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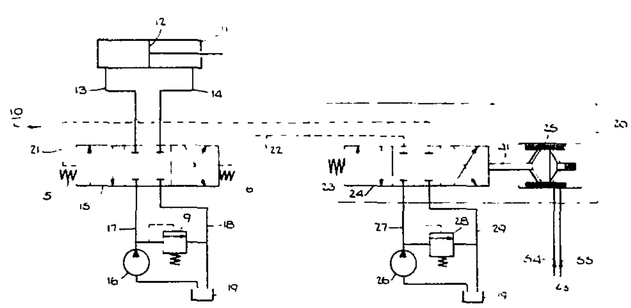
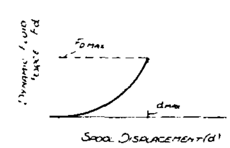
(54) Electro-hydraulic servo activator system.

(57) An electro-hydraulic servo system combines a pilot spool valve (24) with a non-linear solenoid (25) to provide a pilot stage for a main control valve. The non-linear solenoid (25) counteracts the Bernoulli forces that act upon the pilot spool (31) in order to provide an overall desired linear response. The non-linear solenoid comprises an armature (42) with conical pole faces (38, 39) subject to the energizations of oppositely acting energizing coils (44, 45), the armature (42) being biassed towards a normal position by means of a spring (43). An actuator rod (41) couples the armature (42) to the spool (31) of the pilot spool valve (24).





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ELECTRO-HYDRAULIC SERVO ACTUATOR SYSTEM

This invention relates in general to hydraulic systems, and in particular, to a hydraulic system having an improved solenoid actuated pilot spool valve.

A typical electro-hydraulic servo system will include a main spool valve for controlling the direction and quantity of fluid from a source of pressurized fluid, such as a pump, to a fluid actuator, such as a motor. A pilot valve is used to control the position of the main spool by selectively directing fluid from another pressurized source to the ends of the main spool. The pilot valve is itself a spool valve, whose spool position is determined by a force motor, such as a solenoid, acting on one end of the pilot spool in order to control the fluid directed to the ends of the main spool. Linear solenoids are designed to generate a near constant force over the entire distance that the plunger (armature) travels. In other words, linear solenoids exert a constant force as the solenoid air gap changes.

The pilot spool is held in a central or neutral position by relatively light balance springs disposed on opposite ends of the pilot spool. When a solenoid acts on the pilot spool to displace it from its neutral position, a solenoid force is applied to one end of the spool. As the spool moves, it compresses a balance spring until the spring generates an equal and opposite spring force to counteract the solenoid force. Examples of such systems may be found in U.S. Patents Nos. 4,031,813; 3,874,269; and 3,763,746.

Although a solenoid is an inherently non-linear apparatus, one can be modified to operate over a linear range; see, e.g. U.S. Patent No. 3,740,594. Linearly operating solenoids have been used to control pilot spools because such solenoids exert a near constant force over the full length of their air gap for a given electrical input. Thus, in theory, a linear solenoid should yield a one-for-one correspondence between the operator input (an electrical signal), the displacement of the pilot spool (which is resisted by a spring with a linear spring constant), and the resulting displacement of the main spool and the motor.

Unfortunately, such systems do not achieve their desired results. We have observed that such systems will inherently suffer from a reduction in volume of fluid transferred through the pilot spool and in a slower response time. The latter phenomena are believed to be caused by a third, non-linear force which acts against the solenoid force. The source of this third force is believed to be the fluid itself. This force, sometimes referred to as a Bernoulli force, arises from the flow of fluid through the chambers of the pilot spool and acts on the spool to oppose its displacement. The dynamic or Bernoulli force thus opposes the constant force of the linear solenoid, thereby negating the overall desired result of one-for-one correlation between input and output.

Contrary to the traditional use of linear solenoids, we have discovered that a non-linear solenoid whose actuating force increases as the air gap decreases will more effectively counteract the dynamic, Bernoulli forces and thereby yield an overall linear result. Accordingly, a main feature of the present invention is the use of a solenoid having exaggerated, non-linear characteristics for acting upon a pilot spool. Such non-linear characteristics are usually present for example in solenoids having sloped or slanted pole faces which are known per se, rather than the flat pole faces of linear solenoids. With the non-linear Bernoulli forces counteracted by the non-linear solenoid forces, the overall system achieves the desired linear response. Hence, the combination of a pilot spool valve with a non-linear solenoid overcomes the aforementioned problems associated with earlier pilot spool and linear solenoid combinations.

In order that the invention may be clearly understood, exemplary embodiments thereof will hereinafter be described with reference to the accompanying drawings wherein:

Figure 1 is a schematic representation of a pilot operated hydraulic directional control valve system;

Figure 2 is an enlarged view of the solenoid operated pilot valve of Figure 1;

Figures 3 and 4 are graphical representations of the forces acting upon a pilot spool; and

Figure 5 is an electrical schematic representation of a circuit for energizing the coils of the solenoid actuator of Figure 2.

In Figure 1 there is shown an electro-hydraulic servo actuated system 10. That system includes a fluid motor, such as the cylinder 11 with a differential piston 12 which can be translated in either direction by selective application of fluid pressure and flow via service lines 13 and 14. The direction and quantity of fluid applied to service lines 13 and 14 is controlled by main spool valve 15. Hydraulic fluid is drawn from a reservoir 19 and is pressurized by a pump 16 that is in turn connected to spool valve inlet line 17. An outlet line 18 carries fluid away from the spool valve 15. A pressure relief valve 9 is connected between lines 17 and 18 in a manner well known in the art.

Main spool valve 15 operates in a conventional manner. To this end, when the spool valve is displaced to the right, service line 13 is connected with inlet 17 thereby displacing the piston 12 to the right. Likewise, fluid is exhausted from cylinder 11 via the service line 14 which is connected to drain or outlet 18. In a similar manner, the piston 12 can be driven in the opposite direction when spool valve 15 is shifted to the left.

The position of main spool valve 15 is hydraulically controlled by a pilot spool servo actuator system 20. Pilot service lines 21, 22 connect the ends of the main spool valve 15 with the pilot servo actuator system 20. Accordingly, main spool valve 15 is shifted to the left or the right depending upon the fluid pressure and flow applied via service lines 21, 22 which act against the centering springs 5 and 6 of the main spool.

The pilot actuator system 20 includes a pilot spool valve 24 which controls the direction and quantity of pilot fluid supplied via pilot lines 21 and 22. The position of pilot spool 24 is itself determined by a centering spring 23 and a solenoid actuated force motor 25. Pilot fluid is drawn from the same reservoir 19 and is pressurized by a pilot pump 26 that is connected to pilot inlet line 27.

A pilot outlet line 29 is provided for exhausting return fluid through the pilot valves 24 to the reservoir 19. A pilot relief valve 28 is connected between the inlet and outlet lines 27, 29 for relieving excessive pilot pressure in a manner well known in the art.

Turning now to Figure 2, there is shown an enlarged cross-sectional view of the pilot actuator system 20. As can be seen, the pilot spool valve 24 includes a housing 30 having a cylindrical bore 35 with a cylindrical spool 31 slidably mounted therein. A plurality of raised lands 32, 33, 34 on spool 31 are provided for controlling the direction of fluid from the inlet line 27 to the pilot service line ports 21a and 22a in a per se known manner.

The solenoid force motor 25 includes a ferromagnetic housing 40. The housing includes an armature cavity 37 having a pair of oppositely disposed conical pole faces 38, 39. An armature 42 is reciprocally and slidably mounted within the cavity 39. Armature 42 has a central cylindrical body portion and two oppositely disposed, conically shaped end faces 48, 49 that face pole faces 38, 39, respectively. A pair of electromagnetic coils 44, 45 are enclosed in the housing 40, closely adjacent to the armature 42. The coils 44, 45 are separated near the middle of cavity 37 by an insulating disc 46. The armature 42 will be urged towards the left when coil 44 is energized and to the right when coil 45 is energized. Electrical energy is supplied to the respective coils 44, 45 by a pair of leads 54, 55 (see Figure 1). An actuator rod 41 axially mounted on the armature 42 extends from the force motor housing 40 through the pilot spool housing 34 to engage one end of pilot spool 31. Accordingly, the position of the armature 42 and thus the pilot spool 31 will be determined upon the net electro-mechanical force exerted on the armature 42 via the coils 44, 45.

The energizing circuit for coils 44 and 45 is schematically shown in Figure 5. There, a supply voltage V is applied across a rheostat 51 and a parallel combination of three series resistors, R1, R2, and R3. The output of rheostat 51 is applied to an oscillator 56 whose output is in turn a saw tooth shaped voltage signal whose amplitude is representative of the voltage drop between the wiper arm 51a of the rheostat and the ground. The oscillator signal is applied to a comparator 57. The comparator 57 will compare the input oscillator voltage with two fixed voltages, i.e., the voltages between resistors R1-R2 and R2-R3. As a result, the output of the comparator 57 will be a modulated triangular pulse signal whose amplitude is representative of the relative displacement of the rheostat arm 51a from its mid or null point. The comparator output is applied to a pair of pulse width modulating amplifiers 58, 59 whose outputs yield pulse width modulated current signals which are respectively proportional to the relative position of the wiper arm of rheostat 51. Hence, when rheostat 51 is set in its center or null position, the signals imposed upon coil lead 47, 48 will have the same relative width and hence the armature 42 will be held in its central or neutral position. However, as the wiper arm is moved away from its null position, the relative width of the current pulse signals appearing on the respective lines 47, 48 will change and the armature will be moved in the general direction of the larger pulse width signal.

The interaction between the spring, solenoid, and dynamic forces is best explained with reference to

Figures 3 and 4. When the force motor 25 is actuated either to the left or to the right, it applies a solenoid force designated Fs on to the pilot spool 31. That force Fs is opposed by two forces which act upon a pilot spool 31 in a direction opposite to the solenoid force. These two opposing forces include the spring force Fk exerted on the spool by centering spring 23 and a fluid dynamic force, Fd, otherwise known as a Bernoulli force. The latter is so designated because Bernoulli was the first to explain how the passage of a fluid through a variable restricted orifice generated opposing forces upon the means used to constrict the orifice. Such Bernoulli forces are non-linear and are generally represented by the graphical presentation shown in Figure 4.

There it will be seen that the Bernoulli forces Fd will generally reach peak Fd max after which they will fall off. In the case of a pilot spool, the Bernoulli forces can be related to the spool displacement which is the cause of the restriction of the fluid. Hence, it can be said that the Bernoulli forces will reach a maximum (Fd max.) at a given spool displacement, in this case, d max.

We have discovered that such Bernoulli forces can be counterbalanced by a non-linear solenoid which increases its applied force at a rate similar to the Bernoulli forces as the air gap of the solenoid decreases. We have chosen to use a solenoid with conical pole forces 38, 39 and a conical-ended armature 42 in order to emphasize the non-linearity of the force applied by the solenoid as the armature 42 approaches either of the opposite pole faces 38, 39. The conical pole faces 38, 39 serve to concentrate the magnetic field at the end of the air gap, thereby exerting an increasing force on armature 42 as it moves toward one of the pole faces 38, 39.

The length of air gap d on the solenoid is chosen to match the spool displacement which will encounter the maximum Bernoulli forces. As the fluid dynamic forces Fd increase with the spool displacement, the solenoid forces increase in a proportionate amount thereby cancelling one another out and leaving a net force at Fn which approximates a desired linear response. Accordingly, the displacement of the pilot spool, and ultimately, of the main spool itself, is directly proportional to the position of the wiper arm of rheostat 51. As the wiper arm is moved 10 percent from its null position, the pilot spool will move 10 percent from its null position and thereby displace the main spool 10 percent from its null position.

Such a true, overall linear correlation between an input signal and the output displacement of the main spool has not been possible with the usual linear solenoid force motor. Such force motors generally apply a constant force across the whole air gap. So, as the Bernoulli forces increase with the spool displacement, the linear solenoid maintains a constant force and the net force applied to the pilot spool decreases. Of course, to counteract the opposing Bernoulli forces, an operator could increase the power supplied to the coils 44, 45 by adjusting the position of the rheostat 51. As a result, an operator might have to move the rheostat 30 percent of its displacement in order to achieve a 10 percent displacement of the main spool. Hence, in operation, an operator was required to overshoot the rheostat adjustment in order to achieve the desired displacement for the main spool.

However, with the present invention, an operator can now achieve the desired one-for-one correlation between the rheostat position and the displacement of the main spool 15. Thus, the invention will provide for greater precision in both the manual and the automatic operation of electro-hydraulic servo systems.

Claims:-

1. An electrohydraulic servo actuator system comprising:-

a main valve having a shiftable spool for controlling fluid flow through the main valve;

a pilot valve having a displaceable pilot spool for controlling fluid flow through the pilot valve;

a pair of pilot lines connecting the pilot valve with opposite ends of the main spool to shift the main spool in accordance with the displacement of the pilot spool; and

means for displacing the pilot spool with a force that increases in magnitude with the displacement of the pilot spool.

2. The system of claim 1 wherein said displaci means comprises a solenoid having a plunger connected to the pilot spool for displacing the pilot spool with a force that increases as the air gap of the solenoid decreases.

3. A solenoid controlled pilot valve comprising:-

a directional control valve having a pilot spool for controlling the direction and quantity of fluid flow through the valve; and

a non-linear solenoid operable in response to an electric signal for acting upon the pilot spool with a force that increases as the pilot spool is displaced.

4. An electrohydraulic valve comprising:-

a valve body having an internal bore, an inlet port, an outlet port, and two service ports;

a displaceable spool slidably mounted in the bore and having a plurality of raised lands for selectively establishing fluid communication between the inlet port and one service port and between the outlet port and the other service port in accordance with the displacement of the spool;

means for biasing the spool toward a neutral position to block fluid communication between the inlet port and the service ports and for acting on the spool with a force proportional to the displacement of the spool and in a direction opposite to that displacement;

means for generating an electrical signal representative of the desired displacement of said spool;

means for converting the electrical signal in+ a magnetic field; and

a displaceable armature responsive to the magnetic field for acting upon said spool with a force that increases with the displacement of the armature to thereby displace said spool in accordance with the direction and strength of the magnetic field.

5. An electrohydraulic valve system comprising:-

a valve body with inlet, outlet and two service ports;

a spool slidably disposed in the valve body for controlling the direction and quantity of fluid flow through the valve;

a spring for biasing the valve toward a neutral position in which the inlet port is isolated from both service ports;

a non-linear solenoid having an elongated body, an armature cavity inside the body and a pair of opposed walls, one at each end of the cavity;

a pair of electric coils wrapped around the solenoid body for generating oppositely oriented magnetic fields in the armature cavity; and

an armature slidably mounted in the cavity and having a plunger connected to the valve spool for displacing the valve spool with a force that increases as the armature moves toward an end wall.

6. An apparatus comprising a fluid control valve having a movable spool for controlling the quantity and direction of fluid flow through the valve, the spool having a neutral position for blocking fluid flow through the valve, a spring for biasing the spool to its neutral position, the spool being subject to dynamic flow forces in a direction opposing its displacement, and a non-linear solenoid having a plunger for operation on the spool to displace the spool in a desired direction with a force that increases as the air gap of the solenoid decreases.

7. The apparatus of claim 6 wherein the solenoid comprises:-

a housing having an elongated armature cavity therein with walls at opposite ends of the cavity for concentrating a magnetic field in a region adjacent the end walls;

a pair of coils mounted in the housing for carrying current in opposite directions in order to establish magnetic fields of opposite orientation that are concentrated at opposite ends of the housing;

an armature movably mounted in the cavity, spaced from the end walls thereof and having corresponding end surfaces facing end walls, thereby defining a variable air gap between each end surface and corresponding end wall so that the armature is magnetically attracted toward one of the end walls by a magnetic force which increases non-linearly as the air gap between the armature and the wall decreases; and wherein

said plunger extends axially from one end surface of the armature and through the housing for acting upon the spool for displacing said spool in the desired direction by the desired amount.

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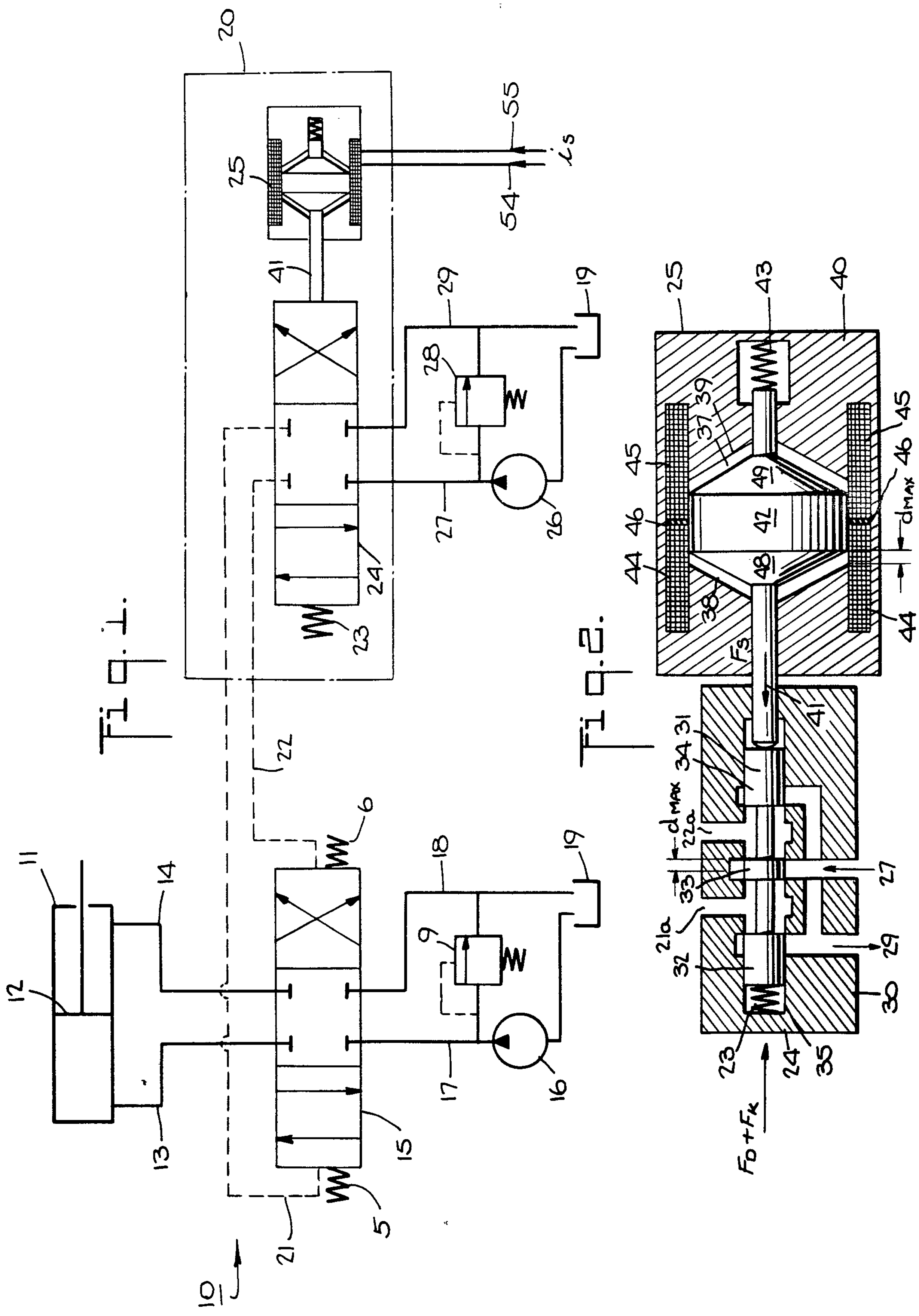

Fig. 1.

Fig. 2.

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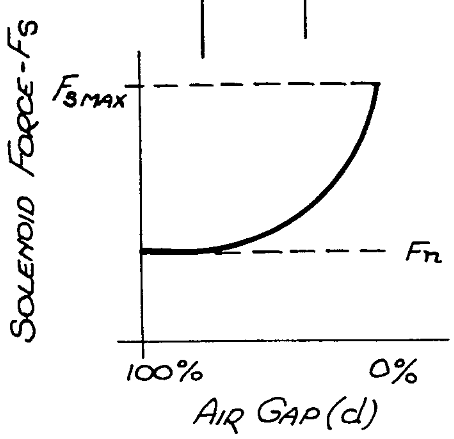

Fig. 3.

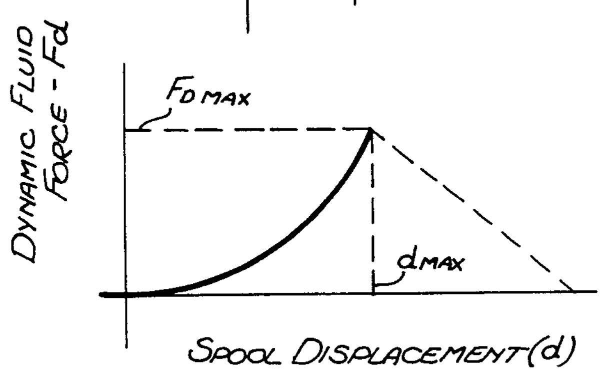

Fig. 4.

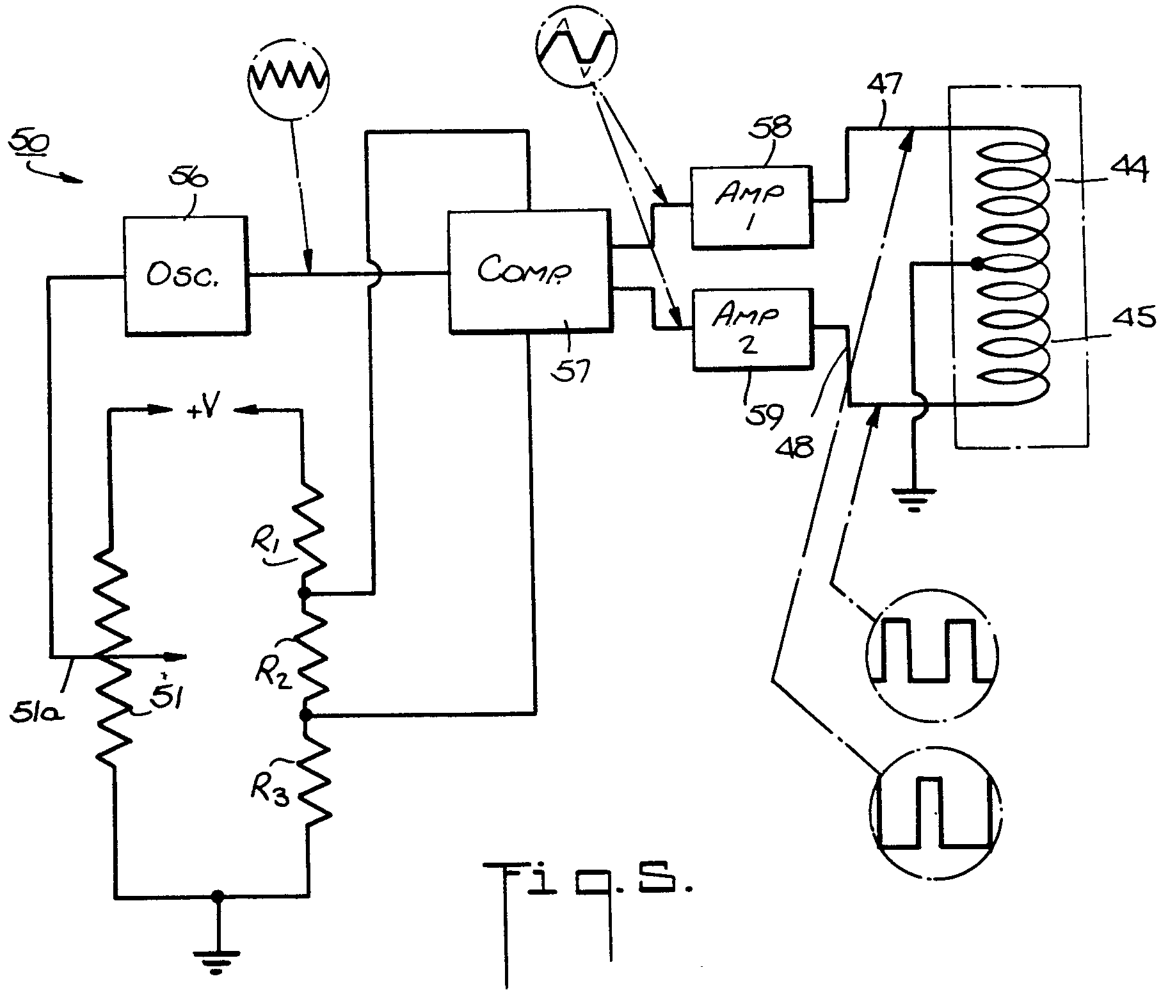

Fig. 5.

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EUROPEAN SEARCH REPORT

0038128

Application number

EP 81 30 1263

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim
	US - A - 4 144 514q (GENERAL ELECTRIC) * Column 5, lines 65-68; column 6, line 1 *	1-3,7
D	US - A - 4 031 813 (SPERRY RAND) * Figure 1 *	1,4-6
D	US - A - 3 740 594 (FEMA CORP.) * Column 4, lines 29-67; column 5, lines 1-24 *	1-3
	GB - A - 656 208 (UNITED AIRCRAFT) * Page 2, lines 98-130; page 3, lines 1-12 *	1-3
	US - A - 3 858 135 (S.A. GRAY) * Figure 2 *	7
A	US - A - 4 071 042 (REGIE NATIONALE DES USINES RENAULT)	
A	US - A - 2 436 992 (H.P.M. DEVELOPMENT CORP.)	
A	FR - A - 2 121 841 (C. METZ)	
A	FR - A - 2 265 162 (M. GRIFFET)	

CLASSIFICATION OF THE APPLICATION (Int. Cl.³)

H 01 F 7/13
F 15 B 13/044

TECHNICAL FIELDS SEARCHED (Int. Cl.³)

H 01 F 7/13
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CATEGORY OF CITED DOCUMENTS

X: particularly relevant
A: technological background
O: non-written disclosure
P: intermediate document
T: theory or principle underlying the invention
E: conflicting application
D: document cited in the application
L: citation for other reasons

&: member of the same patent family, corresponding document

X The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
The Hague	16-07-1981	VANHULLE