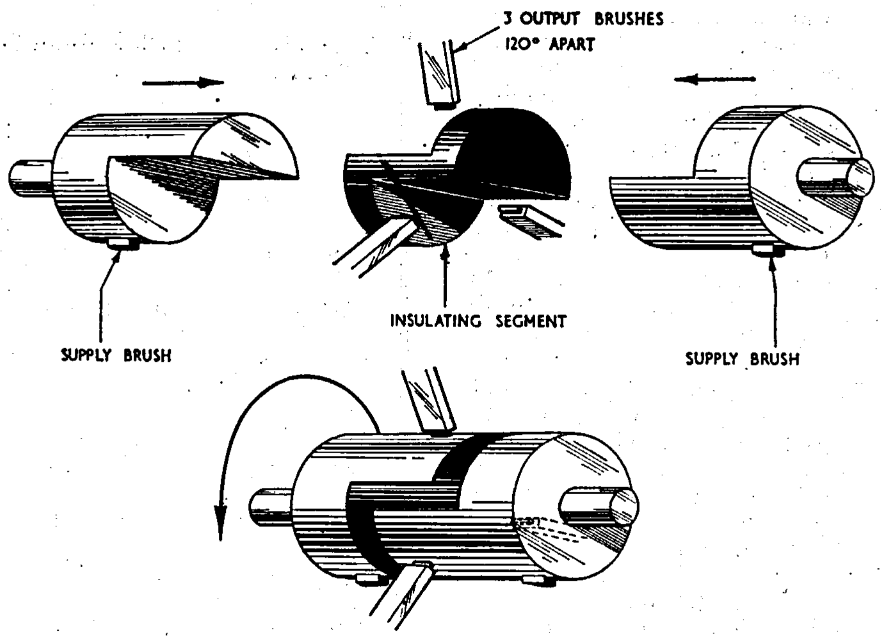


Fig. 6. M-TYPE DRUM TRANSMITTER

tinuous throughout and two of the five brushes, one connected to supply + and the other to supply —, bear on the inner and outer rings respectively. The centre ring is divided into four equal portions by four 'islands' of insulation, each extending over an arc of 15°: the segments so formed are connected to the outer and inner rings alternately. In the middle (divided) ring there is, therefore, a regular +, —, 0 sequence.

The remaining three brushes are positioned to bear on the middle ring, each of the outer brushes being displaced from the centre brush by 60°. With this arrangement there is a change of polarity at one or other of the three pick-up brushes each 15° rotation of the face plate: a 24 (15°) step M-type sequence is thus produced at the output brushes.

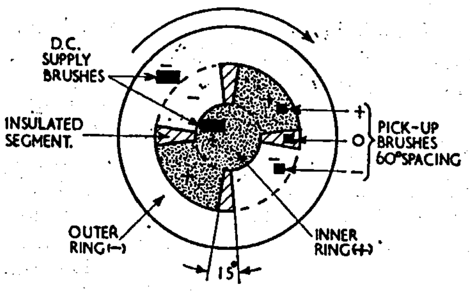


Fig. 7. COMMUTATOR TRANSMITTER

14. **Cam-type transmitter.** There are two main types of cam-operated transmitter, but the more common of the two types, and the one considered here, is the eccentric cam transmitter. It consists of a single circular cam, mounted *eccentrically* on the input shaft and operating three pairs of two-position switches, via push rods. The switches are fitted radially around the cam with 60° spacing as shown in Fig. 8, and the inner contact of each switch is permanently energised, + or — as illustrated. The two switches in a pair are diammetrically opposed and control the polarity on one line feeding the receiver.

With the input shaft in the position shown at (a) of Fig. 8, with maximum eccentricity opposite switch 2, switches 1, 2 and 3 are open; switches 4, 5 and 6 are closed. Thus line 1 is —, line 2 is +, and line 3 is —.

On turning the input shaft through 30° in either direction from the initial position, the maximum eccentricity of the cam wheel is midway between two of the switches. Thus, at position (b) of Fig. 8, switches 1, 2, 3 and 4 are open, and switches 5 and 6

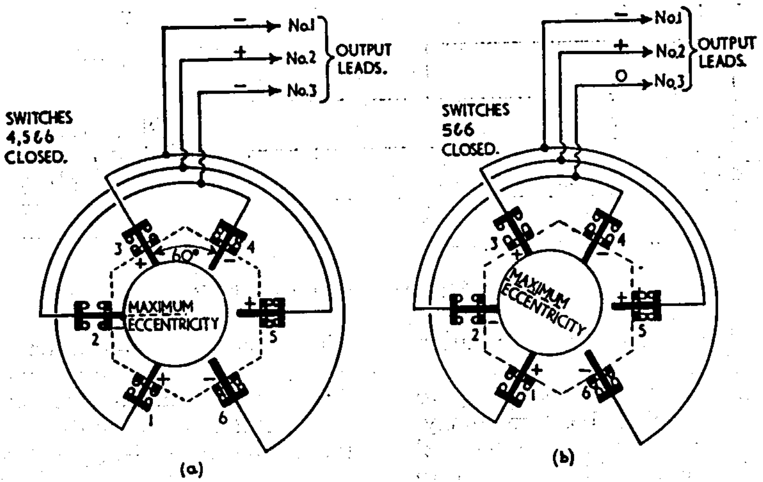


Fig. 8. ECCENTRIC CAM TRANSMITTER

only are closed. In this condition, line 1 is —, line 2 is +, and line 3 is 0.

A standard M-type sequence of line polarity changes at 30° steps is therefore established, 12 steps being provided for each complete revolution.

The drum and commutator transmitters both suffer from brush wear. The eccentric cam transmitter does not. Because of this, the eccentric-cam type is used to a greater extent than the others where a high operating rate has to be maintained.

15. **M-type receivers.** As has already been stated, the stator of an M-type receiver is similar to that of an a.c. induction motor and to that in a Desynn receiver. The rotor, however, may be of the soft iron (inductor) type or it may be a permanent magnet.

The inductor rotor is built up of iron and aluminum laminations, and the laminated rotor continuously re-aligns itself with the resultant field axis of its stator to offer the path of lowest reluctance—i.e., when the laminations are in line with the resultant flux. Since this type of rotor is non-polarized it is possible for it to align itself in either of two positions 180° apart.

The permanent magnet rotor is more common. A disadvantage of the earlier types of rotor magnet was that they tended to become demagnetised after a time. This does not happen with modern materials such as Alnico. Because of the relatively strong magnetic field produced by the magnet, the rotor torque is considerably higher than that of the inductor rotor unit. Higher stepping rates are also achieved for the same reason and, being polarized, the rotor lines up in one position only.

16. **Transmitter and receiver synchronisation.** The fact that the receiver in an M-type transmission system moves in 30° (or 15°) steps is a disadvantage. If greater accuracy is required, the input shaft can be geared up to the transmitter shaft: a 60:1 gear system is common, the transmitter shaft completing 60 revolutions for each revolution of the input shaft. The receiver is equally geared *down* to the output shaft, if a 1:1 input-to-output ratio is required. Although the accuracy of the system is improved 60 times by this means, there is now the possibility of ambiguity. This can be seen as follows:—

The switching sequence is completed in 12 (30°) steps, and with a 60:1 gear system between the input shaft and the transmitter, the sequence is completed for a rotation of only $\frac{360°}{60} = 6°$ of the primary drive, i.e. in 12 steps of $\frac{1}{2}°$ each. Since the transmitter completes 60 revolutions for each revolution of the input shaft, there are 60 different positions in the full 360° movement of the *primary* drive, each separated by 6°, into which the receiver rotor can 'lock' and still follow the M-type sequence. However, in all but one of these positions, the

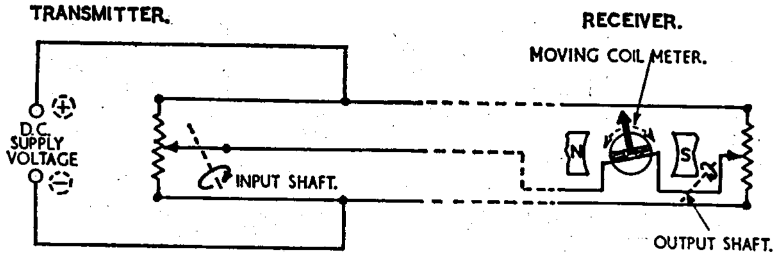


Fig. 9. SIMPLE WHEATSTONE DRIVE

output shaft will be out of synchronisation with the input shaft.

In such circumstances it is necessary to connect to the receiver a local manually-controlled transmitter acting as a 'coarse' control. The coarse control is needed to bring the output shaft into synchronism with the input shaft by comparison of dial readings. When this has been done, the local transmitter is disconnected and the receiver again connected to the transmission line and hence to the remote transmitter.

Wheatstone Bridge System

17. **Introduction.** The accuracies of the Desynn and M-type transmission systems can never be better than about ± 2° because of frictional and resistive losses. Where greater accuracy is required, an error-operated or follow-up system can be used. The Wheatstone bridge system is a typical example for d.c., when continuous rotation is not a requirement.

18. **Circuit and action.** A circuit arrangement is illustrated in Fig. 9. The transmitter and receiver are both potentiometers connected to form a Wheatstone bridge. The wiper on the transmitter potentiometer is controlled by the input shaft. A moving coil meter, acting as the remote indicator is connected between the two wipers, and the arrangement is such that rotation of the moving coil moves the wiper on the receiver: the sense of rotation tends to reduce the coil current to zero.

If the input shaft is rotated, the bridge becomes unbalanced and current flows through the moving coil, which also rotates, moving the pointer and the receiver wiper. This movement continues until the receiver wiper reaches the position at which the bridge becomes balanced. In this way, the receiver wiper (and pointer) copy exactly the movements of the transmitter wiper (and input shaft). The accuracy of this system is better than ± 1°, but the torque developed at the receiver is very small.

Greater output driving torque can be developed by modifying the basic Wheatstone bridge system. The moving coil meter can be replaced by a polarized relay which is used to switch a d.c. supply to a small motor, as shown in Fig. 10.

At balance, the relay is de-energised and the supply to the motor is disconnected.

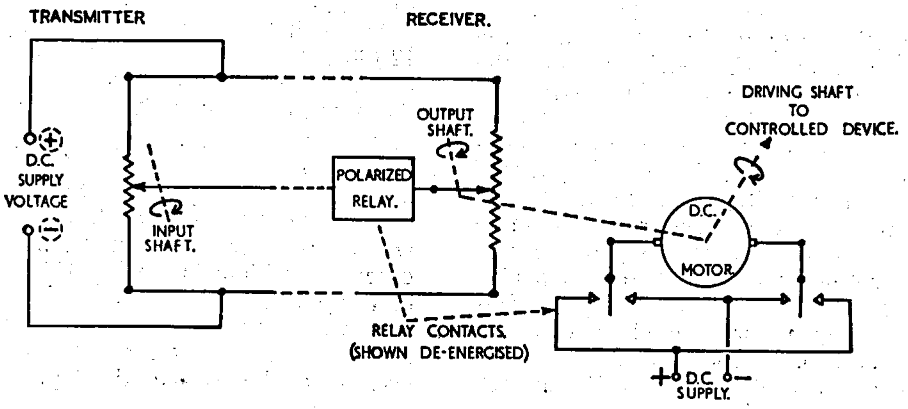


Fig. 10. TORQUE-AMPLIFIED WHEATSTONE DRIVE

If the input shaft is rotated, the bridge becomes unbalanced and the relay is energised. The sense of unbalance determines the direction in which the relay is energised: this, in turn, determines which set of contacts is closed and thus the direction of rotation of the motor. The motor rotates in such a direction that the receiver wiper moves towards the balance condition: at the same time the controlled device is moved to the desired position.

This system is used for remote control and tuning of radio equipment.

A.C. SYSTEMS

Introduction

19. The d.c. transmission systems described earlier are limited in their practical application to remote *indication* of position of a shaft and the transmission of *moderate* torque to a remote device: also, in general, the degree of accuracy is of the order of ± 2°.

Where a remote transmission system is required to operate efficiently with a high degree of accuracy, or where it is required to be used as part of a servomechanism to move a heavy load at a remote point, an a.c. system is generally preferred.

20. A.C. transmission systems have many applications: they include:—

(*a*) Remote indication of position or movement.

(*b*) The transmission of moderate torque to a remote device with a high degree of accuracy.

(*c*) The controlling element in a servomechanism system used to control the position and speed of heavy loads at a remote point.

(*d*) The summation of two or more mechanical movements.

(*e*) Analogue computation.

21. A.C. transmission systems are referred to generally as '*synchros*' because of the self-synchronous characteristic of the systems, i.e., any movement of the input shaft connected to the transmitter is exactly reproduced in the angular movement of the remote output shaft connected directly or indirectly to the receiver.

Synchros are manufactured by many firms and are known by various trade names such as Selsynn, Magslip, Synchrotic, Autosyn, Aysynn, and Telesyn. All of them, however, work on the same basic principles.

22. Synchro systems can be divided into several categories according to their function. The three main categories are as follows:—

(*a*) **Torque synchros.** These are the simplest form of synchro: *no torque amplification* is provided. They are used for the transmission of angular position information by electrical means and for the reproduction of this information by the position of the shaft of the receiver element. Moderate torque only is developed in the output shaft and the main use of torque synchros is in instrument repeater systems.

(*b*) **Control synchros.** These normally form part of a power amplifying servomechanism system. Such a system can provide almost any degree of torque amplification and can therefore be designed to handle heavy loads such as a directional aerial array on a turntable. The control synchro, in effect, provides the data on which the servomechanism acts.

(*c*) **Resolver synchros.** These are used extensively in computers to convert voltages, which represent the cartesian co-ordinates of a point into a shaft position and a voltage which together represent the polar co-ordinates of the point. They can also be used for conversion from polar to cartesian co-ordinates.

Although the construction of these different categories differs in detail, their action can be appreciated by considering the elements used in a basic synchro system.

Basic Synchro System

23. The basic synchro system for transmission of continuous rotation is illustrated in schematic form in Fig. 11. The transmitter and receiver are electrically similar. Each consists of a rotor carrying a single winding, round which is a stator on which are three windings arranged with their axes at 120° in space.

The principle physical difference between transmitter and receiver is that the receiver is usually fitted with low-friction ball bearings on the rotor and a mechanical damper to

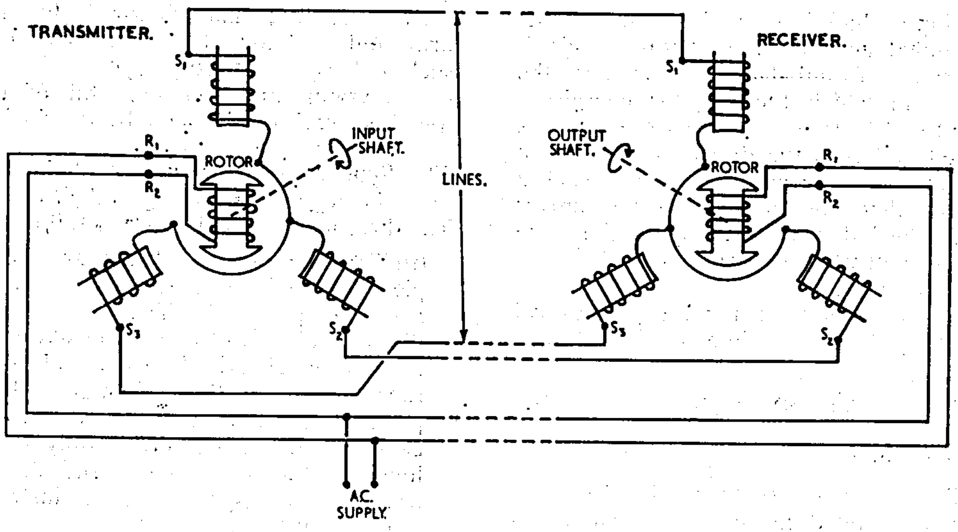


Fig. 11. BASIC SYNCHRO SYSTEM

reduce oscillation, whereas the transmitter is not damped and often has no ball bearings.

In operation, both rotors are energised from an a.c. supply (often 115V 400 c/s) and the corresponding stator connections are joined together by transmission lines.

24. The schematic representation of the synchro unit used in Fig. 11 and shown at (a) of Fig. 12 is useful for certain purposes, but the simplified version of the same symbol, shown at (b) of Fig. 12, is generally sufficient. For detailed circuit diagrams, the symbol shown at (c) is used.

A synchro unit is said to be positioned at *electrical-zero* when the axis of the rotor is in line with the axis of the S_1 winding of the stator. This same position is indicated in Fig. 12(c), when the two arrows are lined up.

Construction of Synchro Unit

25. The construction of a simple form of synchro transmitter is shown in Fig. 13. The construction of a synchro receiver is similar with the addition of an oscillation damper.

The stator body is made up of internally-slotted laminations, in the slots of which are fitted the three sets of windings S_1, S_2, S_3 spaced 120° apart and arranged in a similar fashion to the stator coils of a small three-phase induction motor. Despite the similarity, the stator windings of a synchro unit must not be confused with normal three-phase windings. In a three-phase machine, the voltages in the three windings of the stator are equal in magnitude and 120° apart in phase: in a synchro unit, the voltages are *not equal* in magnitude and

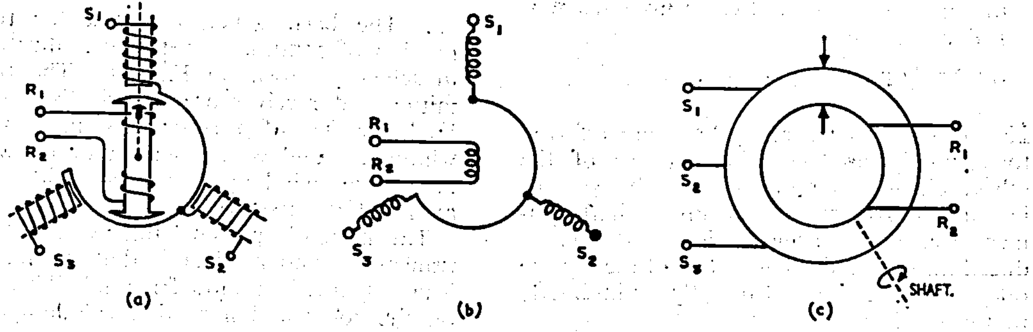


Fig. 12. TORQUE SYNCHRO SYMBOLS

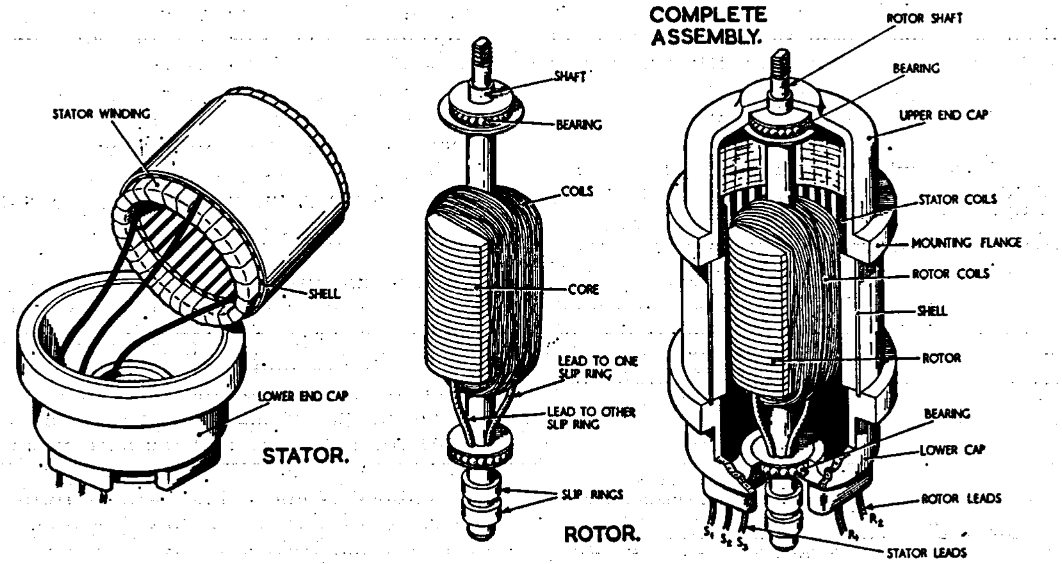


Fig. 13. CONSTRUCTION OF TORQUE SYNCHRO

are either in phase or 180° out of phase with each other: in a synchro unit, the stator windings are said to be "space-phased".

The laminated rotor carries a single winding, the two ends of which are connected, via slip rings and brushes, to two terminals R_1 and R_2, which are in turn connected to the a.c. supply.

Principle of Torque Synchro System

26. **Basic operation.** A simple torque synchro system is illustrated in Fig. 14. The rotors of transmitter (TX = torque transmitter) and receiver (TR = torque receiver) are both energised from the a.c. supply and produce an alternating flux which links with their corresponding stators. Should the relative dispositions of rotor to stator in the two elements be different, the three voltages induced in each of the two stator windings by the alternating fluxes differ: currents then flow between the two stators and a torque is produced in each synchro which is so directed as to eliminate the discrepancy; thus, in effect, to align the two rotors.

Normally, the transmitter rotor is held mechanically by the input shaft and the

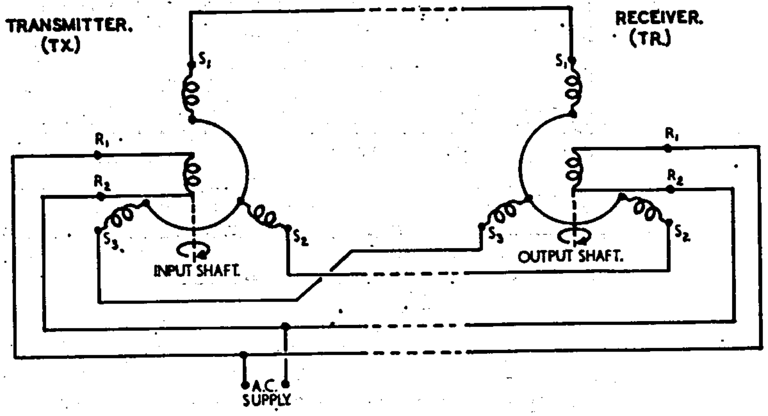


Fig. 14. TORQUE SYNCHRO SYSTEM

receiver rotor is free to turn so that it aligns itself with the transmitter rotor. Thus, in Fig. 14 any movement of the transmitter rotor is repeated synchronously by the movement of the receiver rotor.

27. **Operation of transmitter.** To understand why the receiver rotor follows the transmitter rotor, it is necessary to consider the manner in which the transmitter stator voltages change as the input shaft is turned.

Consider Fig. 15, in which the transmitter rotor is connected to the a.c. supply but the stator windings are disconnected from the receiver. A current flows in the rotor and sets up an alternating magnetic flux in the transmitter: the direction of this flux is along the axis of the rotor winding. The flux links with the stator windings, and induces alternating voltages in each of them. The synchro unit is therefore, like a single-phase transformer in which the rotor winding is the primary and the stator windings are three secondary coils.

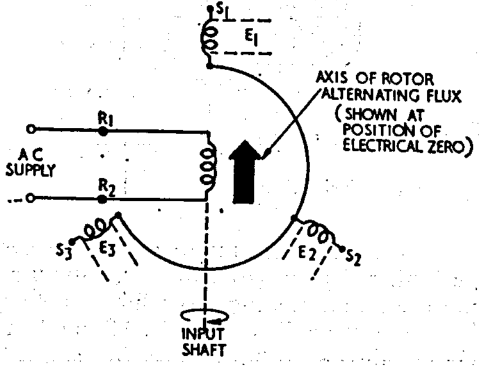


Fig. 15. OPERATION OF SYNCHRO TRANSMITTER (TX)

28. The magnitudes of the voltages induced in the stator windings depend on the relative number of turns in rotor and stator coils and on the orientation of the rotor.

For the position of the rotor in Fig. 15, voltage E_1 has its maximum value (the axis of the rotor winding and the axis of stator coil S_1 are in line): E_1 is also *in phase* with the applied voltage E. As the rotor is turned clockwise from this position, E_1 decreases and becomes zero when the rotor has turned through 90°. Further turning of the rotor causes a voltage of *reversed* phase to appear across the stator coil S_1.

29. Similar reasoning applies for the voltages E_2 and E_3 induced in the stator coils S_2 and S_3 respectively. A graph showing the variations in the magnitudes of the stator voltages with the angular position of the rotor is plotted in Fig. 16.

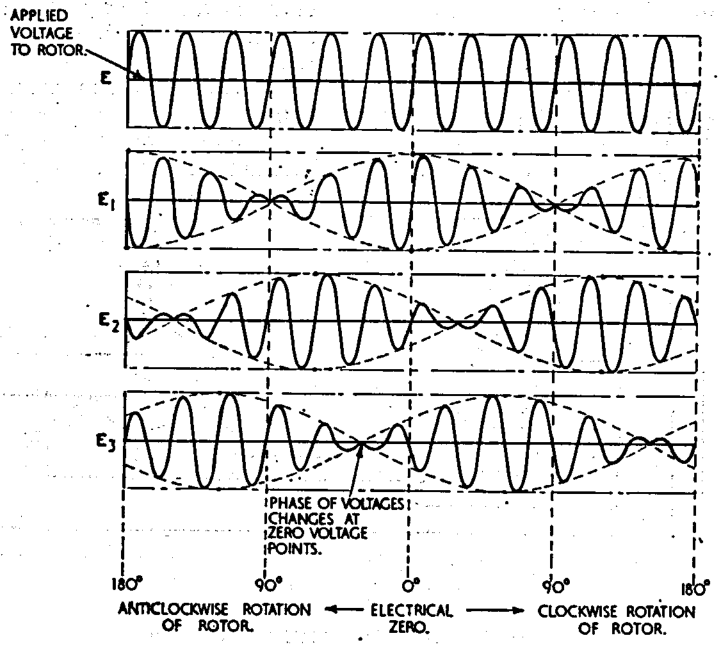


Fig. 16. OUTPUT FROM TRANSMITTER (TX)

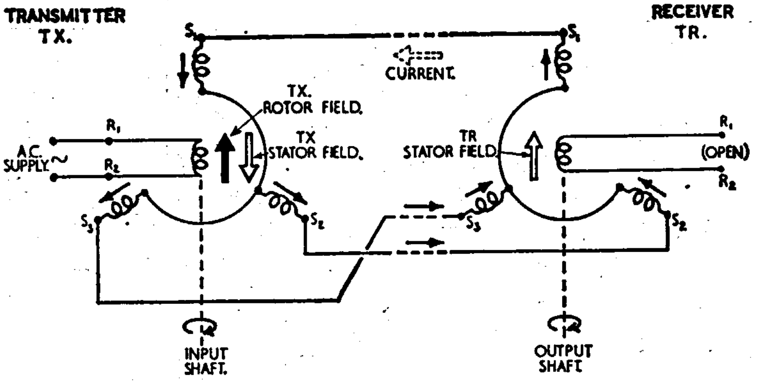


Fig. 17. PRODUCTION OF RECEIVER (TR) STATOR FIELD

It is again emphasised that the stator voltages do *not* constitute a set of three-phase voltages. The stator voltages, in effect, are modulated with sinusoidal envelopes that differ in phase by 120° as the rotor is turned at a constant speed. The individual cycles of the stator voltages, however, are either in phase or 180° out of phase with each other and with the rotor voltage.

30. Consider now what happens when the stator coils in the transmitter and receiver are connected: for the moment, the receiver rotor is disconnected from the supply. The arrangement is shown in Fig. 17.

The voltages induced in the transmitter stator coils by the alternating rotor flux are applied to the receiver stator coils and currents flow through the closed circuits formed by the two sets of stator windings. The magnitude and phase of the current through each coil of the *transmitter* stator depend on the magnitude and phase of the induced voltage in each coil, and this in turn depends on the orientation of the transmitter rotor. The current through each coil of the transmitter stator produces a magnetic field and the three fields combine to form a single resultant magnetic field inside the stator. Since the rotor winding is, in effect, the primary winding of a transformer with the stator windings acting as three secondary coils, the resultant flux produced by the currents in the stator coils must at all times balance that produced by the rotor current: this is normal transformer action. The directions of the transmitter rotor and stator magnetic fields are therefore *opposite* as shown in Fig. 17.

31. **Operation of receiver.** The current flowing through each coil of the *receiver* stator is of the same magnitude as that flowing through the corresponding coil of the transmitter stator. It is however, in the *opposite* direction. Thus, since the transmitter and receiver stators are identical in form, the resultant magnetic field established inside the receiver stator is equal in magnitude but opposite in direction to that produced in the transmitter stator. The receiver stator field thus coincides, both as regards axis line and direction of flux, with that of the *transmitter rotor.* This is also indicated in Fig. 17.

32. A bar of soft iron placed in a magnetic field tends to align itself parallel to the field. Thus the rotor of the synchro receiver tends to turn into alignment with the receiver stator field, even though the rotor winding is open. Operation with open rotor winding is undesirable however, because for a given position of the transmitter rotor, the receiver rotor can take up one of two positions 180° apart: in addition, the torque developed by the receiver is small.

33. These difficulties are avoided if the rotor winding of the receiver is connected to the a.c. input as in Fig. 18. The rotor is now an electromagnet excited by alternating current and is said to be *polarized.* The magnetic field produced by the current in the two rotors are, of course, identical both in magnitude and direction.

The receiver rotor is normally free to turn under the influence of any applied magnetic force: such a force is developed by interaction of receiver rotor and stator fields

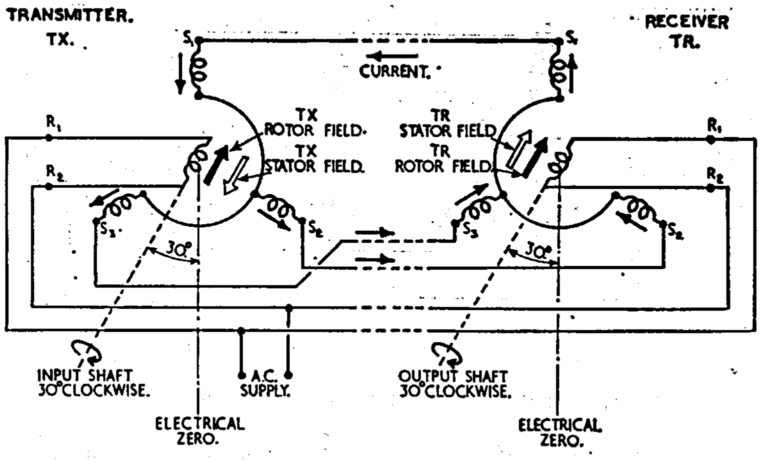


Fig. 18. ALIGNMENT OF OUTPUT AND INPUT SHAFTS

and the receiver rotor turns until the two fields are in alignment. It has already been stated that the receiver stator field coincides with the field of the *transmitter rotor:* hence the receiver rotor synchronously follows any movement of the remote transmitter rotor.

34. **Accuracy and efficiency.** The torque synchro draws negligible current from the supply. This is because the voltage induced in each set of stator windings from their respective rotors are in opposition: thus, when the receiver rotor is correctly aligned with the input shaft, the two sets of voltages balance and negligible stator current is drawn. The only current drawn from the supply under this condition is that required to energise the rotors.

Because the stator currents decrease as the receiver rotor comes into alignment, the torque developed by the receiver rotor also decreases and this produces an inherent inaccuracy in the system: the accuracy is of the order of ± 1°. As the load increases so does the degree of error and also the current drawn from the supply. The torque synchro is, therefore, suitable only for driving relatively light loads such as those used in instrument repeaters.

35. **Magslip.** It is possible to connect several receivers in parallel and drive them from a single transmitter, to give indication in a number of places simultaneously. But in this case, all the units react on each other, so that if one receiver develops a fault all the other receivers give false indications. The interaction can be reduced by using a 'magslip' as the synchro receiver (Fig. 19). The magslip has the normal three-coil stator, but the rotor is a disc of iron having a single tongue projecting under the stator winding. The 'rotor' coil does not in fact rotate, which removes any slip ring friction and the extra friction on the bearings due to the weight of the coil. It is fed from the a.c. supply, and the flux it produces is coupled to the stator by the magnetic slip ring (magslip) between the rotor disc and the rotor polarizing coil. The rotor disc turns until the current in the transmitter and receiver stator coil is zero: the rotor is then in alignment.

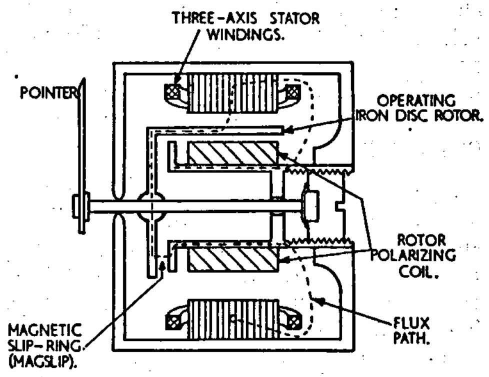
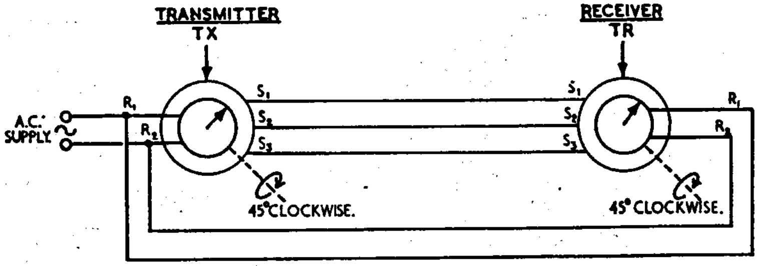
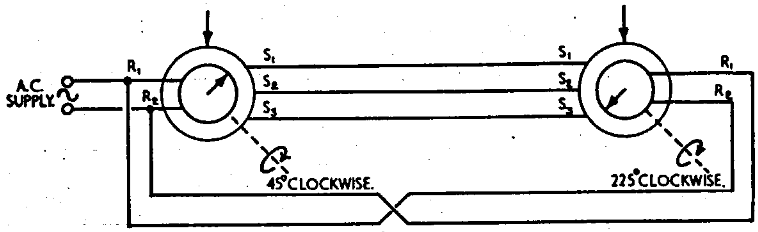


Fig. 19. MAGSLIP

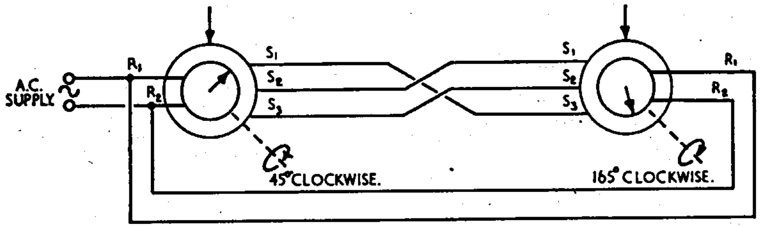
It will be seen that there is a long air-gap in the rotor flux path: consequently, any rotor misalignment has little reaction on the stator flux distribution, and therefore there is little reaction between receivers connected



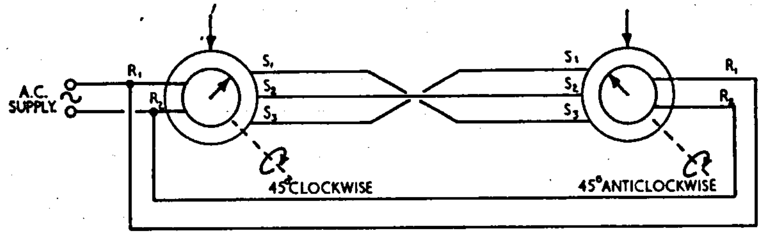
(a) SYMMETRICAL CONNECTIONS–ROTORS MOVE THROUGH SAME ANGLE.



(b) ROTOR CONNECTIONS REVERSED–OUTPUT ROTOR 'LEADS' BY 180°.



(c) 'CYCLIC' SHIFT OF STATOR CONNECTIONS–OUTPUT ROTOR 'LEADS' BY 120°.



(d) TWO STATOR LEADS INTERCHANGED–OUTPUT ROTOR REVERSES DIRECTION OF ROTATION.

Fig. 20. VARIOUS INTERCONNECTIONS IN TORQUE SYNCHRO SYSTEM

in parallel. But the long gap means that the rotor flux is weak and the torque available is very small.

36. **Torque synchro connections.** So far, symmetrical connections only between transmitter and receiver windings have been considered. However, re-arrangement of rotor and stator connections between transmitter and receiver produces different results. The receiver rotor still moves synchronously with the transmitter rotor, but it can do so from a different reference position or in the reverse direction. Fig. 20 illustrates the possibilities.

Torque Differential Synchro Systems

37. **Introduction.** In the torque synchro transmission systems so far considered the 'output' as represented by the angular move-

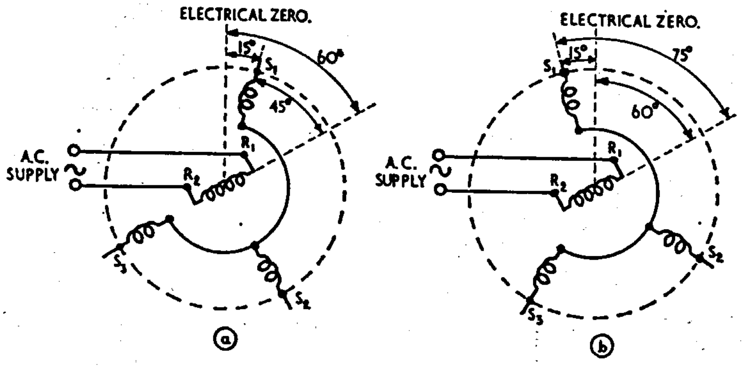


Fig. 21. DIFFERENTIAL ACTION IN TORQUE SYNCHRO SYSTEM

ment of the receiver rotor, is simply a reproduction of a single 'input', i.e., the angular movement of the transmitter rotor.

Under certain conditions, however, it is necessary to transmit *two* angular positions, the synchro receiver indicating the difference or the sum of the two angles.

38. One simple way of achieving this is to rotate the *stator* coils of the synchro transmitter through one angle and the *rotor* through the other angle. This is indicated in Fig. 21. In (a) the rotor is rotated through 60° clockwise from electrical zero and the stator is rotated 15° *in the same direction:* the *relative* angle between rotor and stator is the *difference* between the two angles, namely 45°, and the electrical output of the transmitter is such that the receiver turns 45° clockwise. In (b) the addition of two angles is shown.

Mechanical displacement of both rotor and stator in a synchro transmitter is not generally practicable. It is normally better to insert a torque differential synchro in the transmission chain. This differential synchro can operate either as a transmitter or as a receiver. Since the torque differential transmitter is more common, it will be considered first.

39. **Torque differential transmitter (TDX).** The differential transmitter has a stator identical with that of a synchro transmitter

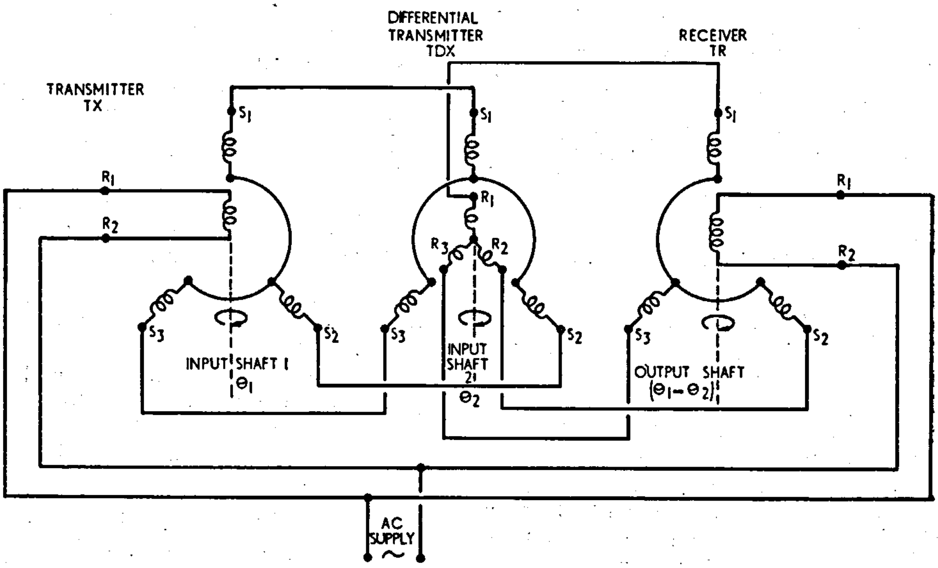


Fig. 22. TORQUE DIFFERENTIAL SYNCHRO SYSTEM

or receiver. It differs from the transmitter or receiver in that it has a *cylindrical,* instead of a two-pole rotor; and the rotor like the stator, has three distributed windings spaced 120° apart.

40. The circuit shown in Fig. 22 is that of a differential synchro system set up for the *subtraction* of two inputs. The arrangement is such that one input shaft turns the transmitter (TX) rotor and a second input shaft drives the differential transmitter (TDX) rotor. The differential transmitter receives an electrical signal corresponding to a certain angular position of the transmitter (TX) rotor: it modifies this signal by an amount corresponding to the angular position of its own rotor: it then transmits the modified electrical output signal to the receiver (TR).

This modified output signal produces an angular position of the flux in the receiver which, for Fig. 22, is the *difference* of the rotor angles of the two transmitters (TX and TDX).

The circuit symbol for a differential synchro transmitter is shown in Fig. 23.

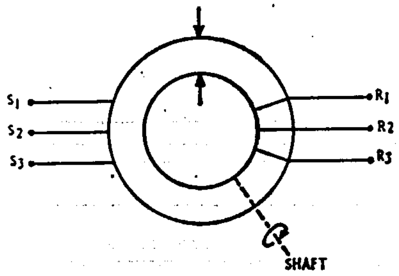


Fig. 23. SYMBOL FOR TORQUE DIFFERENTIAL TRANSMITTER (TDX)

In the differential synchro system, the rotors of the normal transmitter (TX) and receiver (TR) are supplied in parallel with single-phase a.c. The stator windings of the transmitter are connected to the stator windings of the differential transmitter (TDX) and the three windings on the rotor of the latter are connected to the windings of the receiver stator. Note that the rotor of the differential transmitter is *not* connected to the a.c. supply.

41. **Action of TDX.** The action of the torque differential synchro system set up for subtraction is illustrated in Fig. 24.

In (a) both input shafts are at electrical zero and the distribution of current throughout the system is such that the magnetic fields are in the direction shown. Thus the output (TR) rotor also takes up the position of electrical zero.

In (b) shaft 1 is rotated through 60° clockwise and shaft 2 remains at electrical zero. All magnetic fields rotate as shown and the output (TR) rotor also rotates 60° from electrical zero.

In (c) shaft 1 is at electrical zero and shaft 2 is rotated 15° clockwise. The magnetic fields of the transmitter (TX) and the differential transmitter (TDX) remain in the electrical zero position because their position is determined by the orientation of the transmitter (TX) rotor. However a 15° clockwise rotation of the TDX rotor without a change in the position of its field is equivalent to moving the rotor field 15° *anti-clockwise* whilst leaving the rotor at electrical zero. This shift in the position of the TDX rotor field relative to the rotor itself is duplicated in the receiver (TR) stator windings and the output rotor aligns itself with its stator field. Thus the output rotor moves 15° *anti-clockwise* for a 15° *clockwise* movement of the differential (TDX) rotor.

42. It is now easy to see that if both input shafts are rotated simultaneously in a clockwise direction, the receiver rotor turns through an angle equal to the *difference* between the two input angles, i.e., a clockwise movement of the TX rotor gives a clockwise movement of the TR rotor, whereas a clockwise movement of the TDX rotor gives an anti-clockwise movement of the TR rotor. This is illustrated in Fig. 24(d) where the TR rotor turns through (60° − 15°) = 45° clockwise.

43. The differential effect is of course reversed when the differential rotor is moved in the opposite direction to the transmitter rotor. The receiver rotor now moves through an angle equal to the *sum* of the two input angles. However, it is more usual to rotate the input shafts in the same direction and to alter the connections between the various elements to obtain the required output. Various possibilities are illustrated in Fig. 25.

44. **Torque differential receiver (TDR).** A torque differential synchro system can use a

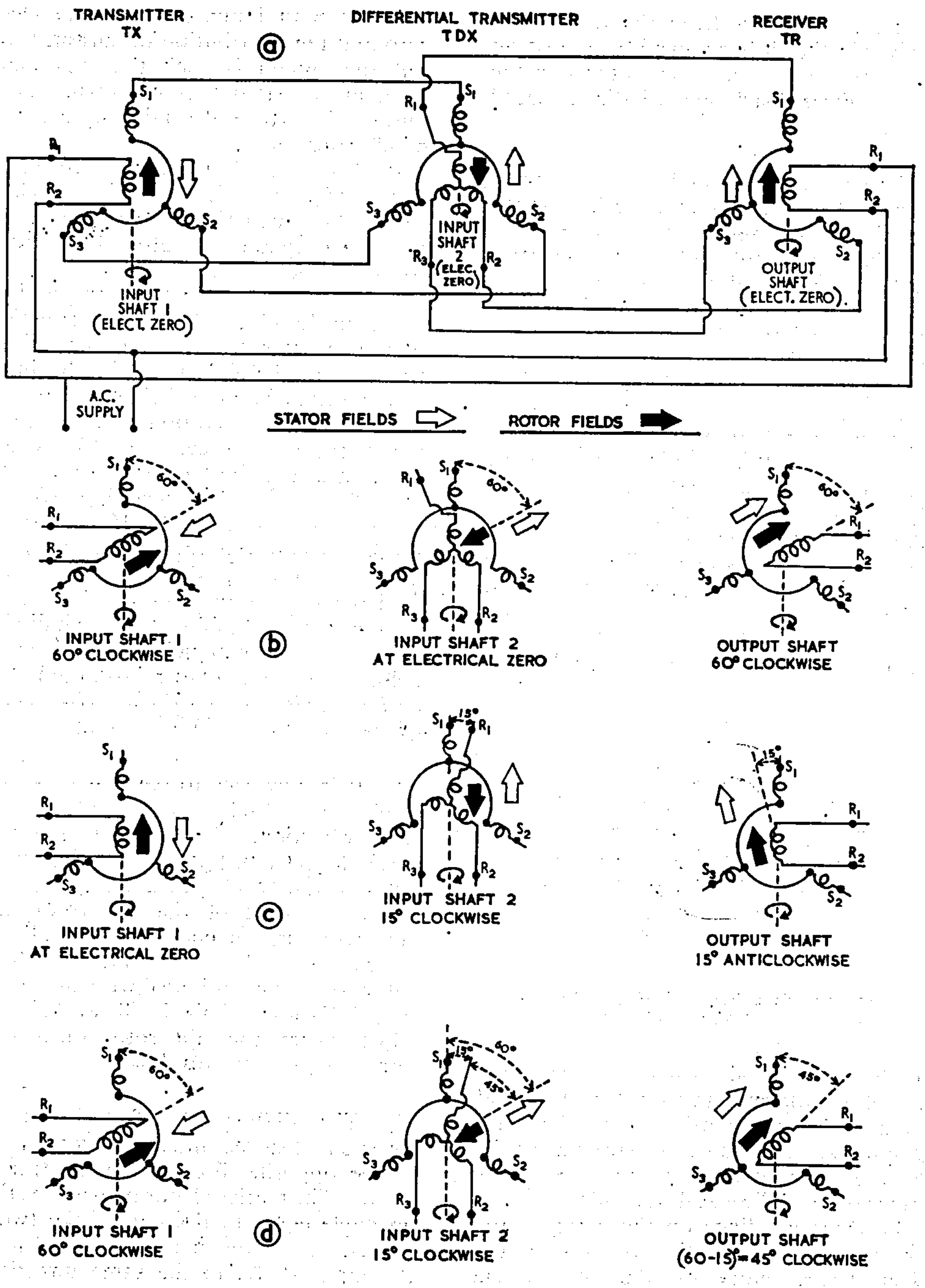
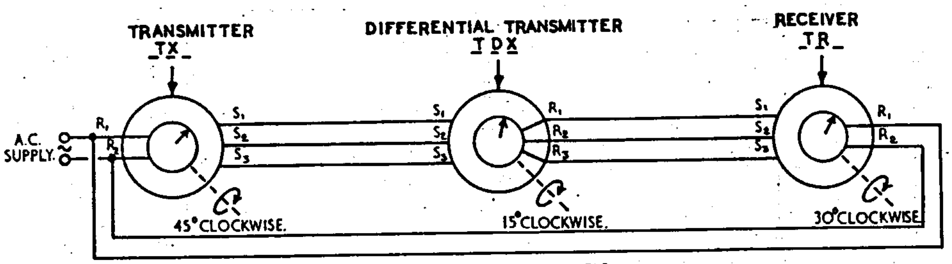


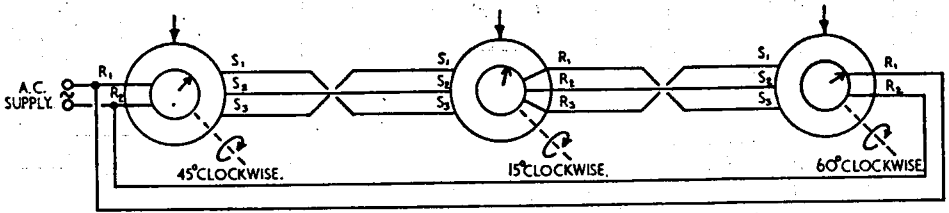
Fig. 24. ACTION OF TORQUE DIFFERENTIAL TRANSMITTER SYSTEM

differential *receiver* in conjunction with two synchro transmitters as shown in Fig. 26.

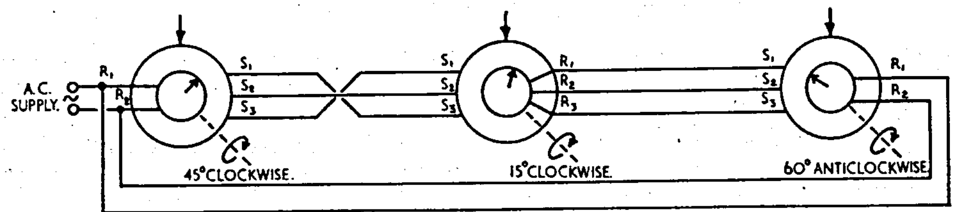
Voltages indicating a 60° clockwise rotation from electrical zero are applied from transmitter A to the stator windings of the differential receiver, and a magnetic field Φ_1 is created along an axis 60° clockwise from electrical zero. The 15° clockwise electrical signal from transmitter B is applied to the rotor windings of the differential receiver and establishes a magnetic field Φ_2 that is 15° clockwise from the rotor electrical



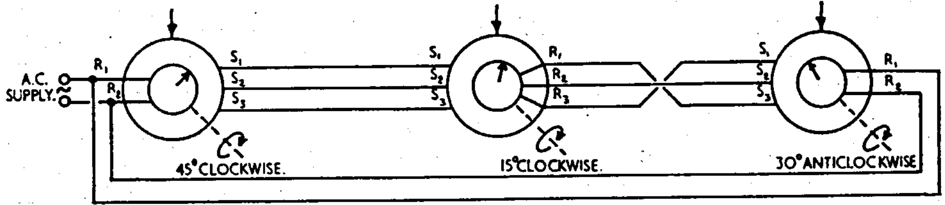
(a) SYMMETRICAL CONNECTIONS: TR. ANGLE = TX. ANGLE. − TDX. ANGLE.



(b) TWO INPUT & OUTPUT LEADS INTERCHANGED: TR. ANGLE. = TX. ANGLE.+ TDX. ANGLE.



(c) TWO INPUT LEADS INTERCHANGED: TR. ANGLE. = −(TX. ANGLE. + TDX. ANGLE.).



(d) TWO OUTPUT LEADS INTERCHANGED: TR. ANGLE. = TDX. ANGLE. − TX. ANGLE.

Fig. 25. VARIOUS INTERCONNECTIONS IN TORQUE DIFFERENTIAL SYSTEM

zero point (R_1 in line with S_1). The differential rotor, if free to turn assumes the position in which Φ_1 and Φ_2 are aligned: this requires a clockwise movement of only 45°. Thus, the output shaft indicates the *difference* (60° clockwise minus 15° clockwise) in the angular displacement of the two input shafts connected to the transmitter rotors.

For the connections shown, the output angle is the angle of transmitter A *minus* the angle of transmitter B. Reversing pairs of connections at the differential receiver can change the relative directions of motion in much the same way as illustrated in Fig. 25 for the differential transmitter.

Control Synchro Systems

45. **Introduction.** In a torque synchro system, the output element exerts a torque which tends to align its rotor with the angle of the input shaft. The action is similar in torque differential synchro systems.

In *control* synchro systems, however, the rotor of the output element does not exert any such torque. Instead, it produces a voltage, sometimes called an *error signal*, which indicates the error of alignment between the input shaft and the output shaft: this has important practical applications in electrical servomechanisms.

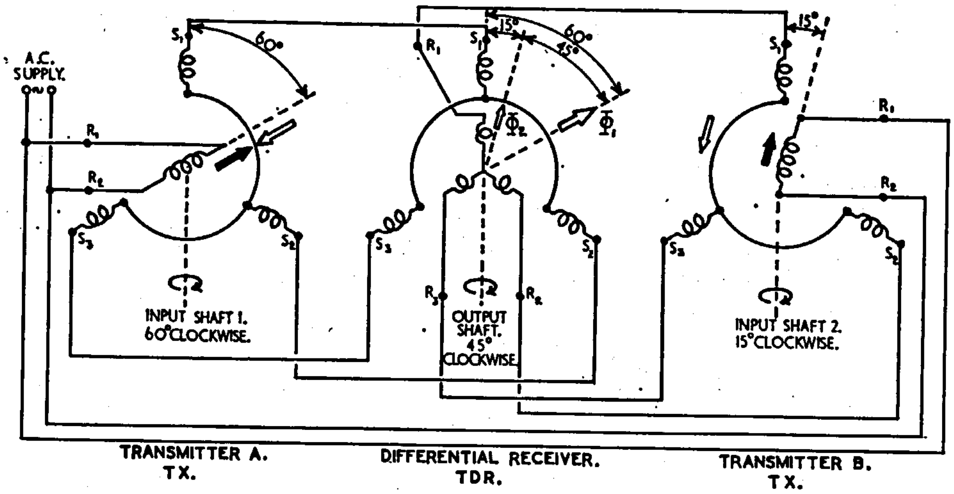


Fig. 26. TORQUE DIFFERENTIAL RECEIVER (TDR) SYSTEM

46. **Circuit.** The basic control synchro system has two elements—a synchro transmitter (TX) and a synchro control transformer (CT) connected as shown in Fig. 27. The transmitter is similar to that used in torque systems: it consists of three stator coils spaced 120° apart, inside which a single-winding, two-pole rotor, energised from the a.c. supply, can be rotated by the input shaft.

The control transformer has a stator similar in design and appearance to that of other synchro units, but with high impedance coils to limit the alternating currents through the windings. The rotor, like that of a normal synchro receiver, carries a single winding which is brought out via slip rings and brushes, to terminals R_1 and R_2. Unlike the receiver rotor, the winding of the control transformer rotor is wound on a *cylindrical* former, thereby ensuring that the rotor is not subjected to any torque when the magnetic field of the transformer stator is displaced. In addition, the rotor of the control transformer is *not energised:* it acts merely as an inductive 'error detector'.

47. **Action.** The control transformer operates as a single-phase transformer having three stationary primary windings and one moveable secondary winding.

When the rotor of the synchro transmitter (TX) is energised, voltages are induced in the transmitter stator windings and applied to the stator windings of the control transformer. The resultant magnetic fields produced when the input shaft is in such a position that the transmitter rotor is at electrical zero are illustrated at (a) of Fig. 28. The alternating stator flux of the control

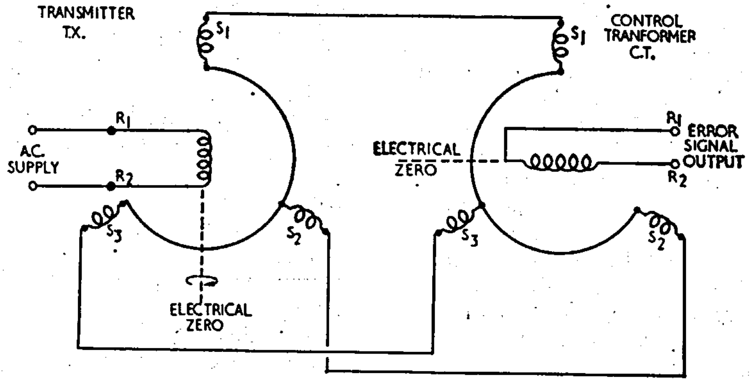


Fig. 27. CONTROL SYNCHRO SYSTEM

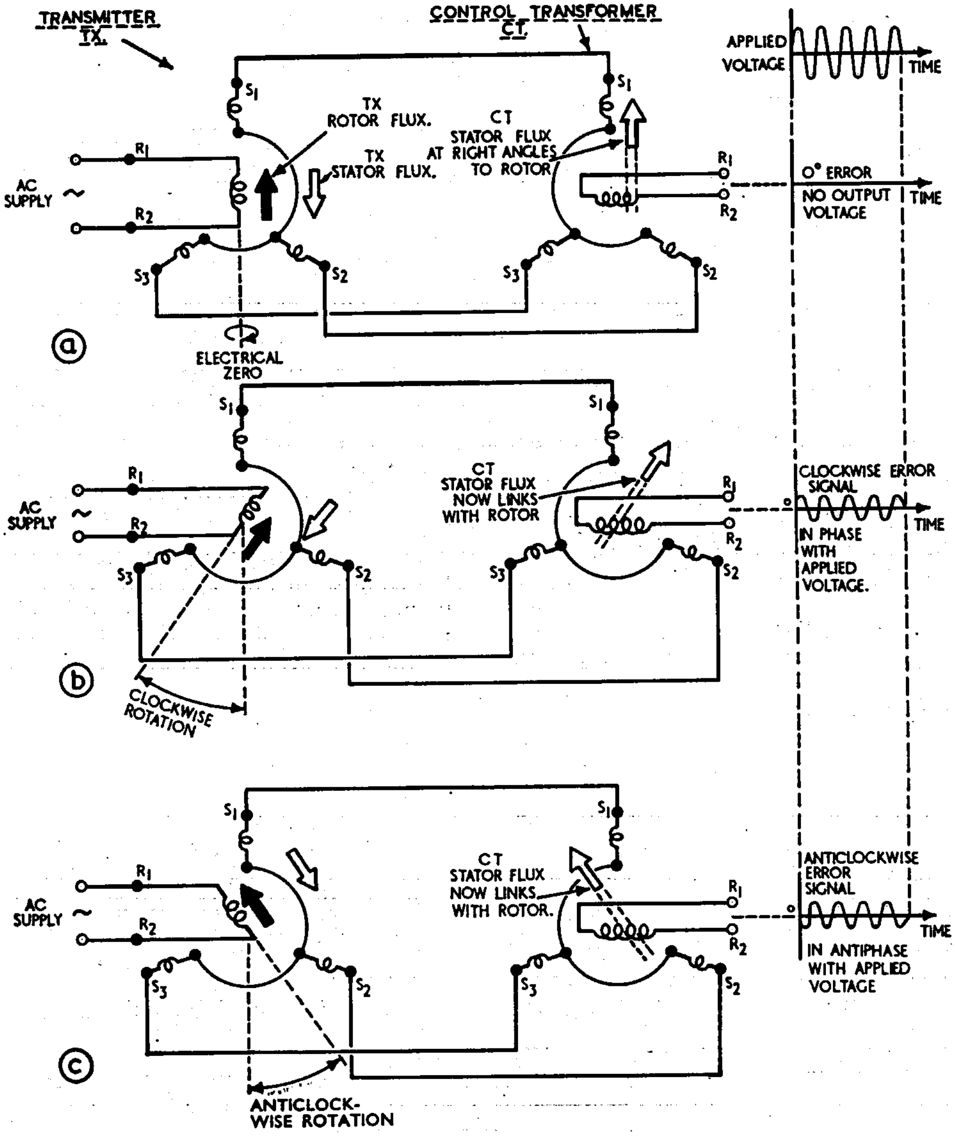
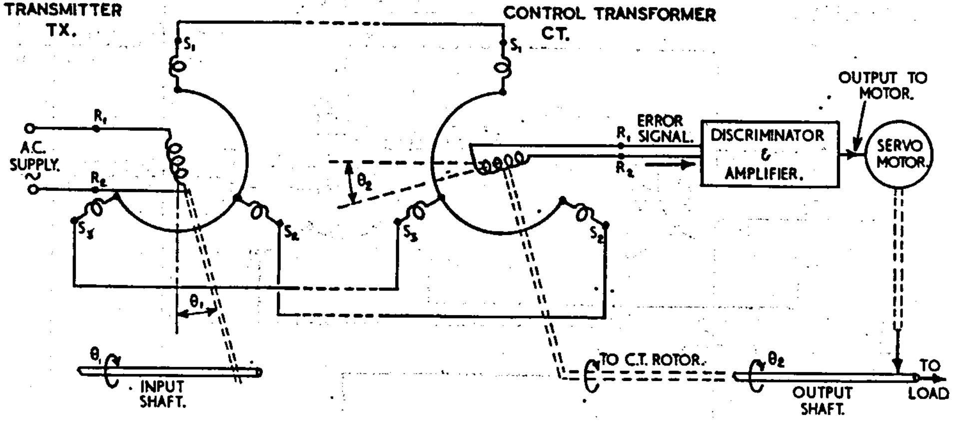


Fig. 28. ACTION OF CONTROL SYNCHRO SYSTEM

transformer induces a voltage in its rotor, the magnitude of which depends upon the position of the rotor relative to the flux: that is, when the rotor axis is at 90° to the flux direction as shown at (a), the induced voltage is zero. Thus note that the electrical zero point of a control transformer is at 90° to the zero points of a synchro transmitter and receiver.

48. If now the input shaft is rotated clockwise from the electrical zero position, the resultant flux in the control transformer stator is displaced from its datum point by the same angle, and the magnitude of the voltage induced in the transformer rotor increases from zero. For the connections shown, the voltage is also *in phase* with the line voltage applied to the transmitter rotor (Fig. 28(b)).

For an anti-clockwise rotation of the input shaft from the electrical zero position, the transformer rotor voltage again increases in magnitude, but this time it is in *anti-phase*



WHEN $\theta_2 = \theta_1$, ERROR VOLTAGE IS ZERO, AND SERVOMECHANISM IS STABLE.

Fig. 29. APPLICATION OF CONTROL SYNCHRO SYSTEM

with the line voltage applied to the transmitter rotor (Fig. 28(c)).

49. **Use.** The error voltage derived from the control transformer rotor varies with the misalignment between the input shaft and the rotor of the transformer (remembering that, in any case, the electrical zero points are displaced from each other by 90°). When the two are 'aligned', there is no error voltage: a misalignment in one sense provides an in-phase error voltage: a misalignment in the other direction produces an anti-phase error voltage: the magnitude of the error voltage in each case depends on the degree of misalignment.

As commonly used in electrical servomechanisms, the synchro control transformer supplies an error signal from its rotor winding to an amplifier that controls a d.c. or a.c. motor. The circuit (Fig. 29) is such, that the speed of the motor is proportional to the magnitude of the error voltage, and the direction of rotation is determined by the phase of the error voltage with respect to the applied a.c.

In normal operation, the servo motor drives the mechanism being controlled (e.g. a radar scanner) and also turns the rotor of the control transformer. The circuit arrangement is such that the transformer rotor is turned into alignment with the input shaft, thereby reducing the error voltage to zero, at which point the servomechanism is stable.

The use of an amplifier and rotor makes the

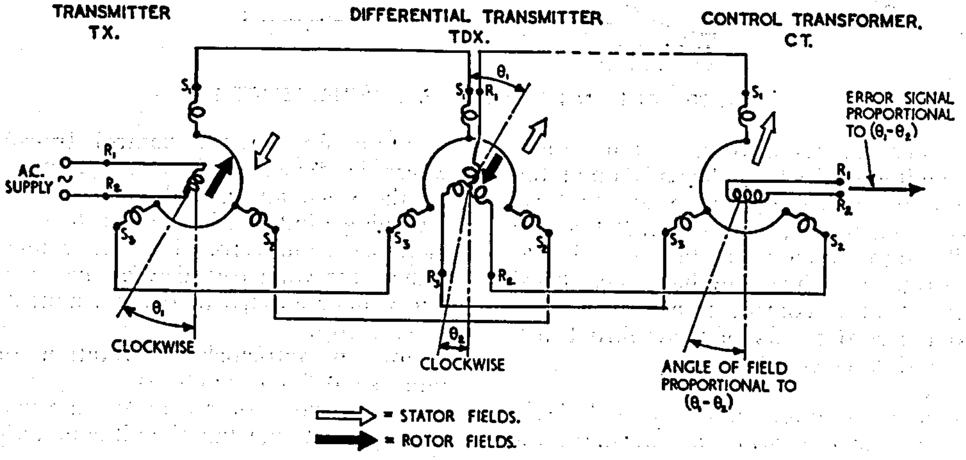


Fig. 30. CONTROL DIFFERENTIAL SYNCHRO SYSTEM

system *torque amplifying* and the output of such a system depends solely upon the power output of the amplifier and servo motor. By means of control synchros, very small units and light controlling forces can operate heavy mechanisms remote from the control point.

50. In the same way that differential synchros can be used in torque transmission systems, so they can be used in control synchro systems to transmit information on the sum or difference of two angles. A simple arrangement is illustrated in Fig. 30.

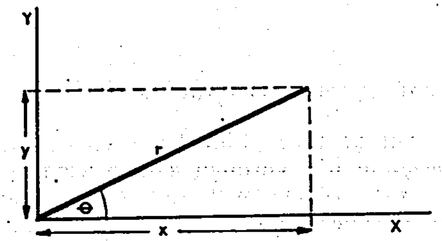


Fig. 31. CO-ORDINATES OF A POINT

Resolver Synchro System

51. **Introduction.** A vector representing an alternating voltage (Fig. 31) can be defined in terms of the *modulus* or length of the vector r, and the *argument* or angle θ it makes to the X axis: these are the polar co-ordinates $r\angle\theta$ of a vector. This same vector can be defined in terms of x and y where $x = r\cos\theta$ and $y = r\sin\theta$: these expressions give the cartesian co-ordinates of the vector.

52. Resolver synchros are employed, generally in analogue computers (see Sect. 20), to convert voltages which represent the cartesian co-ordinates of a point, into a shaft position and a voltage which together represent the polar co-ordinates of that point. They are also used in the reverse manner for conversion from polar to cartesian co-ordinates.

53. **Construction of resolver synchros.** Outwardly, a resolver synchro looks like all the other synchros already dealt with. It has however, four stator and four rotor windings, arranged as shown in Fig. 32. Stator windings S_1 and S_2 are in series and have a common axis which is at right angles to that formed by S_3 and S_4 in series: similarly, rotor windings R_1 and R_2 in series have a common axis which is at right angles to that formed by R_3 and R_4 in series.

54. **Resolution from polar to cartesian co-ordinates.** In Fig. 33 an alternating voltage of magnitude r applied to one of the rotor windings represents the modulus of polar co-ordinate, and the angle θ through which the rotor shaft has turned represents the argument. In this application, only one of the rotor windings is used and the unused winding is normally short-circuited to improve the accuracy, and limit spurious response.

The alternating flux produced by the rotor current links with the stator windings, and voltages are induced in each of the stators. In the position shown in Fig. 33, maximum voltage is induced across that stator coil which is aligned with the rotor in use,

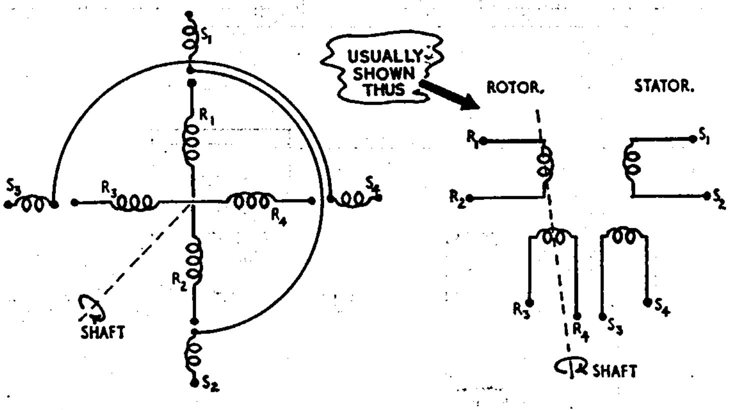


Fig. 32. RESOLVER SYNCHRO

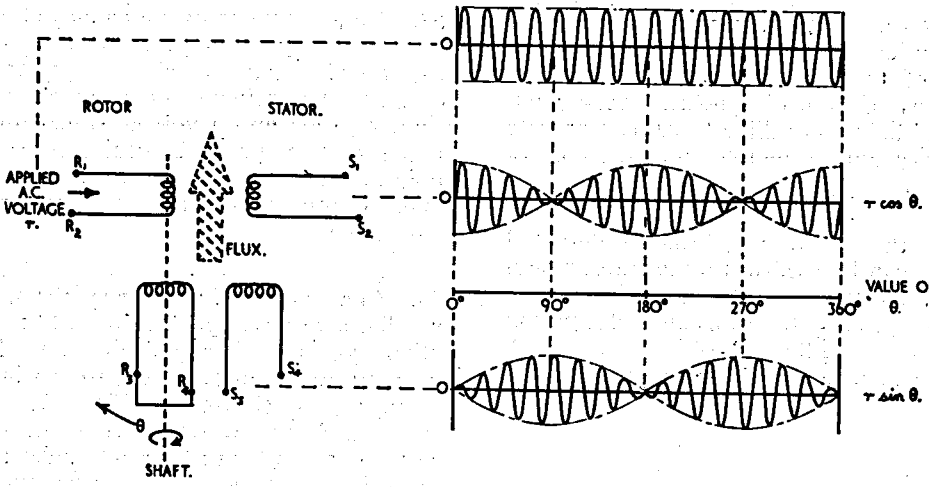


Fig. 33. CONVERSION FROM POLAR TO CARTESIAN CO-ORDINATES

i.e., S_1 S_2 in line with R_1 R_2. No voltage is induced in the other stator coil which is at right angles to the rotor flux. Movement of the rotor at a constant speed will induce voltages across the two stator coils which will vary sinusoidally.

The voltage across that stator coil which is aligned with the rotor at electrical zero will be a maximum at that position and will fall to zero after 90° displacement: this voltage is therefore a measure of the *cosine* of the angle of displacement (cos θ). It is *in phase* with the energising voltage during the first 90° displacement and *in anti-phase* from 90° to 270°, finally rising from zero at 270° to maximum in-phase at 360°. Any angle of displacement can therefore be identified by the amplitude and phase of the induced stator voltages.

Similarly, the stator coil which at datum is at right angles to the energised rotor coil will at that point have zero voltage induced in it. Through a displacement of 90°, this voltage will rise to maximum *in-phase* sinusoidally and is therefore directly proportional to the sine of the displacement angle (sin θ). Again, the phase depends on the angle of displacement and any angle can be identified by the amplitude and phase of the induced stator voltages.

The output from one stator is of the form r cos θ and from the other r sin θ: the sum of these two defines in cartesian co-ordinates the input voltage and shaft rotation $r\angle\theta$.

55. **Resolution from cartesian to polar co-ordinates.** To convert from cartesian to polar co-ordinates a zero-nulling device is required. One arrangement is illustrated in the circuit of Fig. 34. An alternating voltage $V_x = r \cos \theta$ is applied to the cos

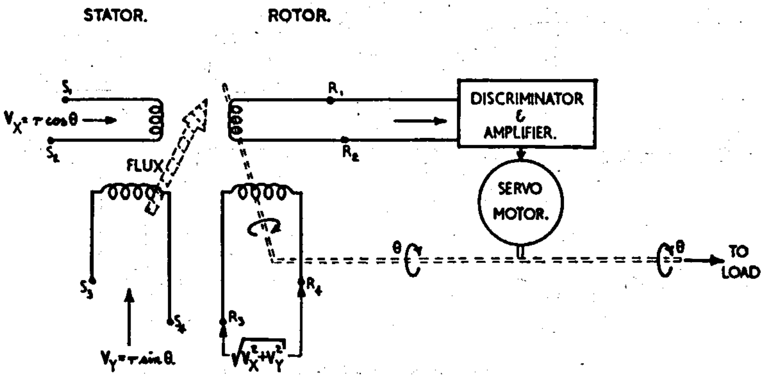


Fig. 34. CONVERSION FROM CARTESIAN TO POLAR CO-ORDINATES

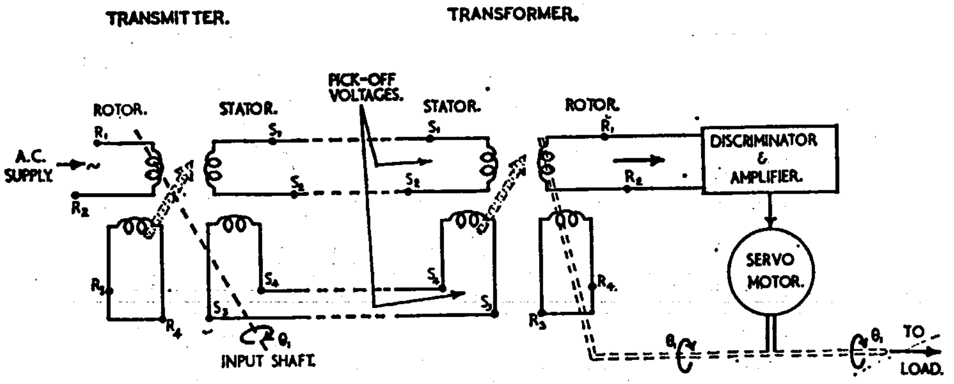


Fig. 35. RESOLVER SYNCHRO AS A REMOTE INDICATOR

stator winding $S_1 S_2$, and $V_y = r \sin \theta$ is applied to the sin stator winding $S_3 S_4$. An alternating flux of amplitude and direction dependent upon these voltages representing the cartesian co-ordinates, is therefore produced inside the stator.

One of the rotor windings $R_1 R_2$ is connected to an amplifier and servo motor which drives the output load and also the rotor in such a direction as to return the rotor to a null position: the motor then stops.

The other rotor winding $R_3 R_4$ has induced in it a voltage proportional to the amplitude of the alternating flux, i.e., proportional to $\sqrt{V_x^2 + V_y^2}$. This voltage represents the modulus r. The shaft position of the rotors represents the argument θ. Thus the input defined in cartesian co-ordinates has been converted to an output in terms of the polar co-ordinates.

56. **Remote indication by resolver synchros.** In some instances it is more convenient to have positional information transmitted in cartesian co-ordinates. The information is then readily available for application to the horizontal and vertical plates of a c.r.t., or for modification by other computer elements. Such instances occur, for example, when transmitting the position of a radar scanner. A typical arrangement is illustrated in Fig. 35. It will be seen that this application is very similar to that of a *control* synchro system with the added advantage that voltages corresponding to the cartesian co-ordinates can be picked off the resolver transformer stator windings.

The voltages induced in the transmitter stator windings from the energised rotor are transmitted via the connecting leads to the stator coils of the transformer, and the resulting magnetic flux of the transformer stator lines up with that of the transmitter rotor. By normal transformer action a voltage is induced in the transformer rotor windings and the output of one of them is fed to an amplifier which, in turn, controls a servo motor. The motor drives the load and at the same time turns the rotor to the null position, i.e., at right angles to the axis of the stator magnetic field. Thus, note that the electrical zero of a resolver transformer, like that of a control transformer, is displaced 90° from that in other synchros. When the rotor is in the null position, the servo motor stops having turned the output shaft through the same angle as the input shaft. Transmission of position has therefore been achieved.

57. **Resolver synchro as a phase-shift device.** A resolver synchro can be used in conjunction with a resistor and a capacitor connected in series across both stator windings, as shown in Fig. 36: this arrangement gives a phase-shifting device. If the rotor is energised, a voltage can be obtained between

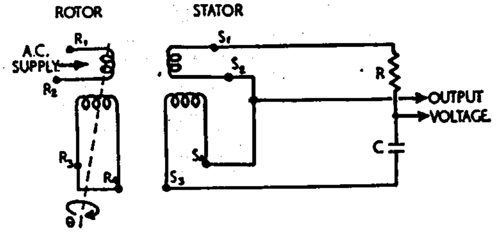


Fig. 36. RESOLVER SYNCHRO AS A PHASE-SHIFT DEVICE

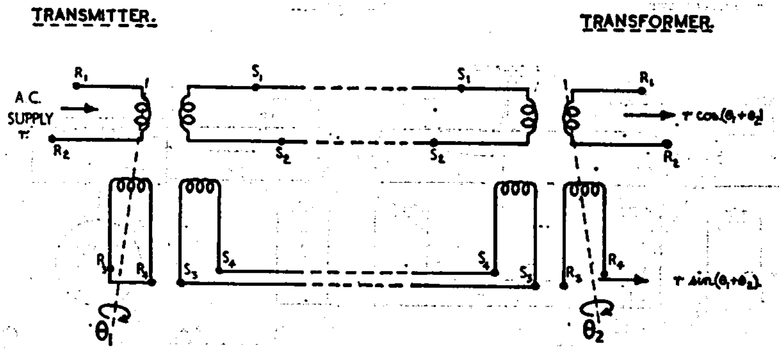


Fig. 37. RESOLVER DIFFERENTIAL SYNCHRO SYSTEM

the common point of both stator windings and a point between the resistor and the capacitor. The phase of this output voltage relative to the input depends on the orientation of the rotor relative to the stator windings: the phase can in fact be varied through 360° by turning the rotor through one complete revolution.

58. **Differential resolution.** It is sometimes necessary to obtain the sine and cosine values of the sum or difference of two inputs. A resolver synchro system arranged to give this is illustrated in Fig. 37.

One input shaft, connected to the transmitter rotors, turns through the angle θ_1: the other input shaft, connected to the transformer rotors, turns *in the same direction* through the angle θ_2. Since the axes of the two rotor windings on the transformer are at right angles to each other, one will give a cos output and the other a sin output. The magnitude and phase of the voltage induced in each output rotor depends on the orientation of each set of rotors relative to their respective set of stator windings, i.e., on the angles through which the input shafts have turned. With the connections shown, the outputs are $r \cos(\theta_1 + \theta_2)$ and $r \sin(\theta_1 + \theta_2)$. A re-arrangement of the connections between transmitter and transformer will give the *difference* of two angles.

59. An alternative arrangement that gives similar results is shown in Fig. 38. In this circuit, a synchro known as a *resolver differential synchro* is used in conjunction with a normal synchro transmitter. In the resolver differential synchro there are two stator windings at right angles to each other, but the rotor is a three space-phased winding. The differential rotor produces a magnetic

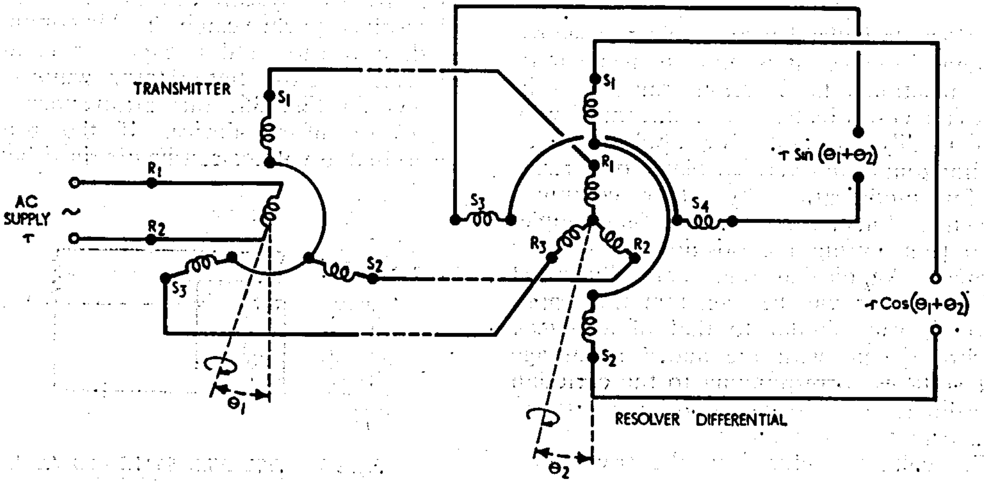


Fig. 38. RESOLVER DIFFERENTIAL SYNCHRO

field in accordance with the electrical signals received from the transmitter.

Due to the normal differential action described earlier, the amplitude and phase of the voltage induced in each stator winding of the differential depends on the relative directions of the stator windings and the rotor flux. The stator windings are arranged with their axes at right angles to give cos and sin outputs, and the position of the rotor flux is determined by the angles of the two input shafts — θ_1 to the transmitter

Systems	Remarks
D.C. SYSTEMS	
Desynn	Provides only sufficient torque to operate small instruments: gives remote indication of dial readings to an accuracy of about ±2°.
M-type	Provides moderate torque, sufficient to drive small mechanisms: accurate to about ±2°. Typical use is to rotate the scanning coils in a c.r.t. in synchronism with a radar aerial.
Wheatstone bridge	An error-operated system, accurate to within ±1°. Does not provide continuous rotation and gives very little torque: can be used as the controlling element in a torque-amplifying system, e.g., remote tuning of radio equipment.
A.C. SYSTEMS	
Torque synchro	Provides only sufficient torque to operate small instruments: efficient and accurate to within ±1°: often used to transmit data such as radar bearings to the place where the information is required.
Torque differential synchro	As for the torque synchro, but provides summation of two input shaft angles: used, for example, to combine a D/F loop reading and a compass reading to give a true bearing.
Control synchro	Gives an electrical output that is dependent on the error in alignment between driving shaft and load shaft. The error signal is normally used as the input to a control system driving a heavy load.
Control differential synchro..	As for control synchro, but provides summation of two input shaft angles.
Resolver synchro	Used in computers to give either cartesian or polar co-ordinates of an input, and for conversation of one to the other: can also be used in a manner similar to that of a control synchro.
Resolver differential synchro	Gives an electrical output in the form of sine and cosine values of the sum or difference of two inputs.

TABLE 2—SUMMARY OF REMOTE INDICATION SYSTEMS

A.L. 18 (*Mar.* 62)

rotor and θ_2 to the differential rotor. Thus, outputs of $r \cos(\theta_1 + \theta_2)$ and $r \sin(\theta_1 + \theta_2)$ or of $r \cos(\theta_1 - \theta_2)$ and $r \sin(\theta_1 - \theta_2)$ are obtained, depending on the connections between the synchros.

Summary

60. This chapter has considered electrical remote indication systems in a general way. It has shown how changes in a physical quantity at one point, as represented by rotation of an input shaft, can be accurately reproduced at a remote point. It has also shown how transmission devices can be incorporated into control systems to give accurate remote control of heavy loads from small units and light operating forces. These control systems will be considered in greater detail in the next chapter (servo-mechanisms). Table 2 lists the devices and systems discussed in this Chapter.

SECTION 19

CHAPTER 2

SERVOMECHANISMS

Paragraph

PART 1, SECTION 19, CHAPTER 2

SERVOMECHANISMS

Introduction

1. The discovery that heat (from coal or oil) can be converted into mechanical energy brought about the industrial revolution, and machines which could use this energy to produce useful results were quickly invented and improved. By controlling such machines, man was able to release large quantities of energy with very little expenditure of energy on his own part.

At first, machines were simple and a human being was quite capable of controlling in detail the various operations that went to complete any process. But as time has passed, machines and processes have become more complicated and results have had to be produced more quickly and more accurately. Thus it has come about that in many cases, man has proved to be an imperfect controller of the machines he has created. It is natural therefore that, wherever possible, the human controller should be replaced by some form of automatic controller.

2. Automatic control systems can include electronic, electro-mechanical, pneumatic, hydraulic and mechanical devices. Such devices are used to perform diverse functions: for example, the automatic piloting of an aircraft, the control of a guided missile, the movement of a radar aerial, keeping a telescope trained on a star, and so on. Nevertheless, regardless of the nature of the quantities handled, the resulting arrangements have a strong family likeness to each other and behave in very similar ways. A common theory is therefore applicable to all forms of automatic control.

The title of this chapter is "Servomechanisms". A servomechanism, in fact, is merely a particular type of automatic control system whose output is the position of a shaft. It is however the most common type of control system in radio engineering, and since the theory which has been developed in its design is now used for all types of control systems, it is convenient to confine the discussion to servomechanisms.

3. A complete treatment of servomechanisms is far beyond the scope of these notes. Only an elementary outline of the basic principles involved and a general idea of the purpose and applications of control systems can be attempted in this chapter. Further information is given in Part 3 of these notes.

4. Chapter 1 has shown that d.c. remote indication and a.c. synchro systems can operate between shafts separated by a considerable distance, but cannot supply torque amplification: the torque delivered to the load can never exceed the input torque. For this reason, and because the error increases when large torques are transmitted, remote indication and synchro systems are employed to turn dials and pointers, to move control valves or to actuate similar low-torque loads.

Automatic control systems, on the other hand, can supply the large torques required to move heavy loads, *and only a very small torque need be applied to the input shaft.* Remote operation is not inherent in servomechanisms but it can be obtained if synchro devices are made part of the system.

5. From any process there is an end-product which can be called the *output*. The production of the output depends on the process, and how the process is affected by the *input*. A control system acts in such a way that the output can be controlled in the optimum manner to give a desired result which bears a definite relationship to the input to the system.

Speed Control of a D.C. Motor

6. Fig. 1 shows an arrangement (known as the "Ward-Leonard" system) that is used for controlling the speed of a d.c. motor driving a load.

The motor armature current is supplied by a d.c. generator which, in turn, is driven at constant speed. The d.c. motor is separately excited, the field current being held constant. The generator is also separately excited, but its field current can be varied by adjusting the controller potentiometer. Any variation in the generator field current varies the generator output

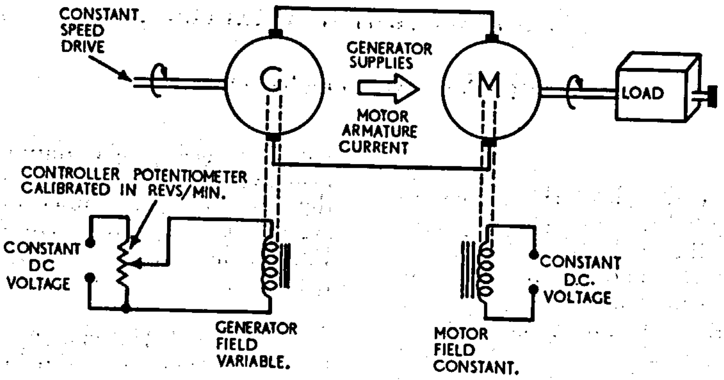


Fig. 1. SIMPLE SPEED CONTROL OF A D.C. MOTOR

voltage and hence the armature current to the motor: thus the *speed* of the motor is varied. If the generator field current is increased, the generated voltage increases, as does the armature current and hence the motor speed. Therefore the controller potentiometer could be calibrated with a scale in revolutions per minute and set for whatever motor speed is required.

With this arrangement, the speed of the output shaft represents the 'output': the 'input' is the setting of the potentiometer. The input can therefore be set to give the desired output which the system should hold constant.

7. In practice, however, speed is not held exactly constant even though ideally the speed of a separately-excited motor is determined by the voltage applied to its armature. Variations in speed arise from a variety of reasons. In particular, variations of *load* conditions will cause varying motor speeds and the output is no longer that demanded by the input.

This system is not good enough if speed control to within a fraction of one per cent is required.

Action of Human Operator

8. It is interesting to discuss at this point the actions that a human operator would take to maintain a constant speed (Fig. 2).

The first action of a human operator is to collect the information or data on which he is to act. He has in mind a picture of the output speed required and at the same time he notes the *actual* output speed. His sole function is to compare the two impressions and so to adjust the system as to reduce the difference, or error, between them: he does this of course by adjusting the controller potentiometer. He is thus, in this connection, primarily an *error-measuring device*, and the amount of error determines how he causes the motor to use energy from the generator to produce the required output speed. Note that the human operator provides a *feedback* link between output and input.

An Improved Method of Speed Control

9. In practice, a more effective and efficient control of output speed can be obtained by replacing the human operator with an automatic control system as shown by the arrange-

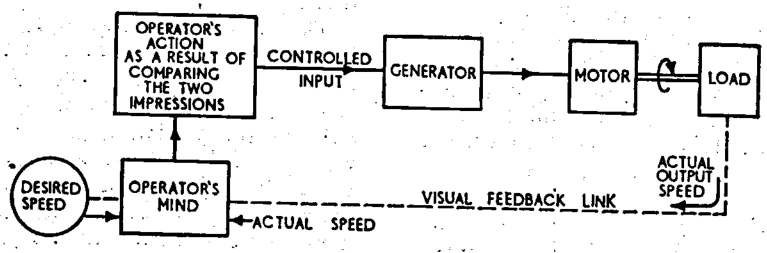


Fig. 2. HOW A HUMAN OPERATOR CONTROLS MOTOR SPEED

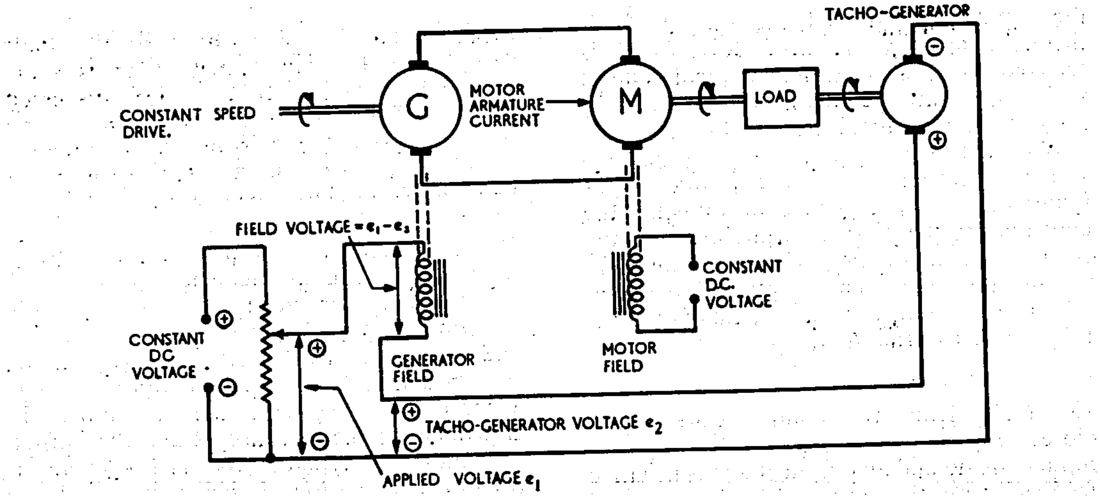


Fig. 3. AN IMPROVED METHOD OF SPEED CONTROL

ment of Fig. 3. The response of the automatic system is better than that of a human operator and the automatic arrangement is not subject to fatigue.

10. **Tachometer-generator.** In Fig. 3, the actual motor speed is measured by connecting a device known as a tachometer-generator or tacho-generator to the output shaft: this produces a voltage proportional to the speed at which it is driven, i.e. the actual output speed. The tacho-generator in the circuit of Fig. 3 is a separately-excited d.c. generator with a constant field and it is so constructed that it produces a generated e.m.f. which is exactly proportional to the rotational speed of its armature. On load, the terminal voltage is still proportional to speed, provided the load current is small enough for armature reaction to have no effect. D.C. tacho-generators usually have quite a small maximum-load current, because the armature is wound with many turns of fine wire, and the commutator has a large number of segments to ensure a relatively smooth d.c. output.

11. The output voltage from the tacho-generator representing the actual speed of the load is compared with the voltage across the controller potentiometer representing the demanded speed: the *difference* between these two voltages causes the flow of generator field current. The connections are such that if the load speed is less than that demanded, the opposition voltage produced by the tacho-generator decreases and the generator field current increases; the generated voltage thus increases as does the motor armature current, and the motor speeds up until it reaches the demanded speed. It follows that if for any reason the load speed tends to change from that demanded, the correct restoring action will automatically be taken.

12. The operations of the circuits shown in Fig. 1 and Fig. 3 differ considerably in detail.

In Fig. 1 the output depends primarily on the input demand, but the accuracy of control is limited because there are no means of controlling other factors that affect the output (such as variation in output load). The accuracy of control therefore depends on the linearity of the system. Such systems are referred to as *open-loop* control systems. An open loop control system is characterized by the lack of error comparison; that is, there is *no feedback* of information from output to input. Because of their limited accuracy, open loop systems are hardly ever used.

In Fig. 3, there is feedback of information from output to input so that the input demand and the output can be compared. The feedback is in opposition to the input and tends to reduce the net input to the system as the output follows the input demand more closely: it is therefore, *negative* feedback. The system is automatically adjusted such as to reduce the error between the input demand and the output: it is therefore an *error-actuated* device and is referred to as a *closed-loop* control system: such systems are the only means of obtaining accurate and predictable control of output.

Both the open-loop and the closed-loop systems discussed above are power amplifying; the energy expended in adjusting the controller to the desired output speed setting is only a small fraction of that expended in turning the load. The amplification comes of course by choosing a motor that is powerful enough to drive the load.

13. Note again the main features of a closed-loop control system: there is an input demand and an output; there is negative feedback from the output which is compared with the input demand; the resulting error is amplified and used to control the power into a servomotor; the servomotor turns the load in such a direction as to reduce the error and ensure that the output follows the input demand.

Position Control Systems

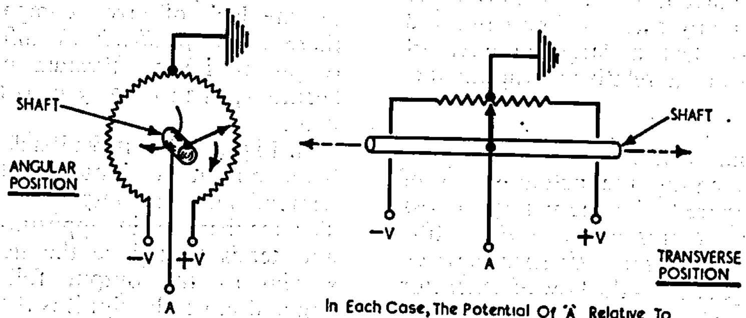
14. For the closed loop speed control system, the quantity fed back and compared with the input demand is a voltage proportional to the *speed* of the output shaft.

A more common type of control system of particular interest in radio engineering is one which controls the angular or transverse *position* of the output shaft. In closed loop position control systems therefore, the quantity to be fed back must be a measure of the output shaft *position*. One of the most convenient ways of providing this feedback is to produce a voltage that is proportional to the position of the shaft at any instant. This can be done by some of the data transmission devices discussed in Chapter 1. However, one of the easiest ways in d.c. systems is to use a potentiometer as shown in Fig. 4. This method will be assumed in subsequent paragraphs.

15. Consider Fig. 5 which shows in block form, the essential elements in a closed loop system for position control. Comparison with Fig. 3 shows that the controller and amplifier are together equivalent to the potentiometer and generator in the Ward-Leonard system: the servomoter is equivalent to the d.c. motor: and the output potentiometer replaces the tacho-generator because here *position* is being measured.

The input is the angular position of the input shaft and the output is the angular position of the output shaft connected to the load. The requirement is that the position of the output shaft should conform with the input demand, i.e., that the output shaft follows precisely the movements of the input shaft.

The input shaft controls a potentiometer that provides a voltage proportional to the angle θ_i of the input shaft. The output shaft similarly controls a potentiometer that provides a voltage proportional to the angle θ_o of the output shaft. The voltage proportional to θ_o is fed back to an error-measuring device where it is compared with the voltage proportional to θ_i. The feedback is such that it is in *opposition* to the input voltage (i.e., negative feedback) and the output from the error-measuring device is an error voltage e proportional to the *difference* between θ_i and θ_o: that is, $e = \theta_i - \theta_o$, and it can be *positive* or *negative*.



In Each Case, The Potential Of 'A' Relative To Earth Gives A Measure Of The Shaft Position.

Fig. 4. PRODUCTION OF VOLTAGE PROPORTIONAL TO SHAFT POSITION

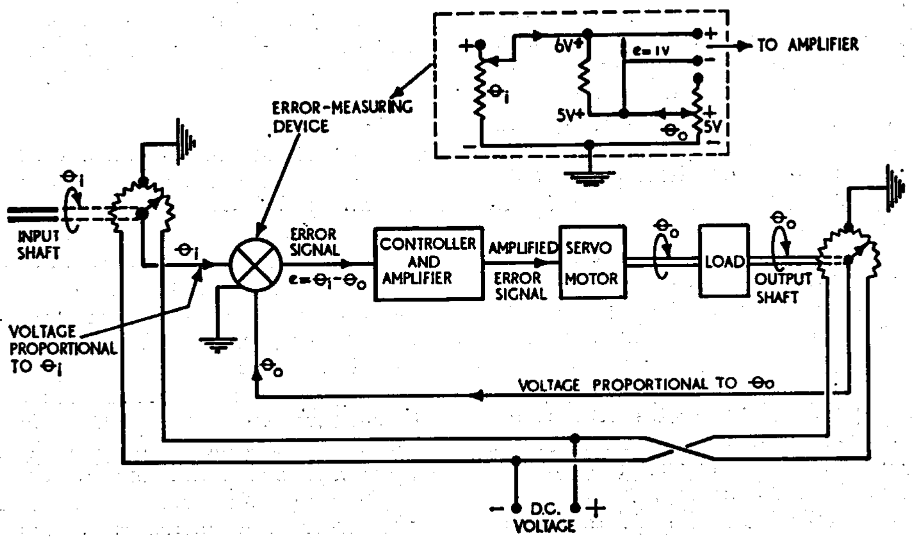


Fig. 5. CLOSED LOOP POSITION CONTROL SYSTEM

16. This error signal is amplified and applied to the motor which then turns the load in a direction depending on the sense of the error signal. The direction of rotation is always such as to tend to reduce the error voltage to zero; that is, to drive the output shaft into alignment with the input shaft. When the voltage proportional to θ_o equals that due to θ_i, the error signal is zero: the motor stops at this point, with input and output shafts aligned.

17. This particular type of closed loop automatic control system defines a true *servomechanism*—an error-actuated, power-amplifying, position control system. For a servomechanism to fulfil its function it must have "follow-up" properties, i.e., the output must be capable of following random variations of input demand over a very wide range. Note again that the final net input voltage is an error voltage, and *not* the simple voltage proportional to the input demand θ_i: this is the first improvement of a servomechanism over an open loop system.

A servomechanism has many applications. It is used, for example to make a searchlight follow its sighting mechanism, to rotate a radar scanner to a desired position, to control aerodynamic surfaces in aircraft and missiles, and so on.

Behaviour of a Simple Servomechanism

18. Consider Fig. 6 which shows in block form the elements in a simple d.c. servomechanism. It is assumed that the output shaft is driving a load, such as a radar scanner, and that it has taken up a position which agrees with the position demanded by the input shaft, i.e., $\theta_o = \theta_i$. The resultant

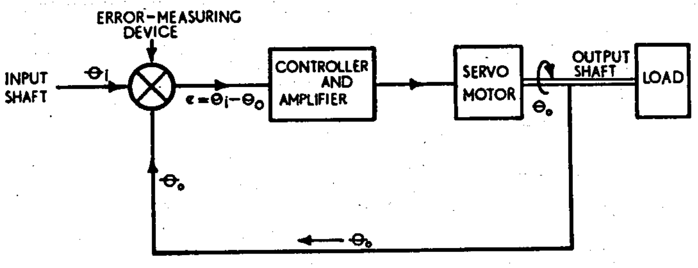


Fig. 6. ELEMENTS IN A SIMPLE D.C. SERVOMECHANISM

error signal ($e = \theta_i - \theta_o$) is zero and the motor is stationary in a steady state condition.

Now suppose that the azimuth bearing of the radar scanner is to be changed from its initial angle to another angle; then the input demand is suddenly changed. The output shaft cannot immediately follow this change in demand because of the inertia of the load. There is therefore now a difference between θ_o and θ_i and the resulting error signal, after amplification, causes the motor to accelerate in an attempt to bring the output shaft to the new demanded position.

As θ_o approaches alignment with θ_i, the error signal and the motor acceleration are progressively reduced until the condition is reached where θ_o again equals θ_i and the error signal is zero: the motor then stops. This is the stable condition of the servomechanism, with the output shaft in the position required by the input demand. It obviously takes time.

19. The period during which the output is changing in response to the change of demand is called the *transient period.* When this period has been completed, the system is said to have reached a *steady state.* The time taken by the system to reach a new steady state after a change of demand (i.e., the time occupied by the transient period) is called the *response time* or the *time lag* of the servomechanism.

Response and Stability of Servomechanisms

20. The change in the value of θ_i if the input demand changes instantaneously from one fixed value to another fixed value in a remote position control system can be represented by a "*step input*" as shown by the graph of Fig. 7(a).

As explained in the preceding paragraphs, initially the system is at rest with $\theta_o = \theta_i$, and at *a* θ_i suddenly changes to a new value: θ_o cannot follow immediately and the error therefore, increases from zero to θ_i (Fig. 7(c)) and a large torque is applied to the load. As the load accelerates and θ_o increases, so the error and torque are reduced until at *b* θ_o reaches the required value and they become zero.

However, unless special precautions are taken, a servomechanism will oscillate readily. Thus, by the time θ_o reaches the required value at *b*, the load has acquired considerable momentum and consequently overshoots. The error now increases in the *opposite* sense and a reverse torque is applied which eventually brings the load to rest at *c*, and then accelerates it back again until once more it passes through the required position at *d*. But again it has acquired kinetic energy in the period *c* to *d* and another overshoot occurs at *d*.

21. This process can continue indefinitely if the frictional losses in the system are negligible, and the system oscillates continuously, being unstable and useless: it is said to "*hunt*".

Where there are frictional losses, a damped train of oscillations results as shown in Fig. 7(b): in this case, the output shaft oscillates several times about its new position before coming to rest.

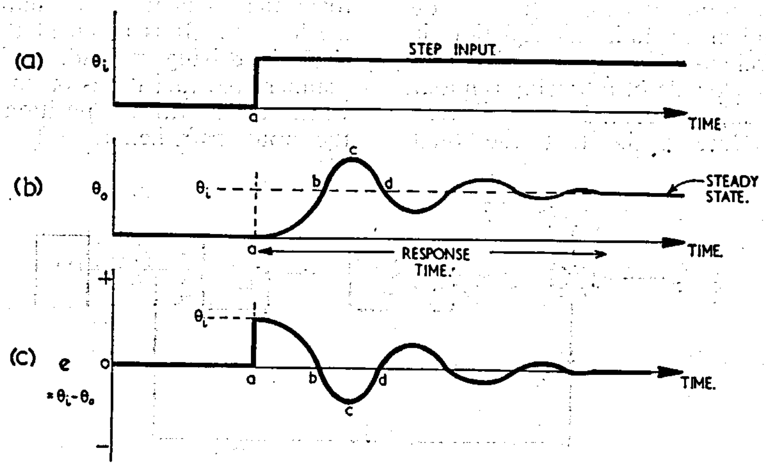


Fig. 7. RESPONSE OF A SERVOMECHANISM TO A STEP INPUT

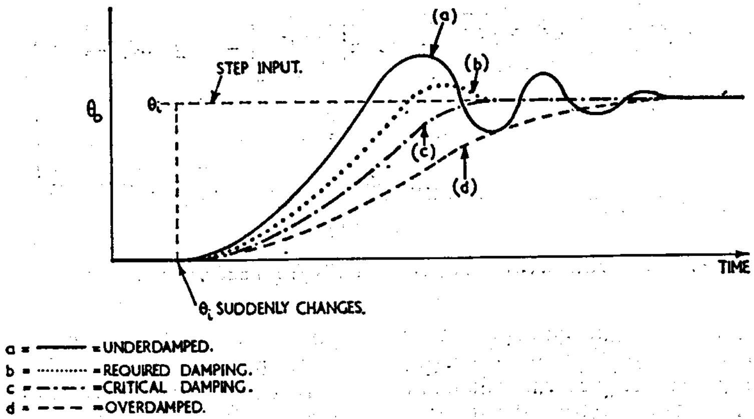


Fig. 8. EFFECT OF DIFFERENT DEGREES OF DAMPING

To avoid oscillations and subsequent hunting, friction or damping is necessary. As will be seen later, the effect of frictional damping can be given by electrical means; hence *damping* is a more general term than friction.

22. Different degrees of damping produce different response curves. Fig. 8 illustrates typical response curves: where there is overshooting and transient oscillation, as in (a), the system is *under-damped:* where there is no overshooting or oscillation, as in (d), the system is *over-damped: critical damping*, as in (c), marks the boundary between a non-oscillatory and an oscillatory response.

The response reaches its final value more quickly if there is under-damping: if there is too much under-damping, however, the response is oscillatory. For these reasons, practical servomechanisms are designed to have *slightly less* than critical damping (about 0·75 times critical damping): this is illustrated in curve (b) which shows only one overshoot.

Viscous Damping

23. The main requirement in a remote position control (*r.p.c.*) system is that the output shaft should follow the input demand precisely and with minimum time lag. It has been shown that for a rapid response time the damping of the system should be slightly less than critical damping. The frictional losses inherent in a servomechanism produce some damping, but usually very much less than that required to ensure a rapid response time and a short settling-down period. It is therefore necessary to introduce additional damping into the system to obtain the required transient performance.

24. One obvious method is to increase the friction in the system by inserting some form of *brake* on the output shaft, as indicated in Fig. 9. This can be achieved either by putting a mechanical friction plate device on the motor shaft or by causing a copper disc, mounted on the output shaft, to rotate between the poles of a horseshoe permanent magnet (eddy current damping).

With a suitable amount of such damping the required response can be obtained; it is necessary, however, that the amount of damping be accurately adjustable.

25. Viscous friction damping, as this method is called, is not a good method and is used

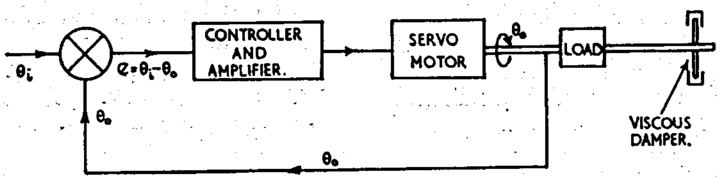


Fig. 9. VISCOUS DAMPING

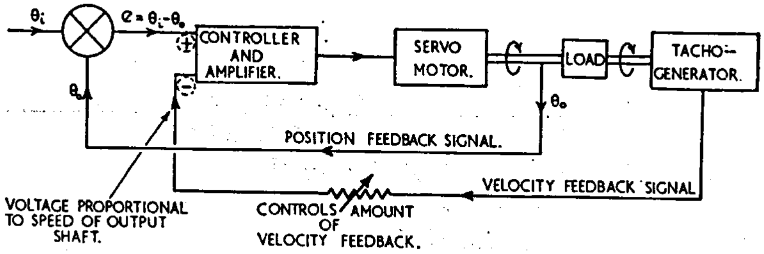


Fig. 10. ARRANGEMENT FOR VELOCITY FEEDBACK DAMPING

only on very *small* servomechanisms. One obvious disadvantage is that it dissipates energy and therefore reduces the efficiency of the control system. Also, the energy absorbed by the viscous damper is dissipated in the form of heat, and in large servomechanisms elaborate and expensive cooling arrangements would have to be provided to get rid of the heat from the brake.

In fact any form of damping on the output side of the control system has serious disadvantages because of the much higher power levels at this end of the system. Because of this it is usual to insert the required damping on the input side of the servomechanism. In this case, the damping must be *electrical* in nature and takes the form of a modification to the error signal.

Velocity Feedback Damping

26. Since a r.p.c. servomechanism is self correcting, it tends to remain quite stable when the input shaft is stationary. Thus, damping is required only during the *transient* period which follows a change in input demand. As previously explained, the instability is produced by the load's acquired momentum, resulting in an overshoot.

27. It is interesting to see how a human controller, faced with the same task of causing a motor to move a load from one position to another, is able to do so without causing instability or wasting energy. On receipt of his instructions, corresponding to a step input of position, the human controller will cause the driving motor to apply a torque accelerating the load. As the load gathers speed and approaches the required position, the controller anticipates that it will overshoot and therefore *reverses* the torque.

Under this condition, the load is driving against the motor and no energy is being dissipated in the load: there is therefore no power loss such as is obtained with viscous damping.

If the controller is skilful, the result is that the load comes to rest just as it reaches the required position: overshooting with resultant instability is therefore prevented.

28. In the case of the servomechanism, this behaviour is imitated by attaching a tacho-generator to the output shaft as in Fig. 10.

The tacho-generator produces a voltage proportional to the angular velocity of the output shaft, and a suitable fraction of this voltage is fed back to the input of the amplifier in *opposition* to the error signal (negative feedback); this is known as *velocity feedback*.

29. It has been shown earlier that the error signal $e = (\theta_i - \theta_o)$, where θ_i is a voltage proportional to the input demand and θ_o is a voltage proportional to the output shaft position.

With velocity feedback, a voltage proportional to the *speed* of the output shaft is fed back to the input of the amplifier in opposition to the error signal. Thus, the *net input* to the amplifier is a voltage proportional to the error *minus* a voltage proportional to the speed of the output shaft.

The aim with velocity feedback is to reduce the net input to the amplifier to zero and then to reverse it *before* the output shaft reaches its final position: if the amount of feedback is correctly adjusted the result is that the momentum of the load, acting against the reversed torque, causes the load to come to rest just as it reaches the required position: this obviously reduces the risk of overshooting and subsequent instability.

30. This action is illustrated in Fig. 11. Initially, the error signal predominates and the load is accelerated. As the load velocity

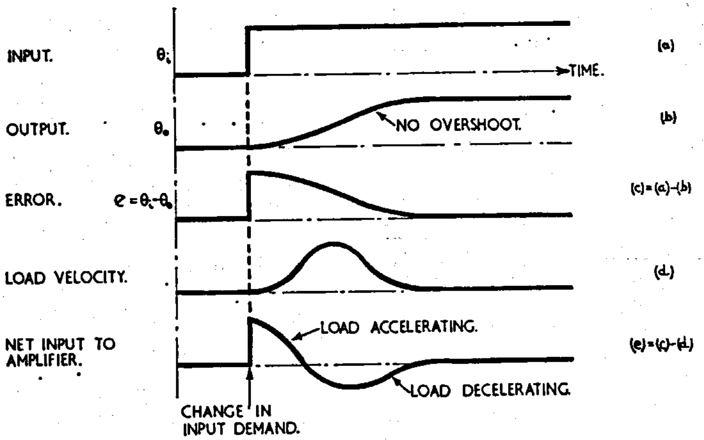


Fig. 11. PRINCIPLE OF VELOCITY FEEDBACK DAMPING

rises and the error falls (i.e., input and output shafts coming into alignment), the net input to the amplifier drops rapidly and then increases in the *opposite* sense, so that a decelerating torque is applied to the load before it reaches the required position.

31. In addition to the advantage over a physical damping system of not causing a waste of energy, the velocity feedback method of damping possesses the important practical advantage that the amount of voltage fed back, and hence the degree of damping, can be simply controlled by inserting a potentiometer in the velocity feedback path. This is a method of damping frequently used in r.p.c. systems.

Velocity Lag

32. Velocity feedback provides a satisfactory means of obtaining the required response in r.p.c. systems because in the steady state such systems are quite stable. However, where the servomotor is required to rotate a load with a constant angular *velocity*, the disadvantage of velocity feedback becomes apparent.

Suppose the servomechanism load is a radar aerial that is required to rotate with a constant velocity. In such a system, a *ramp function input* is used as a means of investigating the servomechanism behaviour, in the same way that a step input is appropriate in r.p.c. systems.

A ramp input is illustrated in Fig. 12(a): it corresponds to the input shaft suddenly being rotated with a constant angular velocity, i.e., θ_i increasing linearly with time.

33. For a servomechanism of this type, with velocity feedback, the transient period is as already discussed. However the final result, after the initial transients have died out, is that the output shaft rotates *at the same speed* as the input shaft but lags behind it by some constant angle (see Fig. 12(b)).

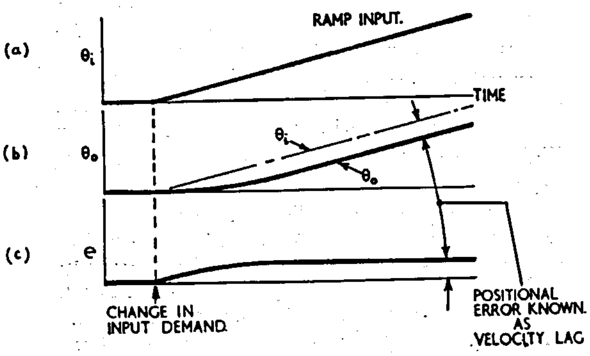


Fig. 12. RESPONSE OF A SERVOMECHANISM TO A RAMP INPUT

The resultant instantaneous *positional* error between input and output shafts is known as "*velocity error*" or "*velocity lag*". Its effect can be quite serious; it can result, for instance, in wrong radar bearings of a target.

34. In a velocity feedback system, velocity lag arises in the following way. Since the output shaft is rotating, the tacho-generator is producing a velocity feedback voltage

input to the amplifier. On the other hand, since the load is being rotated with a constant velocity, it is neither being accelerated nor decelerated, so *no torque* is required from the motor; that is, the *net input* to the amplifier must be zero (neglecting friction at bearings and wind resistance).

It has been shown that the net input, with velocity feedback, is a voltage proportional to the error *minus* a voltage proportional to the speed of the output shaft. Thus, if the net input is to be zero, and a voltage proportional to output speed is being fed back from the tacho-generator in opposition to the input, *there must be a balancing error signal.* There is, therefore, always an error signal in this system (and consequently an error) to compensate for the velocity feedback signal. The error signal, if it is to cancel that due to velocity feedback, must be proportional to the speed of the output shaft, and so velocity lag is proportional to output velocity.

Error-rate Damping

35. It has been shown that viscous damping improves the *transient* response of servomechanisms, but because of power losses it is used only on small servo systems. Velocity feedback similarly improves the transient response without introducing power losses and is, therefore, generally preferable in all but very small servo systems.

In r.p.c. systems, either of these two forms of damping can produce the required result, because it is only the *transient* performance that is important: the steady state error is zero in any case.

However, in angular velocity control systems, although velocity feedback improves the transient performance, it also unfortunately gives rise to a steady state error known as velocity lag. Steps must therefore be taken to reduce this error in servomechanisms required to rotate a load at constant speed.

36. Velocity lag is proportional to the speed of the output (and input) shaft. Therefore, if some other signal proportional to speed can be used to offset the velocity feedback, the error can be made zero. This could be done with the arrangement shown in Fig. 13.

One tacho-generator is mounted on the *output* shaft and produces a voltage proportional to the speed of this shaft. A second tacho-generator mounted on the *input* shaft produces a voltage proportional to input speed. There are therefore *three* input signals to the amplifier, and for the connections shown, the combined input is a voltage proportional to error *plus* a voltage proportional to input speed *minus* a voltage proportional to output speed.

In the steady state, the input and output shafts in a velocity feedback system rotate at the same speed, and in this condition the velocity lag is caused by the constant signal produced by the output tacho-generator. In the system of Fig. 13, this signal is exactly cancelled in the steady state, by the signal from the input tacho-generator. Therefore since the *net input* to the amplifier is required to be zero, the error signal (e) itself can be zero; that is, the system will have zero velocity lag.

37. The system outlined in para. 36 is not, in fact, a practicable proposition because of the difficulty of ensuring that the outputs from the two tacho-generators remain constant with time. Fortunately, a simplification is possible in which both tacho-generators can be dispensed with.

For velocity damping of *step position* inputs, a feedback voltage proportional to

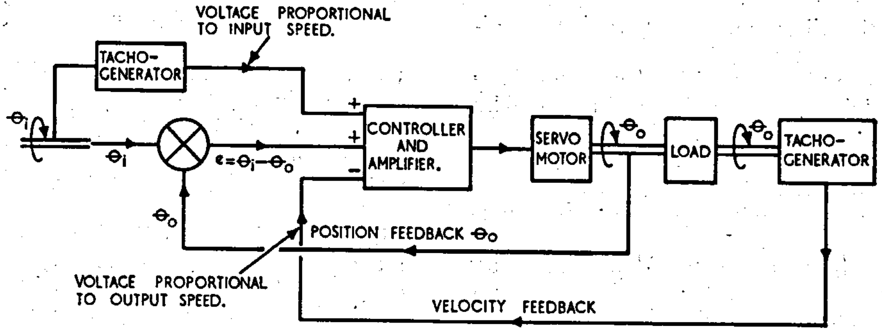


Fig. 13. METHOD FOR REDUCING VELOCITY LAG

the speed of the output shaft is required. This, however, introduces velocity lag in servomechanisms required to rotate a load at constant speed, and to avoid or reduce this form of error, a voltage proportional to the speed of the input *minus* the speed of the output is required; that is, a voltage proportional to speed of (input—output) or proportional to speed of (error signal).

In the same way as the velocity of the output shaft equals the rate of change of θ_o with time, so velocity of error equals rate of change of *error* with time. This is obtained by *differentiating* the error with respect to time.

Thus by differentiating the error signal and combining the derivative with the actual error at the input to the amplifier, the *net input* to the amplifier is a voltage proportional to the error *plus* a voltage proportional to speed of (input—output). This is the same form as that given in para. 36. The result will therefore be the same, so that in the steady state the system has zero velocity lag.

38. An arrangement for providing this is illustrated in Fig. 14. This method of stabilization is called "derivative of error compensation" or *error-rate damping*.

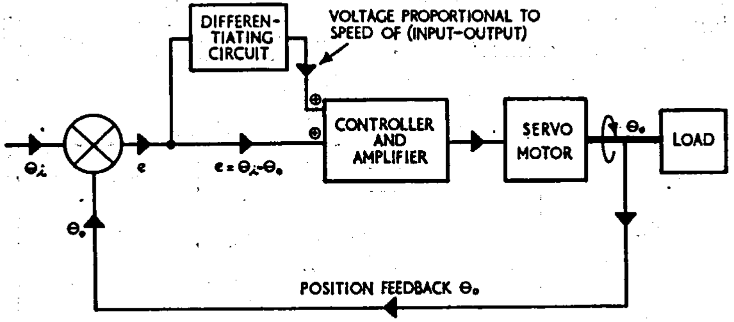
Use of Stabilizing Networks

39. Stabilization of a servomechanism to obtain a good *transient* response in a r.p.c. system and a good *steady state* response in a velocity system can also be obtained by inserting a suitable network in the input to the servo amplifier. A typical circuit, known as a *phase-advance* network, is illustrated in Fig. 15.

For a *position control* system, if the servomechanism is subjected to a step position input, the error jumps immediately to its maximum value, because the output shaft momentarily will not move. Initially, therefore, since the capacitor cannot charge instantaneously, the full error voltage is developed across R_2 and applied to the amplifier, and the motor accelerates rapidly. As the capacitor charges, the voltage across it rises and the input to the amplifier *falls;* the motor torque, therefore, also drops. The effect of the network is initially to cause the load to accelerate quickly. The resistor R_1 is inserted to allow C to discharge on a pre-arranged time constant.

40. As the load approaches the required position, the error voltage falls. However, if the values of the components have been correctly chosen, the charge acquired by the capacitor during the initial period now causes the voltage across it to exceed the error voltage. Thus the voltage applied to the amplifier is now *negative* even though the error voltage is still slightly positive. In other words, a retarding torque is applied to the load *before* it reaches the required position: overshooting is prevented and stability during the transient period consequently improved.

41. For a *ramp* input, this system has almost zero error in the steady state: that is, velocity lag has been virtually eliminated. In the steady state, zero torque is required (no acceleration or deceleration) and for this condition to be satisfied, the input to the amplifier must also be zero. The net.



NET INPUT TO AMPLIFIER IS A VOLTAGE PROPORTIONAL TO ERROR PLUS A VOLTAGE PROPORTIONAL TO SPEED OF (INPUT-OUTPUT)

Fig. 14. ERROR-RATE DAMPING ARRANGEMENT

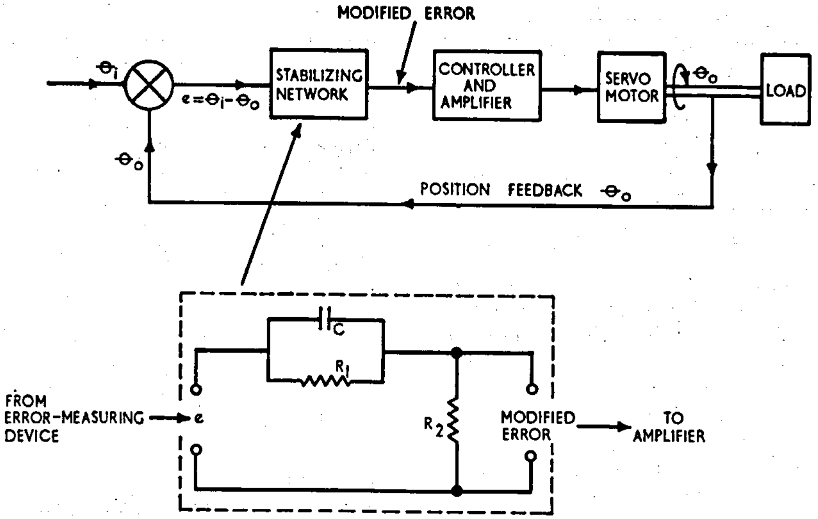


Fig. 15. USE OF STABILIZING NETWORK TO REDUCE VELOCITY LAG

work however will only supply zero voltage to the amplifier if the input to the network is zero, i.e., if the error is zero.

Transient Velocity Damping

42. In an angular velocity control system, velocity feedback is used to improve the transient response: the only effect it has once the steady state is reached, is to introduce velocity lag. During a state of steady rotation, the velocity feedback signal, which is the cause of velocity lag, is itself constant and therefore provides no damping. It is only during the transient period that the velocity feedback signal is changing and therefore providing damping.

If it were possible to use only the *changing* part of the velocity feedback signal during the transient period and not the *constant* part during steady rotation, velocity lag would be reduced. If this could be arranged, there would be no velocity feedback signal at the amplifier input under conditions of steady rotation and no error signal would be required to offset it, i.e., the velocity lag would be zero (neglecting inherent friction).

43. A simple method of achieving this is shown in Fig. 16. A voltage proportional to the speed of the output shaft is produced by the tacho-generator and this is applied to a CR network: that part of the velocity feedback signal appearing across R is applied to the amplifier input in *opposition* to the error signal.

The time constant of the CR circuit is such that only *variations* of voltage applied across the combination are developed across R and applied to the amplifier. If the velocity feedback signal is constant (as it will be during steady rotation) then the voltage across R falls to zero with a time constant

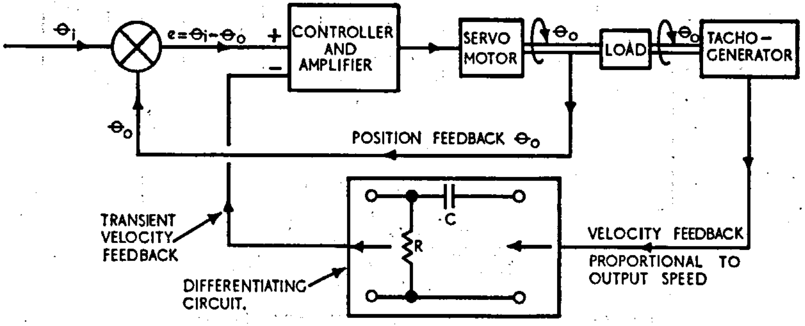


Fig. 16. TRANSIENT VELOCITY FEEDBACK

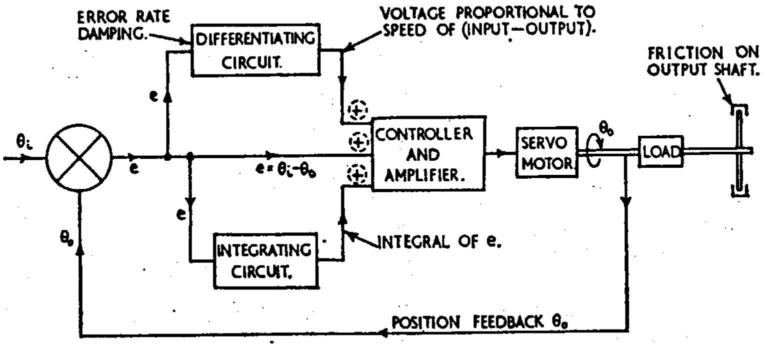


Fig. 17. INTEGRAL OF ERROR COMPENSATION

of CR and the capacitor charges to this voltage. In other words, the tacho-generator output is *differentiated* by CR so that velocity feedback damping is effective only during the time that the output velocity is changing, i.e., during the transient period. This is the requirement.

This method of stabilization is known as *transient velocity feedback damping:* an alternative name is *acceleration feedback damping*, because the damping is effective only when the load velocity is changing.

Integral of Error Compensation

44. It has been assumed so far that the inherent damping and frictional losses in a servomechanism are so small that they can be neglected. Because of this, it was stated that in the steady state with a ramp input, no acceleration or deceleration was required and the input to the amplifier under such conditions was required to be zero.

However, in practice, there will always be a small amount of damping due to bearing and commutator friction; also in large aerials driven by a servomechanism wind friction will introduce damping: the damping is quite insufficient to produce a stabilized performance and for this reason additional damping, of one of the forms described in the preceding paragraphs, has to be provided.

Nevertheless, the fact that there is inherent damping in these systems means that some torque is required on the output shaft even in the steady state for a ramp input, and a finite error will exist.

45. One method of reducing the steady state error in a velocity control system is illustrated in Fig. 17.

It is assumed that some inherent damping is present on the output shaft but that it is insufficient to provide a correctly damped response: error-rate damping is, therefore, provided as well. To reduce the velocity lag that results from the inherent frictional damping, the amplifier is also supplied with the *integral* of the error.

46. Neglecting the operation of the integrator for the moment, it has been shown earlier that in the steady state for a ramp input, there is a steady error known as velocity lag due to the friction on the output shaft. This is illustrated in Fig. 18.

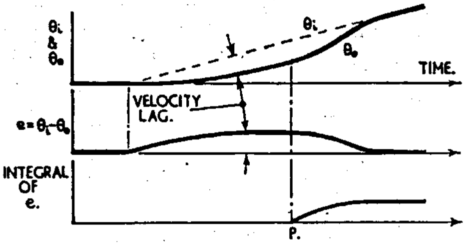


Fig. 18. PRINCIPLE OF INTEGRAL OF ERROR COMPENSATION METHOD

Suppose now that the error signal is applied to the integrator and that this circuit becomes effective at point P in Fig. 18. The operation of the integrator is such that its output increases continuously in the presence of an error. Thus the total input to the amplifier starts to increase and the output torque consequently becomes greater than that absorbed by friction in the system: the excess torque accelerates the load and the output shaft starts to catch up on the input shaft. As it does so, the error is reduced and the integrator output increases more slowly with time.

Nevertheless, as long as there is a finite error, the integrator output continues to increase with time. Thus equilibrium is established and a steady state attained only when the error signal has fallen to zero, at which point the integrator output remains constant at the required level.

47. This method of stabilization obviously has tremendous advantages, but unless the integrating circuit is carefully designed, over-correction can result and the error-rate damping provided may be insufficient to prevent oscillation. Under-correction is just as bad, because the effect then is that the output shaft catches up on the input shaft only very slowly. Design is therefore very critical.

The integrator circuit commonly takes the form of a series CR network connected in a phase-lag circuit, the output being derived from the voltage across C. The time constant is very important.

Summary of Stabilization Methods

48. The effects of the various methods used for obtaining stability in servomechanisms are illustrated in Fig. 19. The approximate response to step input and ramp input functions are shown and appropriate remarks are included.

Power Requirements of a Servomechanism

49. In the preceding paragraphs a broad outline of the basic principles involved in the operation of servomechanisms and of the steps taken to improve stability have been considered. To complete the picture it is necessary to have another look at the essential elements of a servomechanism so that some idea of the range of applications can be obtained.

50. It has already been stated that in a servomechanism much greater power is associated with the output than is available from the source of the input signal: in this sense therefore a servomechanism can be looked upon as a power amplifier.

The power requirements may be small or may be very great, depending on the job the servomechanism has to do. In what may be termed 'instrument servos', the drive power required is only a few watts. In other systems that are required to control the movement of large radar scanners, the output power required may be of the order of kilowatts.

51. Some idea of this range of application is given in the illustration of Fig. 20. In (a) the servomechanism is required to rotate the large radar scanner: the size of the load is such that the power output required is of the order of 100 kilowatts.

In (b) on the other hand, the equipment shown is carried in an aircraft and is used

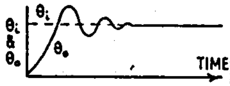
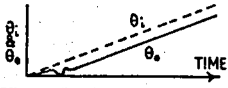
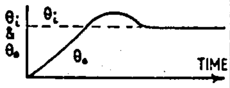
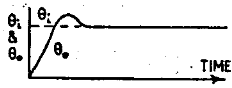
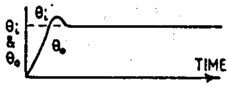
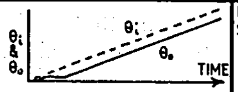
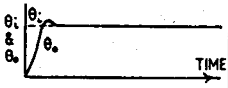
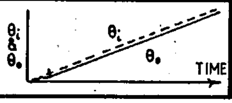
METHOD OF DAMPING.	RESPONSE TO STEP INPUT.	RESPONSE TO RAMP INPUT.	REMARKS.
INHERENT FRICTION. (UNDERDAMPED)			FAST OSCILLATORY RESPONSE, (CONSIDERABLE HUNTING): SMALL VELOCITY LAG:
VISCOUS DAMPING.			SLOW DAMPED RESPONSE: LARGE VELOCITY LAG: USEFUL ONLY ON SMALL SERVOS BECAUSE OF POWER LOSSES.
VELOCITY FEEDBACK DAMPING.			FAST DAMPED RESPONSE: LARGE VELOCITY LAG: SATISFACTORY FOR MOST R.P.C. SYSTEMS.
ERROR-RATE DAMPING. PHASE-ADVANCE NETWORK. TRANSIENT VELOCITY FEEDBACK DAMPING.			FAST DAMPED RESPONSE: SMALL VELOCITY LAG:
INTEGRAL OF ERROR.			FAST DAMPED RESPONSE: PRACTICALLY ZERO VELOCITY LAG: DIFFICULT TO MAINTAIN STABILITY:

Fig. 19. COMPARISON OF DAMPING METHODS

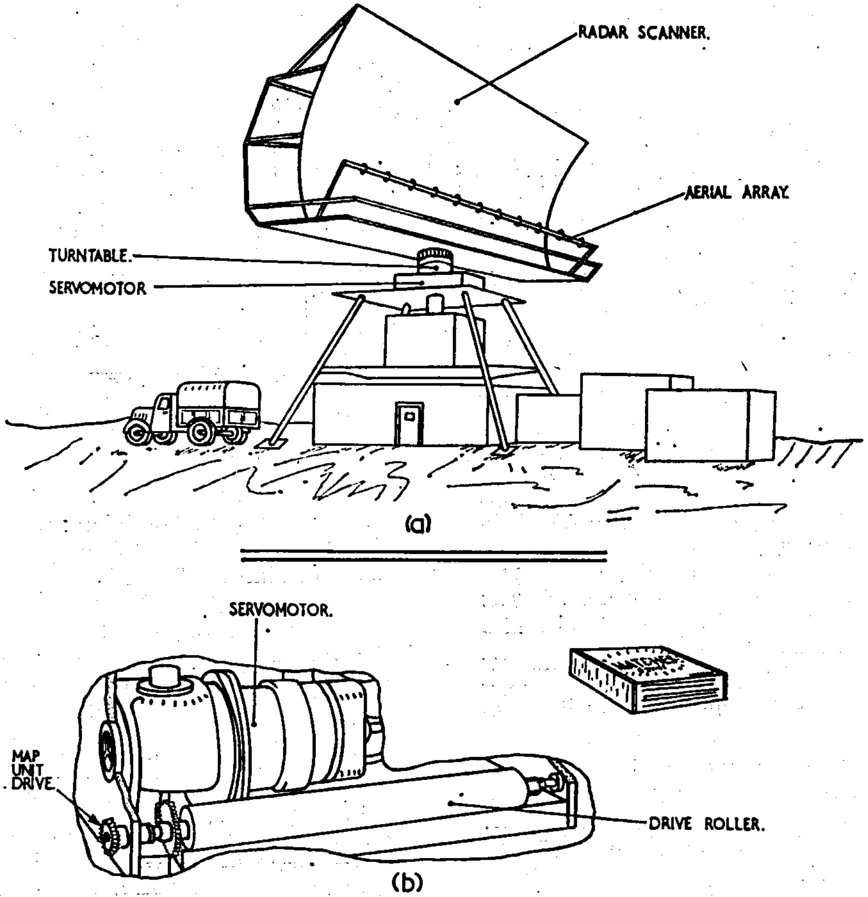


Fig. 20. RANGE OF APPLICATION OF SERVOMECHANISMS

to produce a map of the ground over which the aircraft is flying: a servomechanism is required to drive the roller at a speed proportional to the ground speed of the aircraft: it is a small mechanism, the power output requirements being of the order of a few watts.

Components in a Servomechanism

52. Fig. 21 shows the essential elements in a r.p.c. servomechanism. Brief notes on each of these elements for varying applications and power requirements are given in the following paragraphs.

53. **Error-measuring device.** In d.c. systems, the input and output shafts are commonly connected to potentiometer wipers that pick off d.c. voltages proportional to θ_i and θ_o respectively. The error-measuring device in this case is merely the arrangement of the connections at the amplifier such that

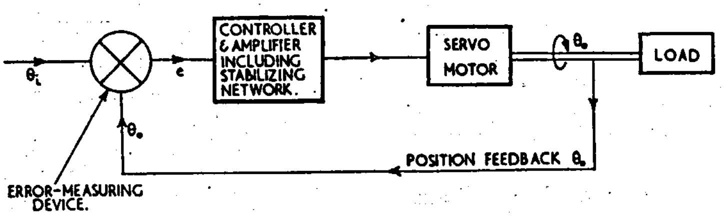


Fig. 21. ESSENTIAL ELEMENTS IN A R.P.C. SERVOMECHANISM

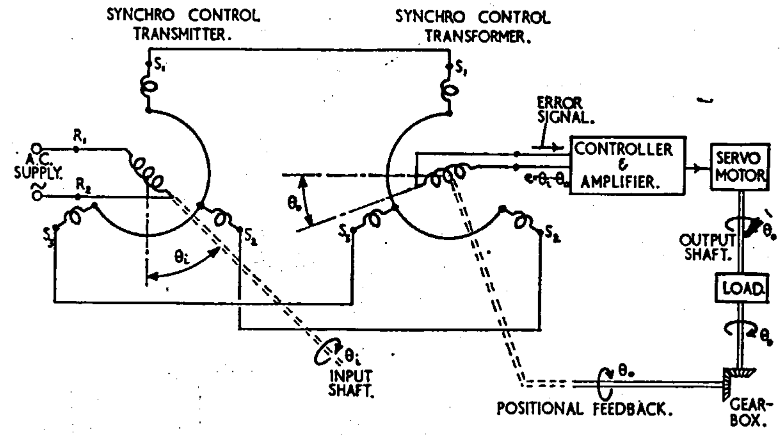


Fig. 22. A.C. ERROR-MEASURING DEVICE

the input to the amplifier is the error voltage proportional to $\theta_i - \theta_o$.

In a.c. systems, a control synchro system is usual as the error-measuring device. This has been dealt with in Chapter 1 and a typical arrangement is illustrated in Fig. 22. This shows that the input to the amplifier is an a.c. error signal proportional to $\theta_i - \theta_o$.

54. Controller, amplifier and servomotor. The components used in these stages, and their size and complexity, are determined by the power output requirements of the servomechanism.

(*a*) *Low-power d.c. servos.* In small d.c. servomechanisms where the power output required is of the order of a few watts, the error signal is applied to a static d.c. amplifier or several such amplifiers in cascade. Either thermionic hard valve or magnetic amplifiers can be used and the circuit will include the usual stabilizing arrangements to ensure the required response. The d.c. output of the amplifier controls the armature current of a separately-excited d.c. motor, thereby controlling the speed and direction of the output load. Where velocity feedback or transient velocity feedback is required, the feedback voltage can be obtained from a small d.c. tacho-generator mounted on the output shaft which produces a voltage proportional to speed. In certain cases, the back e.m.f. of the motor itself can be utilized.

(*b*) *Lower-power a.c. servos.* In small a.c. systems, the a.c. error signal from the control synchro is amplified through hard valve or magnetic amplifiers: the amplified signal can then be applied to one of the field windings of the driving motor—usually a two-phase induction motor (see Sect. 5, Chap. 4). It will be remembered that the magnitude and phase of the output voltage from a control synchro depends on the magnitude and sense of the error and is either in phase or in anti-phase with the reference alternating voltage. If the reference voltage is applied to one field winding of the two-phase induction motor through a 90° phase shifting network, and the amplified error signal is applied to the quadrature field winding, the motor rotates. Since the field due to the error is now either 90° leading or 90° lagging on the reference field, the speed and direction of rotation of the motor depends on the magnitude and sense of the error.

An *a.c. tacho-generator* is used to give velocity or transient velocity feedback. The a.c. tacho-generator produces an alternating voltage at a constant frequency, but the *magnitude* of the generated voltage is directly proportional to the speed at which the generator is driven, i.e., the output speed of the servomechanism. The rotor is a 'drag-cup' or hollow brass cylinder, but the principles of operation can be more easily explained by considering a squirrel-cage rotor, i.e., made up of a large number of uninsulated coils as illustrated in Fig. 23(a). As the rotor rotates, voltages are induced in the coils by interaction with the primary field: at any instant, maximum e.m.f. is induced in the coil passing through the primary axis, i.e.,

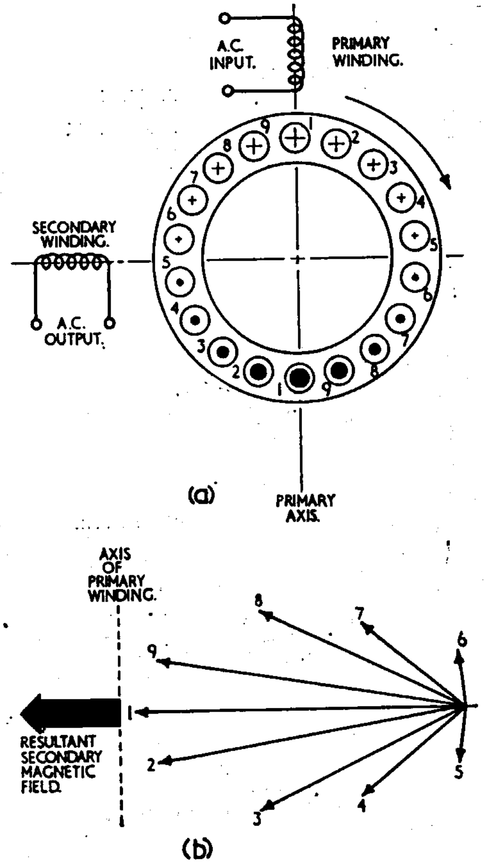


Fig. 23. A.C. TACHO-GENERATOR PRINCIPLE

in coil 1 of Fig. 23 (a). The e.m.f.s induced in the other coils are progressively less as the axis of the coil departs from the primary axis. However, the resultant of all the secondary fields produced by the currents induced in the coils from the primary field is, at any instant, at *right angles* to the axis of the primary field (Fig. 23(b)). This secondary field oscillates at the frequency of the supply current but its *magnitude* is proportional to the speed of the rotor. The secondary stator winding of the tacho-generator is at right angles to the primary winding and so has a voltage induced in it by the *secondary* field only: this is the output voltage. A typical a.c. tacho-generator provides a signal output of approximately 0·5V per 1000 r.p.m. of rotor.

(*c*) *Moderate-power servos.* In most r.p.c. systems where the power requirements are in excess of about 100 watts, a separately-excited d.c. motor is used to drive the load. The input to the system, on the other hand, is usually from a synchro control transformer and is therefore an a.c. error signal. There must then be conversion from a.c. to d.c. in the servomechanism. The small a.c. error signal is amplified in a static hard valve or magnetic amplifier and is then applied to a special type of rectifier known as a *phase-sensitive rectifier*. It was noted earlier that the magnitude and phase of the voltage from a synchro control transformer depends on the magnitude and sense of the error. A simple rectifier takes no account of phase difference so that a rectifier circuit sensitive to phase is required. A phase-sensitive rectifier is supplied with a reference alternating voltage against which to compare the phase of the error voltage, and it produces an output of the correct polarity depending on that comparison (Fig. 24).

The output from the phase-sensitive rectifier is, in effect, a d.c. voltage of magnitude and polarity depending on the magnitude and sense of the error. This voltage is further amplified through hard valve or magnetic amplifiers before being applied to the power-amplifying stage.

The maximum power available at the output of a hard valve amplifier is usually limited by economic considerations to about 20 watts. Magnetic amplifiers or gas-filled valve amplifiers (e.g. thyratron) can, however, be designed to produce outputs of the order of a few kilowatts. Where this is sufficient, the power amplifier controls the power into the armature of a separately-excited d.c. motor that drives the load. The speed and direction of rotation of the load depend on the magnitude and sense of the error signal. The circuit will include the usual stabilizing and feedback circuits to improve the response of the servomechanism.

(*d*) *High-power servos.* If the power required is of the order of that needed to rotate the radar scanner of Fig. 20(a) (i.e., about 100 kilowatts) it is more practical to use rotating machinery in the power-amplifying stage. A typical arrangement is shown in Fig. 25.

The output from the static valve or

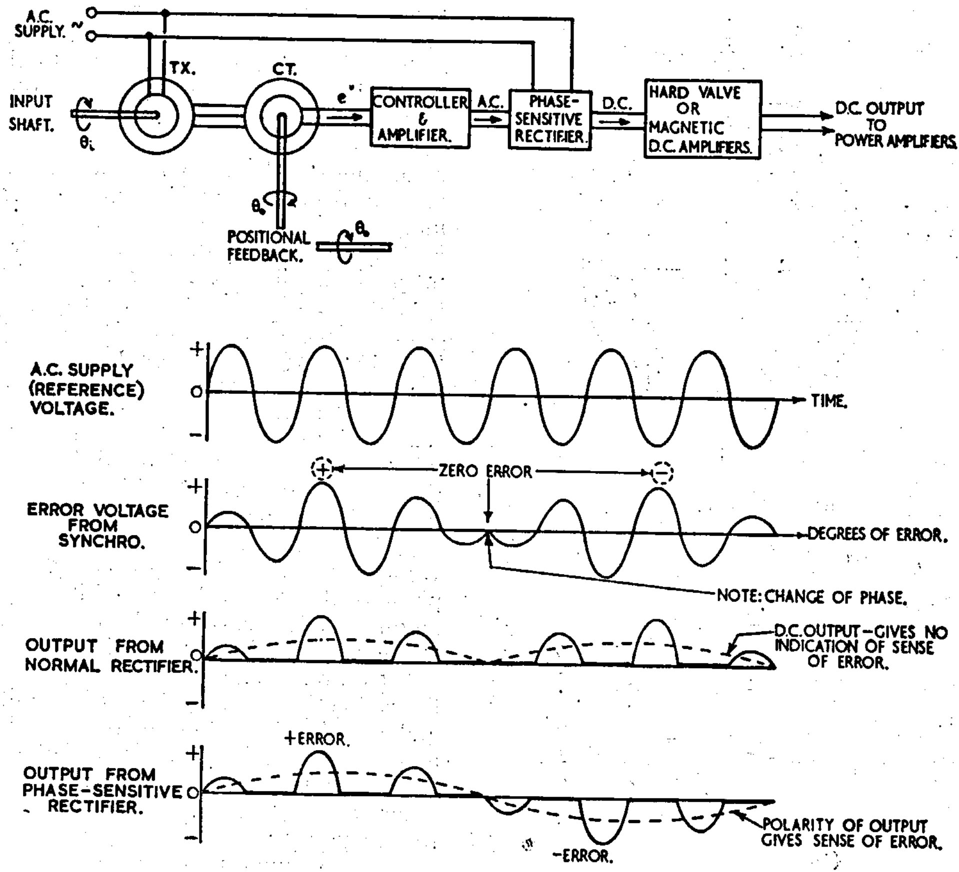


Fig. 24. OPERATION OF PHASE-SENSITIVE RECTIFIER

magnetic amplifier energises the field of a small exciter generator G_1 which is capable of producing an output of, say, 100 watts. This in turn is sufficient to energise the field of the main generator G_2 which may produce an output of, say, 10 kilowatts to drive the separately-excited motor M. Power amplification has thus been achieved.

This system can be extended to produce outputs of the order of several hundreds of kilowatts by connecting a number of generators in cascade. It is, however, more economical to group two or even three generators inside one casing. This is the method adopted in the Amplidyne and Metadyne generator systems.

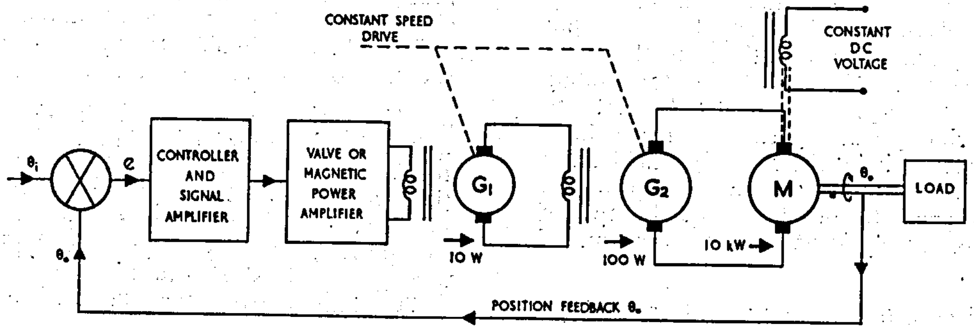
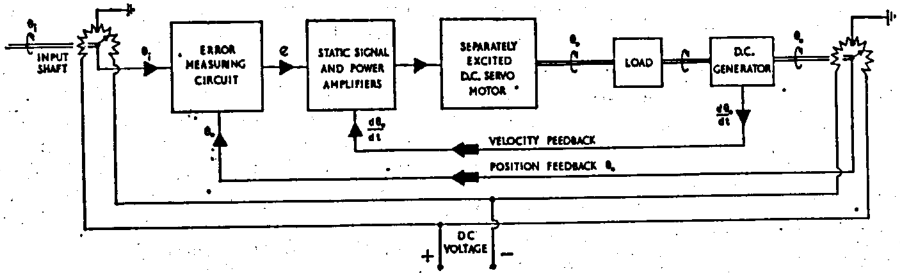
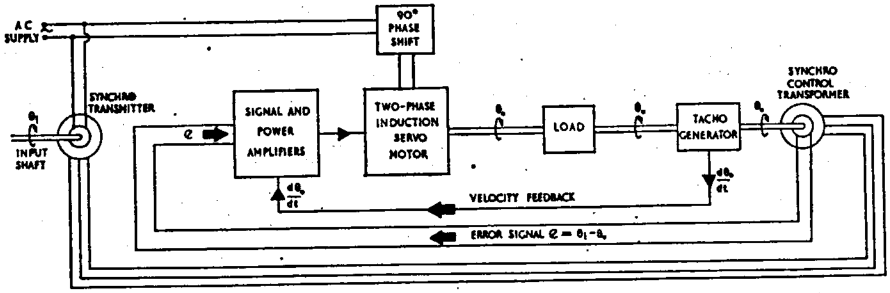


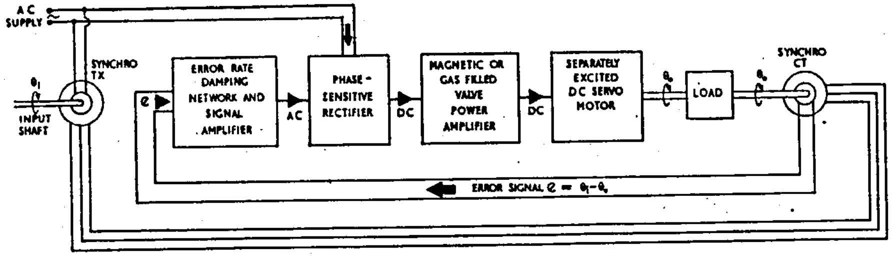
Fig. 25. USE OF ROTARY POWER AMPLIFIERS



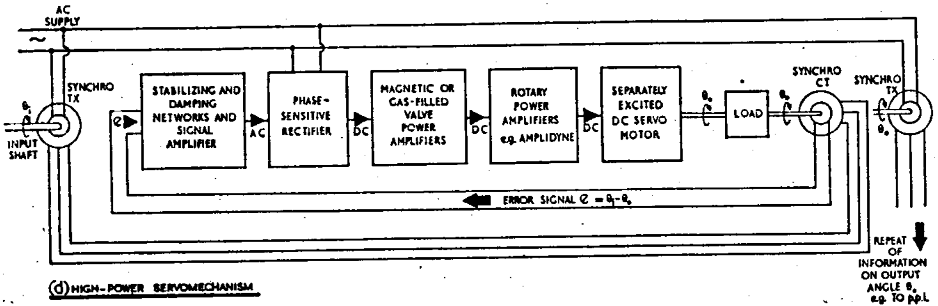
(a) LOW-POWER D.C. SERVOMECHANISM



(b) LOW-POWER A.C. SERVOMECHANISM



(c) MODERATE-POWER SERVOMECHANISM



(d) HIGH-POWER SERVOMECHANISM

Fig. 26. SOME TYPICAL SERVOMECHANISM ARRANGEMENTS

Summary

55. This chapter has considered briefly the operation of a basic servomechanism and its behaviour to step input and ramp input functions: the steps taken to improve stability were also discussed. Mention was made of the range of applications of servomechanisms, and a general outline of the methods adopted to cover this range was given. These specimen methods are illustrated in the block diagrams of Fig. 26.

It should be noted however that there is considerable room for manœuvre on the part of the designer within this broad area. Because of this, discussion has intentionally been kept at block diagram level.

Circuit details of servo amplifiers (including magnetic and thyratron amplifiers), phase-sensitive rectifiers and generator power-amplifier systems of the Amplidyne type are considered in the more appropriate part of these notes—Part 3.