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

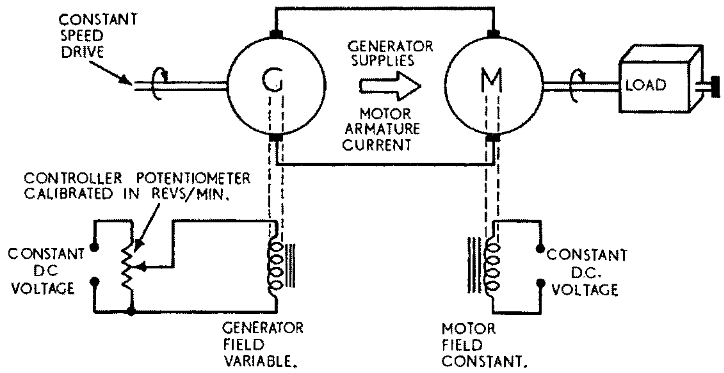

Fig. 1. SIMPLE SPEED CONTROL OF A D.C. MOTOR

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-

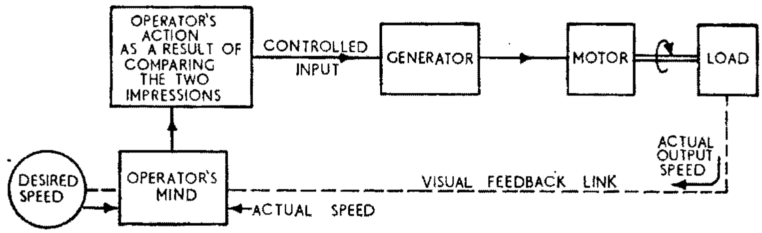

Fig. 2. HOW A HUMAN OPERATOR CONTROLS MOTOR SPEED

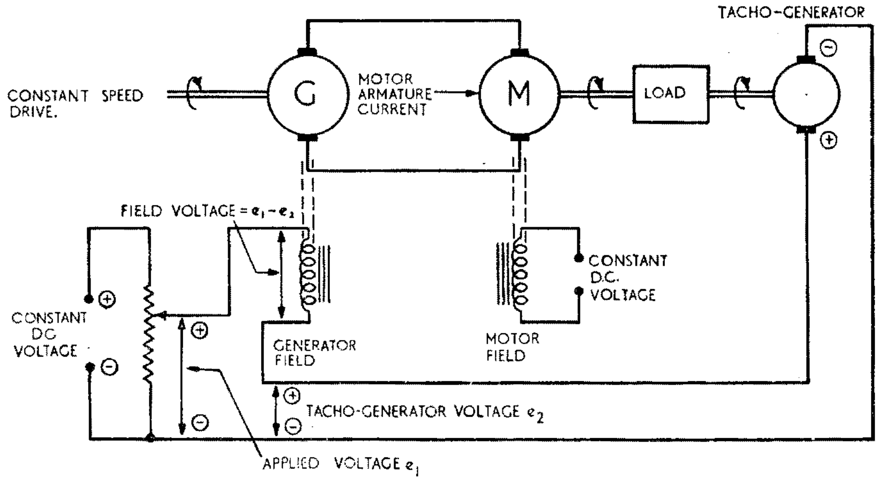

Fig. 3. AN IMPROVED METHOD OF SPEED CONTROL

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*.

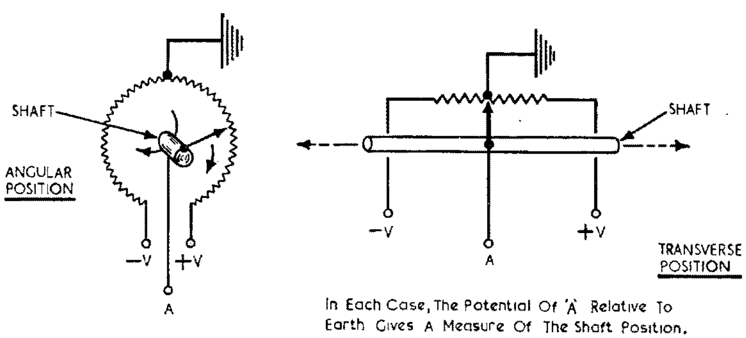

Fig. 4. PRODUCTION OF VOLTAGE PROPORTIONAL TO SHAFT POSITION

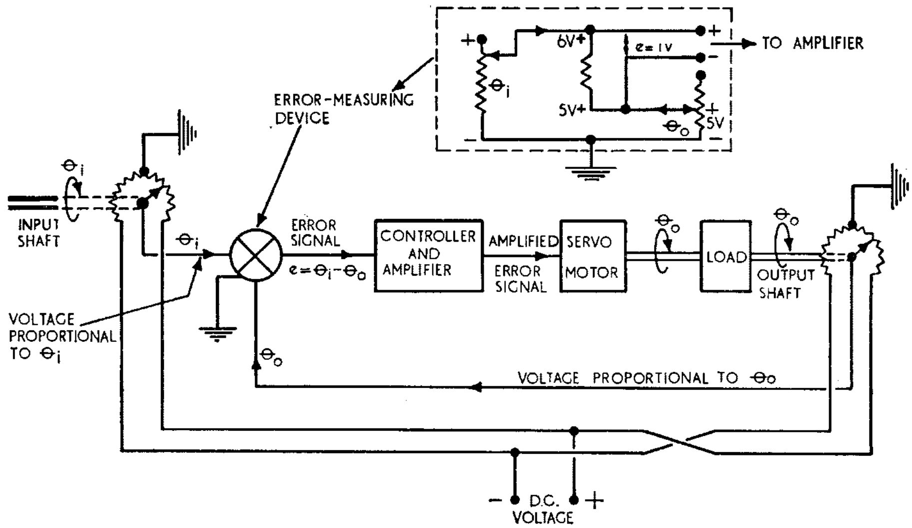

Fig. 5. CLOSED LOOP POSITION CONTROL SYSTEM

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

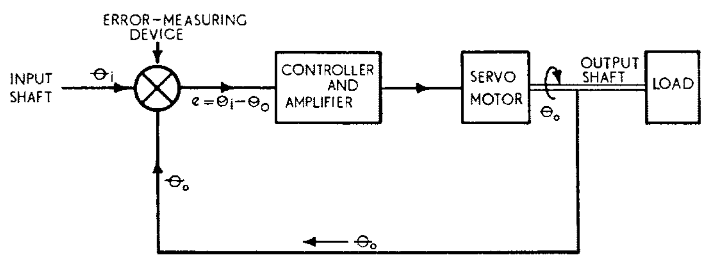

Fig. 6. ELEMENTS IN A SIMPLE D.C. SERVOMECHANISM

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.

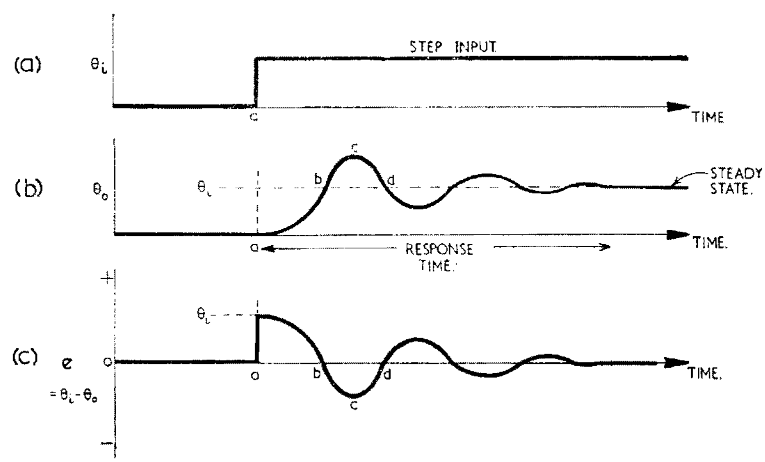

Fig. 7. RESPONSE OF A SERVOMECHANISM TO A STEP INPUT

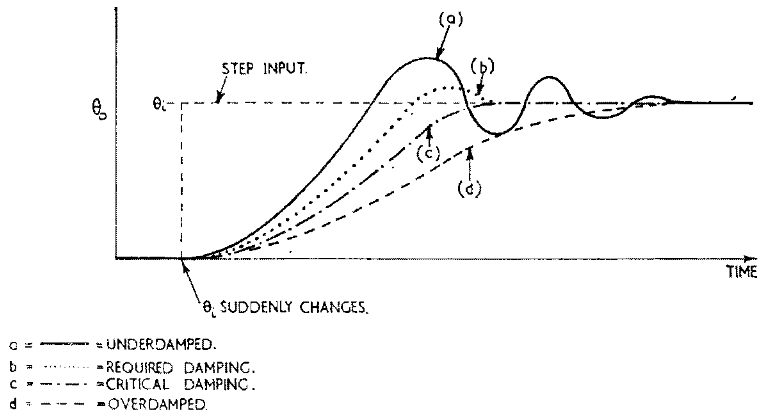

Fig. 8. EFFECT OF DIFFERENT DEGREES OF DAMPING

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

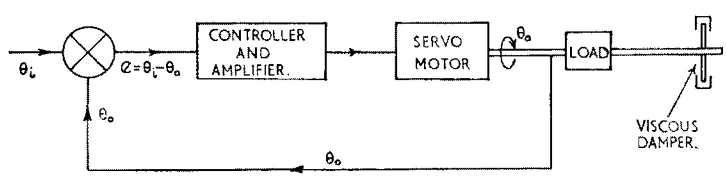

Fig. 9. VISCOUS DAMPING

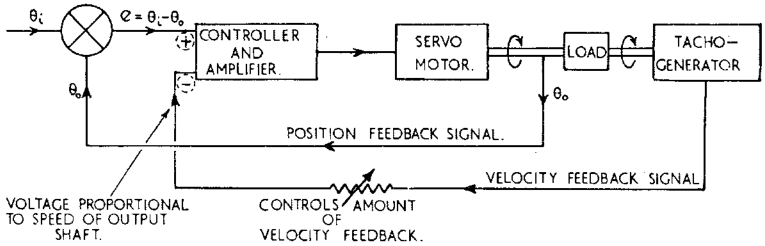

Fig. 10. ARRANGEMENT FOR VELOCITY FEEDBACK DAMPING

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

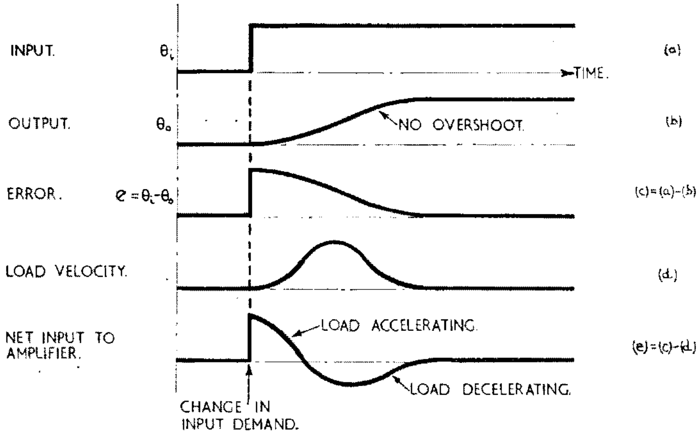

Fig. 11. PRINCIPLE OF VELOCITY FEEDBACK DAMPING

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)).

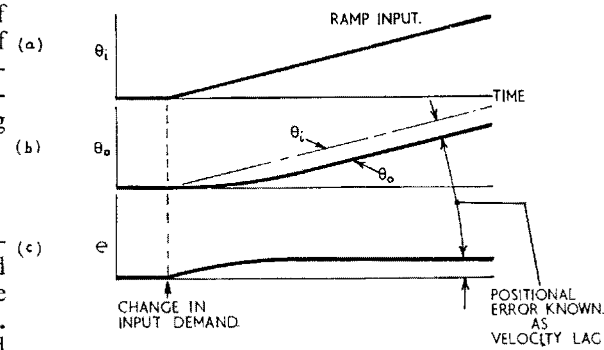

Fig. 12. RESPONSE OF A SERVOMECHANISM TO A RAMP INPUT

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

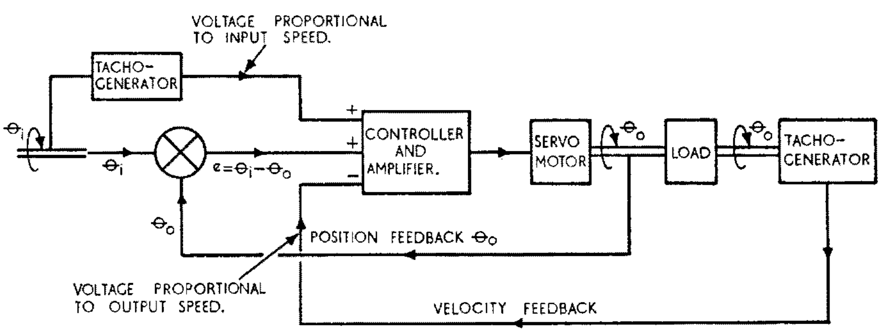

Fig. 13. METHOD FOR REDUCING VELOCITY LAG

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_0 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-

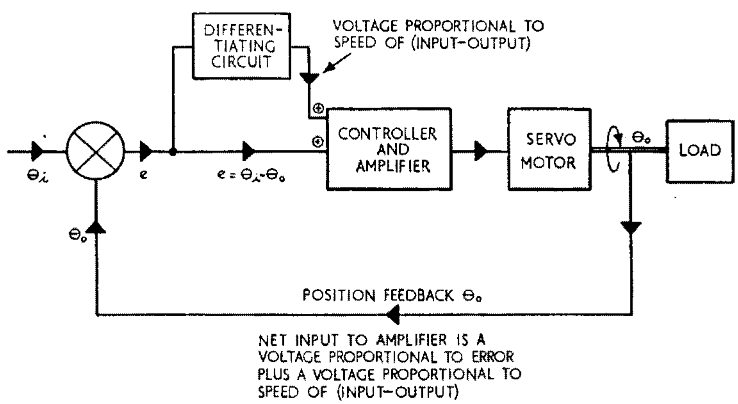

Fig. 14. ERROR-RATE DAMPING ARRANGEMENT

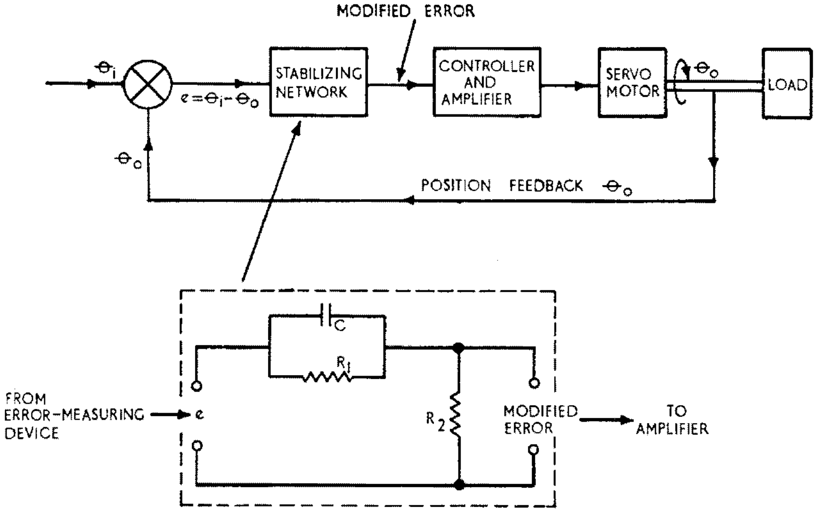

Fig. 15. USE OF STABILIZING NETWORK TO REDUCE VELOCITY LAG

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

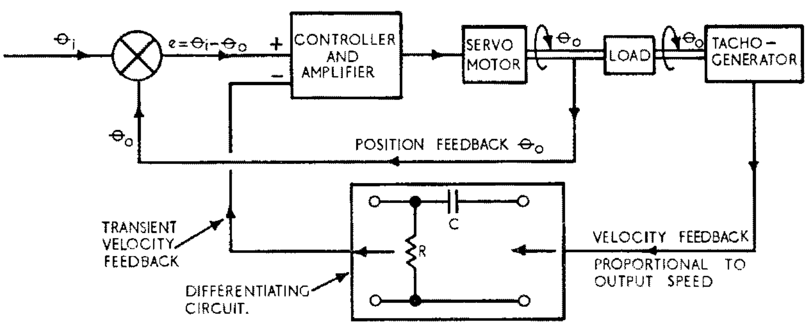

Fig. 16. TRANSIENT VELOCITY FEEDBACK

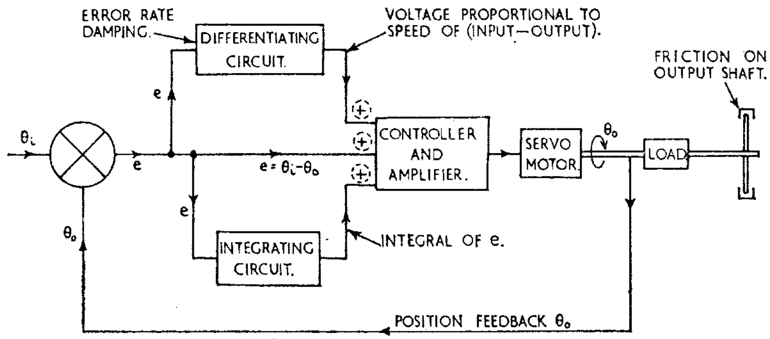

Fig. 17. INTEGRAL OF ERROR COMPENSATION

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

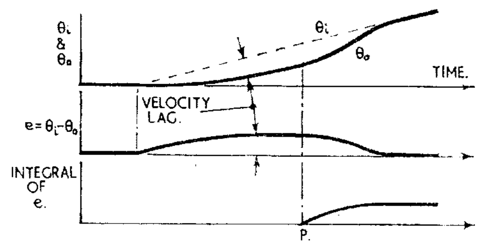

Fig. 18. PRINCIPLE OF INTEGRAL OF ERROR COMPENSATION METHOD

velocity lag due to the friction on the output shaft. This is illustrated in Fig. 18.

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

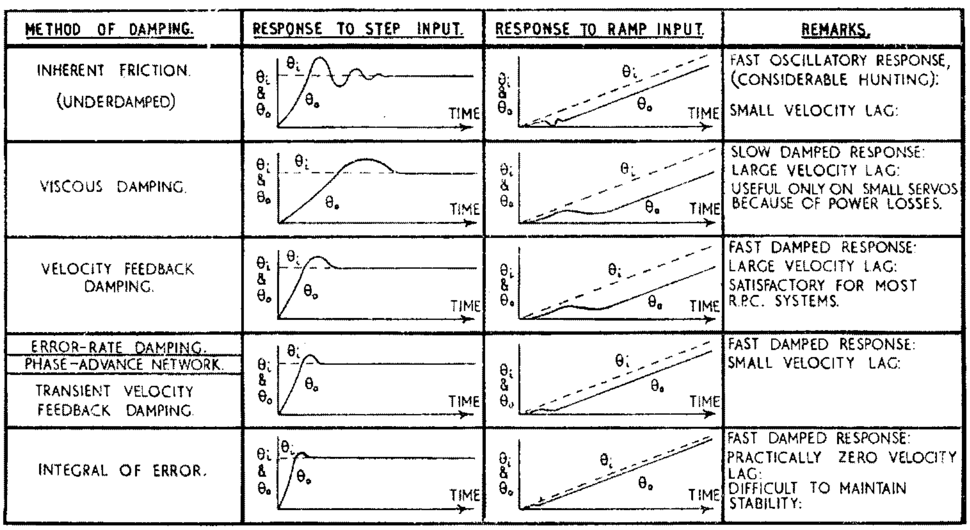

Fig. 19. COMPARISON OF DAMPING METHODS

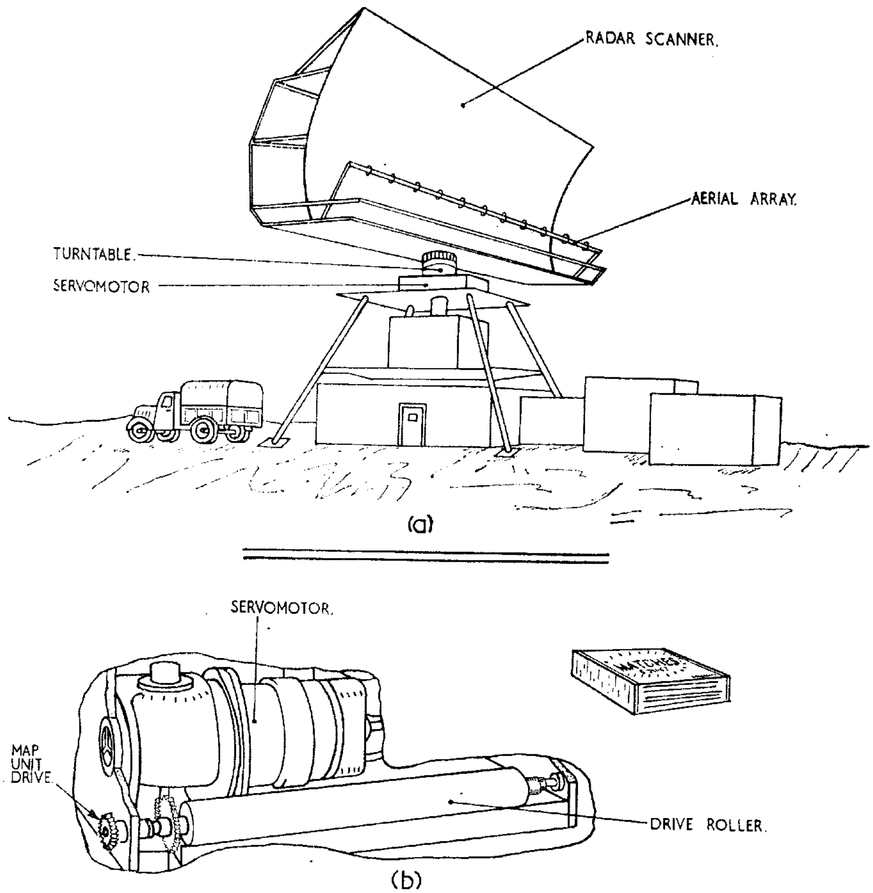

Fig. 20. RANGE OF APPLICATION OF SERVOMECHANISMS

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

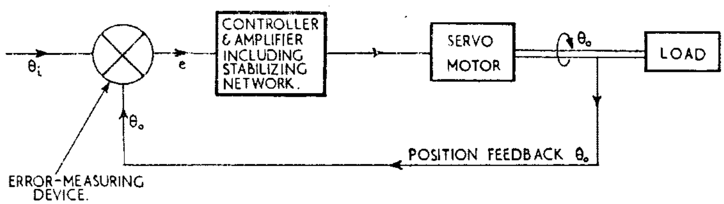

Fig. 21. ESSENTIAL ELEMENTS IN A R.P.C. SERVOMECHANISM

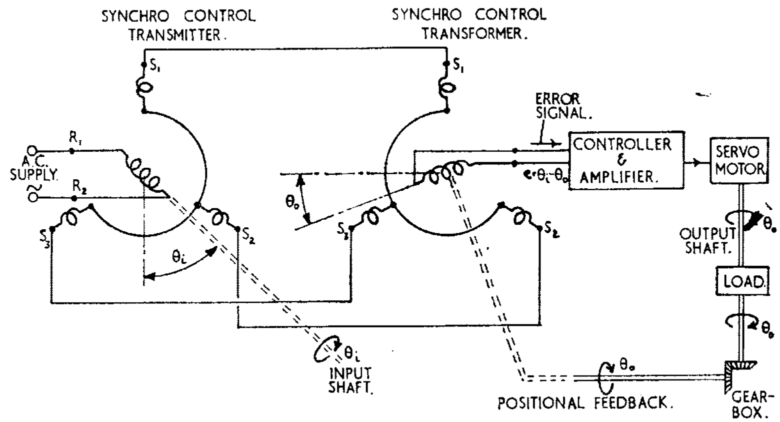

Fig. 22. A.C. ERROR-MEASURING DEVICE

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.,

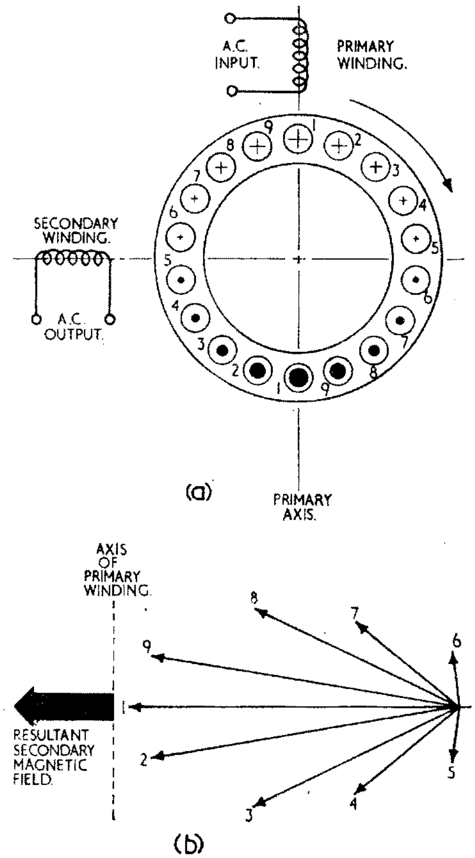

Fig. 23. A.C. TACHO-GENERATOR PRINCIPLE

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

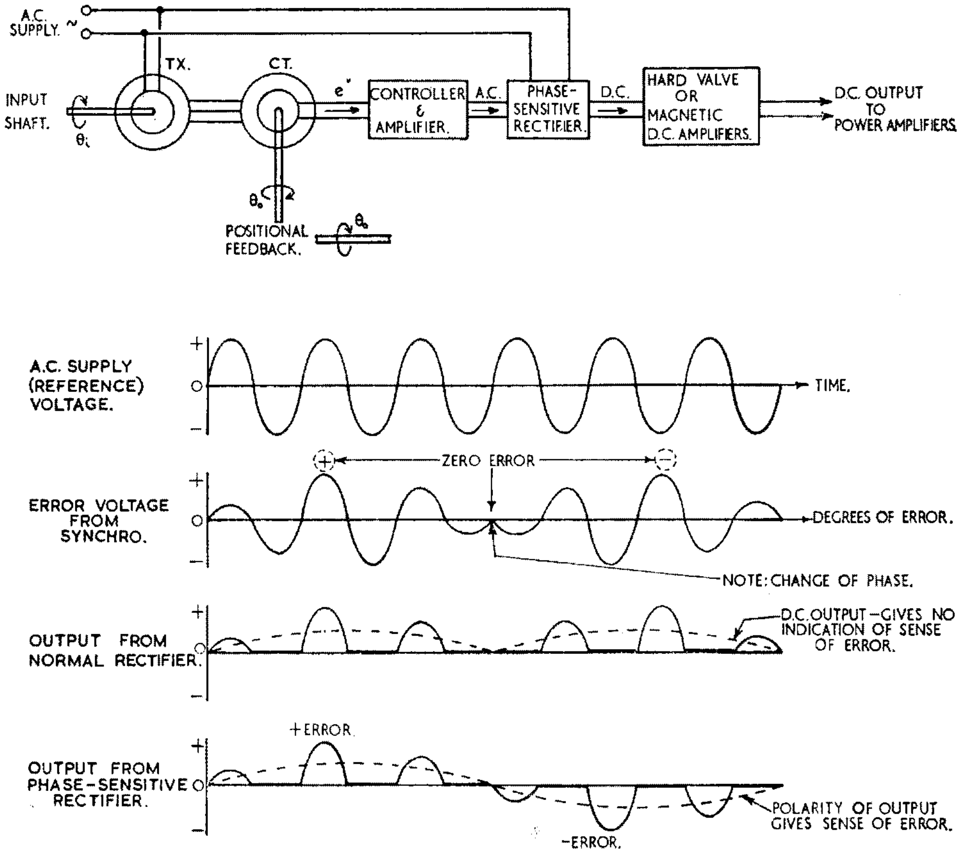

Fig. 24. OPERATION OF PHASE-SENSITIVE RECTIFIER

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.

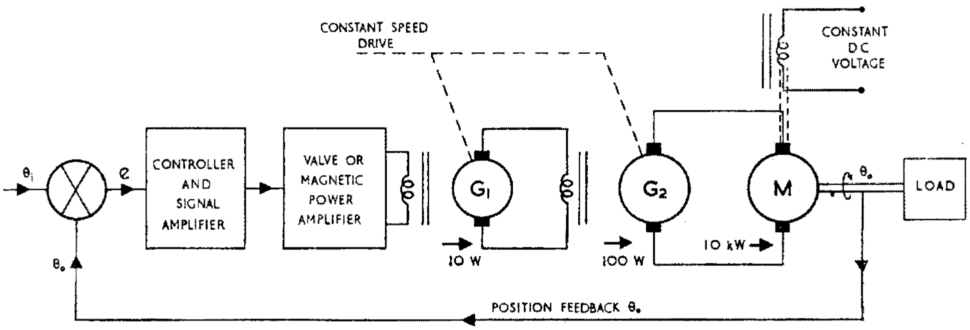

Fig. 25. USE OF ROTARY POWER AMPLIFIERS

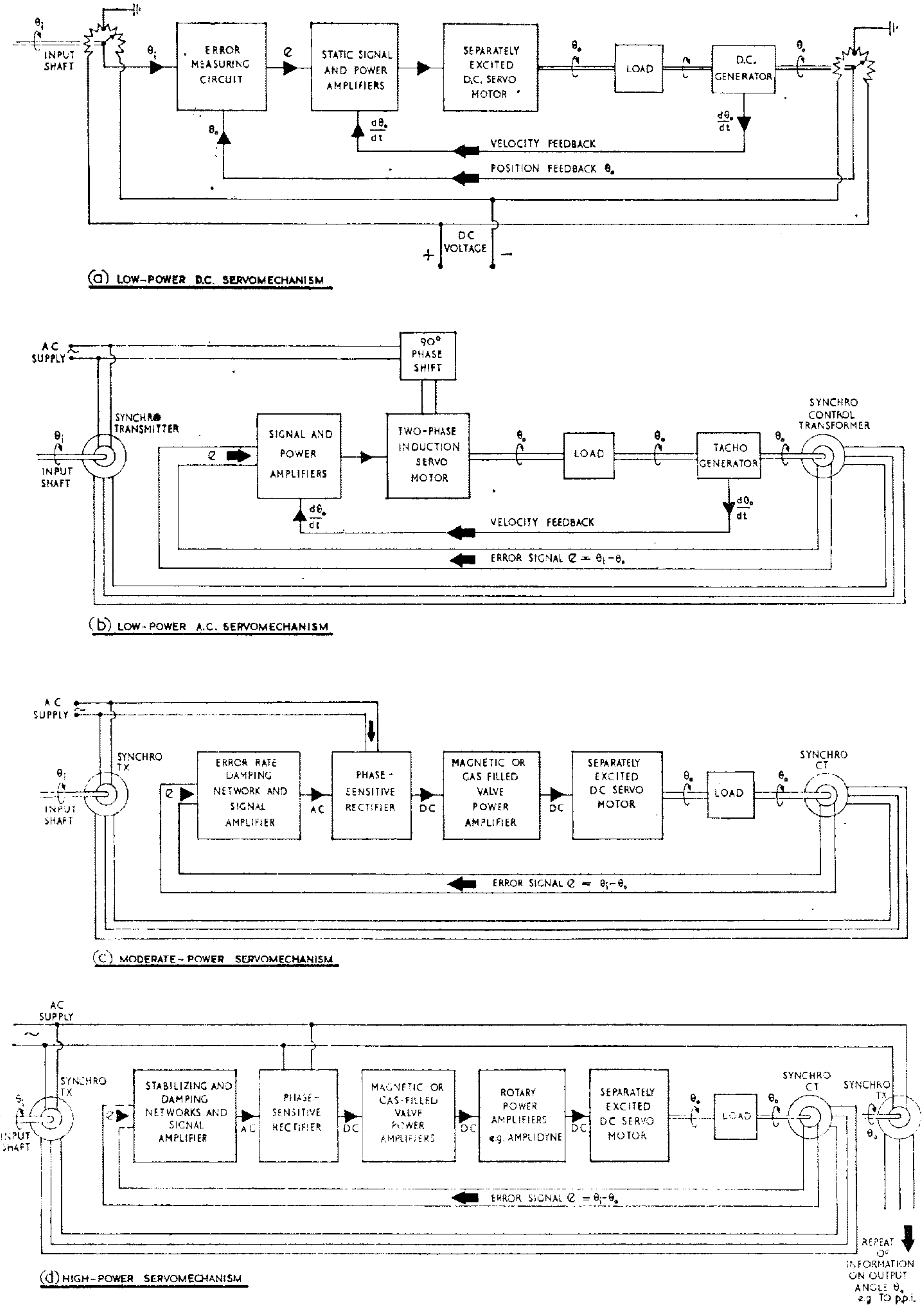

Fig. 26. SOME TYPICAL SERVOMECHANISM ARRANGEMENTS

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.