

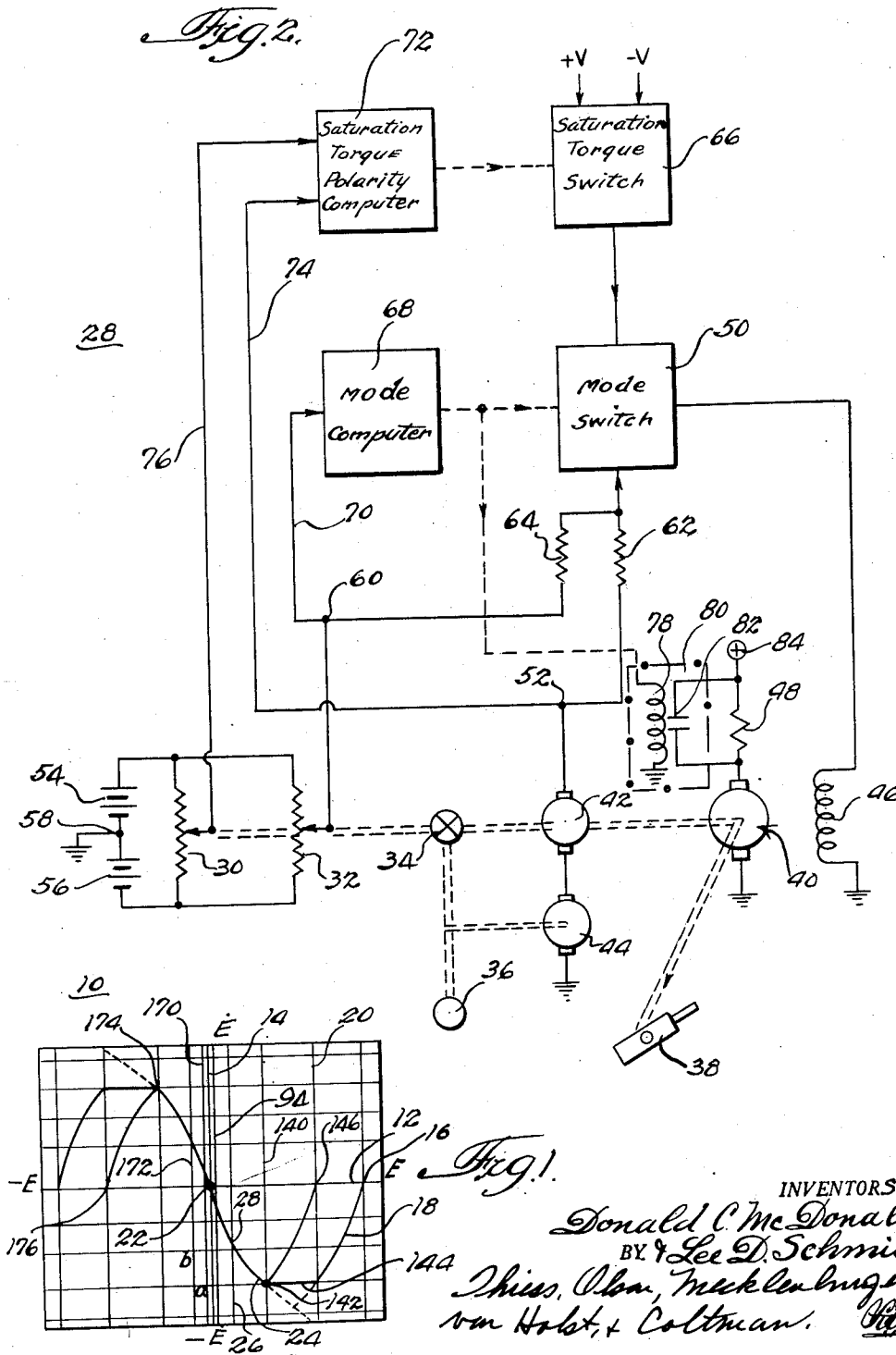
June 18, 1957

D. C. McDONALD ET AL
MULTIPLE MODE SERVOMECHANISMS

2,796,569

Filed Dec. 13, 1954

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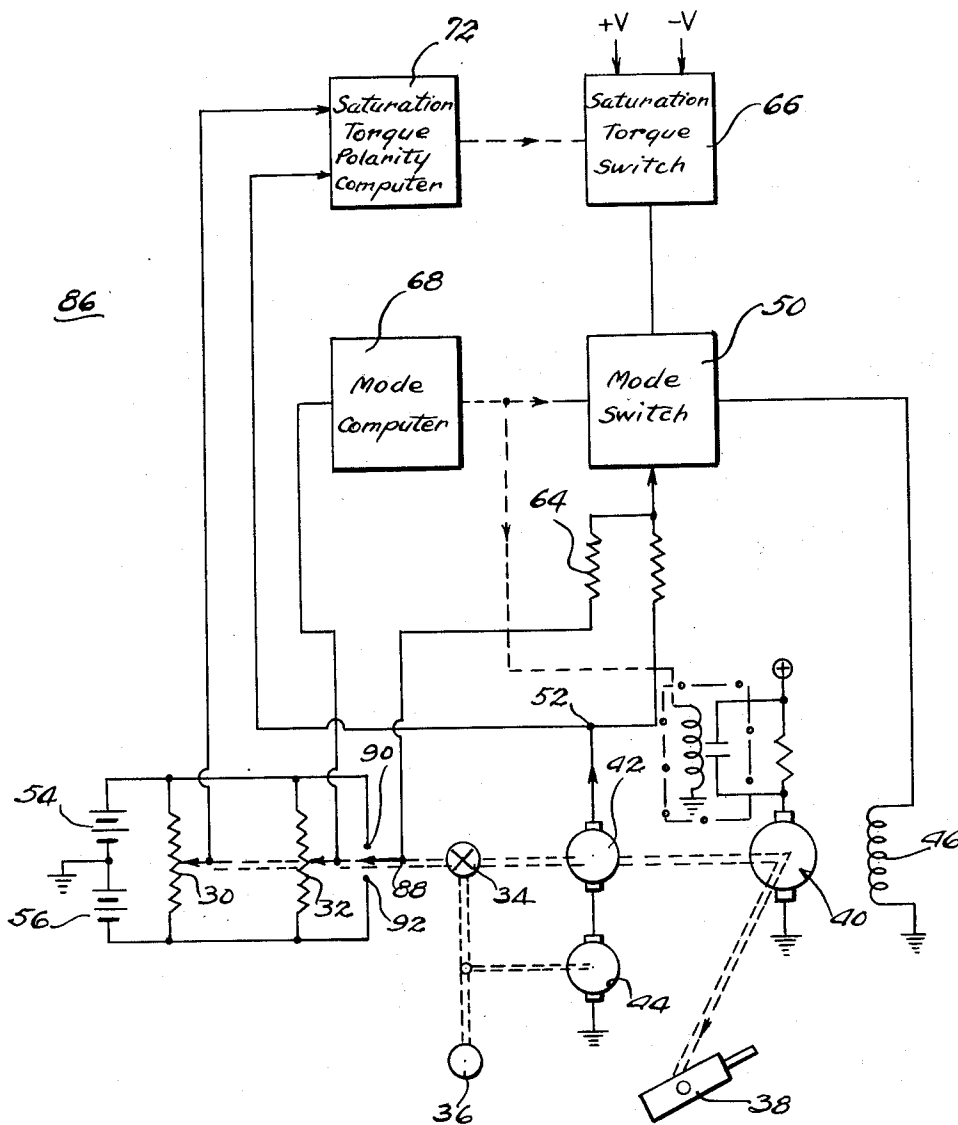
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Filed Dec. 13, 1954

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Fig. 3.



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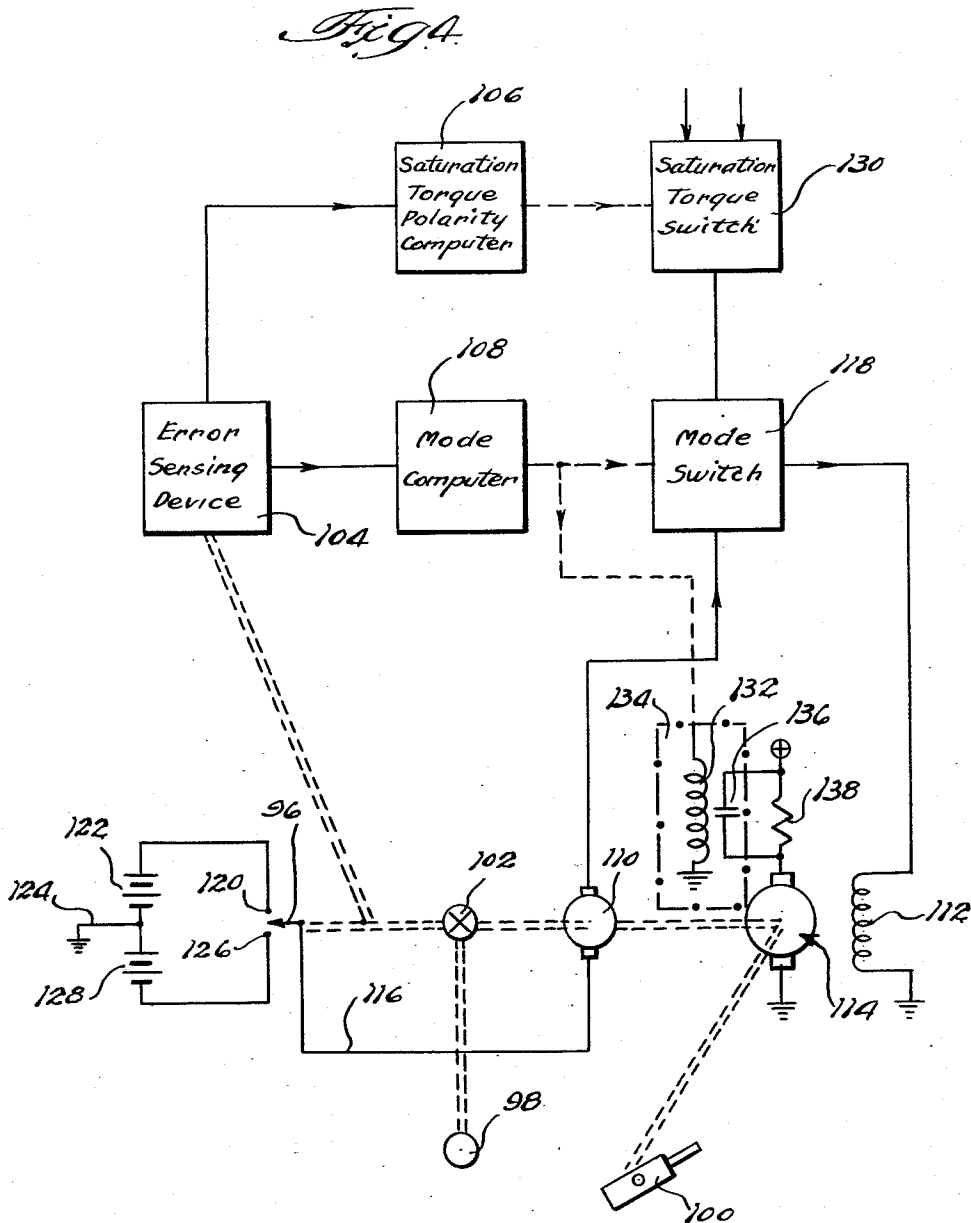
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Filed Dec. 13, 1954

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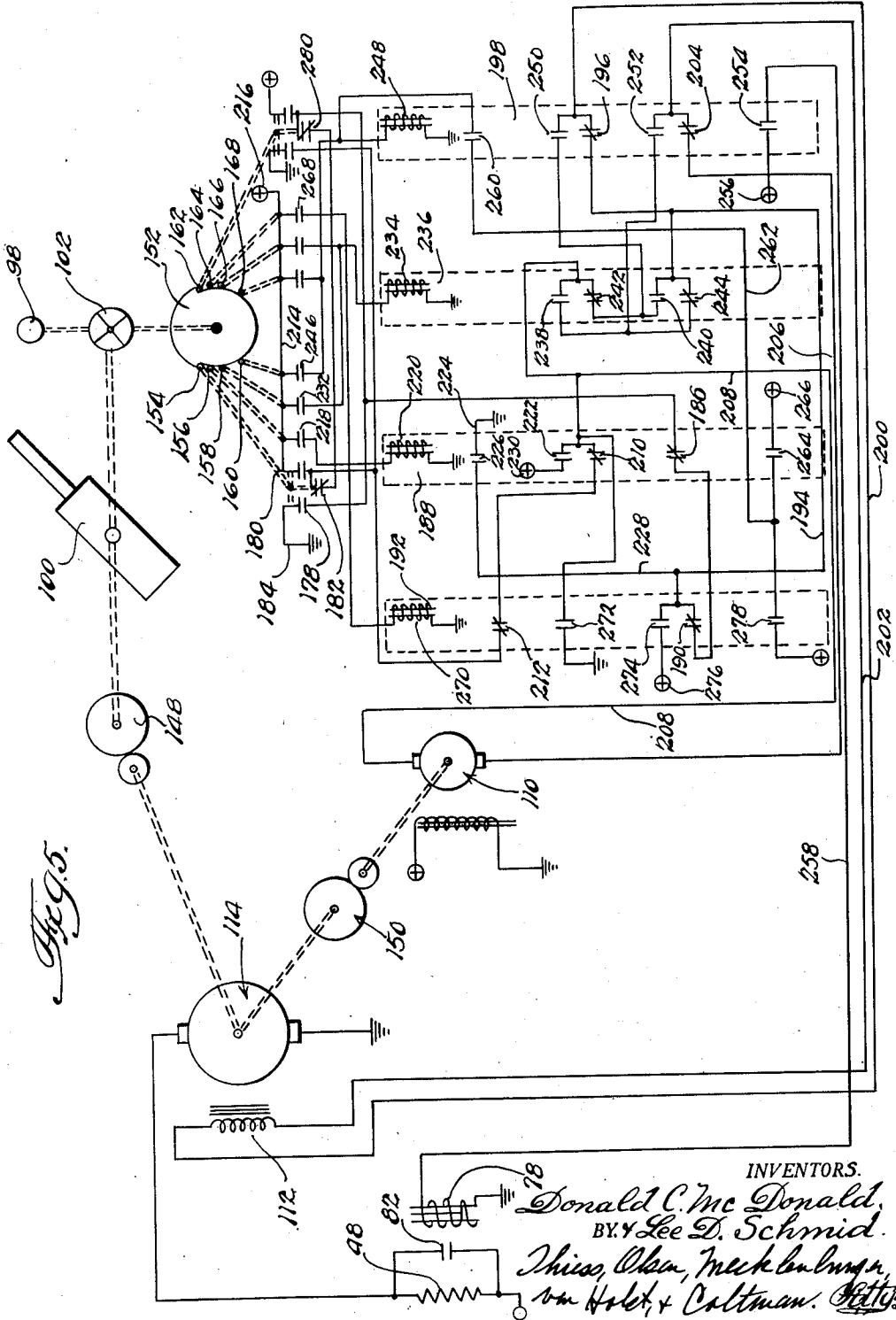
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MULTIPLE MODE SERVOMECHANISMS

Filed Dec. 13, 1954

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2,796,569

MULTIPLE MODE SERVOMECHANISMS

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Application December 13, 1954, Serial No. 474,963

20 Claims. (Cl. 318—32)

This invention relates to improved servomechanisms and more particularly to an improved multiple mode servomechanism wherein switch means are employed for both mode switching and control purposes within the various modes.

In the growing field of servomechanism research the systems are becoming increasingly complex and powerful. Vacuum tube amplifiers, magnetic amplifiers, potentiometers and the like must be constructed to adequately handle large amounts of power, dissipate large amounts of heat and still withstand the shocks of impact and vibration normally encountered in field use. To construct amplifiers and the like having these characteristics is costly and results in massive control systems. As weight is an important factor in aircraft and vehicular controls, such increases in mass and complexity are highly undesirable. In the co-pending application of Donald C. McDonald, Ser. No. 287,955, filed on May 15, 1952, now Patent No. 2,777,285, a system of multiple mode operation is disclosed in which the desired accuracy, stability and speed of response are attained for small values of error through the use of linear amplifiers while for large values of error the amplifiers and control system may be by-passed producing optimum response for large error values while reducing the cost and complexity of the amplifiers and associated equipment.

In a preferred form of the multiple mode system, linear control of the output driving means is provided for small values of error and/or error rate whereby the torque of the output bears a proportional relationship to an integro-differential function of the error, while in the outer mode of operation, that is when there are substantial differences between the position and/or velocity of the output relative to the input, the amplifier which normally produces linear control is by-passed and the full torque of the motive means is utilized. Such a system is believed to produce the optimum characteristics of any servo system having mechanical components of limited capacity. The purpose of additional research in the field of servomechanisms is therefore primarily directed to the simplification of the control equipment and the consequent reduction in the weight and complexity of the entire system.

It is therefore one object of this invention to provide an improved servomechanism capable of producing optimum speed of response and static accuracy with a minimum of or no overshoot and employing a greatly simplified mechanical system.

It is another object of this invention to provide an improved servomechanism having inherent amplification in the driving means whereby all vacuum tube amplifiers, magnetic amplifiers and the like may be eliminated.

It is still another object of this invention to provide an improved servomechanism having multiple modes of operation.

It is a further object of this invention to provide an improved multiple mode servomechanism in which control within the various modes and transition between the

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various modes are accomplished by simple switching devices.

It is still another object of this invention to provide an improved multiple mode servomechanism in which all control functions and mode transitions are performed by mechanical switch means whereby discontinuous servomechanism operation produces a minimum of overshoot and optimum positional accuracy.

It is still another object of this invention to provide an improved multiple mode servomechanism in which a damping signal bearing a proportional relationship to the output velocity is employed selectively in the output drive means to produce a plurality of operating modes, the point of insertion of said damping signal differing from the point of removal thereof.

It is another object of this invention to provide an improved servomechanism in which a torque reversal is effected at a predetermined time by switch means to cause error and error rate to approach the zero values coincidentally.

It is another object of this invention to provide an improved servomechanism having a simplified computer for determining full torque reversal to effect simultaneous positional and velocity agreement between a controller and a load.

It is still another object of this invention to provide an improved servomechanism in which simple cam means and mechanical switches are employed for control and mode switching purposes.

Further and additional objects of this invention will become obvious from a consideration of this description, the accompanying drawings and the appended claims.

In one form of this invention a simple electromechanical device requiring no amplifiers or the like is utilized to control a driving motor for positioning a massive load rapidly and accurately in response to the manipulation of a simple hand wheel input. More particularly the hand wheel and load are coupled together through a differential device whereby an error signal is generated which operates a plurality of cam means to actuate various switches for applying corrective force to the load. The corrective forces which are applied to the load vary in accordance with the magnitude of the error and in accordance with the velocity of the output when said velocity is within predetermined ranges. Switch means are also provided to effect instantaneous full torque reversal at a predetermined time to cause simultaneous positional and velocity agreement between the controller and the load.

For a more complete understanding of this invention reference will now be made to the accompanying drawings wherein:

Fig. 1 is a phase plane portrait illustrating the operation of one embodiment of this invention;

Fig. 2 is a block diagram of one embodiment of this invention;

Fig. 3 is a block diagram of an alternate embodiment of this invention;

Fig. 4 is a block diagram of a third embodiment of this invention; and

Fig. 5 is a detailed diagrammatic illustration of the various components of the embodiment of Fig. 4.

Theory of operation

Referring now to the drawings and more particularly to Fig. 1 a conventional phase plane diagram is shown having positive and negative errors plotted along the abscissa 12 and positive and negative error rates plotted along the ordinate 14. The operation of a second order servomechanism may clearly be understood from a phase plane portrait of the system. If a positive step function of error is introduced into the system being diagrammed,

the system will be positioned at point 16 in the phase plane diagram. This will actuate the control mechanism to introduce a negative error velocity to reduce the error to zero. Therefore, the system will follow the curve 18 illustrating increased negative velocity with decreasing positive error. The shape of the curve 18 is determined by the inertia of the system, and the type of signal applied to the prime mover.

In accordance with the teaching of the above identified application, the magnitude of error at the point 16 will determine the mode of operation. If the error is small the system will be energized in a low power mode with various forms of damping to insure a minimum of zero overshoot and good static accuracy. In inner mode operation the trace of the portrait curve will always have a small slope. If the magnitude of error is large, it is desirable to apply the maximum power of the prime mover with little or no damping in order to reduce the error in a minimum time. This will produce a portrait such as curve 13 having a very steep slope. In the diagram of Fig. 1 the ordinate 20 is the mode boundary and therefore the point 16 defines an error magnitude in the outer mode, thus producing the maximum torque in the prime mover. The shape of the curve 18 in the outer mode is determined by the maximum torque of the prime mover and the inertia of the entire system and is parabolic in nature.

A torque reversal curve 24, starting at the origin 22 and having a shape which is a mirror image of the full torque operating curve 18, is drawn in the lower right hand quadrant of the phase plane 10. If the maximum torque is applied to the load for an error indicated at point 16 but is reversed at the instant that the operating curve 18 intersects the torque reversal curve 24, the error and error rate will approach zero coincidentally producing optimum response from the system. While the value of error at which the system enters outer mode operation is defined by ordinate 20, it is believed clear that a substantial amount of hysteresis is desired in the system so that a small reduction in the error will not cause the system to immediately return to inner mode operation. As will be described with respect to the various embodiments herein shown, a second mode boundary 26 is established and this boundary is effective only for values of decreasing error. Therefore, as the system follows the torque reversal curve 24 to the origin it will shift to inner mode operation at point 28. Inner mode operation may either be typical linear servo operation or it may be a low power contactor mode with output damping, as will be described hereinafter. Further reference will be made to the phase plane diagram 10 as each of the embodiments herein disclosed is discussed in detail.

Linear system

The first embodiment 28 is illustrated in Fig. 2 in which two potentiometers 30 and 32 are driven from the output of a differential 34. The position of the output of differential 34 is determined by the relative positions of an input such as hand wheel 36 and a load such as gun 38. The various dotted lines interconnecting these components illustrate direct mechanical couplings so that the load 38, a drive motor 40, an output tachometer generator 42, and one input of the differential 34 are all mechanically coupled. These various devices may be coupled through gear means to provide a substantial reduction in speed for the load 38. Similarly, the input 36, input tachometer generator 44, and one input of the differential 34 are all mechanically coupled. The purpose of this system is to energize the motor 40 to produce positional agreement between the input 36 and the load 38 at all times. This is accomplished through a control system which determines the energization of field winding 46 of the motor 40 and also controls the insertion or removal of a resistor 48 in the armature circuit of motor 40.

In this system two modes of operation are provided. The inner or linear mode provides a direct connection through mode switch 50 between the field winding 46 of motor 40 and the potentiometer 32 and tachometer generators 42 and 44. The armatures of tachometer generators 42 and 44 are connected in series opposition so that any voltage appearing at point 52 will represent the difference between the input and output velocities, i. e., error rate. The potentiometer 32 is a linear device and has a pair of voltage sources 54 and 56 connected thereacross with a common ground 58 therebetween whereby the center position on the linear potentiometer 32 will produce a zero voltage at point 60, while positive or negative displacements of the wiper of potentiometer 32 will produce positive or negative voltages respectively at point 60. The voltages appearing at points 52 and 60 are applied through resistors 62 and 64 respectively to the field winding 46 in an additive relationship so that the excitation of field winding 46 in the inner mode will follow the function $k_1 E - k_2 \dot{E}$. By applying this signal directly through the mode switch 50 to the field winding 46 inherent amplification in the field winding is utilized, thus eliminating the need for vacuum tube amplifiers and the like. While this system is highly desirable for small values of error, the time required to reduce large values of error is excessive. Therefore, for large error values the mode switch 50 is actuated whereby a fixed positive or negative voltage is applied through saturation torque switch 66 and mode switch 50 to the field winding 46. The voltages thus applied are selected to produce the maximum output of the motor 40. The mode switch 50 is actuated by a mode computer 68 which is energized from the linear potentiometer 32 through conductor 70. Thus, whenever the error exceeds a predetermined maximum for inner mode operation the mode computer senses this error magnitude and actuates the mode switch 50.

To utilize a full torque mode it is desirable that a computer be employed to reverse the full torque at such a time that the system will follow the torque reversal curve 24 of Fig. 1 producing zero error and error rate simultaneously. To do this a saturation torque polarity computer 72 controls the saturation torque switch 66. The switch will selectively apply large fixed voltages to the field winding 46, the polarity thereof being selected to eliminate the error. The computer 72 is energized through conductor 74 from point 52 at which a voltage appears representative of error rate. The computer 72 is also energized through conductor 76 from a nonlinear potentiometer 30 connected across the bipolar voltage sources 54 and 56. The potentiometer 30 is selected to produce a signal proportional to the square root of the error and is applied to the saturation torque polarity computer 72 in a subtractive relationship with the error rate output applied through conductor 74. The signal applied to the computer 72 follows the function $k_3 \dot{E} - \sqrt{E}$. This function defines the torque reversal curve 24 of the phase plane diagram. Therefore when the voltage applied to computer 72, which may be a simple relay coil, falls to a predetermined value close to zero, the saturation torque reversing switch will be actuated.

In addition to applying a large fixed voltage to field winding 46, the mode computer 68 energizes a coil 78 in relay 80 to close associated contacts 82 and thus bypass armature resistor 48. A direct connection is thereby provided between the armature of motor 40, voltage terminal 84, and ground. Maximum output is thereby attained from motor 40 when the system is operating in the outer mode. Means is also provided in the mode computer 68 to maintain outer mode operation while the system is following the curve 18 and the curve 24 until the error and/or error rate are reduced to predetermined values at which time the system returns to the low power inner mode operation. This delay in return to the inner mode may be accomplished merely by the hysteresis

which is inherent in an electromagnetic relay in the mode switch or it may be produced by contact arrangements which provide locking circuits for the mode switch.

Discontinuous inner mode system

Referring now to Fig. 3, an alternate embodiment of this invention is illustrated in which inner mode operation is discontinuous in character. The system 86 of Fig. 3 includes all of the apparatus above described with respect to Fig. 2 having an input 36 and load 38 connected together through a differential 34 to produce an error signal which operates a nonlinear potentiometer 30 and linear potentiometer 32. In addition to the potentiometers 30 and 32 the output of differential 34 also actuates a two-position switch 88 which is connected through resistor 64 to the mode switch 50. Thus, in the inner mode, when mode switch 50 applies the signal from the tachometer generator appearing at point 52 and the signal from the contactor 88 to the field winding 46, the operation of the motor 40 is not linear with respect to error and error rate, but has a discontinuous error characteristic. Thus, when a negative error of predetermined magnitude exists in the system, differential 34 causes contact arm 38 to engage contact 90 applying the fixed positive potential of source 54 to the field winding 46 through resistor 64 and mode switch 50. Similarly, if a substantial positive error exists, contact arm 88 engages contact 92 providing negative excitation from voltage source 56 in the field winding 46. While this type of inner mode operation is less accurate than the system of Fig. 2, it has certain features which compensate for this inaccuracy.

The linear potentiometer 32 is, in this embodiment, required to handle very little power as it energizes only the mode computer 68 while the contactor 88 is designed to handle the substantial power necessary to energize the field winding 46. With the use of the saturation torque polarity computer 72 whereby error and error rate simultaneously approach zero, the inner mode may be designed to include only a small area of the phase plane, thus removing many detrimental effects from contactor operation. The ordinate 94 of the phase plane diagram defines the positive error magnitude at which the contactor 88 engages contact 92 and this therefore defines the maximum allowable error in the system. The nonlinear potentiometer 30 and tachometer generators 42 and 44 function in this embodiment in precisely the same manner as described above to energize the computer 72 and thus control the operation of torque switch 66 to apply maximum torque to the field winding 46 in an appropriate direction to reduce the error and error rate simultaneously.

System utilizing torque reversal based on error only

Another alternate form of the invention is illustrated in Fig. 4 wherein both of the potentiometers in the controller are eliminated and a simple error sensing contactor 96 is employed. In this system an input hand wheel 98 and a load 100 are coupled mechanically to a differential 102, the output of which represents the instantaneous value of the error. The output of differential 102 controls the contactor 96 and an error sensing device 104 which actuates both a saturation torque polarity computer 106 and a mode computer 108. A single tachometer generator 110 driven from the output is employed in this embodiment so that output damping rather than error rate damping is applied to the field winding 112 of output motor 114. One armature terminal of tachometer generator 110 is connected through conductor 116 to the contactor 96 and the other terminal thereof is applied through mode switch 118 to the field winding 112 whenever the system is operating in the inner mode. When a negative error is experienced the contact arm 96 engages contact 120 applying positive voltage source 122 to the field winding. This circuit may be traced from ground 124 through positive voltage source 122, contact 120, contact arm 96, conductor 116, tachometer gen-

erator 110, mode switch 118 and field winding 112 to ground. Similarly, if a positive error is experienced, contact arm 96 engages contact 126 applying a negative voltage from source 128 to the circuit just described.

As already described, whenever an error of predetermined magnitude is sensed by the error sensing device 104 the mode computer 108 is energized to actuate the mode switch 118 and apply the output of saturation torque switch 130 to the field winding 112. At the same time, the inner mode circuit above described is opened and the coil 132 of relay 134 is energized to close contacts 136, thus by-passing armature resistance 138.

In this embodiment saturation torque polarity is determined by error only and the computer 106 is not actuated by a signal combining error and error rate as previously described. Therefore, the torque reversal curve 24 of the phase plane portrait 10 is no longer employed, but instead a single ordinate 140 determines torque reversal. It will be apparent that from the broad theory above described, if a vertical ordinate is employed as a torque reversal line and the full torque operation of the system follows the general contour of torque reversal curve 24, a family of curves, one of which goes through the original, may be followed by the system. Thus it would be possible for this system to substantially overshoot or undershoot the origin of the phase plane diagram. To avoid this type of erratic operation all saturation torque reversal will occur at the single point 142 in the phase plane diagram. As will be clear, torque reversal at a single point in the phase plane is possible because the system is one of limited capabilities and thus the motor 114 will have a maximum speed for given field and armature voltages. Thus, irrespective of the initial error, the full torque of the prime mover will cause the system to follow a line in a common family with curve 18 up to the maximum output velocity corresponding to a line 144. This horizontal line on a diagram plotting error versus error rate assumes, for the sake of illustration, a step function error input and not a continually varying input, although the theory is quickly applicable to continually varying functions. Torque reversal will always occur at point 142 on line 144. To insure proper torque reversal at the point 142 for all outer mode operation it is necessary that the mode boundary 20 be established at an error value at least as great as that represented by point 146 in the diagram. It is believed clear that if the mode boundary 20 were closer to the origin than the point 146, torque reversal would occur along the line 140 with a relatively small negative error rate, causing the system to go to zero error rate while an error still exists.

Detailed description of system utilizing torque reversal based on error only

For a detailed description of the operation of the embodiment of Fig. 4 reference will now be made to Fig. 5 wherein the load 100 is driven by the motor 114 through gear means 148. One typical example of such gear means provides a reduction ratio of 396-1. The tachometer generator 110 is also mechanically driven by motor 114 through similar gear means 150. The gear means 150 is normally selected to increase the speed of rotation of the tachometer generator 110 relative to the speed of motor armature 114. The gun 100 is mechanically connected to differential 102 as is the input hand wheel 98. The output of differential 102 is directly coupled to a cam 152 which has a plurality of cam followers associated therewith, said cam followers performing the operations described with respect to the inner mode control 96, mode computer 108, and saturation torque computer 106. The cam followers actuate a plurality of microswitches which in turn control four relays which function as mode switches and saturation torque switches. To understand the details of the mechanisms disclosed, the circuits of the micro-

switches and associated relays will be traced for various magnitudes of error. Comparing the phase plane diagram of Fig. 1 with the cam followers associated with cam 152: The first follower 154 is actuated to initiate inner mode control whenever the error exceeds the boundary indicated by ordinate 94; the follower 156 is actuated whenever the error exceeds the ordinate 26 which determines the return to inner mode operation when the error is being reduced; the follower 158 is raised by cam 152 whenever the error exceeds the ordinate 140 which defines the torque reversal line, which boundary is effective only as the error is being reduced also; and the final follower 160 is actuated whenever the error exceeds the outer mode boundary ordinate 20 and this causes the system to immediately shift to full torque undamped operation. While the left hand side of the phase plane portrait has not been discussed, it is believed clear from the diagram and from the mechanical structure of the embodiment of Fig. 5 that the system possesses bilateral symmetry and thus the system will function in an identical manner for both positive and negative error values. Therefore, the right hand group of cam followers 162, 164, 166 and 168 which correspond to the inner mode boundary 170, inner mode return boundary 172, torque reversal line 174, and outer mode boundary 176, and all of the associated circuitry, will not be discussed in detail.

Inner mode operation

Assuming a small error sufficient to initiate inner mode operation, the follower 154 is lifted by cam 152 to close switch contacts 178 and 180 and to open normally closed contact 182. Inner mode energization of motor 114 is thus initiated through a circuit which may be traced from ground 184 through closed contacts 178, normally closed contacts 186 of relay 188, normally closed contacts 190 of relay 192, conductor 194, normally closed contacts 196 of relay 198, conductor 200, motor field winding 112, conductor 202, normally closed contacts 204 of relay 198, conductor 206, the armature of tachometer generator 110, conductor 208, normally closed contacts 210 of relay 188, normally closed contacts 212 of relay 192, actuated contacts 180 and bus 214 to the positive terminal 216 of a voltage source. Thus, the field winding 112 of motor 114 is energized by the voltage source 216 and the tachometer generator 110 in series to produce contactor mode operation with output damping. The relay coil 78 remains unenergized whereby the resistance 48 remains in the armature circuit of motor 114 to limit the maximum torque of the system.

When the second cam follower 156 is raised for errors greater than the value of ordinate 26, the following circuits are completed. Contact 218 is closed, completing a circuit from positive voltage terminal 216 through bus 214, contacts 218 and coil 220 of relay 188 to ground. This actuates all of the associated contacts of relay 188 and changes the above described circuit for inner mode operation as follows: Switch contact 210 is open and switch contact 222 closed, by-passing the contacts 212 and 190 of relay 192 and completing the inner mode circuit. The inner mode circuit may now be traced from ground 224 through contact 226 of relay 188, conductor 228, conductor 194, contacts 196, conductor 200, field winding 112, conductor 202, contacts 204, conductor 206, the armature of tachometer generator 110, conductor 208 and closed contacts 222 to positive voltage terminal 230 which is common with voltage terminal 216. Thus the mode of operation is unchanged but the various switches are set up for future operation in the outer mode when the system is returning toward the origin after experiencing greater errors.

Similarly, when the cam follower 158 is actuated by the cam 152 indicating errors greater than the torque reversal ordinate 140, the system is positioned for later use in torque reversal. The circuits completed by the actuation of cam follower 158 are as follows: contacts 232 are closed completing a circuit from positive voltage terminal 216 through bus 214, actuated contacts 232 and coil 234 of

torque reversing relay 236 to ground. Relay 236 closes normally open contacts 238 and 240 and opens normally closed contacts 242 and 244. As no circuits have heretofore been described as employing these contacts, the operation of the system is unaffected by the operation of the relay 236 at this time.

Outer mode operation

When the error experienced by cam 152 is sufficient to raise cam follower 160 indicating an error greater than ordinate 20 of the phase plane portrait, contacts 246 are actuated completing the following circuits: Relay 198 is actuated from positive voltage terminal 216 through bus 214, contacts 246, and coil 248 to ground. Actuation of relay 198 opens normally closed contacts 196 and 204 and closes contacts 250, 252 and 254. Full torque operation of the system with minimum output damping is thereby provided. A circuit is completed from positive voltage terminal 256, which is connected to terminals 230 and 216, through contacts 254, conductor 258 and relay 78 to ground. Relay 78 is thus actuated, closing contacts 82 to by-pass resistor 48 producing maximum armature current in motor 114 and consequently maximum motor torque. The tachometer generator 110 is removed from the field circuit by contacts 250 and 252. The field circuit is completed from ground 224 through contacts 226, conductor 228, conductor 194, contacts 240 of relay 236, contacts 250 of relay 198, conductor 200, field winding 112, conductor 202, contacts 252 of relay 198, contacts 238 of relay 236 and contacts 222 of relay 188 to the positive voltage terminal 230. Thus the full positive voltage is applied to the motor field directly with no damping. For all error values greater than the ordinate 20 the maximum possible correcting force is applied to the load 100 from motor 114.

Torque reversal

The coil 248 of relay 198 is locked-in by contacts 260 and will be maintained in an energized condition after cam follower 160 is disengaged by cam 152. The locking circuit may be traced from ground through coil 248, contacts 260 of relay 198, conductor 262 and contacts 264 of relay 188 to positive voltage terminal 266 which is common with terminals 256, 230 and 216.

Assuming that the full torque of the motor 114 has reduced the error to the value defined by torque reversal line 140, the cam follower 158 will return to the normal position opening contact 232 and thus deenergizing coil 234 of relay 236. Contacts 238 and 240 will be opened thereby while contacts 242 and 244 will return to their normally closed positions. This will merely reverse the terminal connections of the motor field winding 112, thus producing full torque reversal. The motor field circuit may now be traced from ground 224 through contacts 226 of relay 188, conductor 228, conductor 194, contacts 244, contacts 252, conductor 202, field winding 112, conductor 200, contacts 250, contacts 242 and contacts 222 to the terminal 230. Thus full torque is applied to the system to reduce the velocity of the load at the maximum rate whereby error and error rate will be reduced to zero coincidentally. The coincidence of zero error and error rate depends on the proper selection of the torque reversal point 142. As the system will contain variables other than those described above, the load may not go precisely to the origin but may overshoot or undershoot that point by a small displacement. Therefore, it is necessary to return to the inner mode wherein more accurate positioning of the load with reduced power and output damping is provided.

Return to inner mode operation

When the error is reduced to the value defined by ordinate 28, cam follower 156 is deactivated, returning the system to inner mode operation. The deactuation of cam follower 156 opens contacts 218 deenergizing coil 220 of relay 188. Deenergizing of relay 188 opens contacts 264,

thus breaking the holding circuit for coil 248, permitting deactuation of relay 198. In so doing, contacts 254 are opened, deenergizing relay 78 and thus opening contacts 82 to reinsert resistance 48 in the armature circuit of motor 114. Deactuation of relay 198 also opens contacts 250 and 252 and closes contacts 196 and 204. The tachometer generator 110 is thereby reinserted in the field circuit as has already been traced in the first example of inner mode operation. The above operation relates solely to the correction of positive errors and as already stated, the system works identically for the correction of negative errors. The relay 192 functions for negative errors in the same manner that the relay 188 functions for positive errors. When the cam follower 164 is actuated contacts 268 are closed energizing coil 270 of relay 192. At the same time contacts 212 are opened and contacts 272 closed providing a ground for the inner mode circuit for reverse energization of the motor field 112. Similarly the contacts 274 close to substitute positive terminal 276 in the field circuit for ground 184 which is utilized for positive errors. A normally open contact 278 is provided on relay 192 and serves precisely the same function as contacts 264 of relay 188.

When within the limits of accuracy of the inner mode, that is, within the area bounded by ordinates 94 and 170, no power is applied to the field winding 112. However, within this area the tachometer generator 110 is applied to the field winding to provide output damping within this range. Thus, overshoot is reduced, and steady state stability added to the system. The field circuit under these conditions may be traced from field winding 112 through conductor 200, contacts 196, conductor 194, contacts 190, contacts 186, normally closed contacts 280, normally closed contacts 182, contacts 212, contacts 210, conductor 208, tachometer 110, conductor 206, contacts 204 and conductor 202 to the opposite terminal of field winding 112.

From the above description it is clear that a system of closed cycle control is provided by this invention which employs only rugged components such as relay contacts and mechanical devices such as cams whereby the need for vacuum tube amplifiers or the like is eliminated. The system produces optimum speed of response and accuracy with a minimum of overshoot giving performance characteristics equal or superior to complex amplifier systems heretofore known. It is a primary purpose of this invention to provide a multiple mode system which will provide substantial hysteresis for maximum efficiency for outer mode operation. Other advantages of this system over prior systems will be manifest to one skilled in the art.

Without further elaboration, the foregoing will so fully explain the character of our invention that others may, by applying current knowledge, readily adapt the same for use under varying conditions of service, while retaining certain features which may properly be said to constitute the essential items of novelty involved, which items are intended to be defined and secured to us by the following claims.

We claim:

1. In a position control system having an output motor means, position controlling means, and means for sensing the difference between the instantaneous positions of said motor means and said controlling means, means actuated by said sensing means to energize said motor means to reduce said difference, damping means to provide a signal for said motor means in accordance with and to oppose the motion thereof, means to remove the output of said damping means from said motor means for values of said difference greater than a predetermined value, and means to apply the output of said damping means to said motor means whenever said difference is reduced to a predetermined magnitude substantially less than said predetermined value.

2. A position control system comprising an output motor means, position controlling means, and means for

sensing the difference between the instantaneous positions of said motor means and said controlling means, means actuated by said sensing means to energize said motor means to reduce said difference, damping means to provide a signal for said motor means in accordance with and to oppose the motion thereof, means to remove the output of said damping means from said motor means for values of said difference greater than a predetermined value, and means to apply the output of said damping means to said motor means whenever said difference is reduced to a predetermined magnitude substantially less than said predetermined value.

3. A position control system comprising an output motor means, position controlling means, and means for sensing the difference between the instantaneous positions of said motor means and said controlling means, means actuated by said sensing means to energize said motor means to reduce said difference, damping means to provide a signal for said motor means bearing a proportional relationship to the velocity of said motor means and to oppose the motion thereof, means to remove the output of said damping means from said motor means for values of said difference greater than a predetermined value, and means to apply the output of said damping means to said motor means whenever said difference is reduced to a predetermined magnitude substantially less than said predetermined value.

4. A position control system comprising an output motor means, position controlling means, and means for sensing the difference between the instantaneous positions of said motor means and said controlling means, means actuated by said sensing means to energize said motor means to reduce said difference, damping means to provide a signal for said motor means bearing a proportional relationship to the velocity of said motor means and to oppose the motion thereof, switch means to remove the output of said damping means from said motor means and to energize said motor means for maximum output for values of said difference greater than a predetermined value, and switch means to apply the output of said damping means to said motor means and to reduce the maximum energization of said motor means whenever said difference is reduced from above said predetermined value to a predetermined magnitude substantially less than said predetermined value.

5. A position control system comprising an output motor means having armature and field means, position controlling means, means for sensing the difference between the instantaneous positions of said motor means and said controlling means, means actuated by said sensing means to energize said field means to reduce said difference, damping means to provide a signal to said field means bearing a proportional relationship to the velocity of said motor means to oppose the motion thereof, switch means to remove the output of said damping means from said motor means and to energize said motor means for maximum output for values of said difference greater than a predetermined value, and switch means to apply the output of said damping means to said motor means and to reduce the maximum energization of said motor means whenever said difference is reduced from above said predetermined value to a predetermined magnitude substantially less than said predetermined value.

6. A position control system comprising an output motor means having armature and field means, position controlling means, means for sensing the difference between the instantaneous positions of said motor means and said controlling means, means actuated by said sensing means to energize said field means to reduce said difference, tachometer generator damping means driven by said motor means to provide a signal to said field means bearing a proportional relationship to the velocity of said motor means to oppose the motion thereof, switch means to remove the output of said damping means from said motor means and to energize said motor means for

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maximum output for values of said difference greater than a predetermined value, and switch means to apply the output of said damping means to said motor means and to reduce the maximum energization of said motor means whenever said difference is reduced from above said predetermined value to a predetermined magnitude substantially less than said predetermined value.

7. A position control system comprising an output motor means, position control controlling means, and means for sensing the difference between the instantaneous positions of said motor means and said controlling means, means actuated by said sensing means to energize said motor means to reduce said difference, damping means to provide a signal for said motor means bearing a proportional relationship to the velocity of said motor means and to oppose the motion thereof, switch means to remove the output of said damping means from said motor means and to energize said motor means for maximum output for values of said difference greater than a predetermined value, means to reverse the maximum energization of said motor means whenever said difference is reduced to a value which will produce a minimum difference and a minimum rate of change of difference coincidently, and switch means to apply the output of said damping means to said motor means and to reduce the maximum energization of said motor means whenever said difference is reduced from above said predetermined value to a predetermined magnitude substantially less than said predetermined value.

4. A position control system comprising an output motor means having armature and field means, position controlling means, means for sensing the difference between the instantaneous positions of said motor means and said controlling means, means actuated by said sensing means to energize said field means to reduce said difference, damping means to provide a signal to said field means bearing a proportional relationship to the velocity of said motor means to oppose the motion thereof, switch means to remove the output of said damping means from said motor means and to energize said motor means for maximum output for values of said difference greater than a predetermined value, means to reverse the maximum energization of said motor means whenever said difference is reduced to a value which will produce a minimum difference and a minimum rate of change of difference coincidentally, and switch means to apply the output of said damping means to said motor means and to reduce the maximum energization of said motor means whenever said difference is reduced from above said predetermined value to a predetermined magnitude substantially less than said predetermined value.

9. In a position control system having an output motor means, position controlling means, and means for sensing the difference between the instantaneous positions of said motor means and said controlling means, switch means actuated by said sensing means to energize said motor means with a fixed limited excitation to reduce said difference, damping means to provide a signal for said motor in accordance with and to oppose the motion thereof, switch means to remove the output of said damping means from said motor means for values of said difference greater than a predetermined value, and switch means to apply the output of said damping means to said motor means whenever said difference is reduced from above said predetermined value to a predetermined magnitude substantially less than said predetermined value.

10. In a position control system having an output motor means, position controlling means, and means for sensing the difference between the instantaneous positions of said motor means and said controlling means, switch means actuated by said sensing means to energize said motor means with a fixed limited excitation to reduce said difference, damping means to provide a signal for said motor in accordance with and to oppose the motion thereof, switch means to remove the output of said damping means

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from said motor means and to energize said motor means with maximum excitation for values of said difference greater than a predetermined value, and switch means to apply the output of said damping means to said motor means whenever said difference is reduced from above said predetermined value to a predetermined magnitude substantially less than said predetermined value.

11. A position control system comprising an output motor means having armature and field means, position controlling means, means for sensing the difference between the instantaneous positions of said motor means and said controlling means, switch means actuated by said sensing means to energize said field means with fixed limited excitation to reduce said difference, damping means to provide a signal to said field means bearing a proportional relationship to the motion of said motor means and in opposition thereto, switch means to remove the output of said damping means from said motor means and to energize said motor means for maximum output for values of said difference greater than a predetermined value, and switch means to apply the output of said damping means to said motor means and to reduce the maximum energization of said motor means whenever said difference is reduced from above said predetermined value to a predetermined magnitude substantially less than said predetermined value.

12. A position control system comprising an output motor means having armature and field means, position controlling means, means for sensing the difference between the instantaneous positions of said motor means and said controlling means, switch means actuated by said sensing means to energize said field means with fixed limited excitation to reduce said difference, damping means to provide a signal to said field means bearing a proportional relationship to the motion of said motor means and in opposition thereto, switch means to remove the output of said damping means from said motor means and to energize said motor means for maximum output for values of said difference greater than a predetermined value, means to reverse the maximum energization of said motor means whenever said difference is reduced to a value which will produce a minimum difference and a minimum rate of change of difference coincidentally, and switch means to apply the output of said damping means to said motor means and to reduce the maximum energization of said motor means whenever said difference is reduced from above said predetermined value to a predetermined magnitude substantially less than said predetermined value.

13. A position control system comprising an output
50 motor means having armature and field means, position
controlling means, means for sensing the difference be-
tween the instantaneous positions of said motor means
and said controlling means, resistance means in series
55 with said armature means to produce limited excitation,
switch means actuated by said sensing means to energize
said field means with fixed limited excitation to reduce
said difference, damping means to provide a signal to
said field means bearing a proportional relationship to the
60 motion of said motor means and in opposition thereto,
switch means to remove the output of said damping
means from said motor means and to remove said resis-
tance means from the armature circuit for values of said
difference greater than a predetermined value, and switch
65 means to apply the output of said damping means to said
motor means and to insert said resistance means in said
armature circuit whenever said difference is reduced from
above said predetermined value to a predetermined mag-
nitude substantially less than said predetermined value.

14. A position control system comprising an output
70 motor means having armature and field means, position
controlling means, means for sensing the difference be-
tween the instantaneous positions of said motor means
and said controlling means, resistance means in series
with said armature means to produce limited excitation,
75 switch means actuated by said sensing means to energize

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said field means with fixed limited excitation to reduce said difference, damping means to provide a signal to said field means bearing a proportional relationship to the motion of said motor means and in opposition thereto, switch means to remove the output of said damping means from said motor means and to remove said resistance means from the armature circuit for values of said difference greater than a known difference, switch means to reverse the energization of said field means for a known difference less than said predetermined value, and switch means to apply the output of said damping means to said motor means and to insert said resistance means in said armature circuit whenever said difference is reduced from above said predetermined value to a predetermined magnitude substantially less than said predetermined value.

15. A position control system comprising an output motor means having armature and field means, position controlling means, means for sensing the difference between the instantaneous positions of said motor means and said controlling means, resistance means in series with said armature means to produce limited excitation, a fixed voltage source to energize said field means, bilateral switch means actuated by said sensing means to apply said voltage source to said field means to reduce said difference, switch means to reverse said voltage source for a known difference, damping means to provide a signal to said field means bearing a proportional relationship to the motion of said motor means, and switch means to remove said resistance and said damping means from the circuits of said motor means for differences of predetermined value.

16. In a position control system having an output motor means, position controlling means, and means for sensing the difference between the instantaneous positions of said motor means and said controlling means, operating means actuated by said sensing means to energize said motor means to reduce said difference, damping means to provide a signal for said motor means in accordance with and to oppose the motion thereof, means to remove the output of said damping means from said motor means for values of said difference greater than a predetermined value, means to apply the output of said damping means to said motor means whenever said difference is reduced to a predetermined magnitude substantially less than said predetermined value, and means to reverse said operating means to produce reverse energization of said motor means for a predetermined ratio of said difference to the rate of change of said difference whereby said difference and rate of change of said difference approach zero substantially coincidently.

17. A position control system comprising an output motor means, position controlling means, and means for sensing the difference between the instantaneous positions of said motor means and said controlling means, means actuated by said sensing means to energize said motor means to reduce said difference, damping means to provide a signal for said motor means bearing a proportional relationship to the velocity of said motor means and to oppose the motion thereof, switch means to remove the output of said damping means from said motor means and to energize said motor means for maximum output for values of said difference greater than a predetermined value, means to reverse the maximum energization of said motor means whenever the ratio of said difference to the rate of change of said difference is reduced to a predetermined value whereby said difference and the rate of change of said difference will approach zero substantially coincidently, and switch means to apply the output of said damping means to said motor means and to reduce the maximum energization of said motor means whenever said difference is reduced from above said predetermined value to a predetermined magnitude substantially less than said predetermined value.

18. In a position control system having an output

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motor means, position controlling means, and means for sensing the difference between the instantaneous positions of said motor means and said controlling means, control means actuated by said sensing means to energize said motor means in a proportional relationship to said difference to reduce said difference, damping means to provide a signal for said motor means in accordance with and to oppose the motion thereof, means to remove the output of said damping means from said motor means for values of said difference greater than a predetermined value, means to apply the output of said damping means to said motor means whenever said difference is reduced to a predetermined magnitude substantially less than said predetermined value, and means to reverse said operating means to produce reverse energization of said motor means for a predetermined ratio of said difference to the rate of change of said difference whereby said difference and rate of change of said difference approach zero substantially coincidently.

19. A position control system comprising an output motor means, position controlling means, and means for sensing the difference between the instantaneous positions of said motor means and said controlling means, control means actuated by said sensing means to energize said motor means in a proportional relationship to the magnitude of said difference to reduce said difference, damping means to provide a signal for said motor means bearing a proportional relationship to the velocity of said motor means and to oppose the motion thereof, switch means to remove the output of said damping means from said motor means and to energize said motor means for maximum output for values of said difference greater than a predetermined value, means to reverse the maximum energization of said motor means whenever the ratio of said difference to the rate of change of said difference is reduced to a predetermined value whereby said difference and the rate of change of said difference will approach zero substantially coincidently, and switch means to apply the output of said damping means to said motor means and to reduce the maximum energization of said motor means whenever said difference is reduced from above said predetermined value to a predetermined magnitude substantially less than said predetermined value.

20. A position control system comprising an output motor means having armature and field means, position controlling means, means for sensing the difference between the instantaneous positions of said motor means and said controlling means, control means actuated by said sensing means to energize said motor means in a proportional relationship to the magnitude of said difference to reduce said difference, damping means to provide a signal to said field means bearing a proportional relationship to the velocity of said motor means to oppose the motion thereof, switch means to remove the output of said damping means from said motor means and to energize said motor means for maximum output for values of said difference greater than a predetermined value, means to reverse the maximum energization of said motor means whenever said difference is reduced to a value which will produce a minimum difference and a minimum rate of change of difference coincidently, and switch means to apply the output of said damping means to said motor means and to reduce the maximum energization of said motor means whenever said difference is reduced from above said predetermined value to a predetermined magnitude substantially less than said predetermined value.

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