April 26, 1949. A. W. HULL 2,468,554

APPARATUS FOR MAGNETIC FIELD INVESTIGATION

Filed March 19, 1943 6 Sheets-Sheet 1

Fig. 1.

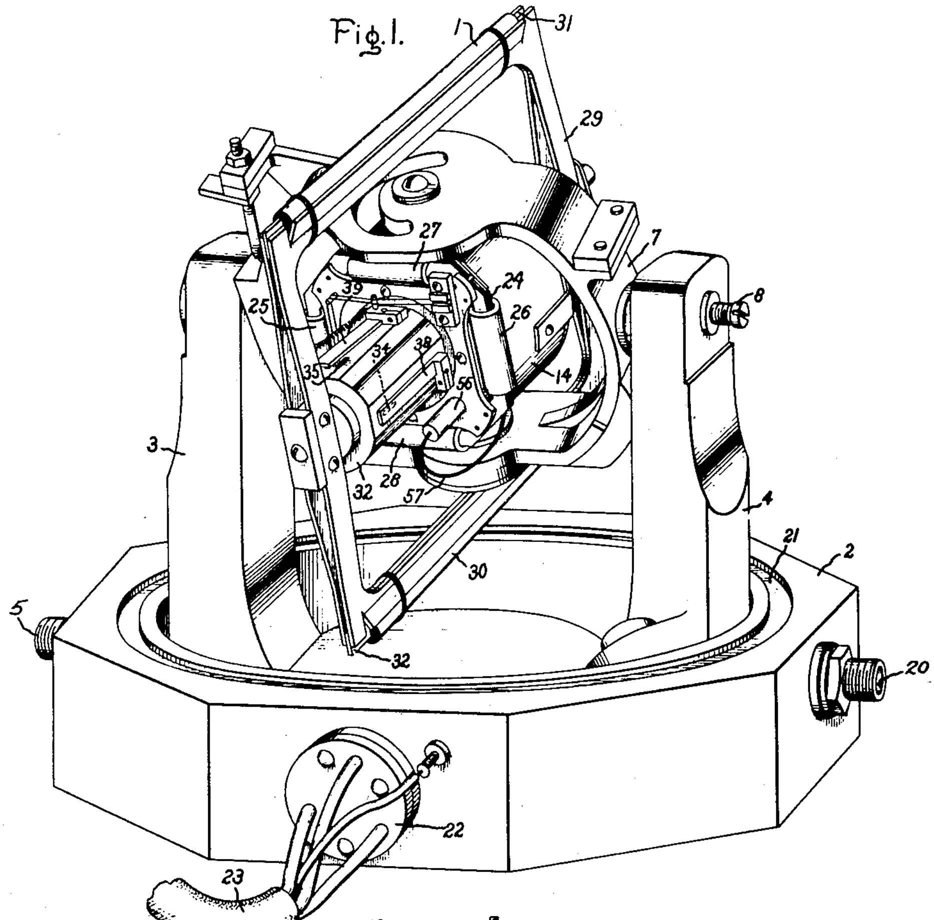
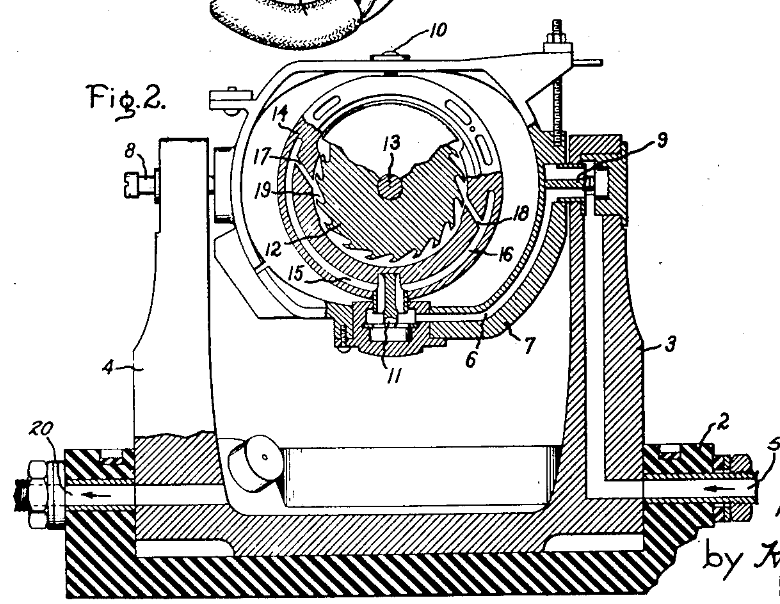


Fig. 2.



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APPARATUS FOR MAGNETIC FIELD INVESTIGATION

Filed March 19, 1943 6 Sheets-Sheet 2

Fig. 3.

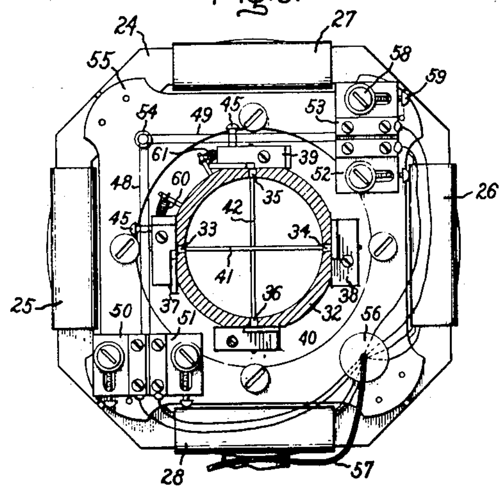


Fig. 4.

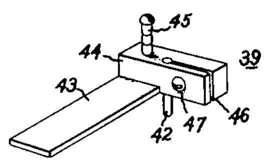
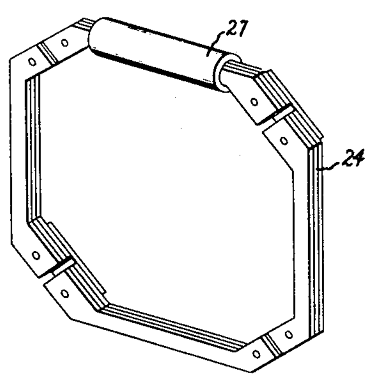


Fig. 5.



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APPARATUS FOR MAGNETIC FIELD INVESTIGATION

Filed March 19, 1943 6 Sheets-Sheet 3

Fig. 6.

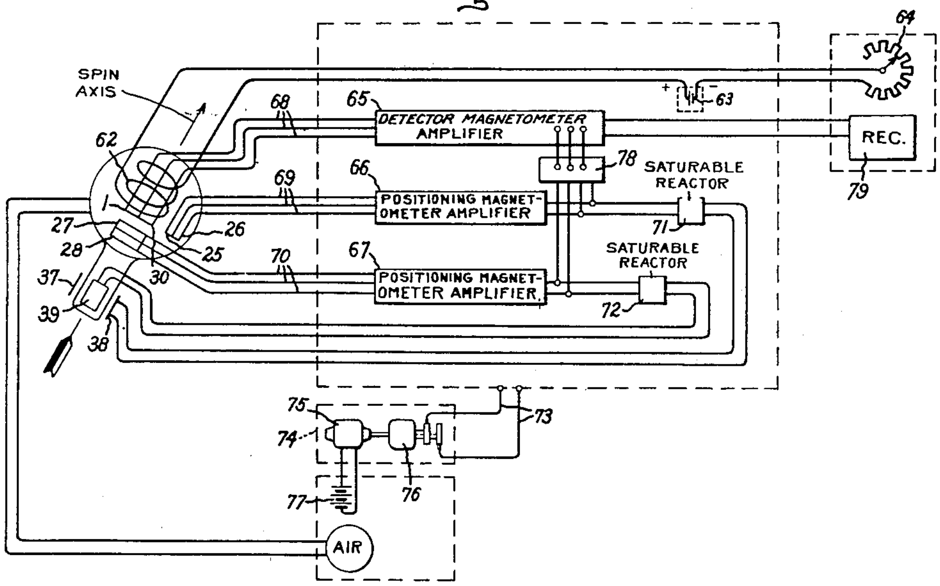

Fig. 7.

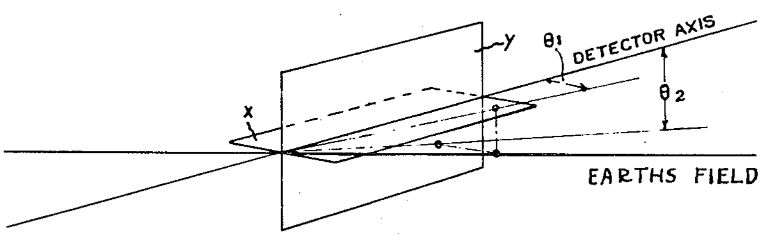

Fig. 8.

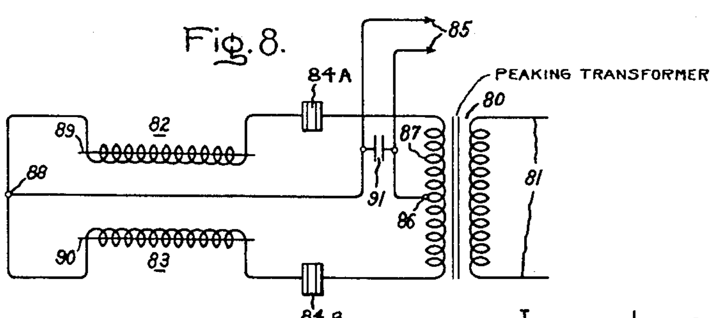

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Fig. 9.

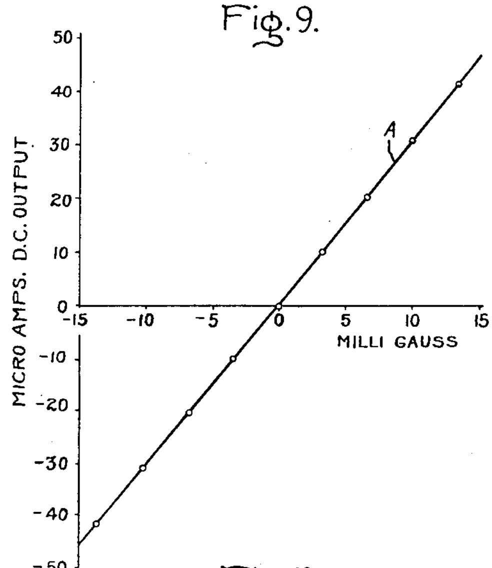

Fig. 10.

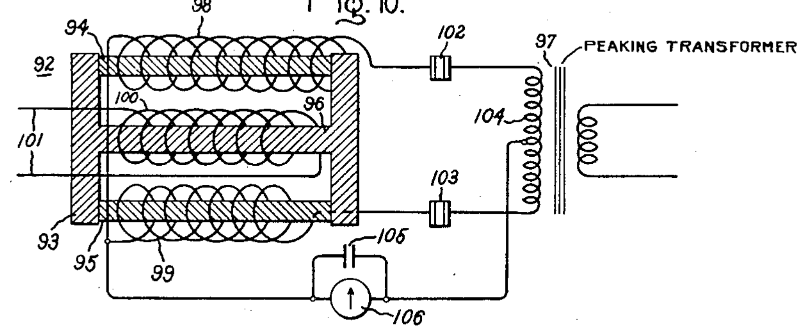

Fig. 11b.

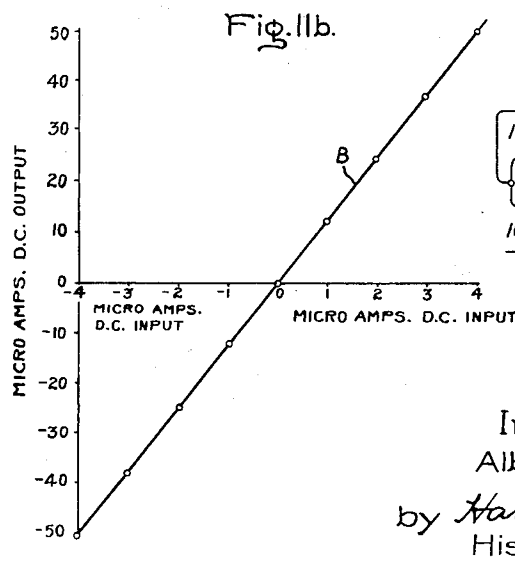

Fig. 11a.

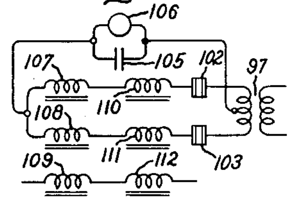

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Fig. 12.

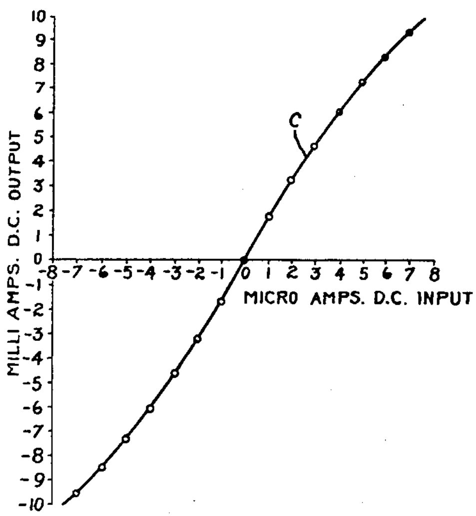


Fig. 14.

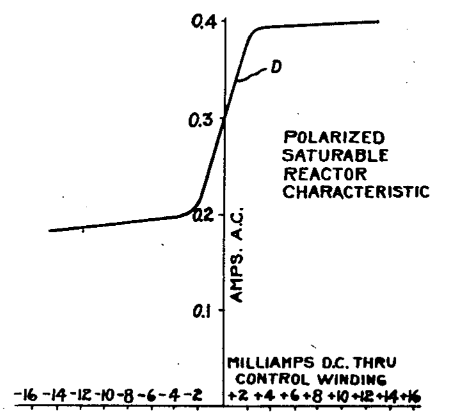
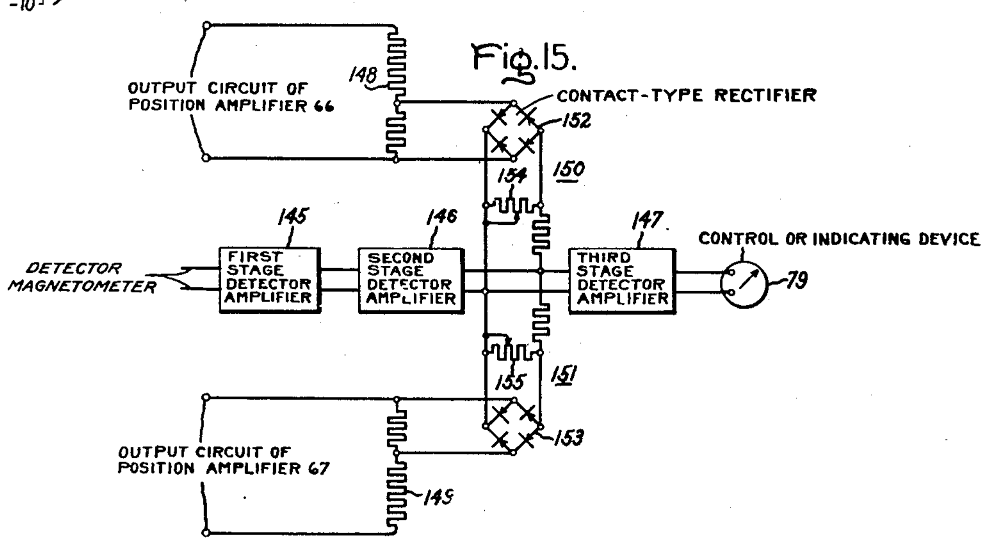


Fig. 15.



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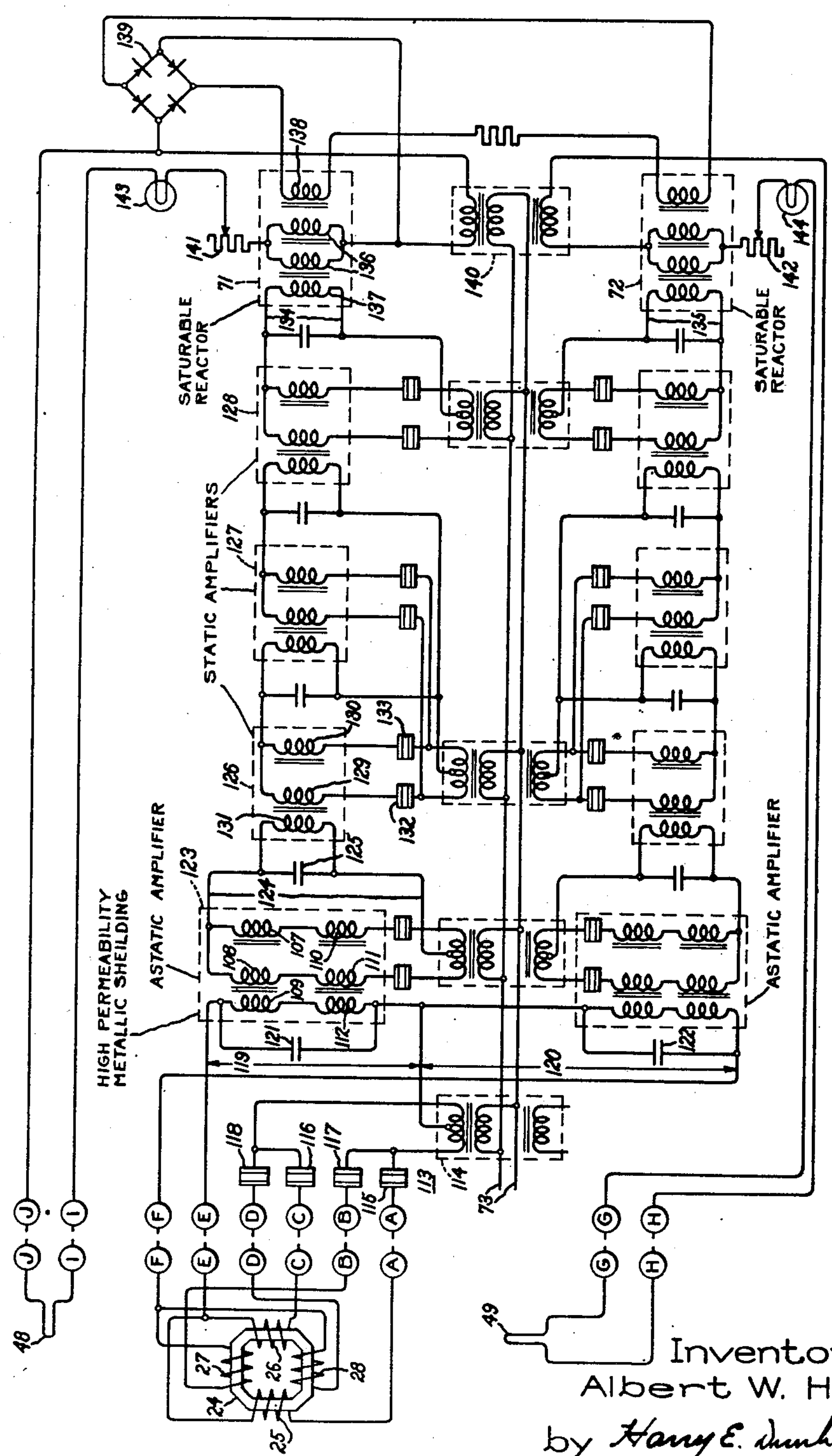
APPARATUS FOR MAGNETIC FIELD INVESTIGATION

Filed March 19, 1947 6 Sheets-Sheet 6

Fig. 13.



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Patented Apr. 26, 1949 2,468,554

UNITED STATES PATENT OFFICE

2,468,554

APPARATUS FOR MAGNETIC FIELD INVESTIGATION

Albert W. Hull, Schenectady, N. Y., assignor to General Electric Company, a corporation of New York

Application March 19, 1943, Serial No. 479,713

10 Claims. (Cl. 175—183)

1

My invention relates to methods and apparatus for investigating magnetic fields, and more particularly to methods and apparatus for detecting, investigating and measuring intensities and anomalies in the earth's magnetic field.

It is an object of my invention to provide new and improved methods and apparatus for investigating magnetic fields.

It is another object of my invention to provide new and improved methods and apparatus for detecting anomalies in the earth's magnetic field such as those produced by the presence of mineral deposits or the presence of metallic bodies.

It is a further object of my invention to provide a new and improved magnetometer which comprises a detecting coil, the axis of which is to be maintained in a predetermined direction with respect to a magnetic field and which is controlled in position by means of a pair of positioning magnetometers comprising a pair of mutually perpendicular coils each perpendicular to the axis of the detecting coil.

It is a still further object of my invention to provide a new and improved system for controlling a gyroscope.

It is a still further object of my invention to provide a new and improved detecting system comprising a detecting coil positionable by a gyroscope and in which the precession of the rotor of the gyroscope is controlled by means of a magnetometer comprising a pair of mutually perpendicular coils for producing electrical quantities in accordance with orthogonal components of a magnetic field, such as two mutually perpendicular components at right angles to the spin axis of the gyroscope.

It is a still further object of my invention to provide new and improved means for investigating a magnetic field which comprises a means for positioning a magnetic detecting coil, positioning magnetometers for the detecting coil and amplifying means of the magnetic type.

Briefly stated, in accordance with one aspect of my invention I provide new and improved methods and apparatus for investigating, detecting, or measuring magnetic fields. One application of my invention is that incident to the investigation of the earth's magnetic field for the purpose of detecting discontinuities or anomalies therein incident to the presence of mineral deposits or extraneous metal objects.

Generally speaking, I provide a magnetic detecting means or magnetometer which comprises a magnetic detecting element, such as a magnetic detecting coil, the axis of which is to be maintained in a predetermined direction in a given magnetic field. One such position is that in which the axis of the detecting coil is in parallelism with the magnetic field under investigation. The magnetic detecting coil is maintained

2

in the desired position, such as one of parallelism with the magnetic field, by a pair of mutually perpendicular positioning magnetic elements comprising means, such as a pair of coils, which are perpendicular to the axis of the magnetic detecting coil and also normally perpendicular to the magnetic field for providing a controlling effect in accordance with deviations of the axes of the coils from a perpendicular relationship with the field. The magnetic detecting element in such an arrangement produces, in conjunction with an associated circuit, an electrical quantity, such as a voltage or current, which is a function of the cosine of the angles between the axis of the coil and the magnetic field, thereby obtaining a high degree of sensitivity to variations in the magnetic field intensity and low sensitivity with respect to the angle of deviation.

The system may be employed in conjunction with a positioning means for maintaining the axis of the coil in the desired relation to a magnetic field as the entire system is moved through the field. One type of mechanical positioning means or servo motor means which may be employed is a gyroscope which may be of the fluid-spun or air-spun type which supports and positions the magnetic detecting coil. By the employment of a gyroscopic element for positioning the magnetic detecting coil, due to the inherency of the gyroscope to maintain the spin axis in a predetermined position in space, the amount of auxiliary controlling action required to maintain the desired alinement of the coil axis is minimized, thereby making it possible to reduce the size and capacity of the auxiliary or positioning apparatus.

The methods of investigating magnetic fields which I provide are particularly useful in detecting discontinuities or anomalies in the earth's magnetic field. One aspect of the methods generally comprises maintaining the axis of a magnetic detecting element or coil substantially parallel to the field by controlling the position thereof in accordance with deviations from the parallel position as measured by other detecting elements and measuring or utilizing the magnetic flux cutting said coil to ascertain the magnitude of the field anomoly.

The methods and system are peculiarly adaptable for slow searches over a relatively small area. The normal magnetic field of the earth is neutralized so that the system affords a zero indication in the absence of an anomaly. Any deviation in the intensity of the magnetic field above or below its normal order causes a positive or negative deflection or indication proportional to the increment of the magnetic field which may be used to determine when the device or system is positioned directly over an anomaly.

For a better understanding of my invention, reference may be had to the following description taken in connection with the accompanying drawings, and its scope will be pointed out in the appended claims. Fig. 1 illustrates an embodiment of my invention as applied to a fluid-spun gyroscope, and Fig. 2 is a cross sectional view of a part of a gyroscope showing the rotor, the housing therefor, and the fluid conduit structure comprising a part of the bracket supporting structure. Fig. 3 is a detailed view of the valve controlling the mechanism for the air-spun gyroscope shown in Fig. 1. Fig. 4 is a detailed view of a control valve for the gyroscope and Fig. 5 is a detailed view of the magnetic core structure comprising a part of the positioning magnetometers. Fig. 6 is a simplified circuit showing the relationship between the elements mounted upon the gyroscope, the magnetic amplifiers for the detecting magnetometer and the positioning magnetometers and the correction means. Fig. 7 is a view presented for the purpose of showing some of the factors involved in correcting the voltage representative of the detector coil position as it is displaced with respect to a magnetic field such as the earth's field. Fig. 8 represents one form of a magnetometer or amplifier circuit which may be employed in the system, and Fig. 9 represents an operating characteristic thereof. Fig. 10 shows a saturable type magnetic amplifier which is employed in the system. Fig. 11*a* is a circuit arrangement of an astatic type magnetic amplifier comprising two units such as that shown in Fig. 10, and Fig. 11*b* represents an amplifying characteristic thereof. Fig. 12 is a calibration curve of a three-stage direct current amplifier employed in the system; Fig. 13 is a general circuit showing the amplifying system connected to the positioning magnetometers and to the control means for the gyroscope valves; Fig. 14 represents an operating characteristic of the saturable reactors employed in the system shown in Fig. 13, and Fig. 15 generally illustrates the manner in which the voltage indicative of magnetic field strength is corrected for errors incident to the position of the coil in the magnetic field, and more particularly shows the manner in which this result is obtained by introducing, into the amplifier circuit for the magnetic detecting coil, voltages proportional to the squares of the angular deviations of the coil axis from a parallel position in the magnetic field.

Referring now to Fig. 1, my invention is there illustrated in perspective view as applied to a gyroscope of the fluid-spun type for positioning a magnetic detecting element, such as a magnetic detecting coil **1**, the axis of which is to be maintained in a predetermined position in a magnetic field such as the earth's magnetic field. While my invention is shown as employing a gyroscope as the positioning means or structure, it is to be appreciated that the broad aspects of my invention are not limited to the employment of this particular positioning means.

The gyroscope comprises a base member **2**, preferably constructed of a relatively light nonmetallic material such as a plastic. The gyroscope is supported by a gimbal, preferably constructed of a relatively light metal such as aluminum having vertical brackets **3** and **4** which serve to support the relatively movable elements of the gyroscope and the magnetometer constructions to be described presently. Where a gyroscope is employed, it may be of the fluid-spun or air-spun type in order to minimize extraneous magnetic disturbances, and the propelling fluid for the gyroscope may be supplied in a manner illustrated in detail in Fig. 2 which represents in partial cross section the base member **2** and vertical bracket **3** as providing a fluid conduit **5** which is in communication with a fluid conduit **6** in a gimbal ring **7**. The gyroscope is susceptible of rotation about mutually perpendicular major and minor gimbal or pivot axes, one of which is constituted by a pair of pins **8** and **9** supported by brackets **4** and **3**, respectively, and the other of which is constituted by pins **10** and **11** which are supported by the gimbal ring **7**. A fluid impelled rotor **12** is rotatable on an axle **13** defining the spin axis of the gyroscope and is positioned within a rotor bearing frame comprising a housing **14** provided with fluid conduits or channels **15** and **16** and nozzles **17** and **18** to direct jets of the fluid against buckets **19** located on the periphery of the rotor **12**. The fluid after impinging upon the buckets is exhausted through a manifold and associated ports, to be described presently, and is discharged through an outlet conduit **20**, the entire gyroscope and magnetometer construction being enclosed by means of a suitable bell-shaped hermetic cover, such as a glass cover (not shown), which is seated in an annular groove **21** in the base member **2**.

Electrical connections to the elements positioned within the covering for the gyroscope may be effected by means of a plug and socket arrangement **22**, and the associated amplifying and control apparatus may be connected thereto by means of a cable **23** to permit location of the control and amplifying apparatus at a point remote from the position of the gyroscope and magnetometer.

In order to maintain the axis of the magnetic detecting coil **1** in a predetermined position, such as in parallelism with a magnetic field, I provide a magnetometer arrangement including a pair of positioning magnetometer elements which are perpendicular with respect to each other and perpendicular to the axis of the magnetic detecting coil **1**, and consequently perpendicular to the magnetic field under consideration when it is desired to maintain the axis of coil **1** parallel to the magnetic field. As one example of the way in which this principle may be employed, I provide a magnetic core structure **24** preferably supported by the structure which moves with the housing **14** and is in fixed relation to coil **1**, and upon which are wound mutually perpendicular positioning magnetometer coils which produce electrical quantities in accordance with orthogonal components in a plane perpendicular to the axis of the detecting coil. The magnetic core structure **24**, which is shown in detail in Fig. 5, may be of substantially rectangular configuration comprising laminations of high permeability metal having wound thereon two pairs of quadrature or diametric coils **25**, **26** and **27**, **28** which measure or detect components of the magnetic field in their respective directions or parallel to their respective axes.

The core structure **24** is secured to the gyroscope housing **14** in a manner sufficiently accurate to insure perpendicularity to the gyroscope spin axis. Also, as shown, the core is preferably arranged so that the axes of the coils **25** and **26** are perpendicular to the gyro gimbal axis **8—9** and the axes of the coils **27** and **28** are perpendicular to the gyro gimbal axis **10—11**. The coils **25—28** measure the components of the magnetic field parallel to their axes, and hence perpendicular to the gyroscope spin axis. These components will be zero when the axis of the detecting coil 1 is in the desired direction of the total field. Consequently, in accordance with my invention, the electrical quantities or signals produced by the magnetic fluxes cutting the magnetometer positioning coils 25—28, are employed to control mechanisms described hereinafter in such direction as to oppose the changes in position of the structure, thereby maintaining the axis in a desired position with an accuracy that is limited only by the sensitivity of the magnetometers and the amount of power which one is willing to employ. The magnetometers constructed in accordance with my invention are sensitive to one gamma which corresponds to one $^1/_{1000}$ degree deviation from the normal to an earth field of 0.59 gauss. Accordingly, an angular accuracy of $^1/_{30}$ degree is practical.

The magnetic detecting element of the system may comprise a pair of coils, one of which is coil 1, supported in the position illustrated by means of a frame 29 carried and positioned by the gyroscope housing 14, and the other of which may constitute a similar magnetic detecting coil 30 positioned below and parallel to coil 1. Coils 1 and 30 preferably comprise a pair of metallic core members or strips 31 and 32 of high permeability metal upon which the wire constituting the coil is wound. These core members or strips, for example, may be approximately 4½ in. long and may be located symmetrically 4½ in. apart having a width of $\frac{1}{16}$ in. and 0.007 in. thickness surrounded by closely wound coils of approximately 2000 turns per inch of 2.8 mil wire.

In order to neutralize the normal earth's field, coils 1 and 30 are provided with unidirectional magnetizing windings so that the system is highly responsive to magnetic flux distributions of the field due to anomalies. This feature is discussed in detail in connection with Fig. 6.

As a means for controlling the precession of the spin axis of the gyroscope in accordance with electrical quantities produced by coils 25—28, the housing structure for the rotor is provided with a manifold 32 through which the impelling fluid flows after driving the rotor 12. Selective or conjoint positioning of the spin axis in the directions perpendicular to the axes of coils 25—28 is obtained by providing the manifold 32 with ports 33 and 34, and ports 35 and 36, arranged at right angles. Only ports 34 and 35 are shown in Fig. 1, and a detailed view of the manifold and associated construction may be obtained by referring to Fig. 3 which will be discussed in detail hereinafter. Ports 33—36, inclusive, are provided with associated valves 37, 38, 39 and 40, preferably of the leaf type, supported by and pivoted on manifold 32. The valves 37 and 38 are mechanically connected or coupled by means of a connecting rod 41, and the valves 39 and 40 are mechanically connected through a rod 42, shown in Fig. 3, so that actuation of valves 37 and 39 produces corresponding movements of the respectively associated valves 38 and 40 the action being such that when valves 37 and 39 are open, valves 38 and 40 are closed, and vice versa.

The details of one of the actuating valves, such as valve 39, are shown in Fig. 4. The valve comprises a metallic strip 43 supported by a metallic block 44 clamped to rod 42 which is seated in apertures provided by manifold 32. An actuating pin 45, which is connected to a thermally expansive means to be described presently, is supported by block 44 and by exertion of a force thereagainst and due to the displacement between the axes of rod 42 and pin 45, a torque is produced effecting movement of the valve and rod 42. In order to secure the valve block 44 to rod 42, block 44 is provided with a longitudinal slot 46 and a tightening screw 47.

The details of the valve actuating mechanism will now be described more particularly by referring to Fig. 3. Briefly stated, I provide means for actuating valves 37—40 in accordance with the electrical quantities produced by coils 25—28, and these means may comprise thermally expansive metallic members for actuating the valves. More particularly, I provide a pair of filamentary elements or wires 48 and 49 of loop configuration which are in engagement with actuating pins 45 of valves 37 and 39, respectively. The wires 48 and 49 are preferably constructed of relatively fine wire, as for example, wire having a diameter of 3 mils and the open ends of which are connected to bracket terminals 50, 51 and 52, 53, respectively. The closed ends of wires 48 and 49 are anchored or supported by a pin 54 which is supported by a metallic frame 55 attached to the magnetic core 24. Electrical connections to coils 25—28 and to terminal brackets 50—53 may be made through a terminal means 56 supported by plate or disk 55. The connections to the terminal means 56 may be made by a multi-conductor pigtail 57 of sufficient length and flexibility to permit free movement of the gyroscope about the major and minor axes.

Terminal brackets 50—53 each comprise adjusting means for controlling the position and tension of the associated thermally expansive wire and comprise adjusting screws 58 and 59 which permit lateral as well as vertical positioning of the open ends of the wires.

Valves 37—40 may be biased to a predetermined initial position, by suitable means such as springs 60 and 61, each having one end thereof anchored to the manifold 32 and the other end of which is connected to a suitable part of the valve structure such as block 44.

The valve mechanism for controlling the precession of the spin axis may be arranged to operate in a number of ways, the manner chosen, of course, being dependent upon the facility of construction and operation. One example of the manner in which the valves may be employed is by controlling the energy supplied to wires 48 and 49 and by adjustment of the biasing means and the terminal brackets 50—53 so that when the magnetometer coils 25—28 establish a plane in exact perpendicularity with the earth's magnetic field, all valves are half open. Under this condition, the reactive forces due to the flow of the impelling fluid through all four valves establish a balanced force condition, producing no movement of the spin axis. Upon deviation from the desired condition of perpendicularity of the plane defined by coils 25—28 to the field, appropriate pairs of valves, or both pairs of valves, are actuated in the desired manner to restore perpendicularity. In this manner, the axes of detector coils 1 and 30 are maintained in positions parallel to the total earth's field.

For example, if in the movement of the gyroscope and magnetometer in a magnetic field the positioning coils 25 and 26 depart from exact perpendicularity with the field, as in a vertical plane perpendicular to the plane of the drawing (Fig. 3), the magnetic flux through these coils by means of associated apparatus causes control of the valves 37 and 38 by either increasing or decreasing the force applied to the actuating pin 45 through wire 48, depending upon the direction of deviation from the neutral or initial position.

In like manner, if the system departs from the desired condition of perpendicularity to the magnetic field under investigation, by movement in a horizontal direction, that is by movement of coils 27 and 28 in a horizontal plane perpendicular to the plane of the drawing, these coils in like manner will cause a change in energization of wire 49 and consequently cause a precession of the spin axis to rotate the spin plane to the desired or initial position, that is the position of perpendicularity to the magnetic field. The change in energization of wire 49 is, of course, dependent upon the direction of rotation of the coils 27 and 28 in the postulated plane. As seen in Fig. 1 the wires cooperating with the valve actuating pins are bent over the pins. As viewed in Fig. 3, the wires 48, 49 would be bent outwardly from the surface of the drawing over pins 45. Contraction and consequent straightening of wires 48, 49 will tend to pull pins 45 toward plate 55, thereby rotating blocks 44 about the axes of rods 42 against the tension bias of springs 60, 61. To take a specific example, suppose that for some reason the axes of the detector coils 1 and 30 swing counterclockwise (Fig. 1) about the gimbal axis 10—11 from the deired parallel relation with the earth's field. Assuming that the direction of the gyro rotation is counterclockwise as viewed in Fig. 2, the output of the detector coils 27 and 28 then decreases the energization of the wire 49 whereupon it contracts upon cooling and exerts a greater force on the pin 45, moving it against the bias of the return spring 61. This causes port 35 to open and port 36 to close by the actions of valves 39 and 40. The reactive force of the rotor impelling fluid escaping from the port 35 exerts a counterclockwise torque on the gyroscope about the gimbal axis 8—9 and as a result the gyro precesses clockwise about the gimbal axis 10—11. When the axes of the detector coils 1 and 30 return to the desired parallel position, the valves 39 and 40 return to their neutral position and the controlling action ceases. If the initial deviation of the detector coils is clockwise, the reverse action takes place, as will be clear from the foregoing. Similarly, a deviation of the detector coils about the gimbal axis 8—9 will cause a corresponding action of the valves 37 and 38. As the magnetometer is moved through a field, such as the earth's field, the changes in the relative directions of the axes of coils 25—28 and the earth's field involve changes in both directions shown as vertical and horizontal directions in Fig. 3 and the above described operations occur conjointly and simultaneously to maintain the axes of coils 1 and 30 in exact parallelism with the field, so that these coils may measure or detect abnormal flux intensities incident to the presence of mineral or oil deposits, obstacles, or metal objects. The component of magnetic flux incident to such anomalies which cuts or threads through the coils produces, through cooperating circuits, an electrical quantity representative of the distorted field.

Fig. 6 is a simplified diagram of a system which I provide showing the general arrangement of the elements thereof; and elements have been assigned reference numerals corresponding to elements described hereinbefore in connection with the gyroscope and magnetometer. The magnetometer elements and the gyroscope are shown diagrammatically and a neutralizing winding 62, mentioned generally above as providing the compensation necessary to balance out the effect of the normal earth's field, is also shown associated with the magnetic detecting coils 1 and 30. In the illustrated embodiment as shown in Fig. 1, the neutralization winding may, for example, comprise two series connected coils wound respectively on the magnetometer elements 1 and 30 outside of the alternating current magnetizing windings and insulated therefrom.

The neutralizing coil 62 may be energized from a suitable source of current, such as a battery 63, through a current controlling or adjusting rheostat 64. In order to produce output voltages responsive to flux cutting not only magnetic detecting coils 1 and 30 but also to produce output voltages responsive to the flux through coils 25—28, I provide magnetometer amplifiers 65, 66 and 67 which are preferably of the magnetic type to be described in detail presently. These amplifiers are connected to the associated elements or coils through magnetometer circuits 68, 69 and 70. Amplifiers 66 and 67 are connected to control valves 37 and 38, and 39 and 40, through saturable reactors 71 and 72, respectively. As explained hereinafter, the energizing circuit for the amplifiers 65—67 and the saturable reactors 71—72 may comprise an alternating current circuit 73 preferably of a frequency considerably higher than ordinary commercial frequency, and the source of such energy may include a motor-generator set 74 comprising a direct current motor 75 and an alternating current generator 76. The motor may be driven from a source of current such as a battery 77.

In accordance with another aspect of my invention, I provide means for modifying the output voltage of detector amplifier 65 in order to compensate for errors in the output voltage incident to the deviations of the axes of coils 1 and 30 from the desired parallel alinement of the coil axes with respect to the magnetic field. Such deviations may occur while the gyro or other positioning means is responding to and correcting for detected deviations. More particularly, I provide means energized from amplifiers 66 and 67 for modifying the output of amplifier 65 in a manner proportional to the squares of the angular deviations of the axes of said detecting coils 1 and 30 from the direction of the field as measured in mutually perpendicular planes parallel to the axes, thereby constituting first order corrections for the errors incident to these deviations. This means may comprise a compensating or correcting element 78 shown in detail in Fig. 15 and described more specifically hereinafter. However, the general nature of the method of compensating the detector circuit and amplifier for deviations incident to the position of the detector coil axis will now be considered in connection with Fig. 7.

If ϕ_1 and ϕ_2 be considered as the angles between the axis of either detector coil 1 or 30 and the earth's magnetic field in two rectangular planes through the axis of the coils, the magnetic field H parallel to the axis will be:

$$H = H_0 \cos \phi_1 \cos \phi_2 \qquad (1)$$

where H_0 is the value of the earth's field and ϕ_1 and ϕ_2 lie, respectively, in the mutually perpendicular x and y planes. The positioning coils 25 and 26 may be considered as lying in the y plane and the positioning coils 27 and 28 may be considered as lying in the x plane.

For all angles less than one degree, equation (1) may be simplified to:

$$H=H_0(1-\phi_1^2)(1-\phi_2^2)$$

or

$$H=H_0(1-\phi_1^2-\phi_2^2) \quad (2)$$

If e_1 and e_2 are considered as the output voltages of the two sets of positioning magnetometers perpendicular to the axis, or axes, of the detector coil, or coils, and in the x and y planes, respectively, the output voltages may be stated as follows:

$$e_1=K_1 \sin \phi_1=K_1\phi_1$$
$$e_2=K_2 \sin \phi_2=K_2\phi_2 \quad (3)$$

It will be noted, upon referring to Equation 2, that if the axis of the detector coil is displaced from the direction of the total earth's field H_0, the detector coils will measure not the desired total field, H_0, but a lesser value dependent upon the magnitude of the component H of the total field in a direction of the detector axis. It will also be noted that the desired value H_0 and the actual measured value H of magnetic field intensity are related by factors involving the squares of the angles ϕ_1 and ϕ_2, these angles being measured in the x and y planes by the positioning magnetometers **25**—**28**. Consequently, I provide in the correcting element **78** means for introducing into the amplifier **65** voltages which are proportional to the squares of the voltages produced by amplifiers **66** and **67** over the operating range. Upon inspection of Equations 3, it is then readily appreciated that by utilizing a voltage, or voltages, which are proportional to the squares of the positioning magnetometer voltages, and adding these voltages to the voltage of amplifier **65**, the output voltage or current of the amplifier **65** is caused to represent accurately the intensity of the magnetic field for each position of the magnetic detecting coils. As will be explained hereinafter, the correcting element **78** may comprise elements having nonlinear current-voltage characteristics to produce output voltages which vary in proportion to the squares of the input voltage or voltages. Consequently, the component voltages e_1' and e_2' at the output terminals of the correcting element **78** may be expressed as follows:

$$e_1'=K_1'e_1^2$$
$$e_2'=K_2'e_2^2 \quad (4)$$

Proper fractions of these voltages, added to the detector voltage, are capable of correcting the positioning errors for small angles.

The presence of discontinuities or anomalies in the earth's field may be utilized for control or observance purposes by the employment of the output voltage of the amplifier **65** in a control or indicating arrangement. For the purpose of illustrating such application, I have merely chosen to represent a recording or indicating device **79** energized in response to an electrical quantity produced by amplifier **65**. Such a device may, for example, be a zero center galvanometer.

In Fig. 8 there is illustrated a simplified circuit which may be employed in several places in the instant detecting system, as magnetometer circuit elements or as amplifier circuit elements. The broad features of the circuit arrangement shown in Fig. 8 are disclosed and claimed in United States Patent No. 2,016,977, granted October 8, 1935 upon an application of Henry P. Thomas and which is assigned to the assignee of the present application. Briefly stated, the circuit of Fig. 8 comprises nonlinear elements and magnetically responsive elements arranged to produce a net rectifying effect of an alternating current when a controlling component of flux is established in the magnetic elements.

In a system of this nature, I employ an improvement wherein alternating current energy is supplied to the magnetometer or amplifying circuit in peaked wave form by using a peaking transformer **80** which may be of a saturable type energized from an alternating current circuit **81** preferably having a frequency greater than ordinary commercial frequencies. I have found that at a frequency of 800 cycles per second such a peaking device serves to obtain a substantial reduction in the noise level.

An important advantage in the use of a peaking transformer **80** is to render the magnetometer circuit free of even harmonic voltages and currents. The importance of this consideration will be appreciated due to the nature of the rectifying action produced by the magnetically responsive elements **82** and **83** and the nonlinear impedance elements **84a** and **84b** which are energized in a bi-phase circuit arrangement wherein an output circuit **85** is connected between an intermediate or neutral connection **86** of secondary winding **87** and a common juncture **88** of the two paths constituting the bi-phase circuit.

The magnetically responsive elements **82** and **83** comprise core structures or members **89** and **90** of high permeability metal in order to render the magnetometer circuit highly responsive to the presence of a superimposed flux of either polarity incident either to an associated control winding or due to the presence of a relatively weak space magnetic field, such as the earth's magnetic field. The nonlinear elements **84a** and **84b** may be constructed of a material such as disclosed and claimed in United States Letters Patent No. 1,822,742, granted September 8, 1931 upon an application of Karl B. McEachron. A by-pass capacitance **91** may be connected in the position illustrated.

Concerning the general principles of operation of the circuit shown in Fig. 8, it may be stated that with no unidirectional flux effective or present in the core structures **89** and **90** the circuit does not rectify. Upon the application of unidirectional fluxes to the core members **89** and **90**, that is upon the impression of a magnetic field parallel to the axes of these members, even harmonics are produced, giving a rectified or unidirectional output current which is supplied to circuit **85**. This output voltage or current is proportional to the intensity of the magnetic field and reverses in sign with the reversal in direction of the field as shown in Fig. 9 where curve A represents the relationship between the field intensity in milli-gauss and the direct current output in microamperes.

The circuit shown in Fig. 8 may be employed as a magnetometer in each of circuits **68**—**70**. In such instances, the magnetic detecting coils correspond to the windings about core members **89** and **90**. For example, where the circuit of Fig. 8 is employed as the detector magnetometer, coils **1** and **30** with their associated core members or strips **31** and **32** constitute a part of the magnetometer circuit and are connected to the nonlinear resistances **84a** and **84b**. In like manner, the positioning coils **25**, **26** and **27**, **28** are connected in and comprise part of such magnetometer circuits.

In operation as a magnetometer positionable in space, the circuit of Fig. 8 produces an output electrical quantity such as a voltage or a current responsive to the components of a magnetic field parallel to the axes of the elements 82 and 83. That is, when the elements 82 and 83 are parallel to a component of a magnetic field, the flux of the field linking the coils establishes a unidirectional magnetization of the associated core members, causing the production of an output voltage or current the polarity of which depends upon the direction of the field linking the coils. When the axes of the elements 82 and 83 are perpendicular to the field, the output voltage or current of the associated magnetometer circuit is zero.

Fig. 10 diagrammatically illustrates a magnetic-type amplifier which may be employed as elements or stages of the amplifiers 65—67 generally described above. Certain general aspects of the amplifier shown in Fig. 10 are disclosed and broadly claimed in copending United States patent application Serial No. 407,961 of Hendrik D. Middel, filed August 22, 1941, now United States Letters Patent No. 2,388,070, issued October 30, 1945, entitled "Electromagnetic apparatus," and which is assigned to the assignee of the present application. A further improvement is illustrated in the amplifier circuit of Fig. 10, namely the provision of peaking means such as a saturable transformer for supplying only odd harmonic components of voltages to the circuit. The magnetic amplifier comprises a saturable type reactor 92 including a magnetic core structure 93 having saturable legs 94 and 95 and a middle leg 96. The alternating current part of the direct current amplifier is essentially similar to the magnetometer circuit of Fig. 8 and comprises a peaking transformer 97, alternating current windings 98 and 99 wound about the saturable legs 94 and 95 of the reactor 92, and an input or control winding 100 connected to an input circuit 101. Elements 102 and 103, having nonlinear current-impedance characteristics, are connected in series relation between windings 98 and 99 and terminals of secondary winding 104 of transformer 97. A by-pass capacitance 105 may be connected across an instrument or control device 106 responsive to the amplified current produced by the circuit.

The saturable legs 94 and 95 are preferably constructed of a high permeability metal. Upon transmission of a current to winding 100, flux is established in core 93 which traverses the saturable legs 94 and 95, producing a rectified or direct output current of reversible polarity in accordance with the same principles described hereinbefore in connection with the circuit of Fig. 8. Where it is desired to amplify small currents, two or more such amplifying circuits may be combined in an astatic arrangement in order to minimize the effect of the earth's field or the effect of any extraneous field.

Fig. 11*a* represents such an astatic arrangement or stage, and certain elements thereof have been assigned reference numerals corresponding to related elements shown in Fig. 10. In the astatic arrangement of Fig. 11*a*, one saturable reactor comprises alternating current windings 107 and 108 and an input winding 109, and the other saturable reactor comprises alternating current windings 110 and 111 having an input winding 112. In order to minimize the effect of external or extraneous fields, the windings 107 and 110, and 108 and 111 are, respectively, in opposition with respect to external fields so that the net effect on the rectifying properties of the bi-phase circuit arrangement including nonlinear elements 102 and 103 is zero by producing opposite or opposing individual effects. The input windings 109 and 112, however, are connected to act accumulatively or in series with respect to an input circuit connected thereacross.

Curve B of Fig. 11*b* is the calibration curve of such an astatic unit or stage. It will be noted that the response is linear. The linear response is obtainable throughout the whole operating range, which extends from the input "noise" level of about 10^{-9} amperes through an output range that may vary from one milliampere to several hundred milliamperes according to the size and power of the magnetic structure.

If desired, a number of these astatic units may be connected in series relation to obtain the desired amplification. Curve C of Fig. 12 represents the calibration curve of a three-stage amplifier supplying an 800 ohm load. The linear portion of the output curve is limited by the size and power of the output unit of the amplifier, the curve shown being for a satisfactory amplifier capable of providing an output which is substantially linear for output currents of from 5 milliamperes in the negative to 5 milliamperes in the positive polarity.

In Fig. 13, I have there illustrated somewhat in detail the positioning magnetometer circuits, the amplifiers therefor and the saturable reactors which may be employed between the output circuits of the amplifiers and the gyroscope valve controlling mechanism, showing in particular the thermally expansive control elements 48 and 49. A magnetometer circuit 113 essentially similar to the circuit of Fig. 8 may be employed for producing voltages incident to the positions of the magnetic detecting coils 25—28 and comprises two such circuits employing a single energizing peaking transformer 114. Nonlinear impedance elements 115—118 are, respectively, connected in series relation between a secondary winding of peaking transformer 114 and magnetic detecting coils 25—28 and serve to supply a control current to output circuits 119 and 120 across which are connected by-passing capacitances 121 and 122. The output circuits 119 and 120 are connected to amplifiers which may be of the type described in connection with Figs. 8 and 10. At least one stage of each of the amplifier systems may be of the astatic type shown in Fig. 11*a*, also disclosed and claimed in above mentioned application Serial No. 407,961. For example, the first stage of amplification may comprise an astatic amplifier 123 in which the elements have been assigned reference numerals corresponding to elements shown in Fig. 11*a*. In order to decrease still further the sensitivity of the astatic stages to external fields, each stage may be shielded by a covering of a high permeability metal, thereby minimizing or eliminating the effect of the earth's field. An output circuit 124 of the astatic amplifier 123 may also be provided with a by-pass capacitance 125 and is connected to the input circuit of further magnetic amplifiers which may comprise three static magnetic amplifiers 126, 127 and 128 of the type described above in connection with Fig. 10, each having alternating current windings 129 and 130 and an input winding 131. The alternating current windings 129 and 130 are, of course, connected to nonlinear impedance elements 132 and 133. If desired, the static stages of amplification may also be shielded.

The amplifying system connected to the output circuit 120 may be similar to that described above in connection with the output circuit 119 and is represented in Fig. 13 as being of similar character. The output circuits 134 and 135 of the amplifiers are connected to controlling devices, such as saturable reactors 71 and 72, (see Fig. 6) which control the amount of current transmitted to the thermally expansive elements or wires 48 and 49 comprising parts of the valve controlling mechanism, the controlling action of which has been described above.

Each of the saturable reactors 71 and 72 comprises a saturable magnetic core structure and associated variable impedance alternating current windings 136, an input or control winding 137, and a unidirectional polarizing or magnetizing means, such as a permanent magnet or a polarizing winding 138, which is energized by a suitable source of unidirectional current which may comprise a full wave rectifier 139 energized from a secondary winding of transformer 140.

The polarized saturable reactors 71 and 72 are energized from alternating current circuit 73 which may be of a frequency substantially greater than commercial frequencies, such as one having a frequency of 800 cycles. The energization of each of the polarizing windings 138 is adjusted to establish the zero value of the input current curve to a position corresponding to the center of the output current curve, as illustrated in Fig. 14 where curve D represents the input-output characteristics of saturable reactors 71 and 72.

The saturable reactors 71 and 72 are polarized in order to render the reactors selectively responsive to both positive and negative values of the input current and to afford substantially continuous and contiguous linear regions of response throughout predetermined positive and negative ranges of the input current. Where such an amplifying system and control system are employed to amplify electrical quantities, such as voltages which are determined by a movable or positionable device to be maintained in a desired alinement, such as the above described magnetometer coils 25—28, it will be appreciated that the controlling elements, such as saturable reactors 71 and 72, must be capable of differentiating between directional deviations from a desired normal or reference position. Consequently, the provision of the polarizing means to establish the center of the output current curve at the zero value of the control current range establishes this selective feature.

Furthermore, due to the saturable characteristics of the reactors 71 and 72, and upon referring to Fig. 14, it will be noted that beyond the predetermined linear control region, the output current or the alternating current transmitted by the reactors assumes relatively constant maximum and minimum values, thereby making it possible to control the limits of the energy transmitted to the thermally expansive wires 48 and 49 of the valve controlling mechanism for the above described positioning apparatus, and consequently preventing any cumulative action which tends to cause the control system to run away under conditions involving large angular deviations of the magnetic detecting coil axis.

Means for adjusting the value of the current transmitted to the thermally expansive elements 48 and 49 may be provided in the output circuits of the saturable reactors 71 and 72 and may comprise variable resistances 141 and 142. Lamps 143 and 144 may be included in the output circuits as a means for observing the operation of the device.

Fig. 15 shows the manner in which the voltage derived from the magnetic detection circuit may be corrected for errors incident to the angular deviations between the axes of coils 1 and 30 and the desired positions of these axes with respect to the magnetic field. The magnetometer circuit 68 connected to coils 1 and 30, as shown in Fig. 6, may furnish the input excitation for amplifier 65 which, in turn, may include three stages of magnetic amplification including an astatic amplifier 145, and second and third stages 146 and 147 of static amplification. The astatic stage 145 may be a balanced arrangement such as that shown in Fig. 11*a*, preferably provided with a shield of low permeability metal; and the second and third stages 146 and 147 may be the same as 145, or may be similar to amplifiers 126—128 shown in Fig. 13.

The output circuits of the position amplifiers 66 and 67 are employed for introducing into the amplifier system for the detecting circuit comprising coils 1 and 30, a correction voltage or voltages proportional to the squares of the respective outputs of the position amplifiers in accordance with the principles outlined above in connection with Fig. 7. One way in which this correction voltage may be introduced into the detector amplifier is by deriving predetermined components of the output voltage of amplifiers 66 and 67 by voltage dividers 148 and 149 and impressing these components in a part of the detector amplifier 65 as shown generally in Fig. 6. More specifically, one way in which this result may be obtained is by impressing these voltage components between stages of the detector amplifier, as shown in Fig. 15, the voltages being introduced between the second and third stages. In accordance with Equations 3 and 4 discussed above, it will be appreciated that the correction voltages introduced into the detection amplifier should vary as the squares of the voltages derived from the positioning magnetometers or the magnetometer amplifiers 66 and 67.

In order to obtain the above described squared relationship between output and input voltages, I provide circuits 150 and 151 which comprise, respectively, nonlinear elements, such as dry or contact-type rectifiers 152 and 153, the output circuits of which are connected between amplifier stages 146 and 147 through suitable impedance elements such as resistances. It is to be understood that the nonlinear or squared relationship between output voltage and input voltage produced by contact rectifiers 152 and 153 is due to the rectifying characteristic of contact rectifiers, such as copper oxide rectifiers or selenium rectifiers, by operating these devices within the nonlinear range of their characteristics. The magnitudes of the correction voltages supplied to the amplifiers may be controlled by any suitable expedient such as variable resistances 154 and 155. It is important that the contact-type rectifiers 152 and 153 operate within the above described range. Furthermore, the circuit resistance should be maintained at a small value compared to that of the rectifiers in order to obtain the most effective utilization of this characteristic.

The above described system is particularly applicable to the investigation of the earth's magnetic field for the purpose of determining the location of mineral or oil deposits, metallic bodies, etc. Although not limited thereto, the above described system may be mounted on a moving vehicle such as an aircraft and employed for the location of submerged undersea craft. Upon movement of the system, and particularly the gyroscope and magnetometer shown in Fig. 1, through the earth's magnetic field, the magnetic detecting coils 1 and 30 are maintained in parallelism with the total earth's field and in the absence of anomalies the indicating or control device 79 affords a zero indication, the normal intensity of the earth's field being neutralized or compensated for by means of neutralizing winding 62 shown in Fig. 6. Upon passing over an anomaly or upon approaching such a discontinuity in the earth's field, the device 79 will afford an indication, either positive or negative, depending upon the intensity of the distorted field. For example, suppose the detecting device is being moved towards a large metallic object which tends to concentrate the earth's field so that in the area surrounding the object, the intensity of the earth's field is greater or less than normal, depending on the pattern of the warped or distorted magnetic flux. The proximity of such an object will be indicated by a deflection of the instrument 79 which will be deflected from its normal zero center position corresponding to the normal intensity of the earth's field. By noting the magnitude and sign of the deflection of instrument 79, as the area surrounding the object to be detected is traversed, the approximate location of the object or anomaly may be determined.

In the process of locating an anomaly by noting changes in the measured intensity of the earth's field, it is of utmost importance to prevent spurious variations in the indicated intensity due to factors other than the variations of the intensity being measured. The principal cause for such spurious variations or indications is a failure to maintain a constant orientation between the axis of the intensity measuring instrument and the direction of the measured field. It will be noted that, in accordance with my invention, the effect of the unavoidable orientation errors, due to finite interval of time required for the gyroscope or other servo positioning means to operate, is greatly reduced by keeping the measuring axis of the intensity measuring instrument in the general direction of the total earth's field as distinguished from the direction of the horizontal or vertical components thereof. In this manner unavoidable orientation errors of the measuring axis cause only relatively small changes in the indicated output of the measuring device, since the error varies as the cosine of the error angle and for angles near zero, this value is small. Also, as pointed out above, the effect of unavoidable orientation errors is still further reduced by compensation of the intensity indicating instrument in accordance with orientation errors detected by the positioning magnetometers 25—28, which, being normally positioned perpendicular to the measured field, are very sensitive to small orientation errors.

The system is constructed of elements peculiarly adaptable for the conditions imposed by air travel inasmuch as the control elements are of rugged construction and character. The amplifying and magnetometer circuits are of particular note in this respect inasmuch as no moving or readily breakable parts are involved.

The above described system also performs with a high degree of accuracy even though subjected to vibration incident to carriage in aircraft, the system being capable of affording accurate indications of field discontinuities or anomalies even though subjected to continuous vibration of the nature encountered in aircraft.

While I have shown and described my invention as applied to a particular system comprising elements of specific character, it will be obvious to those skilled in the art that changes and modifications may be made without departing from my invention, and I, therefore, aim in the appended claims to cover all such changes and modifications as fall within the true spirit and scope of my invention.

What I claim as new and desire to secure by Letters Patent of the United States is:

1. In combination, a magnetic detecting element for producing an electrical quantity in accordance with the intensity of a magnetic field, positioning means for said element comprising a pair of coils, the axes of said pair of coils being aligned in respectively different directions perpendicular to said element, an amplifier for said detecting element, a pair of amplifiers for said coils each connected to a different one thereof, and means connected between the first mentioned amplifier and said second mentioned amplifiers for introducing in the former a correction factor proportional to the squares of the respective output electrical quantities of the second mentioned amplifiers.

2. In combination, a magnetic detecting element for producing an electrical quantity in accordance with the intensity of a magnetic field, positioning means for said element comprising a pair of coils, the axes of said pair of coils being aligned in respectively different directions perpendicular to said element, an amplifier for said detecting element, a pair of amplifiers for said coils each connected to a different one thereof, a pair of rectifiers connected between the last mentioned amplifiers and the first mentioned amplifier for introducing therein a correction factor proportional to the squares of the respective output electrical quantities of the second mentioned amplifiers.

3. In combination, a magnetic detecting coil the axis of which is positionable in a magnetic field, positioning means for said coil comprising a pair of mutually perpendicular coils perpendicular to said axis, amplifying means connected to said detecting coil, a pair of amplifiers each connected to a different one of said pair of coils, and means controlled by said pair of amplifiers for modifying an output electrical quantity of the first mentioned amplifier in a manner proportional to the squares of the outputs of said perpendicular coils thereby constituting first order corrections for the errors incident to these deviations.

4. In combination, a magnetic detecting coil the axis of which is positionable in a magnetic field, positioning means for said coil comprising a pair of mutually perpendicular coils perpendicular to said axis, magnetic type amplifying means connected to said detecting coil, separate magnetic amplifying means connected to said pair of coils, and means energized by the last mentioned amplifying means for modifying an output electrical quantity of the first mentioned

amplifying means in a manner proportional to the squares of the outputs of said perpendicular coils thereby constituting first order corrections for the errors incident to these deviations.

5. In combination, a magnetic detecting coil the axis of which is positionable in a magnetic field, positioning means for said coil comprising a pair of mutually perpendicular coils perpendicular to said axis, amplifying means connected to said detecting coil comprising at least three stages of magnetic amplification comprising at least one astatic stage, shielding means for the astatic stage, a pair of separate amplifying means each connected to a different one of said pair of coils and each including at least one shielded astatic magnetic stage, and means energized by the last mentioned amplifying means for modifying an output electrical quantity of the first mentioned amplifying means in a manner proportional to the squares of the outputs of said pair of mutually perpendicular coils thereby constituting first order corrections for the errors incident to these deviations.

6. In combination, a magnetic detecting element for producing an electrical quantity in accordance with the intensity of the magnetic field, positioning means for said element comprising a pair of mutually perpendicular coils perpendicular to said element, an amplifier for said detecting element, a pair of amplifiers for said coils each connected to a different one thereof, and means comprising contact-type rectifiers connected between the first mentioned amplifier and the second mentioned amplifiers for introducing in the former a correction factor proportional to the squares of the respective outputs of the second mentioned amplifiers.

7. In combination, a magnetic detecting element for producing an electrical quantity in accordance with the intensity of a magnetic field, positioning means for said element comprising a coil movable with and perpendicular to said element, and means for correcting said electrical quantity for errors incident to the angular position of said element with respect to said field comprising a rectifier of the contact type responsive to said coil for modifying said electrical quantity in a manner proportional to the square of the controlling effect of said coil.

8. In combination, a magnetic detecting coil, a pair of mutually perpendicular positioning coils for producing electrical quantities in accordance with deviations of the axes of said positioning coils from positions perpendicular to a magnetic field, a gyroscope rotor, a housing for said rotor, a pivotal support for said housing comprising major and minor axes, said detecting coil and said positioning coils being mounted on said housing, means for supplying a propelling fluid to said housing, a manifold supported by said housing and having mutually perpendicular ports with associated valves for controlling the precession of the spin axis of said rotor to position said housing about said major and minor axes, metallic means having appreciable temperature coefficients of expansion for positioning said valves, and means including said positioning coils for variably energizing said metallic means.

9. In combination, a magnetic detecting coil; a pair of positioning coils; a support for said detecting coil and said positioning coils, each of said coils being supported in an axially perpendicular position with respect to each of the other two of said coils; a gyroscopic rotor supported in bearings carried by said support for rotating said support about two mutually perpendicular axes, precessing means for said rotor; and means for selectively actuating said precessing means in response to signals developed in either one of said positioning coils upon a change in alignment of the axis of such coil from a position perpendicular to the direction of the total earth's magnetic field whereby the axis of said detecting coil is continuously maintained in said direction.

10. In combination, a magnetic detecting element for producing an electrical quantity in accordance with the intensity of a magnetic field, positioning means for said element comprising a pair of coils angularly arranged with respect to each other and at a predetermined angle from said element, an amplifier for said detecting element, a pair of amplifiers for said coils each connected to a different one thereof, and means connected between said detecting element amplifier and said coil amplifiers for introducing in said detecting element amplifier a correction factor proportional to a function of the respective output electrical quantities of said coil amplifiers, said function being determined by the said angular relationship between said coils and said element.

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Disclaimer

2,468,554.—*Albert W. Hull*, Schenectady, N. Y. Apparatus for Magnetic Field Investigation. Patent dated Apr. 26, 1949. Disclaimer filed June 21, 1951, by the assignee, *General Electric Company*.

Hereby enters this disclaimer to claims 1, 2, 3, and 10 of said patent.

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