Oct. 9, 1956 G. H. STEPHENSON 2,766,412

ELECTRIC SERVOMOTOR SYSTEM

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FIG. 1.

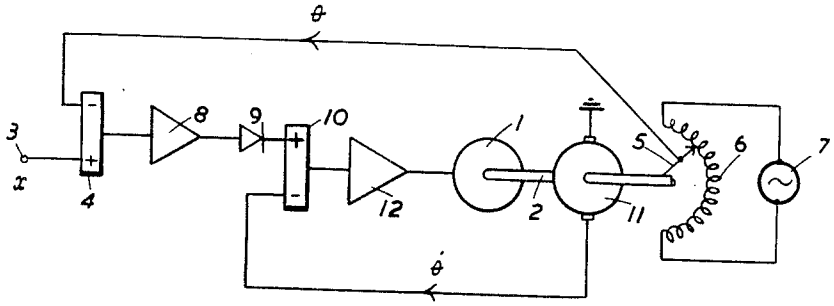


FIG. 2.

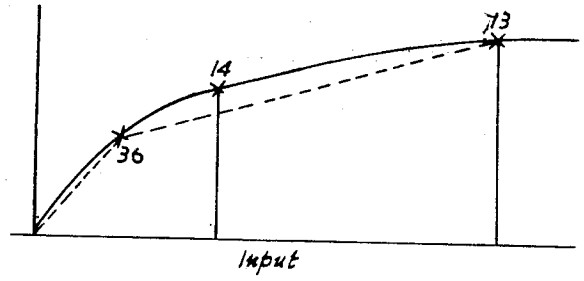


FIG. 3.

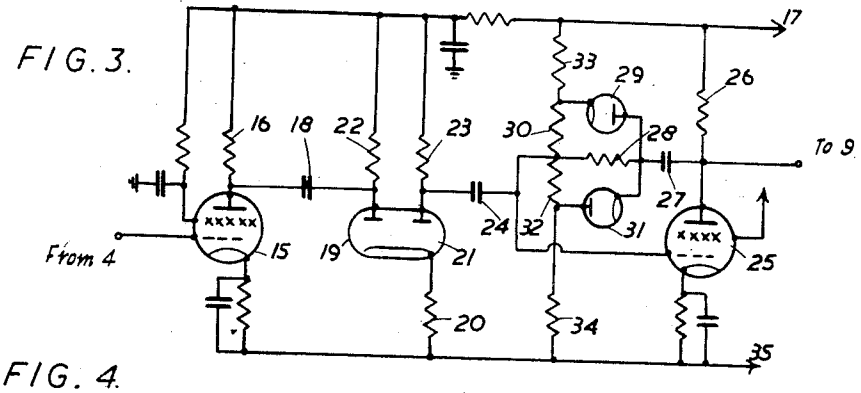
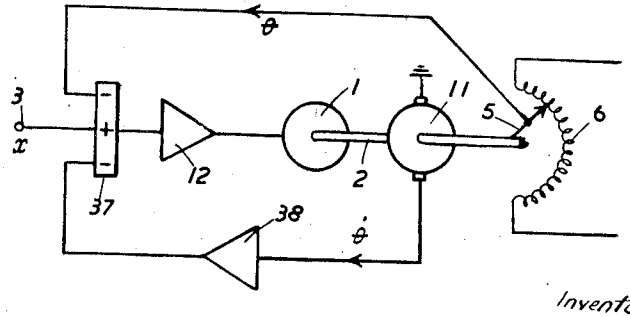


FIG. 4.



Inventor

GEOFFREY HUSON STEPHENSON

By Ralph E. Atherton

Attorney

United States Patent Office

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ELECTRIC SERVOMOTOR SYSTEM

Geoffrey Huson Stephenson, Ealing, London, England, assignor to Electric & Musical Industries Limited, Hayes, England, a company of Great Britain

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4 Claims. (Cl. 318—28)

This invention relates to servo-mechanism.

In servo-mechanism the input signal is frequently expressed as a voltage and the mechanism comprises a servo-motor which is arranged to operate to reduce to zero any difference between the input signal and a voltage signal dependent on the displacement effected by the servo-motor. In most applications of servo-mechanism it is desirable that said difference should be reduced to zero as rapidly as possible, and the object of the present invention is to provide improved servo-mechanism with a view to approaching this desideratum more closely than has hitherto been the case.

According to the present invention, there is provided servo-mechanism including a servo-motor for effecting a displacement in response to an input signal, means for setting up a first signal dependent on the displacement which the servo-motor is required to make, means for setting up a second signal dependent on the velocity of the servo-motor, means for comparing said signals, and means responsive to the compared signals for applying driving force to rotate the servo-motor in the sense to reduce said first signal when said first signal exceeds said second signal and for applying decelerating force to the servo-motor when the second signal exceeds said first signal, the means for setting up at least one of said signals having a nonlinear characteristic dimensioned in dependence upon the deceleration law of the servo-motor to cause the second signal to exceed the first signal effectively at the instant when the first signal corresponds to the displacement required to bring the servo-motor to rest under said decelerating force.

In order that the said invention may be clearly understood and readily carried into effect, the same will now be more fully described with reference to the drawing, in which:

Figure 1 illustrates diagrammatically one application of the present invention,

Figure 2 is a graph explanatory of the operation of Figure 1,

Figure 3 is a diagrammatic detail view of part of Figure 1, and

Figure 4 illustrates a modification of Figure 1.

Referring to the drawing, the servo-mechanism illustrated in Figure 1 comprises an electrically driven servo-motor 1 adapted to drive a shaft 2 to cause the angular displacement of the latter to assume a value representative of the input signal to the servo-motor. The input signal, x say, is applied in the form of an alternating voltage at a terminal 3 and it is fed to a subtracting circuit 4 in which the signal x has subtracted from it a signal representative of the angular displacement θ of the shaft 2. The latter signal is derived from a potentiometer contact 5. The contact 5 is driven by the shaft 2 and moves over a potentiometer winding 6 to which is applied an alternating reference voltage from a suitable source 7. The difference signal from the circuit 4 is linearly proportional to $(x-\theta)$ and is representative at any instant of the displacement required of the servo-

motor. This difference signal, which is hereinafter denoted as $(x-\theta)$, is fed to a nonlinear amplifier 8, which will be described in more detail hereinafter. The signal output of the amplifier 8 which is non-linearly related to $(x-\theta)$, is rectified in a rectifier 9 and thence fed to a further subtracting circuit 10 in which there is subtracted from it a D. C. signal representative of the angular velocity of the shaft 2 or a function thereof, the angular velocity being denoted by $\dot{\theta}$. In the present example the last-mentioned signal is derived from a tacho-generator 11 driven by the shaft 2, and is therefore linearly proportional to $\dot{\theta}$. The resultant signal from the subtracting circuit 10 is fed to a high gain amplifier 12, the output of this amplifier forming the signal which drives the motor 1. The gain of the amplifier 12 is arranged to be sufficiently high that maximum forward torque is applied to the motor 1 if the rectified output of the amplifier 8 significantly exceeds the signal representative of $\dot{\theta}$, whereas maximum reverse torque is applied to the motor if the latter signal significantly exceeds the former.

The amplifier 8 is arranged to have a characteristic of a form such as illustrated by the full line graph in Figure 2. The abscissae of this graph represent the amplitude of the input signal to the amplifier 8 while the ordinates represent the amplitude of the output signal. The curved part of the graph is drawn to conform to the law relating the angular velocity of the shaft 2 to its angular displacement from the position in which it finally comes to rest, when the motor 1 is under maximum decelerating torque. The graph is therefore uniquely determined by the constants of the servo-system and is prepared by making the abscissae represent, on a suitable scale, the angular displacement of the shaft 2 from the position in which it finally comes to rest and making the ordinates represent the angular velocity at the corresponding displacement. The horizontal part of the graph to the right of the point 13 represents the equilibrium velocity of the servo-motor under maximum torque and, when this condition prevails, a point representing the instantaneous value of $(x-\theta)$ moves along the graph from right to left since, as aforesaid, the abscissae of the graph represent the displacement which has yet to be made before the servo-motor comes to rest. The point 13, as will hereinafter appear, corresponds to the application of the maximum possible decelerating force to the servo-motor, produced by a reversal of torque so that maximum torque is now applied in the opposite sense, and the curve to the left of the point 13 represents the ensuing deceleration of the motor.

For example, if, at a given instant, the input signal has a value such as to cause the signal representative of $(x-\theta)$ to exceed the value given by the point 13 on the graph (such a value being represented by an abscissa to the right of 13) and the motor is under maximum positive with a sense to cause rotation of the shaft 2 to reduce the difference $(x-\theta)$. Until the point 13 is reached, the value of the output of the amplifier 8 remains constant and just exceeding the signal representative of $\dot{\theta}$, the latter also being constant since the motor 1 is running at its equilibrium velocity. As the difference $(x-\theta)$ becomes less than represented by the point 13, the output of the amplifier 8 decreases in accordance with the curved part of the graph to the left of 13. However, the motor 1 tends to continue running at its equilibrium velocity, thus causing the signal representative of $\dot{\theta}$ to exceed the output of the amplifier 8. Maximum reverse torque is thus almost immediately applied to the motor 1 and it is decelerated in accordance with the curved part of the graph. The signal representative of $\dot{\theta}$ then decreases in accordance with the same law as the output of the amplifier 8, remaining

just in excess of said output. Maximum reverse torque is thus maintained in the motor 1, and it is therefore brought to rest in the shortest possible time. Moreover, by reason of the characteristic of the amplifier 8, at the instant when the velocity of the shaft 2 becomes zero, the difference $(x-\theta)$ becomes equal to zero, and the torque is removed from the motor 1. If at a subsequent instant, an input signal x again varies so as to make the output of the amplifier 8 that represented by, say, the point 14 on the graph, full positive torque is applied to the motor 1 and the shaft 2 is accelerated in accordance with a curve of similar form to the deceleration curve of Figure 2. The output of the amplifier then decreases in dependence upon $(x-\theta)$ in accordance with the curved part of the graph, while the signal representative of $\dot{\theta}$ increases from zero along the same part of the graph. At a point intermediate the origin and the point 14, the signal representative of $\dot{\theta}$ exceeds the output of the amplifier 8 and full reverse torque is applied to the motor to decelerate it. This condition is maintained until the motor has been brought to rest and as above described this occurs at the instant when $(x-\theta)$ is equal to zero. From the foregoing, therefore, it will be apparent that in the ideal case the servo-motor operates to produce equality between x and $\dot{\theta}$ in the shortest possible time for all variations of x. In practice, of course, the ideal is not wholly obtainable but nevertheless it is possible to approach it closely.

Figure 3 illustrates a form of amplifier suitable for use as the amplifier 8. It comprises a thermionic valve 15 to the control electrode of which the output from the circuit 4 is applied. The valve 15 has its anode connected, by means of a resistance 16 to the positive terminal indicated at 17, of a voltage supply source, and the valve 15 is a screen grid valve so that current variations are set up at its anode conforming substantially to the input applied to its control electrode. The anode of the valve 15 is coupled by a condenser 18 to the anode of a diode valve 19 whose cathode is coupled by a resistance 20 by a second diode valve 21. The anodes of the diode valves 19 and 21 are respectively connected to the terminal 17 by resistances 22 and 23. The anode of the diode valve 21 is coupled by a condenser 24 to the control electrode of a further valve 25 which has an anode load resistance 26. The anode of the valve 25 is coupled to the control electrode thereof for negative feedback by means of a condenser 27 and a resistance 28, across the latter of which are connected, as shown, a diode 29 in series with a resistance 30 and a diode 31 in series with a resistance 32. The resistances 30 and 32 each have a magnitude of about one-tenth that of the resistance 28. Moreover, the diodes 29 and 31 are connected in mutually reverse polarities as shown. By reason of the negative feedback which is variable in dependence upon the amplitude of the input signal as will hereinafter appear, the valve 25 operates with a low input impedance and functions effectively as a current amplifier. The junction of the diode 29 and the resistance 30 is connected to the positive terminal 17 by a resistance 33 while the junction of 31 and 32 is connected by a resistance 34 to the negative terminal of the voltage source, indicated at 35. The output signal of the amplifier is taken from the anode of the valve 25 and applied to the rectifier 9.

The diodes 19 and 21 operate as a current limiter in such a way that if the voltage variations fed to the anode of the valve 19 by the condenser 18 exceed a given amplitude, alternate half-cycles thereof are limited by one or other of the diodes 19 and 21. In this way if the current variations at the anode of the valve 15 exceed a given amplitude, namely that represented by the abscissae of 13 in Figure 2, the output signal at the anode of the valve 25 remains constant, and the amplifier characteristic conforms to the horizontal part of the graph in Figure 2. By reason of the resistances 30, 32, 33 and 34 the diodes 29 and 31 are equally biassed, and in the absence of signals at the anode of the valve 25 are maintained in a non-conducting state. If the current variations fed to the control electrode of the valve 25 are such that the amplitude of the potential variations at the anode of said valve does not exceed the bias applied to the diode valves 29 and 31 the latter valves remain non-conducting, and feedback is applied solely by the resistance 28. Under these conditions the amplifier gain is represented by the slope of dotted line from the origin to the point 36 in Figure 2. If the current variations have, however, an amplitude to cause the amplitude of the potential variation to exceed the bias applied to the diode valves 29 and 31, the latter valves become conducting respectively on alternate half-cycles of the voltage variations. When either diode is conducting the resistance 28 is effectively shunted by either of the resistances 30 and 32, and the feedback resistance between the anode and control electrode of the valve 25 is reduced approximately by a factor of 10. The negative feedback is therefore substantially increased and the gain of the amplifier is correspondingly reduced. By a suitable choice of the bias applied to the diode valves 29 and 31 it is arranged that the diodes 29 and 31 become conducting when the current variations applied to the control electrode of the valve 25 have an amplitude represented by the abscissa of the point 36. With input signals of an amplitude to cause the diode valves 29 and 31 to conduct, the gain of the amplifier is represented by the slope of the dotted line between the points 36 and 13 in Figure 2. Therefore by suitable choice of the parameters for the amplifier 8, its characteristic is made to conform closely to the ideal characteristic shown in full lines in Figure 2. In practice some curvature is introduced by the diodes 19, 21, and 29, 31 when operating near limiting conditions so that the separate parts of the amplifier characteristic merge gradually one into another. It is of course possible by using more stages of limitation to make the amplifier characteristic conform even more closely than indicated to the ideal characteristic.

In the modification of the invention illustrated in Figure 4, instead of using an amplifier 8, a signal linearly proportional to $\dot{\theta}$ obtained from the tachogenerator 11 is passed through a non-linear device 38 and the output of the device 38 is fed to a subtracting circuit 37. To this circuit 37 there is also fed the input signal x and a signal linearly proportional to θ, in such manner that the output of the circuit 37 is representative of the difference between $(x-\theta)$ and the output of 38. The device 38 is arranged to have a characteristic which is effectively the inverse of that shown in Figure 2, so that the output from the circut 38 is a signal curvilinearly dependent upon its argument $\dot{\theta}$ but linearly dependent upon θ in the same way as $(x-\theta)$. The output of the circuit 37 therefore corresponds to the output of the device 10 in Figure 1, and it is fed via the high gain amplifier 12 to the servo-motor 1. The operation of this modification is substantially the same as that shown in Figure 1. In either case for values of $\dot{\theta}$ less than the equilibrium velocity of the servo-motor 1, equal values of the signal dependent upon $(x-\theta)$ and of the signal dependent upon $\dot{\theta}$ (as fed to the device 10 or 37 as the case may be) respectively represent such values of $(x-\theta)$ and $\dot{\theta}$ that under maximum reverse torque, the deceleration of the servo-motor theoretically causes $(x-\theta)$ and $\dot{\theta}$ to be simultaneously zero. As aforesaid, this theoretical result cannot be exactly attained in practice, and the following claims are, it is to be understood, subject to this practical limitation.

What I claim is:

1. Servo-mechanism including a servo-motor, an element displaceable by said servo-motor, means for deriving a first feedback signal dependent on the displacement of said element, means for deriving a second feed-

back signal depending on the velocity of said element, means responsive to the difference between an input signal and said first feedback signal to derive a displacement error signal, means for comparing said error signal and said second feedback signal, and means responsive to the compared signals for applying a fixed driving force to the servo-motor to displace said element in the sense to reduce said error signal when said error signal exceeds said second feedback signal and for applying a fixed decelerating force to said servo-motor when said feedback signal exceeds said error signal, the means for deriving at least one of said compared signals having a non-linear characteristic dependent on the deceleration law of the servo-motor under said decelerating force to cause the second feedback signal to exceed said error signal only when said error signal corresponds to the displacement of said element involved in bringing the servo-motor to rest under said decelerating force.

2. Servo-mechanism including a servo-motor, an element displaceable by said servo-motor, means for deriving a first feedback signal dependent on the displacement of said element, means for deriving a second feedback signal dependent on the velocity of said element, means responsive to the difference between an input signal and said first feedback signal to derive a displacement error signal, means for comparing said error signal and said second feedback signal, and means responsive to the compared signals for applying a predetermined torque to said servo-motor to displace said element in a sense to reduce said error signal when said error signal exceeds said second feedback signal and for applying a predetermined reverse torque to the servo-motor when said second feedback signal exceeds said error signal, the means for deriving at least one of said compared signals having a non-linear characteristic dependent on the velocity-displacement law of the servo-motor under said reverse torque to cause said second feedback signal to exceed said error signal only when said error signal corresponds to the displacement of said element involved in bringing the servo-motor to rest under said reverse torque.

3. Servo-mechanism including a servo-motor, an element displaceable by said servo-motor, means for deriving a first feedback signal linearly proportional to the displacement of said element, means for deriving a second signal linearly proportional to the velocity of said element, means responsive to the differences between an input signal and said first feedback signal to derive a displacement error signal, means for comparing said error signal and said second feedback signal for applying a predetermined torque to the servo-motor to displace said element in a sense to reduce said error signal when said error signal exceeds said second feedback signal and for

applying a predetermined reverse torque to the servo-motor when said second feedback signal exceeds said error signal, said means for deriving said error signal comprising means for differentially combining said input signal and said first feedback signal and an amplifier for amplifying the resultant of said combined signals, said amplifier having a non-linear characteristic dependent on the deceleration law of the servo-motor under said reverse torque to cause said second feedback signal to exceed said error signal only when said error signal corresponds to the displacement of said element involved in bringing said servo-motor to rest under said reverse torque.

4. Servo-mechanism including a servo-motor, an element displaceable by said servo-motor, means for deriving a first feedback signal linearly proportional to the displacement of said element, means for deriving a second feedback signal dependent on the velocity of said element, means responsive to the differences between an input signal and said first feedback signal to derive a displacement error signal, means for comparing said error signal and said second feedback signal, and means responsive to the compared signals for applying a predetermined torque to the servo-motor to displace said element in the sense to reduce said error signal when said error signal exceeds said second feedback signal and for applying a predetermined reverse torque to said servo-motor when the second feedback signal exceeds said error signal, said means for deriving said second feedback signal comprising means for deriving a signal linearly proportional to the velocity of said element and an amplifier for amplifying said linearly proportional signal and having a non-linear characteristic dependent on the deceleration law of said servo-motor under said reverse torque to cause said second feedback signal to exceed said error signal only when said error signal corresponds to the displacement of said element involved in bringing said servo-motor to rest under said reverse torque.

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