

May 7, 1946.

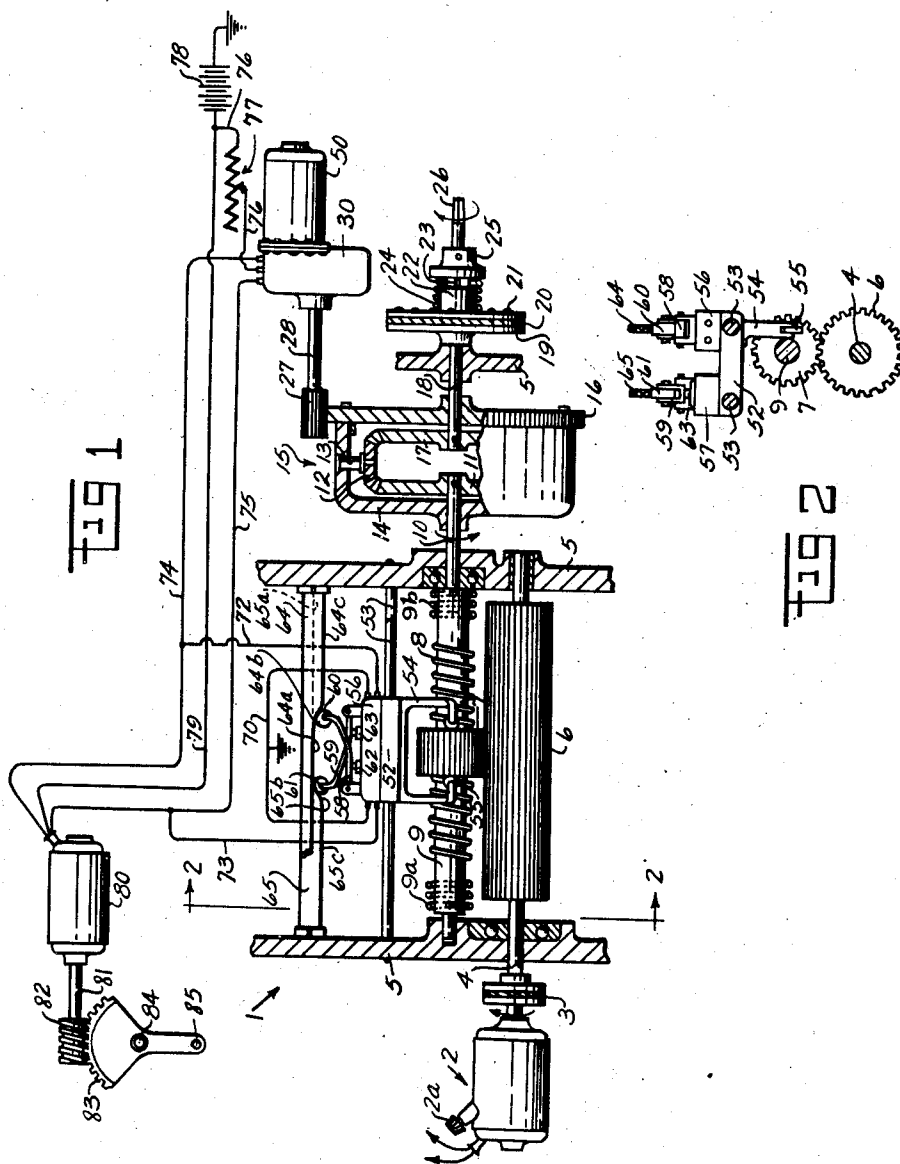
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2,399,685

DIFFERENTIAL SPEED RESPONSIVE DEVICE

Filed Feb. 9, 1943

7 Sheets-Sheet 1



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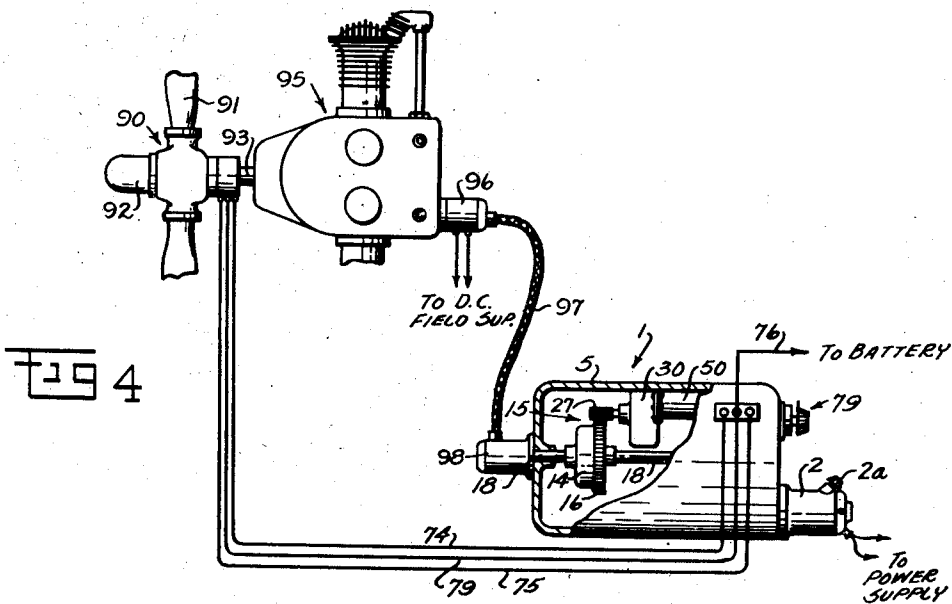
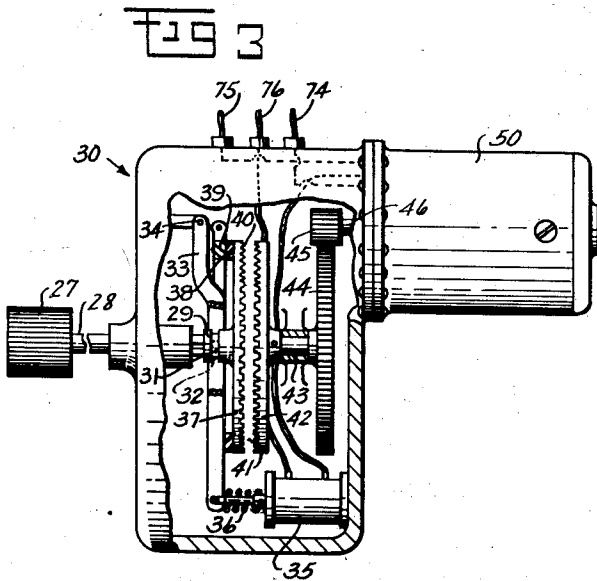
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DIFFERENTIAL SPEED RESPONSIVE DEVICE

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7 Sheets-Sheet 2



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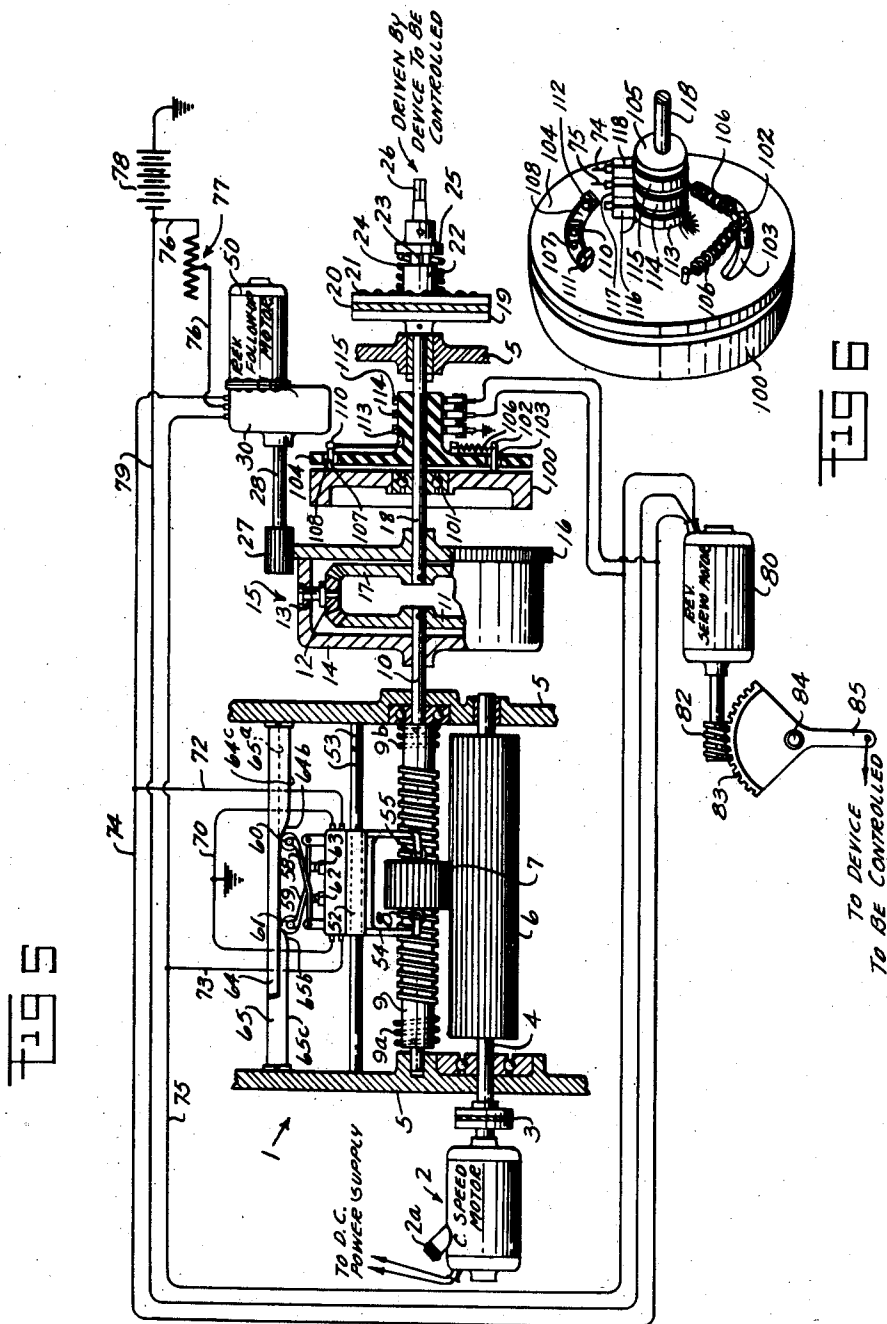
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DIFFERENTIAL SPEED RESPONSIVE DEVICE

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7 Sheets-Sheet 3



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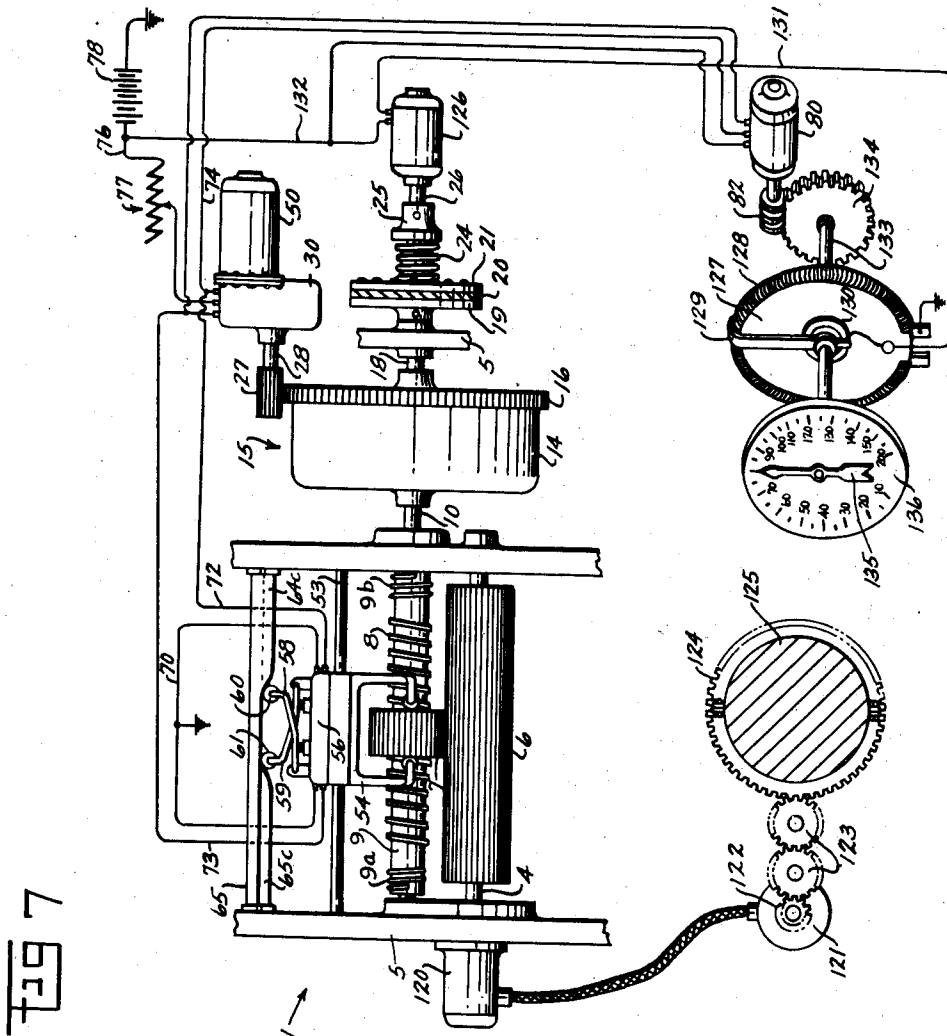
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DIFFERENTIAL SPEED RESPONSIVE DEVICE

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7 Sheets-Sheet 4



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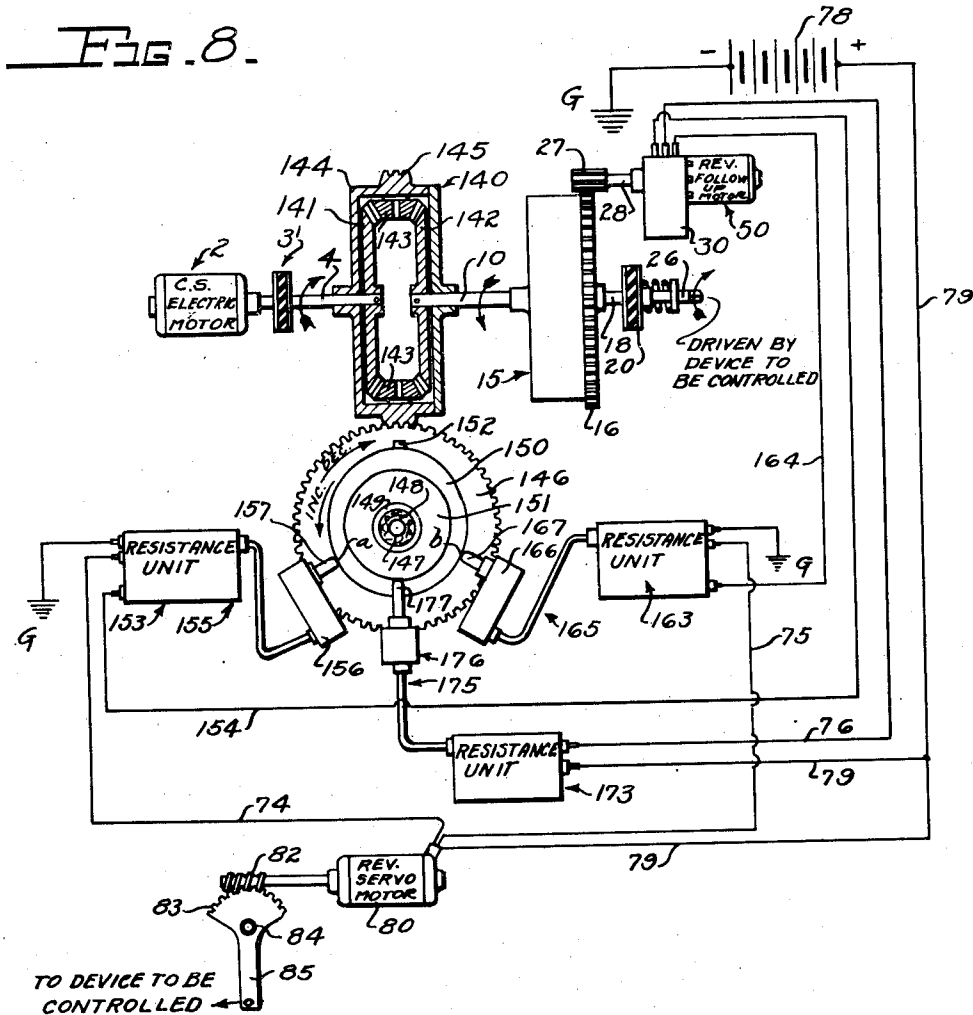
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DIFFERENTIAL SPEED RESPONSIVE DEVICE

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7 Sheets-Sheet 5



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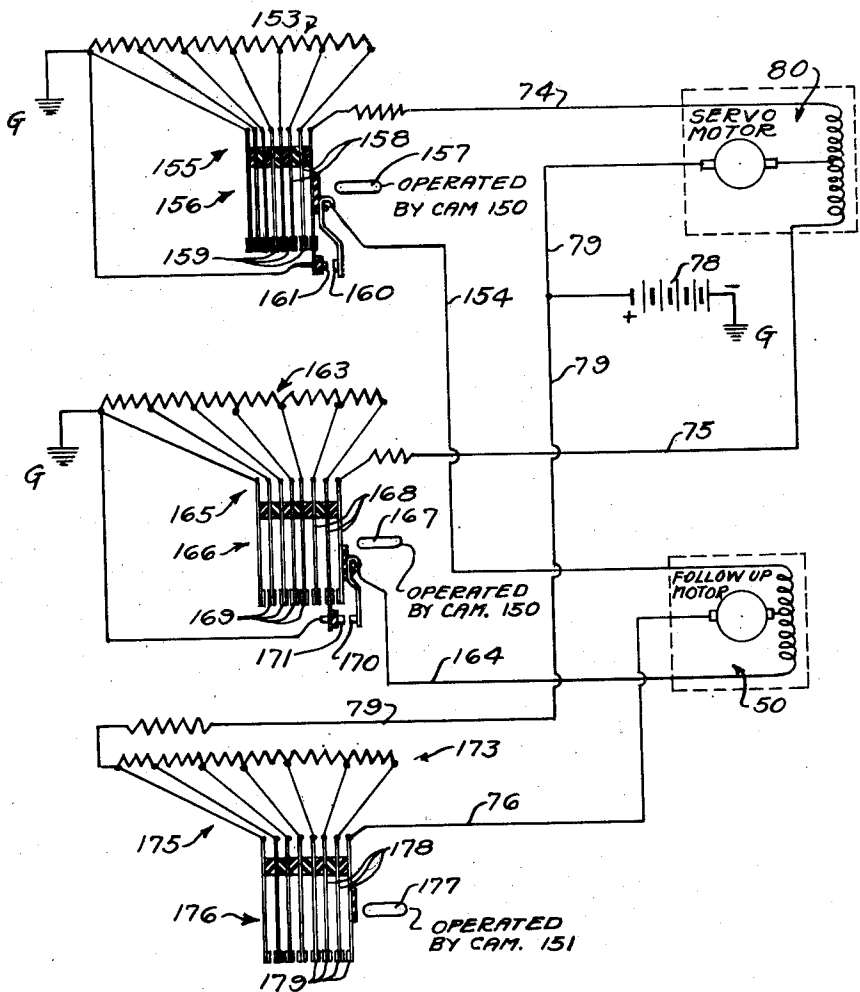
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DIFFERENTIAL SPEED RESPONSIVE DEVICE

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FIG. 9.



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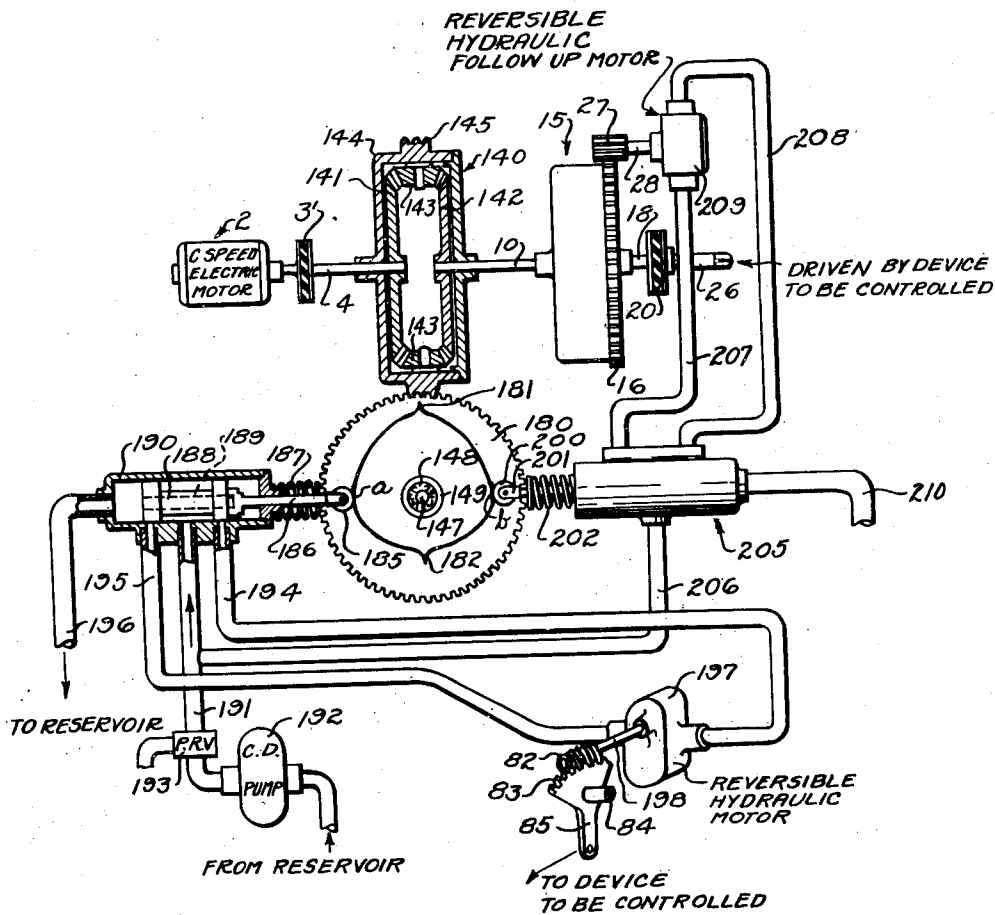
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FIG. 10.



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UNITED STATES PATENT OFFICE

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DIFFERENTIAL SPEED RESPONSIVE DEVICE

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Application February 9, 1943, Serial No. 475,297

16 Claims. (Cl. 264-9)

(Granted under the act of March 3, 1883, as amended April 30, 1928; 370 O. G. 757)

The invention described herein may be manufactured and used by or for the Government for governmental purposes, without the payment to me of any royalty thereon.

This invention relates to improvements in differential governors for use in the control of the speed of prime movers or as a synchronizer in maintaining a predetermined relation in the speeds of two relatively moving shafts, or plurality of prime movers.

The differential type of governor, though invented more than one hundred years ago, has never been widely used due to hunting characteristics present in the original form of the governor and in subsequent modifications thereof of which I am aware. If we take the case of a simple differential governor, in which the differential carrier or equivalent element is either directly or indirectly employed to actuate a control element upon displacement of the carrier in either direction from a neutral position, any departure in speed causing carrier displacement will initiate a control effect tending to cause the prime mover or other controlled device to return to the desired speed. The prime mover will be restored to the equilibrium speed condition however with the control element and carrier in a position other than the neutral position so that an over control will result which will start a continuous oscillation, the prime mover speed oscillating about the equilibrium speed value but never again attaining a constant value, and any change in load on the prime mover or other controlled device will in general make matters worse. The introduction of high viscous damping into such a control system obviously may reduce the amplitude of hunting oscillations to a negligible value but will also destroy the main advantage of the differential governors sensitivity, i. e. its ability to detect and utilize small changes in speed for initiating a control effect.

I am aware that it has already been proposed in the U. S. Patent to Donald M. Berges, Serial No. 2,160,324, to employ in a propeller pitch control mechanism a differential governor to axially shift a contact in either of two directions to engage either of a pair of pitch changing motor controlling contacts to energize the motor, and the pitch changing motor being connected by a follow-up to shift the said pair of contacts to stop the motor upon the proper pitch correction being made. This system, however, while an improvement over prior devices, is likely to hunt, because the inertia of the pitch chang-

ing motor will cause it to overrun the equilibrium position, which will initiate hunting.

In accordance with the present invention, a follow-up is employed which is entirely independent, so far as its rate of operation is concerned, from the movement of the controlled element, and further the follow-up speed is adjustable to adapt the governor to any particular prime mover irrespective of its inertia characteristics. The governor in accordance with the present invention also differs radically from previous proposals in that the follow-up is introduced directly into the differential control unit so that the controlling element thereof is always restored to a predetermined neutral position. The governor control within a predetermined part of its control range is of the proportionalizing type, i. e. the control effect produced is proportional to the off speed, and throughout the balance of its range the control effect may be of constant rate. Further, a governor in accordance with the invention may be constructed to include anticipating or acceleration responsive control which is very desirable for meeting certain governing requirements and by reducing time lag in the control system provides an additional anti-hunting feature.

The differential governor in accordance with the invention may be used to particular advantage as an engine speed control device by controlling the propeller pitch either in single or multiengine aircraft to replace the conventional centrifugal governor, with the advantage that in multiengine installations the need for separate engine synchronizing apparatus is eliminated, with a consequent saving of weight. Further, the governor in accordance with the invention can be adapted by regulation of its follow-up characteristics to any prime mover control, irrespective of the "characteristic time" or inertia characteristics thereof.

The novel structure of the speed responsive device in accordance with the present invention may also be employed as a speed indicating mechanism instead of as a governor, i. e., the mechanism is employed to position a pointer to indicate the instant speed of a rotating shaft.

It is therefore an object of the invention to provide a differential governor for controlling the speed of a prime mover in which the governor has stable governing characteristics.

It is a further object of the invention to provide a speed controlling apparatus including a differential type speed responsive means for controlling a servomotor and including restoring

means operatively connected to the speed responsive means, the rate of operation of the restoring means being manually or automatically adjustable and independent of the rate of operation of said servomotor.

It is another object of the invention to provide in governing apparatus of the character described, a differential speed responsive means having a control element displaceable from a neutral position in accordance with the departure in speed of a device to be controlled from a predetermined constant speed and of follow-up means operative through the differential to restore the control element to a predetermined neutral position.

It is another object of the invention to provide speed controlling apparatus including a servomotor adapted to position a speed controlling element, control means for the servomotor, a three-element differential having a first element driven at a constant speed, a second element driven by the device to be controlled, and a third element movable from a neutral position in response to the difference in speed between the first and second elements, operative connections between the third element and the control means of the servomotor and follow-up means operative to superimpose a correcting speed on one of said first or second elements to restore the third element to the predetermined initial position prior to or upon the prime mover's returning to the desired speed, the follow-up means being designed to prevent overrunning upon the third differential element's returning to the neutral position.

Another object of the invention is the provision, in a differential governor of the character described having an element shiftable from a neutral position upon a change in speed of a device such as a prime mover from a desired constant speed, of follow-up means operative to restore the said element to the neutral position prior to or at the instant when the prime mover is restored to the desired speed and in which the rate of follow-up is either constant or bears a predetermined relation to the magnitude of the speed deviation.

A further object of the invention is to provide a differential governor which incorporates means to effect an anticipatory control which is a function of the velocity or rate at which the speed of a controlled device departs from a desired speed.

Other objects of the invention not enumerated above will become apparent by reference to the detailed description of the invention hereinafter given and to the appended drawings in which:

Fig. 1 is a schematic view, partly in section, illustrating the constructional features of a differential speed responsive device in accordance with the invention;

Fig. 2 is a view taken on line 2—2 of Fig. 1;

Fig. 3 is an enlarged view, partly in section, illustrating details of a clutch and brake mechanism employed in conjunction with a follow-up motor of Fig. 1;

Fig. 4 is a schematic illustration of the application of the differential governor of Fig. 1 to the control of a variable pitch propeller, and the system may readily be extended for use as a multi-engine synchronizing and governing system;

Fig. 5 is a schematic view, partly in section, illustrating the governor of Fig. 1 equipped with an acceleration responsive control;

Fig. 6 is a perspective view of the acceleration

responsive control means of the governor of Fig. 5;

Fig. 7 is a schematic view illustrating the speed responsive mechanism of Fig. 1 employed as a speed measuring means;

Fig. 8 is a schematic view of a modification of the governor of Fig. 1 in which the speed of the servomotor and the follow-up motor is automatically varied as a function of the off-speed condition;

Fig. 9 is a schematic view illustrating the electrical wiring of the governor of Fig. 8; and

Fig. 10 is a schematic illustration of a further modification of the governor of Fig. 1 employing hydraulic servo and follow-up motors, the operating speeds of which are automatically controlled in accordance with the off speed condition, this modification being the hydraulic counterpart of the governor of Fig. 9.

Referring now to Fig. 1, which illustrates a differential speed responsive device or governor of general application, the reference character 1 indicates the governor generally, which includes a small constant-speed motor 2 which may be of the governor controlled type well known in the instrument art, the speed setting of the governor being adjustable by a setting knob 2a, or may be a synchronous motor supplied from a constant frequency source, the supply current frequency being adjustable to vary the motor speed, the known speed of the motor 2 being employed as a reference in the manner well known in the art. The motor 2 through a slip clutch 3 drives a shaft 4 which is suitably rotatably mounted for rotation in bearings carried by supports 5 which form a part of a casing structure (not shown) which encloses the governor mechanism. The shaft 4 has an elongated gear 6 pressed thereon and rotatable with the shaft, the gear 6 meshing with a pinion gear 7 which is internally threaded to form a nut which is mounted on the threads 8 of a shaft 9 which is parallel with the axis of shaft 4 and gear 6, and also rotatably supported by the casing structure 5, the pinion nut 7 being slidable along the teeth of gear 6. The shaft 9 adjacent the ends of the threaded portion is made the same diameter as the root diameter of the threads so that the pinion nut 7 may rotate freely thereon after running off the threads 8. Small compression springs 9a and 9b secured to the shaft 9 insure that the pinion nut 7 will ratchet in contact on the ends of thread 8 if it runs off at either end thereof.

The threaded shaft 9 has an extension shaft 10 formed integral therewith, on the outer end of which a bevel gear 11 is secured, the gear 11 forming one of the side gears of a differential, generally indicated by the reference numeral 15. The side gear 11 meshes with a pair of bevel planet pinions 12 which are rotatably mounted on studs 13 fixed to a housing or carrier 14. The carrier 14 is provided with a suitable central bearing hub which provides for free rotation of the carrier about the axis of shaft 10. The carrier or housing 14 is closed at its outer end by a gear 16 having a central bearing hub and having its toothed periphery projecting beyond the housing 14, the gear teeth serving as a means to rotate the carrier 14. The differential unit 15 is completed by a second bevel side gear 17 which meshes with the planet pinions 12 and is secured on the inner end of a shaft 18 which is rotatably journaled in the bearing hub of the gear 16. Shaft 18 is suitably rotatably journaled in a bearing supported by the casing structure 5 and has a driven clutch disc

19 secured to its outer end. The disc 19 is engaged by a friction disc 20 made of any suitable material giving the proper coefficient of friction, this disc being secured to a driving disc 21 which has a hub 22 slidably keyed to a sleeve 23. An annular compression spring 24 which surrounds the hub 22 applies an axial force to the plate 21 and friction facing 20 sufficient to transmit drive from the sleeve 23 to the shaft 18, but under abnormal torques permits slipping. The spring 24 at its outer end engages an abutment 25 formed integrally with the driving sleeve 23, the latter being pinned to a driving shaft 26 which may be drivingly connected to the device such as a prime mover, electric motor, or the like, which is to be controlled.

If we assume that gear 16 and carrier 14 of the differential 15 are to be held stationary, rotation of shaft 26 in the direction indicated by the arrow will through clutch elements 19—20—21 drive shaft 18 in a corresponding or clockwise direction, which in turn will cause rotation of side gear 17, which through planet pinions 12 will rotate the side gear 11 and shaft 10 in an opposite or counterclockwise direction. Counterclockwise rotation of shaft 10 will correspondingly rotate threaded shaft 9 and cause an axial feeding movement of pinion nut 7 to the right as seen in Fig. 1. If the pinion nut 7 is rotated in a counterclockwise sense by a clockwise rotation of the elongated gear 6, which rotation is imparted from shaft 4 when driven by motor 2, no feeding movement of the pinion nut 7 along the threads 8 of shaft 9 will result provided pinion nut 7 is rotated at the same speed as threaded shaft 9.

If the pinion nut 7 is initially in the middle of the threaded portion 8 of shaft 9, and shaft 26 should increase in speed from a speed equal to, or in a predetermined ratio to, the speed of constant-speed motor 2 as determined by the ratio of gearing between gear 6 and pinion nut 7, the pinion nut 7 will move axially to the right with a velocity dependent upon the number of threads per inch of threaded shaft 9 and also on the magnitude of the speed variation or off speed of shaft 26 from the desired constant speed. Similarly, a reduction in speed of shaft 26 from the desired value will cause an axial feeding of pinion nut 7 to the left from the neutral position as seen in Fig. 1.

If the gear 17 of the differential 15 is assumed to be stationary and carrier 14 rotated by gear 16 in a clockwise sense, planet pinions 12 will rotate in a clockwise sense looking from above and will cause a clockwise rotation of side gear 11 with a velocity equal to twice the speed of the carrier 14. Rotation of the carrier 14 in the counterclockwise sense will produce rotation of side gear 11 in a corresponding direction. If now shaft 26 be considered as rotating in the direction of the arrow (Fig. 1), and differential carrier 14 is rotated in a clockwise sense, the speed of shaft 10 will be decreased from the speed it would otherwise have with the differential carrier locked, and similarly the speed of shaft 10 will be increased by counterclockwise rotation of carrier 14 above the speed it would have as imparted through the differential 15 from shaft 26.

It should be noted at this point, however, that the proper action of the follow-up drive can only be obtained by proper design of the clutch elements 19—25, i. e. the minimum torque which must be developed by the follow-up motor 50 must be slightly greater than the torque required to overcome the friction of the differential drive

screw shaft 8, pinion nut 7 as it slides to and fro in its operating cycles. The clutch must not slip when the follow-up motor applies its maximum torque, yet the clutch must be able to slip in the event of a jam in the governor mechanism. In the event that the clutch should slip during operation of the follow-up motor, a hunting condition may result and experiment has shown that if the clutch can transmit a torque approximately twice the friction torque of the driven elements without slipping, satisfactory operation will be obtained. In the event that the speed of the device to be controlled is imparted to the governor through the medium of an electrical motion transmitting means of any of the types well known in the art, the slip characteristics must be the equivalent of the clutch as above noted and in this case the clutch would be eliminated.

It is thus seen that the speed of the output shaft 10 of the differential 15 will be in accordance with the algebraic sum of the separate speeds imparted thereto due to rotation of the differential carrier 14 and from shaft 26. This function of changing the speed of the output shaft 10 through rotation of the carrier 14 of the differential is employed in a novel manner to create a follow-up action tending to always restore pinion nut 7 to its predetermined neutral position after a displacement thereof, which will be hereinafter more fully explained.

In order to cause rotation of the carrier 14 of differential 15 to cause the above-noted follow-up action, the gear 16 meshes with a small pinion gear 27 mounted on a shaft 28 which forms the output member of a clutch mechanism generally indicated by the reference numeral 30. The input drive to clutch 30 is derived from a small electric motor 50 hereinafter termed the follow-up motor.

Referring to Fig. 3 the clutch mechanism 30 is seen to include a clutch shifting collar 29 which is slidably keyed to the output shaft 28 and has an annular groove 31 into which shifting pins 32 are adapted to project. The pins 32 are carried by a shifting yoke 33 pivotally supported as at 34 and having its lower end pivotally connected to the plunger of a solenoid 35 which includes a loading spring 36. The shifting collar 29 has integrally formed therewith at its outer end a disc 37 which on its inner face is adapted to normally engage an annular brake disc 38 which is secured to a stationary annular backing plate 39 which is further supported by the clutch housing. The front face of the disc 37 is provided with projecting clutch teeth 40 which are adapted to be engaged with corresponding teeth 41 formed on a driving clutch disc 42, the latter being secured on the inner end of a shaft 43 which is rotatably journaled in a suitable bearing supported by the clutch housing. A large gear 44 is mounted on the outer end of the shaft 43 to drive the same. A small gear 45 mounted on the armature shaft of the reversible electric follow-up motor 50 drives the gear 43.

The follow-up motor 50, which may be of the split field reversible type, has the solenoid 35 connected in series with the armature lead thereof so that whenever the motor 50 is energized the solenoid 35 is also energized so that the solenoid plunger will pull on the shifting yoke 33 against the resistance of spring 36 and release the clutch disc 37 from engagement with the brake disc 38. Further movement of the shifting collar 29 will engage the clutch teeth 40 and 41 and drivingly connect the output shaft 28 to the motor-driven shaft 43 and in a direction opposite the direction

of rotation of motor 50. When motor 50 and solenoid 35 are de-energized, the force exerted by spring 36 on the shifting yoke 33 will cause the clutch disc 37 to move to the disengaged position, where it contacts brake 38 and prevents further rotation of shaft 28, and the gear 27 then serves to lock the differential carrier 14 against rotation. The pressure exerted by spring 36 and the brake disc 38 is so chosen that torques applied to the differential 15 by shaft 18 will not cause slippage.

It has been described above how differences in speed of rotation between shaft 26, driven by the device to be controlled, and shaft 4, driven by constant-speed motor 2, will cause shifting of the pinion nut 7 in either direction from its neutral position and the means for utilizing the movement of the pinion nut as seen in Figs. 1 and 2 will now be described. A small carriage 52 is slidably mounted on parallel guides 53 so as to move parallel with the axis of the threaded shaft or screw 9, and the carriage is provided with downwardly depending projections 54 which are provided on their lower ends with rollers 55 which respectively engage the pinion nut 7 on its opposite end faces and transmit movement of the pinion nut 7 into a corresponding translatory movement of the carriage 52. A pair of snap-action switches 56 and 57 are mounted on the upper side of the carriage 52 and are movable therewith. The switches 56 and 57 are provided with longitudinally extending, pivotally mounted operating levers 58 and 59 respectively, the levers being provided at their outer ends with rollers 60 and 61 respectively. The levers 58 and 59 are adapted to engage respective switch-operating plungers 62 and 63 (see Fig. 1). The switches 56 and 57 are of a well-known snap-action type such that a deflection of the operating plungers of only a few thousandths of an inch will actuate the switch mechanism and allow a limited further movement of the plungers, or overtravel. The rollers 60 and 61 respectively engage cam plates 64 and 65 which are mounted in a parallel spaced relation and which have respectively lower dwell portions 64a and 65a, rise portions 64b and 65b and upper dwell portions 64c and 65c. The above-noted cam portions are respectively disposed on opposite sides of the vertical centerline representing the neutral or mid position of the pinion nut 7. Movement of the carriage 52 to the right (Fig. 1) will cause roller 60 to engage the cam rise 64b to depress the switch lever 58 which will actuate the plunger 62 to thereby actuate the snap-action contact mechanism of switch 56. The downward movement of plunger 62 will continue until the dwell portion 64c of cam 64 is reached, and thereafter further movement of the carriage 52 to the right will produce no further effect on the switch. While carriage 52 is moving to the right from the neutral position, the roller 61 engages the lower dwell portion 65a of cam 65 so that switch 57 is not operated. In a similar manner movement of carriage 52 to the left (Fig. 1) from the neutral position causes operation of switch lever 59 to operate switch 57 but allows roller 60 to ride on the lower dwell portion 64a of cam 64, leaving switch 56 inoperative.

Referring to Fig. 1, electrical connections are made to the switches 56 and 57 through flexible pig-tail leads, not shown, and one pair of respective switch terminals are connected in parallel to ground by means of a conductor 70, and the remaining pair of switch terminals are respectively connected by means of conductors 72

and 73 to respective conductors 74 and 75. The conductors 74 and 75 are connected at one end to the respective field terminals of the follow-up motor 50. The armature conductor 76 of the follow-up motor 50 is connected in series with an adjustable rheostat 77 to the positive terminal of a battery or other current source 78, the negative terminal of which is grounded. A conductor 79, also connected to the positive terminal of battery 78, is connected to the armature lead of a split field or other type reversible electric servomotor 80, which has its field or other reversing terminals respectively connected to the remaining ends of conductors 74 and 75. It is thus seen that the reversible follow-up motor 50 and the reversible servomotor 80 are connected in parallel and controlled as to direction of rotation by switches 56 and 57, the speed of rotation of the follow-up motor 50 being determined however, by the setting of the adjustable rheostat 77. The speed of the follow-up motor is usually limited so that the follow-up rate remains less than either the master motor 2 or the shaft 26. The follow-up rate in extreme cases, involving large moments of inertia of the prime mover and hence large time lags may be greater than that of the master motor 2. In any case it is adjustable by means of variable resistance 77 to any desired or necessary follow-up rate to secure proper governing operation. It is also to be understood that in place of the single variable resistance 77 separate adjustable resistances may be placed in series with each field coil of the follow-up motor to obtain a different follow-up rate in one sense of governing control than in the other to take care of those cases where the response rate of the device being controlled is different in one direction than the other. One example being in control of engine speed through a variable pitch propeller in which the centrifugal torque on the blades assist in changing pitch in one direction and oppose a pitch change in the opposite direction.

The servomotor 80 has its armature shaft 81 provided with a worm 82 which meshes with the teeth of a gear sector 83 rotatably mounted as at 84 and provided with an actuating lever 85 which may be connected in any suitable manner to the speed-controlling means of the prime motor or other device to be controlled in a manner well known in the art.

OPERATION

The operation of the differential speed responsive device of Fig. 1 when employed to control the speed of rotation of a prime mover or other mechanism such as an electric motor, hydraulic power transmission, or the like is as follows:

The shaft 26 is directly or otherwise connected to the device to be controlled so that the shaft 26 will rotate at a speed equal or proportional to the rotational speed of the controlled device. The lever 85 is suitably connected to the speed control element such as an engine throttle valve, electric motor controlling rheostat, hydraulic control valve, or the like, such that movement of the control lever 85 in opposite directions from a neutral position will cause an increase and decrease respectively in the speed of the controlled device.

The speed of motor 2 is then adjusted to a value such that shaft 4 drives pinion nut 7, through gear 6, at the desired rotational speed of the device to be controlled, and assumed to be in the direction of the arrow in Fig. 1, and if the screw shaft 9 is being rotated in the direction of the

arrow by shaft 10 from differential 15, shaft 18, clutch 19-21 and shaft 26 at a corresponding speed, there will be no displacement of pinion nut 7 from the neutral position as previously explained and servomotor 80 and follow-up motor 50 will be de-energized. If shaft 26 should increase in speed from the desired constant speed, pinion nut 7 will rotate relative to the threaded shaft 9 and will move along the threads 8 axially towards the right, causing switch 56 to be actuated in the manner previously explained. The switch 56, upon closure of the contacts thereof, will, through conductors 73 and 75, immediately energize the servomotor 80 to run in a direction such that control lever 85 will move the control element of the controlled device in a direction to reduce the speed of the said device and cause a corresponding decrease in the speed of shaft 26.

Simultaneous with the energizing of servomotor 80 the follow-up motor 50 is also energized and through the clutch mechanism 30, previously described with reference to Fig. 3, will cause rotation of the output shafts 28 and gear 27 in such a direction that gear 16 and differential carrier 14 will be rotated in a clockwise sense as viewed from shaft 26 looking to the left. This rotation of the differential carrier 14 will cause a reduction in the speed of rotation of shaft 10 of a constant amount depending on the speed of follow-up motor 50 as determined by the setting of the speed-control rheostat 77 thereof. If the departure of the rotational speed of shaft 26 from the desired speed, known as the "off-speed," is of small magnitude, the decrease in speed of shaft 10 due to the follow-up drive will exceed the amount of increase in speed thereof transmitted from shaft 26, and accordingly the screw shaft 9 will lag behind the pinion nut 7 and the motion of the latter will be reversed returning the same axially toward the left until it is again in the neutral position allowing switch 56 to return to its initial open position de-energizing servomotor 80 and follow-up motor 50 and through clutch mechanism 30 locking the carrier 14 of differential 15 and allowing the shaft 10 to return to the same speed of rotation as shaft 26.

After completion of the above cycle, servomotor 80 will have made an adjustment on the speed control of the device being controlled, tending to diminish its speed of rotation, but if the control effect was insufficient, the remaining off speed will cause the above cycle to be repeated a number of times until the device to be controlled is restored to the desired constant speed. It will be noted that since the follow-up speed is substantially constant, the time duration of each control cycle will decrease in proportion to the off-speed, as the off-speed decreases, so that servomotor 80 applies a decreasing control movement until the final position is reached, where the speed of the control device is exactly the desired value.

When the speed of shaft 26 falls below the predetermined constant speed, the operation of the device is exactly the reverse of that described above, i. e., such a condition will cause a decrease in the speed of screw shaft 9 relative to pinion nut 7 so that the same will be moved to the left from its neutral position, thereby actuating switch 57 to complete a circuit through conductors 72 and 74, causing servomotor 80 to be energized to rotate in a reverse sense from that as above described, to thereby cause the controlled device to increase its speed. The follow-up motor 50 will also operate in the opposite direction so

as to cause clockwise rotation of the differential carrier 14, causing the speed of shaft 10 to be increased to restore the pinion nut 7 to its initial neutral position. The repetition of control cycles will be the same in character, depending on the value of the off speed, as for the overspeed condition.

It will be noted that after the value of the off speed exceeds a predetermined follow-up speed, the follow-up is not capable of introducing a sufficient increase or decrease in the speed of shaft 10 and screw shaft 9 to offset the effect of the off speed so that the pinion nut will thereafter continue its movement to the right or left of the neutral position, depending on whether the off speed is an overspeed or underspeed condition. Under such circumstances the switch 56 or 57 will remain closed so that servomotor 80 will operate continuously until the effect on the controlled device becomes effective to change the speed of shaft 26 sufficient to allow the follow-up drive to restore the pinion nut to the neutral position. In the event that the pinion nut runs off the threads 8, it will continue to rotate on one of the thread root diameter portions of shaft 9 ratcheting against the ends of the thread due to the action of either of the buffer springs 9a or 9b. As soon as the servomotor 80, then operating at its maximum rate, reduces or increases the speed of shaft 26, as the case might be, to a point where the follow-up speed becomes dominant, the pinion nut 7 will be returned to its neutral position and the final speed correction will proceed in cycles as above described. The follow-up rate may be adjusted so that it is possible that servomotor 80 will, during the maximum displacement of the pinion nut 7, have produced an overcontrol effect so that the pinion nut 7 will move, due to follow-up action, past the neutral position in the opposite sense, causing the character of the control to be reversed to cancel the overcontrol. This action will cause several oscillations in the speed of the controlled device about the equilibrium position; but the amplitude of such oscillations will be continually reduced, since the follow-up action will produce an effect similar to damping. For many types of governing installations this character of control is preferable, since the time required to reach equilibrium speed is a minimum.

It will be evident from the above description of the governor of Fig. 1 that the same operates on the proportionalizing principle, i. e., that the control effect produced is proportional to the required control, i. e., to the existing off-speed condition, but the proportionalizing is with respect to time, since the time duration of each control cycle within the normal governing range is proportional to the value of the off-speed at the beginning of the cycle.

In control installations where oscillations about the equilibrium speed are undesirable, the follow-up speed of motor 50 may be made sufficiently high that the pinion nut 7 may always be returned to the neutral position irrespective of the value of the off speed, so that the governing action will be aperiodic or dead beat, i. e., upon any departure in speed of the controlled device from the desired speed the governor will cause a progressive speed correction to be made which will, if plotted as a curve against time, terminate at the equilibrium speed value. Such operation will necessarily involve approaching the equilibrium speed in steps of decreasing magnitude, which will accordingly increase the total

time required to restore the controlled device to equilibrium speed.

It is thus seen that by adjusting the speed of operation of the follow-up motor 50 through rheostat 77, it is possible to obtain widely varying governing characteristics so that the same governor without change may be applied to the control of a large number of devices, each having a different governing requirement, this feature being of particular value in the control of variable pitch propellers for aircraft, since one type governor can be employed regardless of the inertia characteristics of the particular engine-propeller combination.

In order to illustrate the application of a governor of the type illustrated in Fig. 1 to the control of the speed of a prime mover such as an aircraft engine by controlling the pitch of the propeller blades, reference is made to Fig. 4 in which the controllable pitch propeller is generally indicated by the reference numeral 90 and having the adjustable pitch blades 91 adapted to be adjusted by a reversible electric motor 92 in a manner well known in the art. The propeller 90 is driven by the crankshaft 93 of a conventional aircraft engine 95. An alternating-current generator 96, driven by the engine, delivers current by means of conductors 97 to synchronous electric motor 98 which thus runs at a speed equal or proportional to the rotational speed of engine 95. This particular means for transmitting engine speed to the governor may be replaced by any other suitable type motion-transmitting means, such as a flexible shaft drive, a Selsyn transmitter and receiver, or a contact interruptor device driven by the engine and adapted to control an impulse motor or the like. The synchronous motor 98 is directly connected to the shaft 18 of a governor 1 of a character identical with the governor of Fig. 1, the electrical transmission permitting slip and thus eliminating the necessity for shaft 26 and clutch 19-21. The conductors 74, 75 and 79 are connected through the usual brushes and slip rings to the reversible pitch-changing motor 92 which then serves as the equivalent of the servomotor 80 of Fig. 1.

The speed setting of constant-speed motor 2 is adjusted by actuation of the speed-setting control knob 2a so that it corresponds with the desired engine speed, and if the engine departs from this speed, governor 1 will energize the pitch-changing motor 92 to effect a change in the pitch of the propeller to restore the engine to the desired speed. The regulating characteristics of the governor 1 are adjusted to suit the particular engine-propeller characteristics by means of the rheostat 79 which controls the speed of the follow-up motor as previously described with reference to the device in Fig. 1. The operation of the governor in Fig. 4 in no way differs from that as previously described.

The arrangement of Fig. 4 may be extended to use as a combined governing and synchronizing system for a plurality of engines by simply providing a separate governor unit of the character described for each engine and driving the constant-speed side (shaft 4 Fig. 1) of each governor from a common constant reference speed motor. In this arrangement all the governor units would be mounted in a single casing, and all of the constant speed driving shafts would be connected by bevel gears or the like to a single shaft driven by a constant-speed motor such as motor 2, Figs. 1 and 4. If then any motor departed in speed from the desired speed, its sep-

arate governor unit would react to adjust the pitch of the propeller associated with the said engine to cause the engine speed to be restored to equilibrium with the selected reference speed.

Since all of the governors would employ a common reference speed, all of the engines will be maintained in synchronism so far as speed of rotation is concerned. As an alternative, one engine may be employed as a reference speed source to drive the reference speed sides of the governors for the remaining engines so that the controlled engines will follow the speed changes of the master engine, the latter being controlled by a separate governor which may differ from the type herein disclosed.

As an alternative arrangement, a separate governor may be mounted on each engine to be directly driven thereby and the constant speed sides of the governors being driven from a single adjustable constant speed source by remote drives.

It should also be understood that where the governor of Fig. 1 is applied to control an electric servomotor on which the load is heavy, such as the electric propeller pitch changing motor of Fig. 4, the governor controlled switches may be employed to close relays which in turn are operative to control the energizing of the servomotor, thus avoiding transmitting heavy currents through the governor controlled contacts or switches. Since the above modes of synchronizing engines are readily apparent, no illustration thereof is believed necessary in the drawings.

The governor of Fig. 1, as previously explained, operates in a series of cycles when the off-speed is below a predetermined value, and this is true even though the rate of change of speed of the controlled device is large so as to cause a sufficient accumulation of off-speed revolutions to eventually cause the servomotor to operate continuously at its maximum rate. It is well known in the art of governing the minimizing of time lag in the governing system is essential but that this cannot usually be accomplished without affecting the stability of the governor. However, if a separate means is employed, responsive to the rate of change of speed of the device to be controlled which is effective to impart an immediate control upon the rate of change of speed exceeding a predetermined value, the time lag can be reduced to a minimum without adversely affecting the stability of the governor. Such combined governors in the prior art have usually consisted of centrifugal weights which are so arranged as to also respond to accelerations, as well as the change in speed, of a flywheel or the like to which the governor is attached, or comprised a combined gyroscopic and centrifugal governor.

So far as I am aware, however, it has never been proposed to employ an acceleration-responsive or anticipatory control means in combination with a differential type of governor, for the reason that the oscillatory nature of the control of such a governor would render the acceleration-responsive means ineffective and the latter would make the oscillation problem worse. The combination of a differential governor, however, of the character of the present invention which, due to the provision of the novel follow-up, is inherently stable, with an acceleration-responsive control means, gives a combination which overcomes the lack of rapid response above noted when the rate of change of speed of the controlled device is large, but also greatly reduces the total

time required to attain equilibrium speed conditions and, in fact, adds to the anti-hunting characteristics of the governor.

The provision of the anticipatory control means to a governor of the character of Fig. 1 is illustrated in Fig. 5, in which parts common to Fig. 1 are indicated by the same reference numerals. The anticipating control means, as seen in Figs. 5 and 6, comprises a small flywheel or inertia element 100, freely rotatably mounted by means of a ball bearing 101 on the shaft 18, the flywheel 100 being provided with a pin 102, which projects through an arcuate aperture 103 in a disc 104 of insulating material, having a hub 105 secured to shaft 18 to rotate therewith. The pin 102 is yieldingly connected by means of adjustable tension springs 106 to the disc 104 so that the flywheel is caused to rotate with the disc, but any acceleration or deceleration of shaft 18 will cause flywheel 100 to rotate relative to disc 104 and shaft 18.

As seen in Fig. 6, the flywheel 100 is also provided with a second pin 107 projecting through a second arcuate aperture 108 in the driving disc 104, and this pin carries a double electrical contact 110, which is adapted to engage either of a pair of adjustable contacts 111 and 112 respectively disposed on opposite sides thereof. The contacts 110, 111 and 112 are respectively electrically connected by flexible leads to slip rings 113, 114 and 115, which in turn are engaged by brushes 116, 117 and 118 respectively. Brush 116 is connected to ground and hence serves as a connection to the grounded terminal of the battery 78. Brush 117 is connected to conductor 75 beyond the connection of conductor 73 thereto, so that contacts 110 and 111 serve as a switch means connected in parallel with switch 56 and operative to energize the servomotor 80, irrespective of whether switch 56 is open or closed. Similarly, brush 118 is connected to conductor 74 beyond the connection of conductor 72 thereto, so that contact means 110 and 112 serve as a switch connected in parallel with switch 57 and operative to energize servomotor 80 independent of whether switch 57 is open or closed.

Operation of anticipatory control

The tension of springs 106 is initially adjusted so that predetermined values of acceleration or deceleration of shaft 18 will not cause the inertia element to rotate relative to shaft 18 and disc 104 an amount sufficient to cause engagement of contact 110 with either of contacts 111 and 112. The governor in this range will then operate exactly as described with reference to Fig. 1.

If the shafts 26 and 18, however, are accelerated beyond the predetermined value, inertia element 100 will lag behind shaft 18 and disc 104 and will tension one of the springs 106 sufficient to cause contacts 110 and 111 to engage, which will energize servomotor 80 to rotate in the same sense as when energized by switch 56 but to operate at its maximum rate to apply a correction tending to reduce the speed of the device being controlled. The remaining portions of the governor 1 will operate in the previously described manner, but the actuation of switch 56 will not affect the operation of motor 80 as long as the acceleration or rate of change of speed exceeds the predetermined value. When the servomotor 80 has operated for a sufficient length of time to reduce the acceleration of shafts 26 and 18 below the predetermined value, the tension of the active spring 106 will overcome the

inertia lag of the element 104 and will cause disengagement of contacts 110 and 111, thereby restoring the control function to the governor structure of Fig. 1, which will then function in the manner above described, i. e., if the accumulated value of the off-speed revolutions is sufficient to cause continuous movement of the pinion nut 7 to the right from the neutral position or to have actually run off the thread on shaft 9, servomotor 80 will continue to operate at its maximum rate. If the off-speed revolutions accumulated during operation of the acceleration-responsive means do not exceed a predetermined value, the control will be of the interrupted character as previously described, until the equilibrium speed is reached.

If the device being controlled should cause a deceleration of the shafts 26 and 18 beyond the predetermined value, the inertia element 100 will tend to continue rotation at the equilibrium speed and will tension the other of the pair of springs 106 sufficient to allow contact 110 to engage contact 112 to cause servomotor 80 to be actuated in the reverse sense from that as above described, causing the servomotor to adjust the speed-control means of the controlled device to increase the speed thereof. The contacts 110 and 112 will be disengaged when the deceleration is reduced to the predetermined minimum value, and the governor will thereafter be effective through switch 57 to finally restore the controlled device to the desired equilibrium speed.

It will be noted that the particular value of equilibrium speed selected has no effect on the anticipatory control, since the inertia element 100 responds only to accelerations or decelerations, i. e., to rate of change of speed, and by this token is also independent of the magnitude of the off-speed. The acceleration-responsive device, being rate-responsive, is able to anticipate large speed departures and initiate a corresponding corrective influence before the governor proper can respond and thus reduces the time lag in the control system to a minimum, thereby bringing the governor-control response more closely in phase with the speed changes and materially reducing any tendency to hunt.

It is to be understood that a differential governor provided with anticipatory control can be applied to control variable pitch propellers or for any other purpose to which the governor of Fig. 1 is applicable.

Fig. 7 illustrates the adaptation of the speed-responsive device of Fig. 1 to use as a speed-measuring means, and in this figure all parts common to that of Fig. 1 are indicated by the same reference numerals as in Fig. 1.

Referring to Fig. 7, the shaft 4 and gear 6 are driven by an electrical self-synchronous receiver 120 such as a Selsyn, the rotor of which in turn is driven in synchronism with the rotor of a corresponding remote self-synchronous transmitter 121 electrically connected to the receiver. The rotor of the transmitter 121 is driven by gear 122 and idler gears 123 from a ring gear 124 mounted on the shaft 125 which may, for example, be the propeller shaft of a ship. In the event that shaft 125 is reversible as to rotation, an automatic tumbler gear unidirectional drive (not shown), may be inserted in the gear train between gears 122 and 124 so that transmitter 121 is always driven in the same direction irrespective of the direction of rotation of shaft 125. The gear 6 of the speed-responsive mechanism 1 is thus

driven at a speed proportional to the speed of shaft 125.

The shaft 26 of the speed-responsive mechanism 1, instead of being driven by a controlled prime mover, is driven by a small, variable-speed, electric motor 126, whose speed is automatically adjusted, so that, so long as shaft 125 rotates at a constant speed, motor 126 will be driven at a speed proportional thereto, and is effective to drive screw shaft 9 through the medium of shafts 26 and 18, differential 15, and shaft 10, so that pinion nut 7 does not move axially on threads 8. The motor 126 is controlled as to speed of rotation by a variable resistance unit 127, having a resistance winding 128, one end of which is grounded and the winding is engaged by a wiper arm 129 which also wipingly engages a circular contact strip 130 connected by conductor 131 to one lead of motor 126, the other lead of which is connected to the positive side of battery 78. The wiper arm 129 is fixed to a rotatable shaft 133 which has a gear 134 fixed to one end and driven by a worm 82, in turn driven by servomotor 80 as in the device of Fig. 1. The outer end of shaft 133 has a pointer 135 affixed thereto which is adapted to cooperate with a dial 136, having suitable speed indicia thereon. The device of Fig. 7, except as above noted, is identical with that of the governor of Fig. 1 employing the same form of control of the servomotor 80 and follow-up motor 50.

Operation of the device of Fig. 7

The rotation of shaft 125 is electrically transmitted to the gear 6 as above described, which rotates pinion nut 7 on the threads 8 of shaft 9, and if shaft 9 is rotated in the proper direction and at the proper speed, the axial feeding movement of pinion nut 7, due to rotation thereof by gear 6, will be offset by the contrary feeding effect of the rotation of shaft 9 by shaft 10, through differential 15, from input shaft 26, the latter being driven by motor 126. For the particular equilibrium of speeds between motor 126 and shaft 125 there will be a corresponding definite position of the rheostat wiper contact arm 129 and shaft 133, so that pointer 135 will indicate the existing speed of shaft 125.

If, for example, the speed of shaft 125 increases, pinion nut 7 will move axially toward the left from its neutral position and close the contacts of switch 56, which will energize servomotor 80 to run in a direction to drive shaft 133 in a clockwise direction, cutting out resistance in series with motor 126 so that the latter increases its speed. The follow-up motor 50 will be energized to restore the pinion nut 7 to its neutral position upon energizing of motor 80, in exactly the same manner as described with reference to Fig. 1, so that the speed of motor 126 will be increased in a series of steps until it is in equal, or proportional, equilibrium with the existing speed of shaft 126, and pinion nut 7 will then remain in the neutral position with servomotor 80 de-energized. The pointer 135 will have moved to a new position corresponding to the new speed value of shaft 125.

If the speed of shaft 125 decreases, the operation of the speed-responsive mechanism will be reversed from that as above described and servomotor 80 will be operated in a series of steps to cause the resistance contact arm 129 to rotate in a counterclockwise sense until sufficient resistance has been inserted in the circuit of motor 126 to reduce the speed of the same to correspond to the reduced speed of shaft 125, and according-

ly, pointer 135 will indicate, relative to dial 136, the new speed of shaft 125.

It is thus seen that the speed of motor 126 is always so controlled by the speed-responsive device 1, that it is proportional to the existing speed of shaft 125 and the setting of the speed-control rheostat 127 can be interpreted in terms of a speed indication. The speeds to be indicated may range from a predetermined low-speed value to the maximum likely to be encountered, and the motor 126 and its associated speed control is selected for the particular speed range for which the device will be employed.

In the speed indicating device illustrated in Fig. 7 the dial 136 would be calibrated for some particular temperature condition and if the ambient temperature varies considerably from the calibration temperature, it is evident that the change in resistance of the windings of the motor 126 and change in the resistance of the speed control means 128 will cause some error in the indicated speed. Where variations in the ambient temperature are such that temperature error compensation is necessary, the error in indication can be substantially corrected by arranging the pointer 135 for free rotation on the end of shaft 133 and coupling the pointer to the shaft by a coiled bimetallic strip which can shift the pointer relative to the shaft 133 an amount to compensate for the error of speed indication due to change in the ambient temperature. This means of securing temperature compensation is well known in the instrument art, being widely employed on altimeters and the like and forms no part of the present invention.

Fig. 8 illustrates a modified form of the governor of Fig. 1, in which the rotational speed of the servomotor and the follow-up motor are respectively controlled in proportion to the existing off-speed so as to further increase the stability of the novel differential governor in accordance with the invention. In this modification, parts common to the device of Fig. 1 are indicated by the same reference numerals as in the latter figure. The modified form of governor of Fig. 8 employs the same type of follow-up as employed in the device of Fig. 1, but employs a conventional differential as the speed difference measuring means and employs speed-control means for both the follow-up motor and servomotor.

Referring to Fig. 8, the constant-speed motor 2 drives the shaft 4 through a slip clutch 3', and shaft 10 is driven through differential 15, shaft 18, slip clutch 20, and shaft 26 in the same manner as in the device of Fig. 1, follow-up motor 50 being adapted to drive through differential 15 in the same manner as in previously described embodiments. The shafts 4 and 10 are respectively connected to bevel side gears 141 and 142 of a conventional differential, generally indicated by the reference numeral 140, the side gears meshing with bevel pinion gears 143 mounted on a rotatable carrier 144, which has formed thereon a helical toothed gear 145 which meshes with a corresponding gear 146. As long as shafts 4 and 10 rotate in opposite directions at equal speeds, carrier 144 will remain stationary, but upon any difference in speed of the said shafts, the carrier will begin to rotate at a speed equal to one-half the difference in speed of the differential side gears and in the direction of the gear having the greater velocity, causing gear 146 to rotate about its axis. The differential 140 is the equivalent of the gears 6 and 7 and screw shaft 9 of Fig. 1, the angular displacement of gear 146 by the rotation

of the differential carrier being equivalent to the axial displacement of pinion nut 7 of the device of Fig. 1.

Gear 146 is adapted to drive a shaft 147 which, through a fibre sleeve 148 forming a slip drive, drives a hub 149 which has two cams 150 and 151 rigidly mounted thereon. The cam 150 has a portion *a-b* of constant radius and has flanks of increasing radius from points *a* and *b* to a stop portion 152. Cam 150 engages a pair of contact-engaging plungers 157 and 167, symmetrically disposed on opposite sides of the vertical centerline of the cam and adapted to be alternately depressed upon counterclockwise and clockwise rotation, respectively, of the cam 150, as seen in Fig. 8. The plungers 157 and 167 are depressed an amount proportional to the rotation of cam 150 from the neutral position, which in turn depends on the angular rotation of gear 146 by differential 140, in accordance with the existing speed difference or off-speed.

The plungers 157 and 167 are adapted to respectively actuate resistance cut-out contacts in units indicated by the reference numerals 156 and 166 respectively and are respectively electrically connected to resistance units 153 and 163, the control contact and resistance unit assemblies being generally indicated by the reference numerals 155 and 165, since such assemblies form a well-known motor-speed-control device known commercially as a "Silverstat."

The second cam 151 is so constructed that upon rotation of the same in either direction from the neutral position, as seen in Fig. 8, a plunger 177 will be depressed an amount proportional to the angular displacement of the cam from the neutral position. The plunger 177 actuates contacts in a control unit 176 adapted to cut-out resistance in a resistance unit 173, which together form a third "Silverstat" or motor-speed-control device 175.

The speed control units 155 and 165 are electrically connected to control the energizing of the servomotor 80, which is adapted to control a prime mover or the like as described with reference to the embodiment of Figs. 1 and 4. The speed-control unit 175 is adapted to control the speed of the follow-up motor 50, so that the follow-up speed is proportional to the existing value of the off-speed, so that the control of the servomotor is substantially in a series of cycles throughout the normal range of speed control.

The electrical circuits of the device of Fig. 8 are illustrated schematically in Fig. 9, and as seen in this figure, the motor-speed-control unit 155 has a resistance unit 153 consisting of a serially connected group of resistances which are connected to a series of flexible contact arms 158, each of which is provided with a contact 159 on its lower end; the contacts being adapted to be successively engaged upon depression by the contact plunger 157. The first contact arm of the series is connected directly to the field coil lead 74 of the servomotor 80, so that engagement of the first contact 159 with the second contact, serves to connect the field of motor 80 through the entire resistance unit to ground, whereby a return circuit is completed to the grounded terminal of battery 78. The plunger 157, as it is deflected, causes engagement of additional contacts 159, which causes resistance units to be successively shorted out, thus reducing the total resistance in the servomotor circuit, causing a corresponding increase in speed for a given direction of rotation of the motor.

The first pair of contact arms 158 carry addi-

tional contacts 160 and 161 respectively, which when closed connect one follow-up motor 50 field coil terminal lead 154 directly to ground, thus connecting the same to the grounded terminal of battery 78, so that motors 50 and 80 will start substantially simultaneously each in one direction of rotation.

The speed-control unit 165 is identical in construction with unit 155, and includes serially connected resistances 163 connected to the flexible contact arms 168, the latter carrying contacts 169, all except the first pair, being adapted when successively closed of shorting out successive resistance units 163 from a circuit connecting the other field terminal of servomotor 80 through lead 75 to ground to complete the circuit to the grounded terminal of battery 78. The first pair of contacts 169 is operative as a switch to connect the entire series of resistance units 163 in series with the field terminal lead 75 of motor 80. The plunger 167, upon deflection thereof by cam 150, in one direction of rotation thereof, causes successive engagement of contacts 169, which, in turn, causes a reduction in the resistance in series with the motor 80 to increase the speed of the motor in proportion to the existing off-speed condition.

The first pair of contact arms 169 carries an additional set of contacts 170-171, which, when closed, connects the other side of the field of follow-up motor 50 through conductor 164 to ground. The contacts 170-171 are closed substantially simultaneously with the closure of the first pair of contacts 169.

The positive terminal of battery 78 is connected by means of conductor 79 directly to the armature lead of servomotor 80 and a branch thereof is connected to the outer end of the serially connected resistance units 173 of speed-control unit 175. The speed-control unit 175 has a contact unit 176 consisting of the flexible contact arms 178, having contacts 179 adapted to be successively closed by depression of the plunger 177 by cam 151. The first pair of contacts 179 serves as a switch to connect the armature lead 76 of follow-up motor 50 to the battery lead 79 through the entire resistance unit 173, and as the plunger 177 is depressed, the resistance in series with the follow-up motor 50 is progressively decreased, allowing the motor to increase its speed.

Operation of the device of Fig. 8

The operation of the device of Fig. 8, taken in conjunction with the circuit diagram Fig. 9, is similar in most respects to the operation of the embodiment of Fig. 1 in that, when shaft 26, for example, increases its speed from the predetermined value, the increase will be reflected through differential 15 to shaft 10, which will cause differential side gear 142 to rotate at a greater rate than side gear 141 so that the carrier 144 rotates counterclockwise looking to the left in Fig. 8, which will cause helical gear 145 to drive mating helical gear 146 in a counterclockwise direction as seen in Fig. 8, causing cams 150 and 151 to rotate in the same direction, depressing plungers 157 and 177, respectively, an amount proportional to the angular rotation of gear 146.

Upon depression of plunger 157, the first pair of contacts 159 of the speed-control unit 155 will close, causing servomotor 80 to operate in a direction to cause the speed-control means of the prime mover or other controlled device (not shown) to decrease its speed, and simultaneous therewith, the contacts 160-161 are closed to energize the follow-up motor 50, which feeds its

revolutions through differential 15 to restore the differential carrier 144 to its neutral position. Upon the first closure of the contacts controlling the servo and follow-up motors, cam-operated plunger 177 closes the first pair of contacts 179, to insert a maximum of resistance in the follow-up motor circuit, so that both the servo and follow-up motors operate at a minimum rate. Upon return of the differential carrier 144 to the neutral position, if there is still an uncorrected speed difference, the cycle will be repeated, but if the speed change or off-speed is sufficiently high in value, the follow-up will not be able to return the differential carrier to the neutral position, and a further set of contacts 159 and 179 will be engaged, cutting out resistance in the servomotor and follow-up motor circuits, allowing their respective speeds to increase, and if this speed is insufficient, resistance will be progressively removed until the maximum speeds of these motors are reached, and if the magnitude of the speed change is not then reduced to the point where follow-up motor 50 can restore the differential carrier 144 to the neutral position, stop 152 will engage the contact plunger 157 to stop further rotation of the cams, and the friction drive thereof from shaft 147 will permit the shaft to slip. By proper design of the resistance units of the motor speed-controls, the servomotor and follow-up motor speeds can be so controlled, through the speed-control means therefor, that the approach of the controlled device to the predetermined speed will be through a series of control cycles during each of which the rate of correction will be nearly proportional to the existing off-speed, and the rate of correction will decrease as equilibrium is approached, definitely eliminating hunting. By varying the amount of resistance shorted out at each successive step by contacts 179, the follow-up characteristics may be varied to conform to any particular governing requirement.

If the speed of shaft 26 decreases from the predetermined constant speed as determined by the speed setting of motor 2, the differential carrier 144 will rotate in a reverse sense from that as above described, causing gear 146 and cams 150 and 151 to rotate in a clockwise sense as seen in Fig. 8, causing plunger 167 to be depressed to start servomotor 80 and follow-up motor 50 in the reverse direction through the medium of the speed-control unit 165, in the same manner as above described with reference to the action of control unit 155. As the plunger 167 is depressed, the speed of servomotor 80 is increased, due to the cutting out of resistance in the circuit thereof, and simultaneously, cam 151 will depress the plunger 177, which will cut out resistance in series with follow-up motor 50. The servomotor 80 will operate in a reverse sense to increase the speed of the controlled device till the equilibrium speed is reached in exactly the same manner as above described with reference to the increased speed condition.

It is obvious that the speed-control units 155 and 165 may be replaced by switches operative to start the servo and follow-up motors in the forward and reverse sense of rotation respectively, the servomotor operating at its maximum rate at all times to effect, for example, propeller pitch change, and speed-control unit 175 may be employed to vary the follow-up motor speed in the same manner as above described.

A further embodiment of the invention in which the speeds of the servomotor and follow-up motor are automatically varied is illustrated in

Fig. 10, and this embodiment is similar to the device of Fig. 8, except that hydraulic servo and follow-up motors are employed in place of electric motors.

Referring now to Fig. 10, it is seen that the governor therein disclosed has the parts including constant-speed motor 2, input shaft 26, follow-up differential 15, speed-difference-detecting differential 140, helical gear 145 driven by the differential carrier 144 and control-actuating gear 146 meshing therewith, identical with the construction illustrated in Fig. 8. The shaft 147 driven by gear 146, drives the fibre sleeve 148, which, in turn, frictionally drives the hub 149 similar to the device of Fig. 8. The remaining structure related to hydraulic control which differs from the embodiment of Fig. 8, will now be described.

The hub 149 has mounted thereon a cam 180, having at the left portion thereof a neutral point *a*, a zone of increasing radial dimensions from point *a* to a stop portion 181, and a zone of decreasing radial dimensions from point *a* to a second stop portion 182. The cam portions above noted cooperate with a cam follower roller 185 engaging the periphery thereof, the roller being adapted to reciprocate a valve stem 186, the roller being urged into contact with the cam by means of a loading spring 187 acting on the valve stem. The valve stem 186 is connected to a conventional spool-type, balanced pressure, piston valve 188, having a central drain passage 189 therethrough, the valve being reciprocable in a cylindrical bore in a valve body 190. The piston valve 188 is adapted, upon being shifted in either direction from the neutral position, to admit fluid under pressure from a conduit 191, which receives said fluid from a pump 192 provided with a pressure relief valve 193, to either one of a pair of conduits 194 and 195, the other conduit of the pair being connected through the valve to a conduit 196 which returns discharged fluid to a reservoir (not shown) from which pump 192 derives its fluid supply.

The conduits 194 and 195 are connected to a reversible hydraulic servomotor 197 which may be of the simple gear type and adapted to run in one direction upon admission of motive fluid from conduit 194 and to run in the reverse direction upon admission of motive fluid from conduit 195. The servomotor 197 has an output shaft 198 which drives a worm 82 which in turn through a gear sector 83 actuates the control lever 85 as in the device of Fig. 1 to thereby control a prime mover or other device to be governed.

The cam 180 has a second neutral point *b* at the right hand portion thereof and increases in radius from point *b* to stop 181 and decreases in radius from point *b* to stop 182. The right hand portion of the cam is generally similar to the right hand portion but the cam contour may be varied to suit the particular relation of the follow-up rate to the existing value of the off-speed condition. A roller type cam follower 200 cooperates with the right hand portion of the cam 180 and is adapted to actuate a valve spindle 201 against the resistance of a return spring 202. The spindle 201 forms a part of a control valve assembly generally indicated at 205 identical in construction with the left hand control valve. The control valve 205 contains a valve (not shown) shiftable by spindle 201 and adapted when shifted in either direction from the neutral position to admit fluid under pressure from a

conduit 206 to either one of a pair of conduits 207 and 208 which are connected to a reversible hydraulic follow-up motor 209 and connecting the other one of the pair of conduits to drain via the control valve 205 and a drain conduit 210 connected thereto from whence the fluid returns to the supply reservoir (not shown). The conduit 206 is connected to the conduit 191 to receive fluid under pressure therefrom delivered by pump 192.

The follow-up motor 209 is adapted to impart a follow-up drive through differential 15 by means of a shaft 28 and gear 27 similar to the device of Fig. 8 the direction of rotation of the hydraulic motor being such as to restore the carrier of differential 140 to the neutral position and its rate of operation being controlled by valve 205 to impart the requisite follow-up drive but being entirely independent of the servomotor 197.

Operation

The operation of the device of Fig. 10 is generally similar to that of the embodiment of Fig. 8 in that the differential carrier 140 will rotate, for example, in a direction to rotate gear 146 in a counterclockwise direction upon an overspeeding of shaft 26 from the desired constant speed, as determined by the speed of motor 2. The displacement of gear 146 as described, will cause cam 180 to rotate in the same sense and cause valve 188 to be moved to the left from the neutral position as seen in Fig. 10, connecting conduit 195 to receive fluid under pressure from conduit 191 in a volumetric quantity dependent upon the amount of valve movement. The conduit 193 is connected to drain through the passage 189 in the valve body. The fluid under pressure delivered through conduit 195 will cause motor 197 to rotate in a direction to cause the device being governed to reduce its speed. The speed of motor 197 for a given capacity is dependent upon the displacement of valve 188 from its neutral position and the rate of operation of the servomotor will be dependent on the angular displacement of the cam 180 which in turn is a function of the existing off-speed condition.

Simultaneous with the movement of valve 188 the cam follower 200 will move to the left from the position shown in Fig. 10 causing valve 205 to admit fluid under pressure into conduit 207 energizing follow-up motor 209 which will cause the carrier of differential 140 to be returned to the neutral position and thus initiating a cyclical control in the same manner as in the previously described embodiments. The displacement of the valve spindle 201 and of the control valve element of the valve assembly 205 is also dependent on the angular rotation of the cam 180 and hence the quantity of fluid admitted to follow-up motor 209 and the follow-up rate will be a function of the off-speed though not necessarily varying in the same relation as the servomotor speed. The time duration of the control cycles will vary as function of the off-speed dependent on the particular contour chosen for the right hand portion of cam 180 which may be made to conform with the governing characteristics desired.

When the character of the off-speed is an underspeed condition the cam 180 will rotate in the opposite sense causing the control valve elements to be displaced in the opposite directions from that as above described reversing the operation of the servo and follow-up motors.

In the event that the off-speed condition is such that the following-up motor cannot return

the carrier of differential 140 to the neutral position, the stops 181 and 182 will be engaged by the respective cam followers and the friction coupling 148 will permit slipping, the servo and follow-up motors then continuing to operate at their maximum rates until the servomotor has effected a sufficient speed correction to enable the follow-up motor to restore the differential carrier to the neutral position and initiating the cyclical control until the equilibrium speed is reached.

While the present invention is concerned with the construction of a novel differential speed responsive device it is to be understood that conventional limit switches may be employed where the application of the device as a governor requires such elements.

While the present invention is primarily concerned with speed control and synchronizing as to speed, experiments with a governor in accordance with the invention have shown that the control is sufficiently sensitive to maintain the driven shaft of a controlled device constant as to phase angle with a reference speed shaft within a range of ten degrees, and which figure could be reduced by employing a finer pitch screw for the pinion nut and increasing the sensitivity of the control switches, the only limiting factor being the ability of the device being controlled to respond to vary small control impulses. These tests have demonstrated that speed responsive mechanism constructed in accordance with the invention is applicable to control of the roll drives of rolling mills, paper mills, winding and reeling devices, conveyors and the like and such use is contemplated in the broad aspects of the invention.

While preferred embodiments of the invention have been illustrated and described, many alterations and changes may be made therein which will be apparent to those skilled in the art as falling within the scope of the invention as defined in the appended claims:

I claim:

1. A speed responsive device comprising: a three-element differential having driving means for a first element thereof, a two-way driving means for a second element thereof, a third element movable from a predetermined neutral position in accordance with the difference between the speed of said first element and the speed of said second element as imparted thereto by one of the drives of the said two-way drive therefor, a reversible speed-control-positioning motor energized in response to deviation of said differential third element from the neutral position, separate reversible power means operatively connected to the other drive of said two-way drive for said differential second element, said separate power means being selectively energized in response to the departure of said differential third element from the neutral position and causing a restoring effect through said differential to return said differential third element to the neutral position.

2. A differential speed responsive device comprising: a first differential having a first element, a rotary input shaft for driving said first element, a second element, a rotary shaft for driving said second element, and a third element movable from a predetermined neutral position in response to the difference in speeds of said first and second differential elements, servo mechanism controlled by said third element in

response to departure thereof from the neutral position, a second differential having two input drives and an output drive, the speed of rotation of the output drive being in accordance with the algebraic sum of the respective input drives of said second differential, a driving connection between the output drive of said second differential and the rotary input shaft for driving the second element of said first differential, means for driving one of the input drives of said second differential in accordance with the rotational speed of a device to be controlled, reversible motor means for driving the other of the input drives of said second differential, and means for energizing said reversible motor means in response to departure of the third element of said first differential from the neutral position.

3. The structure as claimed in claim 2, including means for controlling the rate of operation of said reversible motor means in accordance with the magnitude of the departure of the third element of said first differential from the neutral position.

4. The structure, as claimed in claim 2, including means for controlling the rate of operation of said servo mechanism in response to the magnitude of the departure of the third element of the first differential from the neutral position, and means for controlling the rate of operation of said reversible motor means in accordance with the departure of the said third element of the first differential from the neutral position.

5. A differential governor for the control of a prime mover or the like, comprising: a three-element differential having one element thereof driven at a constant speed, a second element having a two-way driving means therefor, a third element movable from a predetermined neutral position in accordance with the difference in speed of said first two-named differential elements, speed control servo mechanism controlled by said differential third element in response to departure thereof from the said neutral position, said two-way driving means for said differential second element including one drive adapted to be rotated at a velocity proportional to the speed of the device being controlled, and a second drive adapted to algebraically impose its speed upon the output drive of said two-way drive, to thereby tend to restore the third element of said differential to the said neutral position, and means for energizing said second drive upon displacement of said third element from the said neutral position.

6. In a differential speed responsive device, a three-element speed-comparing means, having a first speed input drive, a second speed input drive and an element movable from a predetermined neutral position in accordance with the difference in speeds between said first and second input drives, speed control mechanism controlled by departure of said element from the neutral position, a follow-up drive associated with one of said differential input drives operative to restore the said element to the neutral position after a displacement thereof from the neutral position, said follow-up drive being controlled in response to the departure of said element from the neutral position and operable at a rate independent of the rate of operation of said speed control mechanism, and rate of change of speed responsive means associated with one of said differential input drives and operative in response to a rate of change of speed thereof in

excess of a predetermined value to cause operation of said speed control mechanism irrespective of any control exerted thereon by said differential element.

7. A governor of the class described, comprising: a differential having a first element, a constant speed motor for driving said first element, a second element, an input driving shaft for said second element, a third element, movable in either of two directions from a predetermined neutral position in accordance with the difference in speeds of said first and second elements, a second differential having a separate pair of input drives and an output drive rotatable in accordance with the algebraic sum of the speeds of said input drives, a connection between the output drive of said second differential and the input driving shaft of said second element of said first-named differential, means for driving one of the input drives of said second differential at a speed dependent on the speed of rotation of a device to be governed, a reversible follow-up motor for driving the other of the input drives for said second differential to vary the speed of the output drive of said second differential to cause a restoring effect on the third element of said first-named differential tending to restore the same to the neutral position upon a displacement therefrom, a reversible servomotor adapted to actuate the speed-controlling means of a device to be governed, and control means actuated by the said third element of said first-named differential upon displacement of said third element from the neutral position, said control means being operative to selectively and simultaneously control the energizing said servomotor and said follow-up motor.

8. In a differential governor of the character in which the differential compares an input rotational speed of the device to be governed with an input reference speed and having a movable element operative upon displacement from a predetermined neutral position to control the positioning of a speed control element in accordance with the measured speed difference; the improvement, which comprises: a reversible follow-up power drive, operatively associated with one of the inputs of said differential for algebraically superimposing its speed on said input to produce an effect restoring the differential control element to the predetermined neutral position, said follow-up drive being independent of the rate of operation of the speed control element, and means for energizing said follow-up drive in response to the departure of the movable element from a predetermined neutral position.

9. The structure as claimed in claim 8, in which the means for actuating the speed control element includes a reversible electric servomotor switch-control means for selectively energizing said servomotor, said switch means being selectively actuated by said differential movable element and said reversible follow-up drive including a reversible electric motor selectively controlled as to the energization thereof by said switch-control means, the rate of operation of said follow-up motor being independent of the rate of operation of said servomotor.

10. The structure, as claimed in claim 8, in which the means movable in accordance with the measured speed difference includes a hydraulic control valve means, operative to control the distribution and direction of fluid flow in an associated hydraulic circuit, said circuit includ-

ing a reversible hydraulic positioning motor, adapted to actuate a speed control element, and a second reversible hydraulic motor operatively connected in said follow-up drive to actuate the same, the rate of operation of each motor being independent of the other, but the instant speeds of which are dependent upon the magnitude of the movement of the control valve means from the neutral position in response to movement of the said differential movable element in accordance with the said measured speed difference.

11. A proportionizing differential speed responsive device comprising: a three-element differential having a first element adapted to be driven at a constant speed, a second element adapted to be normally driven at a speed proportional to the instant speed of a device to be controlled, and a third element movable from a predetermined neutral position in accordance with the difference in speeds of said first and second elements, reversible servo mechanism selectively energized by departure of said third element from the neutral position, a two-way drive including a pair of input drives and an output drive, a connection between said output drive and the second element of said differential said input and output drives being constructed and arranged such that said output drive is in accordance with the algebraic sum of the input drives, one of said input drives being adapted to be driven at a speed proportional to the speed of the device to be controlled, reversible power means for driving the other of said input drives at a rate independent of the operation of said servo mechanism, means for selectively energizing said power means responsive to departure of said differential third element from the neutral position to thereby cause a follow-up effect through said differential restoring said differential third element to the neutral position and deenergizing said servo mechanism and said reversible power means, a further existing speed difference causing a cyclical repetition of the operation of said servo mechanism and reversible power means, the time duration of each cycle of operation being proportional to the existing difference in speed between said differential first and second elements.

12. The structure as claimed in claim 11, in which said one of the input drives of said two-way drive includes a slip drive having a torque transmitting capacity substantially greater than the torque required to overcome friction in said two-way drive and the differential elements connected thereto and driven thereby, but said slip drive being adapted to slip upon development of a resisting torque exceeding the capacity of said drive.

13. In a differential governor, a constant reference speed driving means, means driven at a speed proportional to the speed of a device to be controlled, speed difference comparing means op-

eratively connecting said reference speed driving means and said means driven in accordance with the speed of the device to be controlled, said speed comparing means including an element movable in either of two directions from a predetermined neutral position respectively upon an increase or decrease in the speed of the device being controlled from the desired constant speed, speed control servo mechanism selectively energized under the control of said element upon departure thereof from the neutral position and means selectively controlled by said element upon departure thereof from the neutral position for returning said element to the neutral position after a time interval proportional to the speed difference existing at the beginning of the cycle, the control cycles then being repeated each with a time duration proportional to the remaining speed difference at the beginning of the cycle, the servo mechanism being operative for periods of time respectively equal to the time duration of the corresponding control cycle.

14. The structure as claimed in claim 13, in which the means for restoring the movable element of said speed difference comparing means to the neutral position includes motor means operable at a substantially constant rate and selectively energized upon departure of said element from the neutral position under control thereof, and deenergized upon restoration of said element to the neutral position.

15. The structure as claimed in claim 13 in which the means for restoring the movable element of said speed difference comparing means to the neutral position includes motor means operable at a rate substantially proportional to the value of the speed difference and selectively energized upon departure of said element from the neutral position under the control thereof, and deenergized upon restoration of said element to the neutral position.

16. A differential speed responsive control system comprising a three element differential having a first rotatable element, a constant speed drive for said first element, a second rotatable element, a means for driving said second element in accordance with the speed of the device to be controlled, a third element selectively displaceable from a predetermined neutral position upon the occurrence of a difference in speed between the constant speed drive and the means for driving said second element, servomotor control means adapted to be actuated by said third differential element upon displacement thereof from the neutral position, follow-up means adapted to physically restore the differential third element to the neutral position independent of the equalization of speeds between the respective driving means for said differential first and second elements, and means actuated by displacement of said differential third element from the neutral position for selectively controlling the follow-up means.

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