United States Patent [19]

Rorden

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[54] **TRIMMED SUPERCONDUCTIVE MAGNETIC PICKUP COIL CIRCUITS**

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[52] **U.S. Cl.** .... **323/44 F;** 324/43 G

[51] **Int. Cl.**[2] **G05F 7/00**

[58] **Field of Search** .... 324/43 R, 43 G; 323/44 F; 310/15; 317/123, 262 R; 336/DIG. 1; 307/306

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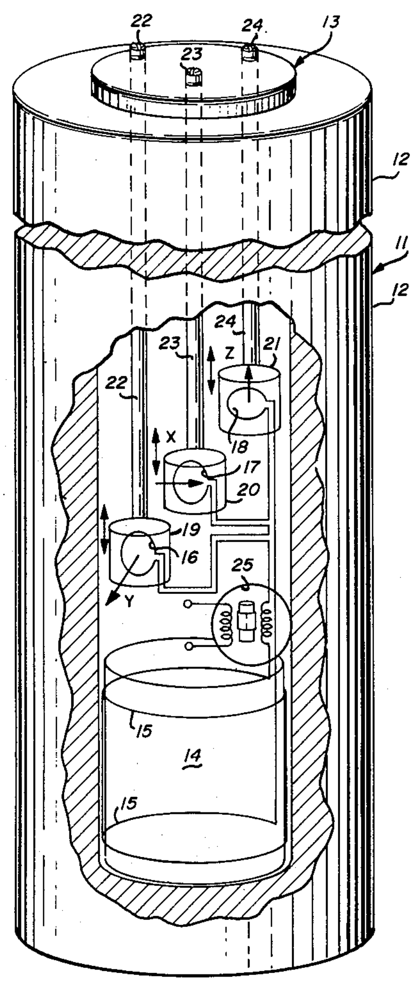
[57] **ABSTRACT**

A primary superconductive magnetic field component or gradient pickup coil circuit is trimmed by means of one or more auxiliary superconductive trim coil circuits electromagnetically coupled to a magnetic flux sensor for sensing the magnetic flux coupled to the sensor by said primary and auxiliary coil circuits. The trim coils each have their respective magnetic axes oriented orthogonally for independent adjustment of trim. An adjustable magnetic shield is provided surrounding each of the respective trim coils for varying the coupling between the respective trim coil and the magnetic field. In this manner transverse and axial balance or trimming of the primary pickup coil circuit is obtained by adjusting the positions of the respective magnetic shields around each of the respective trim coil circuits. In a preferred embodiment, there are three mutually orthogonal trim coil circuits.

9 Claims, 6 Drawing Figures



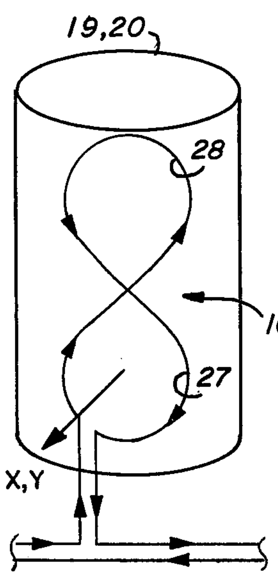
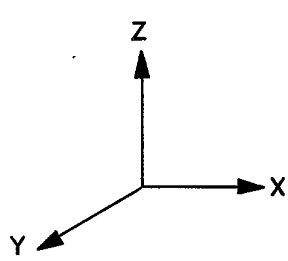


Fig_2



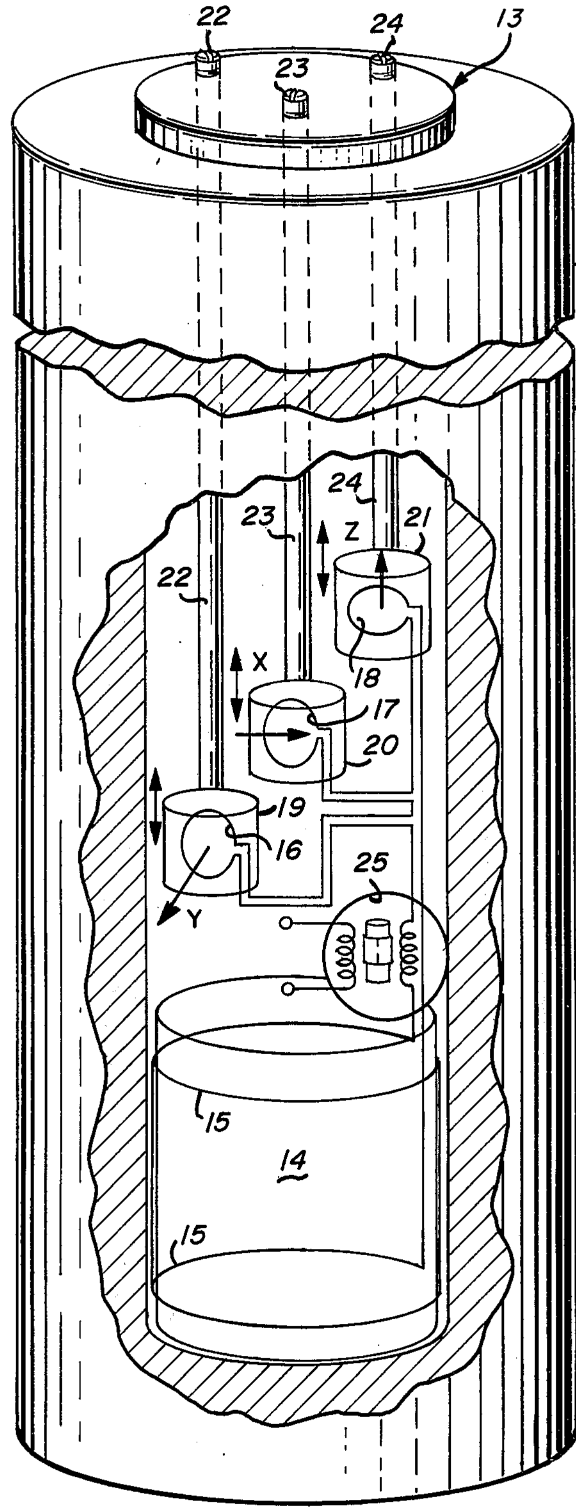


Fig_1

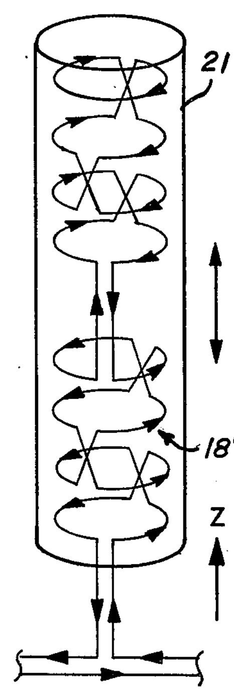


Fig_3

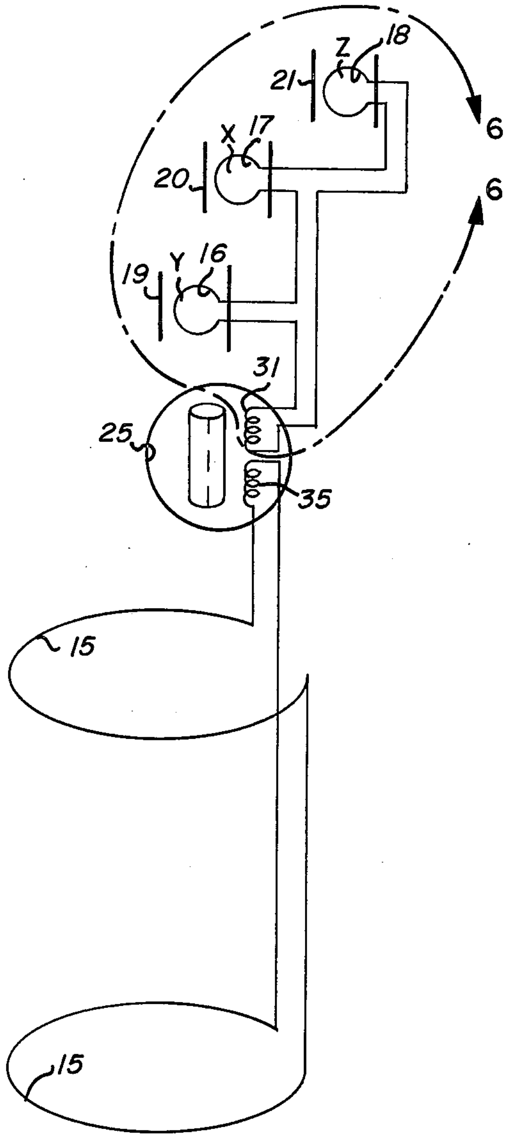


Fig_4

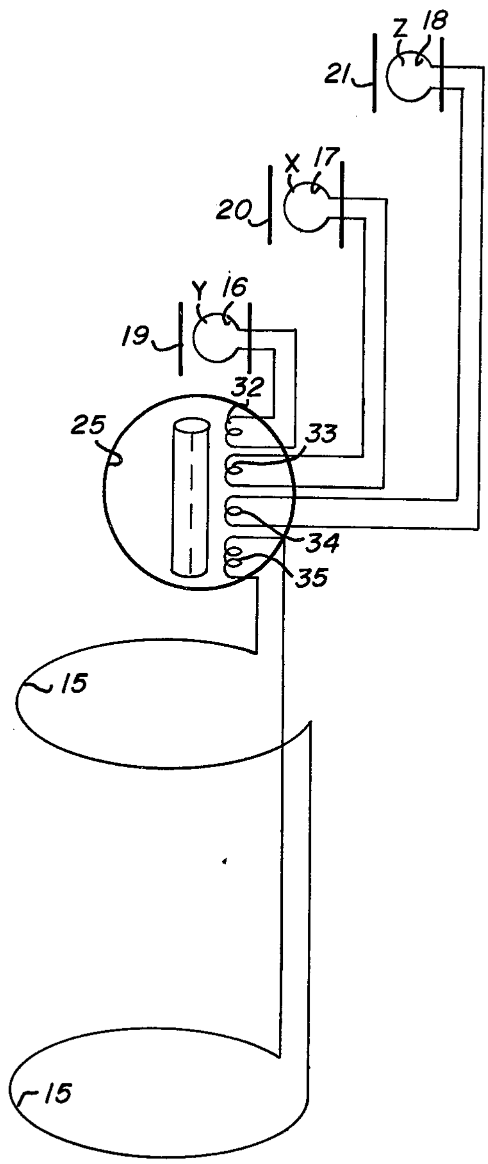


Fig_5

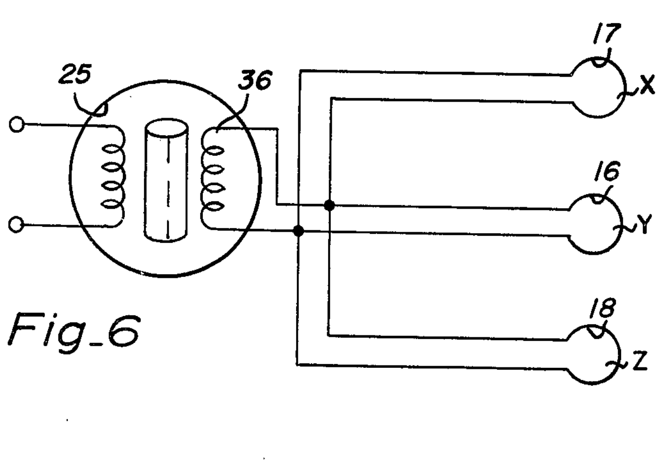


Fig_6

TRIMMED SUPERCONDUCTIVE MAGNETIC PICKUP COIL CIRCUITS

GOVERNMENT CONTRACT

The invention herein described was made in the course of or under a contract or subcontract thereunder, (or grant) with the Department of the Navy.

RELATED CASES

The use of superconductive gradient wound trim coils is disclosed and claimed in copending U.S. application Ser. No. 434,857 filed Jan. 21, 1974 and assigned to the same assignee as the present invention.

BACKGROUND OF THE INVENTION

The invention relates, in general, to superconductive gradiometer or magnetic field measurement instruments wherein auxiliary adjustable superconductive trim coils are electromagnetically coupled to a magnetic flux sensor which also senses the flux coupled to the sensor by the primary field or gradient pickup coil circuit for adjusting the magnetic trim of the primary pickup coil circuit.

DESCRIPTION OF THE PRIOR ART

Heretofore, a primary superconductive gradient pickup coil circuit has been trimmed or balanced (compensated) for axial and transverse misalignments and size differences of the pair of bucking connected pickup coils by means of a plurality of trim or balance coil portions pulled out of the primary gradiometer pickup coil circuit. The trim or balance coils each had their respective magnetic axes oriented relative to the axis of the primary pickup coils by the operator manually twisting the magnetic axis of the respective trim or balance coil relative to the magnetic axis of the primary pickup coils. The adjustment of the balance coils was obtained by manually increasing or decreasing the enclosed area of the respective balance coil and by manually changing its orientation in the magnetic field.

In an alternative prior art gradiometer balance system, the primary magnetic gradiometer pickup coils were trimmed or balanced by means of movable superconductive vanes disposed in the vicinity of the pickup coils and moved such as to shift the degree of magnetic coupling to the magnetic field of one of the primary pickup coils relative to that of the other. In this latter embodiment, transverse balance was obtained by means of vanes disposed about the periphery of the pickup coils, whereas axial balance was obtained by shifting the axial position of a superconductive obstacle disposed intermediate and on the axis of two primary gradiometer pickup coils.

A gradiometer balance system employing superconductive vanes and obstacles for achieving transverse and axial balance is described in a National Bureau of Standards report titled, "Ultrasensitive Superconducting Magnetic Gradiometer, N.B.S. Project No. 2750482, N.B.S. Report No. 10,736 of Mar. 31, 1972" carried out at the U.S. Department of Commerce National Bureau of Standards under the sponsorship of the Department of the Navy under Contract NAonr-13-71.

The problem with the first method of balancing a gradiometer sensing coil circuit which employed small pulled-out loop portions of the primary windings was that this system did not include means for changing the balance of the gradiometer while the coils were superconducting. More particularly, balance was achieved by a series of cut and try experiments wherein a first adjustment of the balance coils was obtained at room temperature, the system was then immersed in liquid helium and rendered superconducting. The balance was noted, the system was then removed from the helium, another adjustment made, and then returned to the helium. Thus, adjustments were made only by repeated cycling of the gradiometer system between a superconducting and normal state. This turned out to be an extremely tedious, time-consuming, and a relatively inaccurate method for obtaining balance of the gradiometer pickup coils.

In the second prior art method of balancing the gradiometer, which employed the movable vanes and obstacles, the adjustment turned out to be highly non-linear, that is, in certain positions of the vanes, a relatively large movement produced a relatively small change in the degree of balance between the pickup coils, whereas in another position a very small movement of the vanes produced a relatively large change in the balance of the gradiometer pickup coils. In addition, there was an objectionable amount of mutual interaction between the various adjustments of the vanes.

SUMMARY OF THE PRESENT INVENTION

The principle object of the present invention is provision of an improved method and apparatus for trimming superconductive primary magnetic pickup coil circuits.

In one feature of the present invention, one or more auxiliary superconductive pickup trim coils are electrically or magnetically coupled with a primary magnetic pickup coil circuit or magnetic flux sensor. A movable superconductive member is disposed adjacent each trim coil for varying the coupling between the magnetic field and the respective trim coil for varying the degree of trim of the primary pickup coil system.

In another feature of the present invention, there are at least two and preferably three mutually orthogonal magnetic pickup trim coils, whereby independent control over the separate trim adjustments is obtained.

In another feature of the present invention, a movable superconductive shield is disposed surrounding a trim coil and is translatable (along the shield axis) for varying the degree of coupling between the magnetic field and the respective trim coil.

In another feature of the present invention, the superconductive trim coil circuit is electrically independent of the superconductive primary magnetic pickup coil circuit and the magnetic flux of the trim coil is combined with magnetic flux of the primary pickup coil in a magnetic flux sensor device, whereby the superconductive primary magnetic pickup coil circuit is uninterrupted by the trim coil circuit.

In another feature of the present invention, a plurality of auxiliary superconductive trim coils are electrically independent of each other, whereby a malfunction of one trim coil does not adversely affect functioning of another of the trim coils.

In another feature of the present invention, the superconductive trim coils are electrically connected in parallel with each other.

Other features and advantages of the present invention will become apparent upon a perusal of the following specification taken in connection with the accompanying drawings wherein:

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic perspective elevational view, partly in section, depicting a superconductive gradiometer employing balance coils of the present invention,

FIG. **2** is an enlarged perspective view of an alternative transverse balance coil,

FIG. **3** is an enlarged perspective view of an alternative axial balance coil,

FIG. **4** is a simplified view of a primary pickup and trim coil portion of a superconductive system similar to that of FIG. **1** showing an alternative embodiment of the present invention,

FIG. **5** is a view similar to that of FIG. **4** depicting an alternative embodiment of the present invention, and

FIG. **6** is a view of an alternative embodiment of a portion of the circuit of FIG. **4** delineated by line **6—6.**

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to FIG. **1**, there is shown a superconductive magnetic sensing device **11** incorporating features of the present invention. The superconductive sensing device **11** includes a conventional non-magnetic liquid helium dewer flask **12** having an axially insertable generally cylindrical insert **13.** The insert **13** is for immersing the superconductive magnetic sensing circuits in the liquid helium reservoir of the dewer flask **12** for cooling and maintaining the temperature of the superconductive circuits at or very near liquid helium temperature.

The insert **13** includes a cylindrical coil form **14**, as of quartz or fiberglass, onto which is wound a primary magnetic pickup coil circuit **15.** In the case of a magnetometer, the primary pickup coil circuit would include only one pickup coil. However, in the case of a gradiometer two or more spaced apart primary pickup coils are employed in the primary pickup coil circuit **15**, as shown in FIG. **1.** In the case of the gradiometer, as shown in FIG. **1**, the pair of primary magnetic field pickup coils **15** are wound in magnetic field bucking relation such that a series current flowing through the coils produces a magnetic field whose direction at the center of one coil is opposite to that at the center of the second coil. In the example as shown in FIG. **1**, the pair of coils **15** are wound on the cylindrical coil form **14** such that their magnetic axes are coaxial with the Z-axis. The coils **15** are wound such that the plane of each coil lies in one of a pair of axially spaced XY planes. In addition, the coils **15** are preferably wound to have equal turns and equal enclosed area, i.e. equal area to within reasonable mechanical tolerances such as one part in a thousand.

A plurality of auxiliary superconductive trim coils **16–18** are electrically connected in series with the primary coils **15.** The trim coils **16–18** are preferably wound with their magnetic axes disposed in mutually orthogonal relation, i.e., in alignment with the Y, X, and Z axes, respectively. The enclosed area of each of the trim coils **16–18** is made to be small compared to the enclosed area of each of the primary coils **15.** In a typical example, each of the auxiliary trim coils **16–18** encloses only 1/300th of the enclosed area of each of the primary coils **15.** The product of enclosed area times the number of turns for the respective trim coil is on the order of preferably A times the same product for each of the primary coils **15**, where A is the accuracy of the physical and electrical alignment of the primary coils to be corrected, i.e. A $\approx$ one part in a thousand.

Superconductive cylindrical magnetic shields **19–21**, as of lead, are disposed surrounding each of the auxiliary trim coils **16–18** respectively. Suitable mechanical actuating mechanisms **22, 23,** and **24,** such as axially captured worm rods, extend axially of the insert **13** and each is mechanically coupled to each of the respective shields **19–21** in a conventional manner, as by rotationally captured nuts traveling on the worm rods with the nuts coupled to the shields, for effecting axial translation of each of the shields **19–21** for varying the coupling between the respective trim coils **16–18** and the magnetic field in which they are immersed.

In the arrangement of FIG. **1**, the trim coils **16–18** are arranged for picking up certain components of trim magnetic flux and for coupling this flux into the circuit of the primary pickup coils **15.** Each component of picked up trim magnetic flux is adjustable by positioning a corresponding one of the respective shields **19–21** between a completely shielding and a completely unshielding position. For the sake of explanation, it will be assumed that each of the trim coils **16–18** couples a positive trim magnetic flux into the primary pickup coil circuit **15.** This positive trim flux is variable by positioning the shields. However, there is no way that such positioning of the shields can couple a trim magnetic flux of negative sign into the primary pickup coil circuit **15.** However, the primary coil circuit **15** can be initially wound such that there is a net negative balance to the flux coupled into the primary circuit **15** such that the positive trim flux coupled into the circuit **15** by the positive trim coils **16–18** is such as to correct both the initial axial and transverse unbalance of the primary pickup coil circuit **15** of the magnetic sensing device.

As an alternative to winding the coils **15** to produce a predetermined sign of the unbalance to be corrected by the auxiliary trim coils, the sense of trim flux coupled into the primary circuit **15** by the respective trim coils **16–18** can be reversed from positive to negative by reversing the electrical connection of the respective coils **16–18** relative to the leads connected to the primary pickup coils **15.** The proper sense of the windings for each of the trim coils **16–18** can be determined empirically and if the trim flux coupled into the primary circuit **15** is of the wrong sense, the connection of that particular trim coil can be reversed.

A magnetic flux sensor **25**, such as a weak-link Josephson effect sensor, is electromagnetically coupled to the combined magnetic flux coupled into the primary pickup coil circuit **15** and into the auxiliary trim coil circuits for deriving an output proportional to the total flux coupled into the trimmed primary pickup coil circuit **15.** Alternative magnetic flux sensors **25** include non-superconductive magnetic flux sensors. Suitable weak-link Josephson effect sensors **25** include a superconductive point contact, a Dayem bridge, and Notary's bridge.

As an alternative to reversing the connection of the individual trim coils **16–18** to achieve the proper sense of the coupled trim flux, gradient-type trim coil circuits **16′, 17′,** and **18′** may be employed. Such coils form the subject matter of the aforecited patent application Ser. No. 434,857 filed Jan. 21, 1974. More particularly, referring now to FIG. **2**, there is shown a suitable X and/or Y trim coil circuit **16′** and **17′** wherein the superconductive trim coil circuit **16′** and **17′** includes first and second loop portions **27** and **28** of substantially equal area wound in the opposite (gradient) sense in the overall shape of a figure "8" such that, if the coil **16'** and **17'** is immersed in a uniform magnetic field, no net flux will be picked up by the superconductive trim coil circuit. The magnetic shield **19** or **20** is movable along the axis of the Figure **8-shaped** trim coil **16'** or **17'** to cause an imbalance in the magnetic flux permeating the respective loops **27** and **28** to cause a trim flux to be picked up by the coil circuit **16'** or **17'** of either positive or negative sense depending on whether the shield **19** or **20** provides more shielding for the upper or lower loop portion **28** or **27**, respectively. When the shield **19** or **20** is axially symmetric relative to the Figure "8" trim pickup coil, zero trim flux will be coupled into the circuit of the primary pickup coil or coils **15**.

Referring now to FIG. **3**, there is shown the gradient-type wound trim coil **18'** alternative to the Z-axis trim coil **18** of FIG. **1**. More particularly, the gradient-wound trim coil **18'**, for providing axial trim for the magnetic field pickup coil circuit **15**, comprises a pair of bucking-series connected coils **18'** coaxially aligned with the Z-axis. The magnetic shield **21** is axially aligned with the Z-axis. The magnetic shield **21** is axially movable relative to the coils **18'** for varying the coupling of magnetic flux between the respective halves of the bucking connected coil pair **18'** and the magnetic field in which the coils are immersed. When the shield **21** is symmetrically disposed relative to the two halves of the winding **18'**, zero magnetic trim flux will be picked up and coupled into circuit with the primary pickup coils **15**. However, as the shield **21** is moved off-center of the auxiliary trim coil pair **18'** the magnetic flux picked up is increased in one-half of the winding relative to the other half to produce either a positive or negative net magnetic trim flux coupling into the circuit of the primary windings **15**.

An advantage of the auxiliary magnetic trim coil circuits of the present invention is that trimming adjustments of all three components of the transverse and axial magnetic field may be made without having to repetitively cycle the primary superconductive pickup coil circuit between the superconductive and normal states. In addition, the adjustments of the auxiliary trim coils are mutually orthogonal, whereby the settings can be independentally optimized without having to readjust the trimming coil circuits for previous adjustments of one or more of the other trim coil circuit adjustments. In addition, the trimming coil circuit adjustments are relatively linear, when contrasted with the adjustments of the prior art superconductive vanes and obstacles.

Referring now to FIG. **4**, there is shown an alternative trimmed gradient coil circuit of the present invention. More particularly, the primary gradient pickup coil circuit **15** is substantially the same as previously described with regard to FIG. **1**. However, the X, Y, and Z axes trim coils **16**, **17**, and **18** are connected in series in a superconductive trim circuit electrically independent of the primary gradiometer pickup coil circuit **15**. In other words, the primary pickup circuit **15**, including its primary winding **35** for coupling the magnetic flux picked up by the gradiometer pickup circuit **15** into the sensor **25**, is electrically separate from a primary winding **31**, employed in series with the superconductive trim coil circuit **16**, **17**, and **18**, for coupling trim magnetic flux into the sensor **25**. The advantage to the circuit of FIG. 4 is that the trim coil circuit does not have to interrupt the primary gradient pickup circuit **15**. This allows substitution of different types of primary pickup coil circuits **15** while allowing use of one trim coil circuit. In addition, the modular construction, which employs a trim coil circuit separate from the primary pickup coil circuit, is less expensive to manufacture, as a malfunction in one or the other of the two circuits does not require that both circuits be replaced.

Referring now to FIG. **5**, there is shown a trimmed primary magnetic pickup circuit **15** similar to that of FIG. **4** but modified to incorporate individual superconductive trim coil circuits **16–18**. More particularly, the circuit of FIG. **5** is similar to that of FIG. **4** in that magnetic flux picked up by the individual trim coil circuits **16**, **17**, and **18** is coupled to and added in the magnetic flux sensor **25** to magnetic flux picked up by the primary pickup coil circuit **15** and coupled to the sensor **25**. However, in the circuit of FIG. **5** each of the respective trim coil circuits **16–18** is electrically independent of the other and each has its respective primary winding in the sensor **25**, namely windings **32**, **33**, and **34**, respectively. In this manner magnetic flux coupled to the sensor by each of the individual trim coil circuits **16**, **17**, and **18** is added to the flux of the primary pickup circuit **15** as coupled to the sensor **25**. An advantage to the circuit of FIG. **5** is that a malfunction in any one of the superconductive circuits **15–18** is independent of the others such that the entire system, in the case of malfunction of one pickup coil, is not rendered inoperative. The malfunction can be repaired by merely repairing one of the circuits as contrasted with having to repair or replace all of the trim and/or primary pickup circuits. As an alternative to the primary sensor windings **32**, **33**, and **34** being coupled directly into the sensor **25**, such windings may be magnetically coupled into the superconductive circuit of the primary pickup circuit **15** such that the flux of the trim coils, instead of being added directly in the sensor, is added indirectly in the sensor **25** through the primary pickup circuit **15** and its inductive winding **35**.

Referring now to FIG. **6**, there is shown an alternative embodiment of the input circuit to the sensor **25**. More particularly, in the circuit of FIG. **6**, the individual trim coil circuits **16**, **17**, and **18** are connected in parallel with a single input primary winding **36** of the sensor **25**. As mentioned above, magnetic flux coupled to the sensor by the individual trim coils **16**, **17**, and **18** is added into the sensor **25** via the input winding **36**. However, it is not necessary that the trim flux be added directly into the input of the sensor **25** but may be coupled into the primary pickup circuit **15** by inductively coupling winding **36** to one of the coils of the primary pickup circuit **15** or by substituting input circuit **36** for input winding **35** of the primary pickup circuit **15**. In the latter embodiment, the trimmed primary pickup circuit **15** would be similar to that of FIG. **1** representing a parallel circuit connection as contrasted with the series circuit embodiment of FIG. **1**.

What is claimed is:

1. In a superconductive magnetic sensor:

superconductive primary pickup coil circuit means for sensing a component of magnetic field or gradient of a magnetic field in which said primary pickup coil circuit means is disposed by picking up a magnetic flux proportional to the sensed magnetic field or magnetic field gradient component;

an auxiliary superconductive trim coil circuit means disposed in said magnetic field common to said pickup coil circuit means for picking up a magnetic flux from said common magnetic field;

sensor means electromagnetically coupled to said primary pickup coil circuit means and to said trim coil circuit means for combining magnetic flux picked up by both said primary pickup coil circuit means and said trim coil circuit means to derive an output proportional to the combined magnetic flux picked up by said primary pickup coil circuit means and by said trim coil circuit means; and

means for varying the coupling of said auxiliary trim coil circuit means to the magnetic field in which it is disposed and while said auxiliary trim coil circuit is in a superconducting state to effect a change in the trim magnetic flux component coupled into said sensor means while said auxiliary trim coil circuit is in a superconducting state.

2. The apparatus of claim **1** wherein said means for varying the coupling of said trim coil means to the magnetic field includes, magnetic shield means disposed for shielding said trim coil means from at least a portion of the magnetic field in which it is disposed, and means for moving said shield means relative to said trim coil means for varying the coupling of said trim coil means to the magnetic field.

3. The apparatus of claim **2** wherein said trim coil means includes first and second trim or balance coils, each of said trim or balance coils being oriented relative to each other such that the magnetic axis of one of said trim or balance coils is mutually orthogonal to the magnetic axis of the other of said trim or balance coils.

4. The apparatus of claim **2** wherein said shield means includes a loop of superconductive material disposed surrounding said trim or balance coils means, said shield means being movable axially to said loop and relative to said trim or balance coil means for varying the coupling of said trim or balance coil means to the magnetic field.

5. The apparatus of claim **3** wherein said trim or balance coil means includes a third superconductive trim or balance coil, each of said first, second, and third trim or balance coils being oriented relative to each other such that the magnetic axis of each one of said trim or balance coils is generally mutually orthogonal to the magnetic axes of the other ones of said trim or balance coils.

6. The apparatus of claim **3** wherein said first and second trim or balance coil means are electrically independent of each other and of said primary pickup coil means.

7. The apparatus of claim **1** wherein said trim or balance coil means is connected in series with said primary superconductive pickup coil means.

8. The apparatus of claim **1** wherein said trim or balance coil means is electrically independent of said primary pickup coil means.

9. The apparatus of claim **6** wherein said first and second trim or balance coil means are electrically connected in parallel with the input to said sensor means.

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