(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) Publication number: **0 200 313 A1**

(12) EUROPEAN PATENT APPLICATION

(21) Application number: **86301815.6**

(51) Int. Cl.⁴: **H01F 15/02**

(22) Date of filing: **13.03.86**

(30) Priority: **01.04.85 US 718149**

(43) Date of publication of application:
10.12.86 Bulletin 86/45

(84) Designated Contracting States:
DE FR GB IT

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(54) Forceless non-contacting power transformer.

(57) A transformer for coupling electrical power from a stationary location to a moving location with a minimum of disturbance forces between the stationary and movable components. The transformer is particularly adapted to coupling power to a magnetically suspended platform. The transformer includes an enclosed core housing (112) two windings, a stationary primary coil (116), and a secondary coil (117) free to move linearly and angularly over a limited displacement, where the secondary coil is affixed to the movable platform (110), thereby enabling energy to be extracted for powering apparatus mounted within the platform.

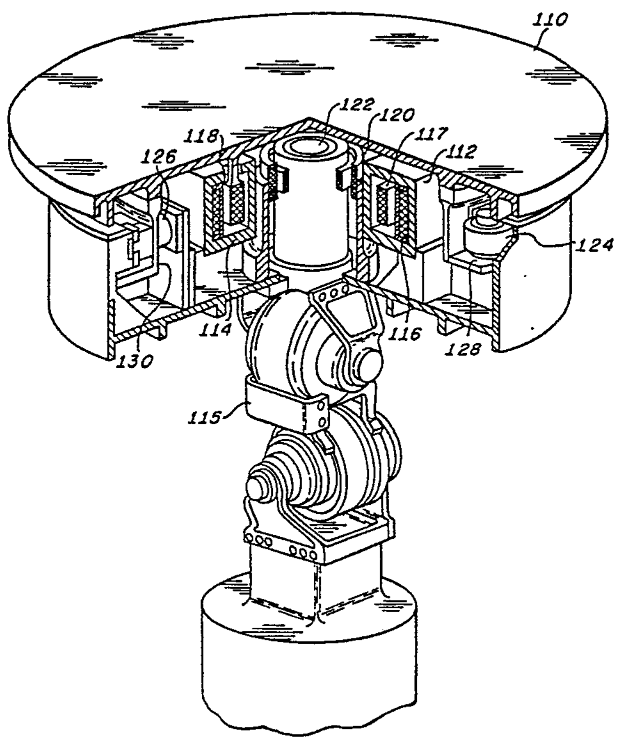

FIG.5.

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FORCELESS NON-CONTACTING POWER TRANSFORMER

This invention relates generally to inductive coupling and more particularly, to transformers where there is relative motion between the primary and secondary windings and minimal reaction forces therebetween.

The invention described herein has particular utility in applications where electrical power is coupled from a stationary location to a moving location with a minimum of interaction between the stationary and movable components. The invention is principally applied to transferring power across magnetically suspended interfaces, where small disturbance forces might affect the magnetic control forces, and where motions over as many as six degrees of freedom are required over a limited range.

Known technologies for coupling electro-magnetic energy across a moving boundary of interface consist of solenoid and rotary transformer type structures. In US -A-4,117,436, a transformer comprising primary and secondary windings axially disposed on a common axis and surrounded by a core of high permeability material is adapted to provide limited relative rotary motion between first and second transformer windings about the axis. The disadvantage of this device is the limited range of freedom of relative motion. Another structure is shown in US -A-4,321,572 in which a rotary transformer has a fixed primary winding and a secondary winding rotatable through a gap in the core structure. This arrangement principally allows full rotational freedom without allowance for motion about other axes. However, the presence of the air gaps in the core of Studer's invention deteriorates electrical performance by greatly reducing the magnetising inductance in relation to the leakage inductance, thereby requiring larger excitation currents and volume to perform a given power transfer, resulting in reduced efficiency.

The present invention improves over the prior art by providing a non-contacting structure that allows motion over six degrees of freedom, provides insignificant reaction forces with respect to the actual control forces applied to a stabilised structure attached thereto, requires no air gap in the core, and provides high efficiency over the required range of motion.

The present invention is defined in the appended claims and provides a power transformer having an enclosed magnetic core substantially without air gaps, a primary winding, and a secondary winding disposed within the core in a manner to permit relative motion between the first and second windings. The first winding is stationary, whilst the movable second winding is positioned radially with respect to the first winding with substantial directional freedom of motion over a limited range. This arrangement provides a substantially constant flux coupling between the two windings over the range of motion of the secondary.

In a preferred embodiment, support members are fixed to the secondary winding for supporting a movable structure, and the core is comprised of a cylindrical ferrite with an annular plate having apertures through which the supporting structure is coupled to the secondary winding.

In a further preferred embodiment, the invention is applied to a magnetically operative suspension for transferring power between stationary and movable structures.

An inductive coupler in accordance with the present invention will now be described in greater detail, by way of example, with reference to the accompanying drawings, in which:-

Figure 1A is a cross-sectional view of a conventional stationary transformer,

Figure 1B is a cross-sectional view of a rotary transformer with a rotatable core and secondary winding,

Figure 1C is a cross-sectional view of a rotary transformer with a stationary core and rotatable second winding,

Figure 1D is a cross-sectional view of the present invention showing a stationary core and movable secondary winding,

Figure 2 is a perspective view in cross-section of the core and coil structure of a preferred inductive coupler of the present invention,

Figure 3 is a plan view of the present invention,

Figure 4 is a cross-sectional view of the present invention taken along line 4-4 of Figure 3,

Figure 5 is a conceptual perspective view of a magnetic suspension system having an inductive coupler as in the present invention, taken in partial cross-section, and

Figure 6 is a cross-sectional view of a flux leakage pattern useful in understanding the present invention.

As above indicated, the inductive coupler of the present invention is particularly adapted for use with a magnetically suspended interface where power must be transferred to a suspended payload with a minimum of interaction with the suspension system. This is particularly critical where the suspension system is of the magnetic type. It is highly desirable to provide complete freedom of movement, albeit over a limited range, and to reduce any mechanical forces and electrical disturbances which may interact with the suspension system. Inductive coupling reduces friction losses because it eliminates sliprings and brushes or flexible wires and the like which increase the friction and reaction forces imposed upon the suspension system.

Furthermore, substantial power must be transferred with high efficiency, since it is intended for a space-environment application where heat dissipation is critical.

Referring now to Figure 1A, a conventional two-winding transformer is shown. A primary coil 10 and a secondary coil 12 are enclosed in a magnetically permeable core 14 such that a magnetic circuit is formed coupling the primary and secondary coils through the core. All parts are stationary with respect to each other and no air gap is required in the magnetic path of the core. Such a transformer may be constructed with a cubic volume or a cylindrical volume depending on whether the core is to be constructed of laminated material or a cast material such as a ferrite.

Figure 1B shows a conventional rotary transformer based on a cylindrical volume concept wherein one coil 16 and part of the magnetic core 18 rotate and one coil 20 and part of the core 22 are stationary. Air gaps 24 in the core allow rotary motion of the secondary with single-axis rotational freedom. The flux path 26 across the gaps causes significant disturbing forces when the rotor is moved from its centred location. This device is of the type described in US -A-No. 2,432,982.

A further improvement is illustrated in Figure 1C, representative of the disclosure of US -A 4,321,572 referred to above in which a magnetic core 28 surrounds stationary primary windings 30 and 31 affixed thereto with an air gap 32 in the core disposed to permit single-axis rotational movement of a second winding 34. Only the secondary coil 34 is movable and no core material is contained therein. The primary coils 30 and 31 and the iron core 28 remain stationary. The gap 32 is located internally in a channel extending traversely of an axial bore, thereby isolating the gap 32 from free space and reducing extraneous flux leakage. The coreless secondary 34 requires no relative motion or flux transfer between moving core paths and thus generates significantly lower forces on the moving body than the device of Figure 1B. However, the core gap 32 inhibits the electrical performance as described above and isolating the core gap 32 in the axial bore limits application with this transformer to a single axis of freedom.

In US -A-4,117,436, the primary and secondary coils are axially aligned on a spindle to permit a limited range of single axis rotary motion. However, none of the structures shown in this reference permit the six degrees of freedom provided by the present invention.

Figure 1D is a cross-sectional view of the inductive coupler of the present invention. A magnetic core 36 is comprised of an annular cup-shaped housing 38 and a cover plate 40 with no air gap at the interface 42. A primary coil or winding 44 is stationary within the core 38. A secondary coil or winding 46 is positioned to allow free motion in all directions over a limited range. The secondary coil 46 supports structural members 48 and 50 affixed thereto with clearance holes 52 bored in the cover plate 40 in a manner which does not interrupt the magnetic circuit.

Since there is no magnetic material in the secondary coil 46, reluctance forces, which are those forces caused by magnetic flux crossing between iron sections separated by a gap, are eliminated. The reluctance force is the principal undesirable force contributor in the prior art and its elimination gives rise to a substantially better performance of the device.

The next significant undesirable force contributor is the interaction of the primary and secondary leakage fields in the coil space. When the secondary coil 46 is centred in the coil space, a symmetrically force balanced condition exists and no net force is exerted on the secondary coil. However, when the secondary coil 46 is translated either radially or axially, an undesirable force is exerted on the secondary coil with its magnitude proportional to the displacement. Since these undesirable forces are a function of the uniformity of the leakage fields, they can be further reduced by increasing the mechanical clearance around the secondary coil to be greater than the desired coil motion, as is explained below with reference to Figure 6.

The undesirable forces on the secondary coil 46 are due to the interaction of the primary and secondary flux leakage fields in the coil space. These undesirable forces can be further reduced by attention to the primary coil leakage field uniformity throughout the space to be occupied by the secondary coil 46. Figure 6 depicts the primary coil leakage flux in the transformer coil space in both direction and magnitude; also showing the envelope of the desired secondary coil motion. If the primary leakage field were perfectly uniform in magnitude and direction over the desired secondary coil motion, no forces would exist. However, it is seen from Figure 6 that the leakage field is strong at the primary coil and weak at the point farthest from the primary coil. One method to improve the leakage field uniformity in the range of motion of the secondary coil 46, and hence to reduce the forces, is to enlarge the mechanical clearances so as to be substantially greater than the desired motion of the secondary coil.

Figure 2 is a perspective view of a preferred embodiment of the invention with a section removed to depict the principal components and their relative positions within the apparatus. The configuration shown is exemplary and not to be construed as limiting. Thus, for example, the axial bore, the positioning of the supports, etc., plays no part in the efficacy of the present invention and may not be required with other mounting arrangements. Other coil dispositions, such as providing a fixed winding on the inner annular wall of a closed core 60, are also useful.

The closed core 60 comprises a magnetically permeable annular ring 62 having a cavity 64 and a cover plate 66. The core 60 is so constructed and arranged that no air gap is permitted at the interface with the cover plate 62. A first winding 68 which may comprise a primary winding for accepting electrical energy is fixedly disposed in the cavity 64 and in stationary contact with the core 62. Positioned within the cavity 64 and radially spaced from the primary winding 68 is a second electrical winding 70 which may comprise a secondary winding for delivering electrical power transferred by inductive coupling to a load, not shown. It may be seen that the core 60, the first winding 68, and the second winding 70 comprise a magnetic circuit and that the second winding is positioned for free movement with respect to the core and first winding, while maintaining substantially constant flux coupling independent of the positional relationship with respect to the first winding.

The closed core 60, which may be comprised of a ceramic based ferrite material, together with the primary coil 68, may be attached to a mounting base and power source, not shown. The secondary coil 70 maintains at least a predetermined clearance from the primary coil 68 and the walls of core 62 to minimise the reaction forces noted above, by assuring operation when the secondary 70 is confined with a region of substantially uniform flux linkages, and is attached by supports 72 to the payload or moving element. The secondary winding 70 is located within the annular cavity 64 bounded by the walls of magnetically permeable core 62 and the primary coil 68. The closed magnetic core 60 surrounds both the primary coil 68 and the secondary coil 70 with no air gap to provide a closed path magnetic circuit coupling the flux from the primary coil to the secondary coil. A cylindrical core with an axial through bore is shown, but this is exemplary, and other shapes, such as a solid cylindrical core or a rectangular core, may also be utilised.

A plurality of apertures 74 is provided for receiving the structural supports 72 with clearance to allow free motion of the secondary coil 70.

Referring now to Figure 3 as well as to Figure 4, in which like reference numerals indicate like components with respect to Figure 3, the magnetically permeable core 80 is made up of two or more components to allow the primary coil 82 and the secondary coil 84 to be assembled into the enclosed core. The core illustrated is comprised of a cup 86 having an essentially cylindrical body with an annular cavity 88 into which the primary coil 82 and the secondary coil 84 are placed. The primary coil 82 is affixed to the outer peripheral wall of the cup 86. An end plate 90 is placed in contact with the core 86 to provide an essentially gapless magnetic circuit. The core assembly 80 is comprised of a highly magnetic permeable material and must be machined to a close tolerance so that no air gap will be alowed in the magnetic circuit. The end plate 90 is provided with apertures 92 through which supports 94, which are fixed to the secondary coil 84, may extend. In order to assure no disturbance of the magnetic field, the supports 94 must be formed of a nonmagnetic material. The supports 94, in turn, will be coupled to a supporting structure, not shown, on which is mounted a payload for receiving the coupled power.

The primary coil 82 is comprised of a toroidal winding of magnetic wire 96 wound on an insulating bobbin 98. While the winding 96 of Figure 4 is a single toroidal coil, the winding may also be comprised of several individual coils connected in series and disposed within the cavity 88.

The secondary coil 84 is a further toroidal winding of magnetic wire 100 on a bobbin 102 which is also formed from an insulating material, such as phenolic plastic. Coil 84 is proportioned to provide a mechanical clearance 104 in the vertical direction and a clearance 106 in a horizontal direction to allow the desired freedom of motion in axial, radial, and angular directions. Preferably, the mechanical clearances will be substantially greater than the desired range of motion of the secondary coil 84 to minimise the effects of magnetic disturbance forces on the structure to which the coil 84 is coupled. Typically, the transformer will provide free movement of 0.05 to 0.50 inches (1.27 mm to 12.7 mm) over six degrees of freedom. It will be clear that while the supports 94 are shown extending through the end plate 90, apertures may alternatively be provided in the base of the core or the sidewalls with appropriate clearances for the primary coil 82.

In a preferred embodiment, wherein the exciting current was applied at an audio frequency of about 10 kHz, the inductive coupler comprised a transformer, wherein the primary coil was wound of seven turns of 525 parallel strands of number 33 AWG insulated copper wire, of the type known as Litz wire to reduce skin effect, and the secondary was wound of two turns of a total of 1750 strands of number 33 AWG Litz wire. The core was fabricated of manganese-zinc ferrite material using flat upper and lower plates and inner and outer rings to form the core. The coil bobbins were machined from cloth-reinforced phenolic plastic with a wall thickness of 0.075 to 0.125 inches (1.905mm to 3.175mm). The transformer leads were terminated at six inches from the transformer body with brass lugs to serve as electrical interfaces to the input and output circuits.

The coupler described above, designed for a 2500 watt power transformer, exhibited a power output substantially independent of the platform displacement with a power transfer efficiency of 99.3%. Secondary coil disturbance forces were about 0.0006 lb-ft (0.008135J) axial and less than 0.003 lb-ft (0.004063J) radial. Motion capability was provided of ± 0.20 inches (5.08m) radial, ± 0.75° tilt, and ± 2° rotation.

Figure 5 shows a magnetically suspended movable platform 110 for a precision pointing mount, including an inductive coupler 112 of the present invention of which toroidal core 114 has an annular chamber with a primary winding 116 fixedly mounted therein and energised by a power source, not shown, coupled to a mount 115. A movable secondary winding 117 is enclosed within the core 114 and affixed to the platform 110 via non-magnetic supports 118. The secondary winding 117 is coupled to energise a payload (not shown), such as optical instruments or an antenna which is mounted on the platform 110, thereby avoiding the use of slip rings or flexible cables. Payload data signals are transmitted through the transformer axial bore via an optical coupler (not shown), housed within an axial enclosure 122 in the mount. The transformer through-hole allows integration with the optical coupler since it requires operation on the centre line of rotation. The enclosed core 114 allows the transformer to be positioned in close proximity to the magnetic bearing assemblies 124 and 126 without imposing undesirable distrubances therebetween due to the flux leakage.

The platform 110 is magnetically supported and oriented to provide six degrees of freedom by magnetic bearing assemblies 124 and 126 cooperating with armatures 128 and 130, respectively, which support the platform. Since the required range of movement is limited, the clearances between the secondary coil 117 and the core primary windings 116 are made sufficiently large that the force versus displacement characteristics, which are a function of the displacement, provide substantially reduced mechanical forces imposed on the movable platform as a result of energising the primary winding and withdrawing energy from the secondary winding.

Referring again to Figure 4, in operation the primary winding 82 is energised by an AC current supply to set up an alternately reversing flux as shown by the flux path 108. Since the flux path 108 is substantially contained within the core 80 and completely surrounds the secondary winding 84, an induced voltage is provided in the secondary winding 84 which is independent of its physical displacement with respect to the primary winding 82. Since all of the core material remains fixed during the motion of the secondary coil 84, there is no magnetic force interaction between permeable magnetic surfaces. Thus, there is provided an essentially forceless restraint of the movement of the secondary winding 84. The secondary coil 84 is free to move throughout the mechanical clearances 104, 106 without significant change in the efficiency of energy transformation. In contrast with the prior art apparatus which utilises a magnetic circuit which provided an airgap for free rotation of one of the magnetic elements, the present invention employs a magnetic circuit with no air gaps, which results in limited leakage flux and thus minimises electromagnetic disturbances. Furthermore, since the movable portion of the transformer contains no permeable materials it is substantially independent of disturbances forces.

Claims

1. An inductive coupler comprising a core -(36;62;86;112) of magnetically permeable material, a first winding (44;68;82;116) and a second winding

(46;70;84;117), characterised in that the core is enclosed, substantially without air gaps, and defines a cavity (64;88) adapted to permit relative motion between the first and second windings positioned therein, in that the first electrical winding is disposed within the cavity in stationary contact with the magnetic core, in that the second electrical winding is disposed radially with respect to the first winding and positioned for movement within the core cavity, the first electrical winding, the second electrical winding and the core being disposed to provide predetermined spacial clearances - (104,106) for motion of the second winding with respect to the first winding and the core, and the first winding, the second winding, and the core being so constructed and arranged as to provide a zone of substantially constant flux density within said clearances, and in that the coupler further comprises means for limiting said motion to predetermined axial, radial, and angular displacements substantially less than said predetermined spacial clearances, and for confining the motion to the zone of substantially constant flux density, so that electrical energisation of the first winding permits transfer of energy to the second winding over the displacement while minimising reaction forces between the first and second windings.

2. An inductive coupler according to claim 1, characterised in that the second winding - (46;70;84) further comprises at least one non-magnetically permeable support member - (48;52;72;94;) affixed thereto and the magnetic core (36;62;86) includes at least one corresponding aperture (52;74;92) for receiving the support member to permit limited displacement between the first - (44;68;82) and second (46;70;84) windings.

3. An inductive coupler according to 1 or 2, characterised in that the magnetic core (36Pts;86;112) is comprised of a body having a generally circular cross section.

4. An inductive coupler according to claim 2, characterised in that the magnetic core (62;86;) is comprised of ferrite material and the cavity (64;88) defines an annular cup for receiving the first and second windings (68;82:70;84), the core including a mating cover plate (60;90), substantially free of an air gap at the interface, and the or each aperture - (74;92) is disposed in the cover plate and aligned with the associated support member (72;94).

5. An inductive coupler according to any of the preceding claims, characterised in that the first winding (44;68;82;116) is adapted for connection to a source of electrical energy, and the second winding (46;70;84;117) is adapted to provide at least a portion of the energy to a load.

6. An inductive coupler according to any of the preceding claims, characterised in that the first and second windings (44;68;82;116: 46;70;84;117) are comprised of a conductor having a plurality of conductive strands (96,100) of predetermined diameters so symmetrically disposed that each strand assumes, substantially to the same extent, a plurality of different possible positions in the cross-section of the conductor, for providing a substantially uniform distribution of current over the cross-section when operative at audio frequencies.

7. An inductive coupler according to any of the preceding claims, characterised in that first and second windings (82:84) are respectively wound on non-conductive, non-metallic, non-magnetic bobbins (98:102), and the second winding is concentrically disposed within the first winding.

8. An inductive coupler according to claim 2 and any of the preceding claims appended thereto, characterised in that the magnetic core (36;62;86;112) is affixed to a support base, and the support members (48;52;72;94) of the second winding (46;70;84;117) are coupled to structure for supporting a movable member.

9. An inductive coupler according to claim 8, characterised in that the supporting structure comprises a magnetically operative suspension having a plurality of stops for limiting motion of the suspension.

10. An inductive coupler according to claim 2, and any of the preceding claims appended thereto, characterised in that the linear movement is limited to a predetermined linear displacement.

11. An inductive coupler according to claim 10, characterised in that the second winding - (46;70;84;117) is provided with a predetermined clearance with respect to the first winding - (44;68;82;116) which exceeds the predetermined linear displacement, and in that the displacement is situated within a region of substantially uniform flux linkages.

12. An inductive coupler according to claim 2, and any of the preceding claims appended thereto, characterised in that the angular movement is limited to a predetermined angular displacement.

13. An inductive coupler according to claim 2, and any of the preceding claims appended thereto, characterised in that the second winding - (46;70;84;117) is provided with a further predetermined clearance with respect to the first winding (44;68;82;116) which exceeds the predetermined angular displacement, and in that the angular displacement is situated within a region of substantially uniform flux linkages.

14. In a magnetically operative suspension of the type having a movable platform (110) for supporting an apparatus to be electrically energised and an aperture (122) in the platform for coupling control signals to a fixed support, an inductive coupler, characterised in that the inductive coupler comprises an enclosed toroidal core of magnetically permeable material (112), defining a magnetic flux path substantially free of air gaps, having an axial bore for transmitting the control signals therethrough, and further defining an annular chamber for receiving first and second electrical windings - (116;117), the first electrical winding (116) being positioned in stationary contact with the magnetic core, the second electrical winding (117) being radially positioned within at least a portion of the first winding, having predetermined spacial clearances with respect to the core and the first winding, and disposed for limited movement therein at least one non-magnetically permeable support member (118) having a first end affixed to the secondary winding (117) and a second end secured to the movable platform (110), the core - (112) being provided with an aperture for receiving the support member therethrough, and means for limiting said movement to predetermined axial, radial and angular deviations substantially less than said predetermined special clearances so that the secondary winding is positioned within a zone of substantially constant flux density, the predetermined clearances being proportioned to exceed the limited movement so as to provide force versus displacement characteristics less than a predetermined value with respect to mechanical forces imposed on the movable platforms as a result of energising the first winding and withdrawing energy coupled therefrom from the second winding.

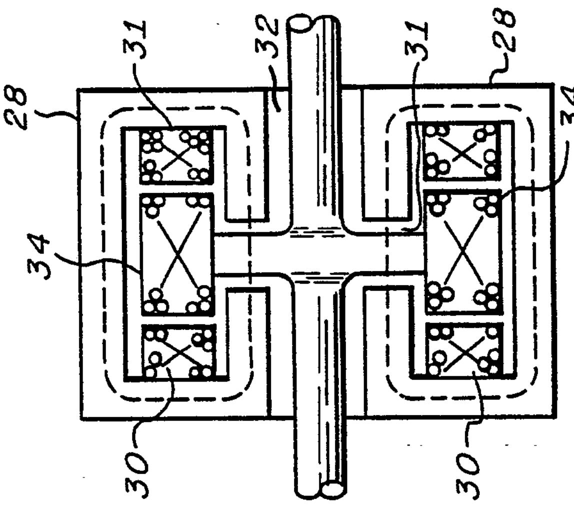

FIG.1c.

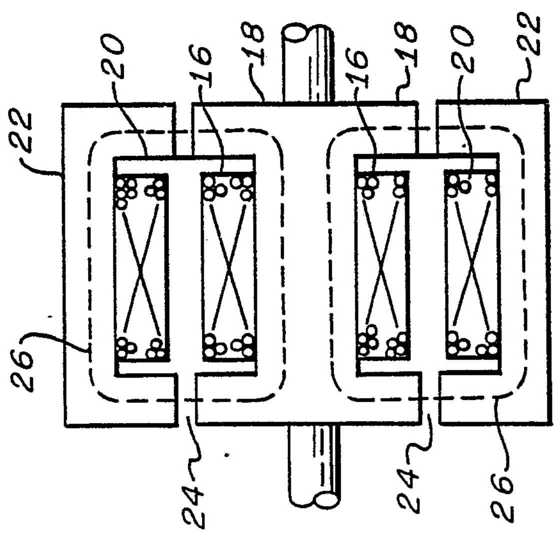

FIG.1b.

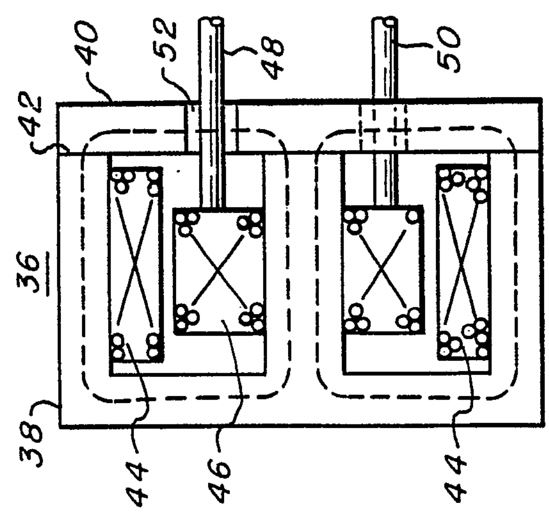

FIG.1d.

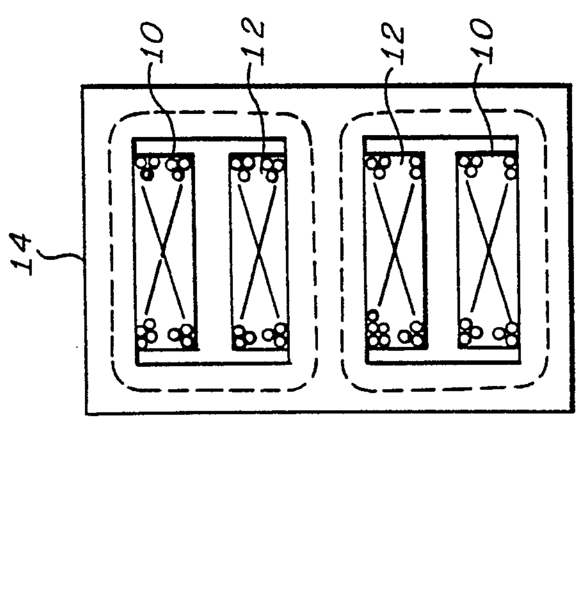

FIG.1a.

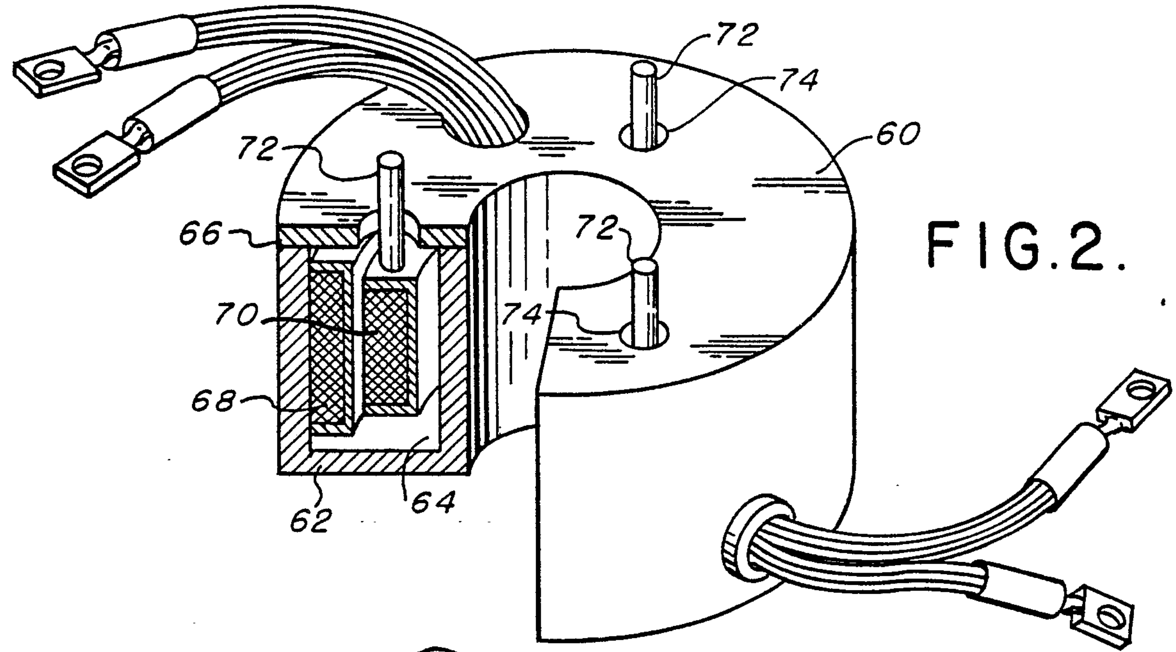

FIG.2.

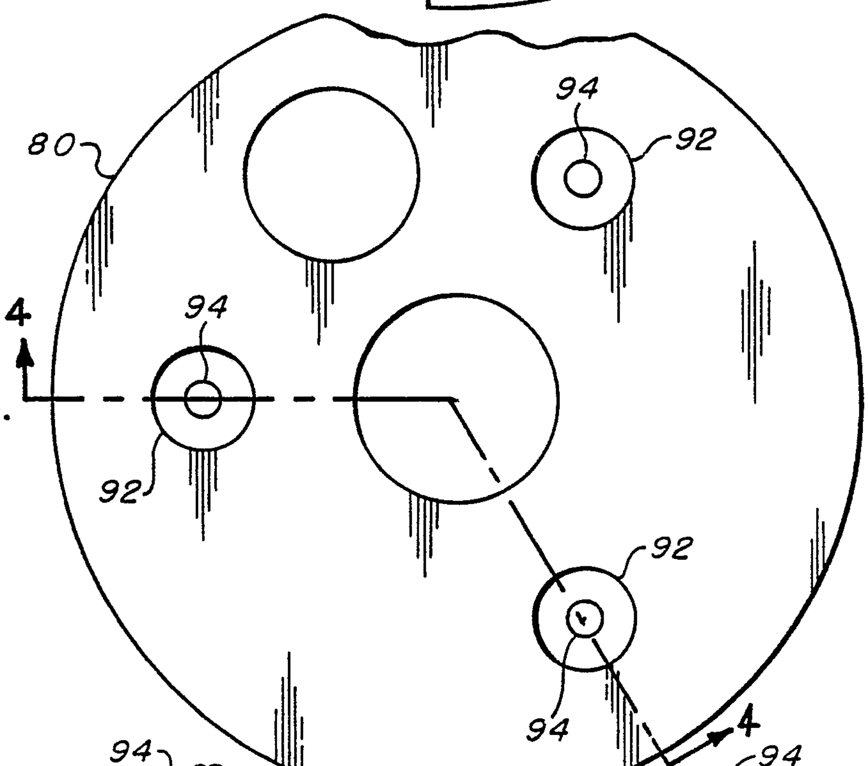

FIG.3.

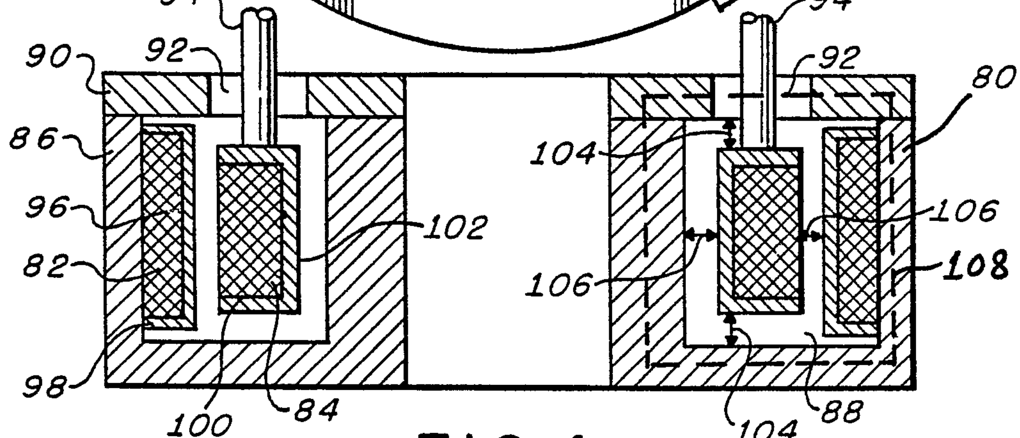

FIG.4.

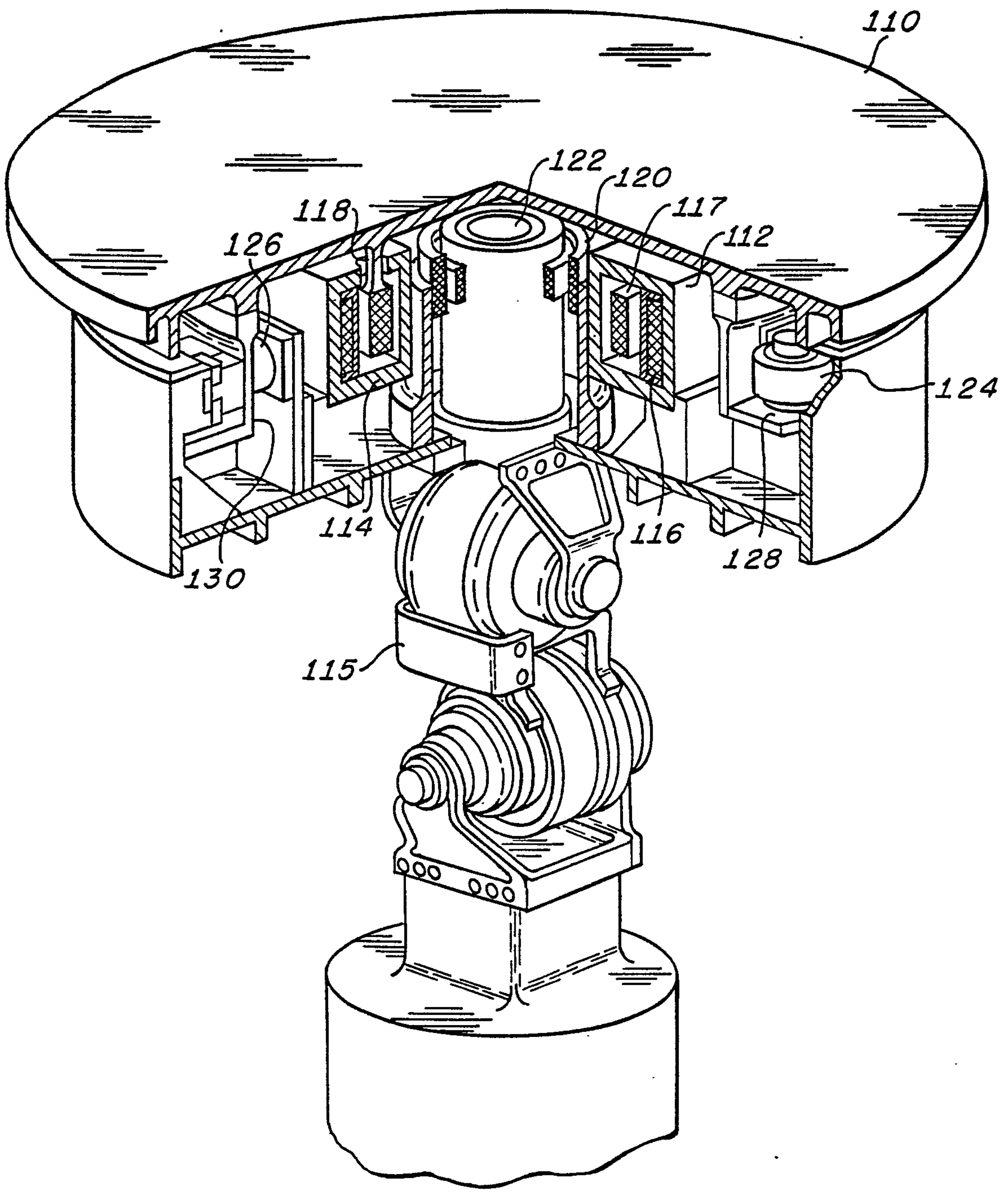

FIG.5.

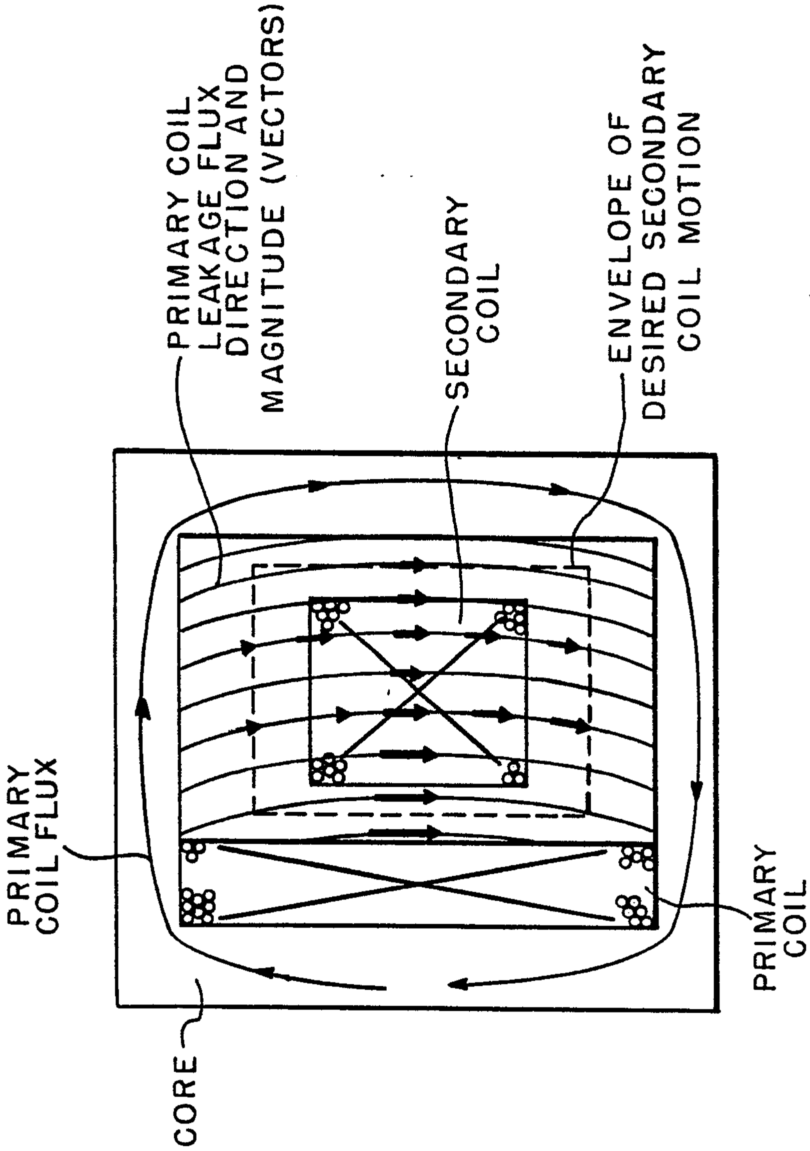
PRIMARY COIL
LEAKAGE FLUX
DIRECTION AND
MAGNITUDE (VECTORS)
SECONDARY
COIL
ENVELOPE OF
DESIRED SECONDARY
COIL MOTION
PRIMARY
COIL FLUX
PRIMARY
COIL
CORE

FIG.6.

European Patent Office

EUROPEAN SEARCH REPORT

Application number: EP 86301815.6

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.4)
A	US - A - 4 303 902 (LESSTER) * Abstract; claims 1-10; fig. 7-10 *	1-14	H 01 F 15/02
D,A	US - A - 4 117 436 (MAC LENNAN) * Abstract; fig. 1-4 *	1-14	
D,A	US - A - 4 321 572 (STUDER) * Abstract; fig. 1-6 *	1-14	
D,A	US - A - 2 432 982 (BRADDON) * Claims 1-4; fig. 1-6 *	1-14	

TECHNICAL FIELDS SEARCHED (Int. Cl.4)

H 01 F 15/00
H 01 F 23/00

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
VIENNA	03-07-1986	VAKIL

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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