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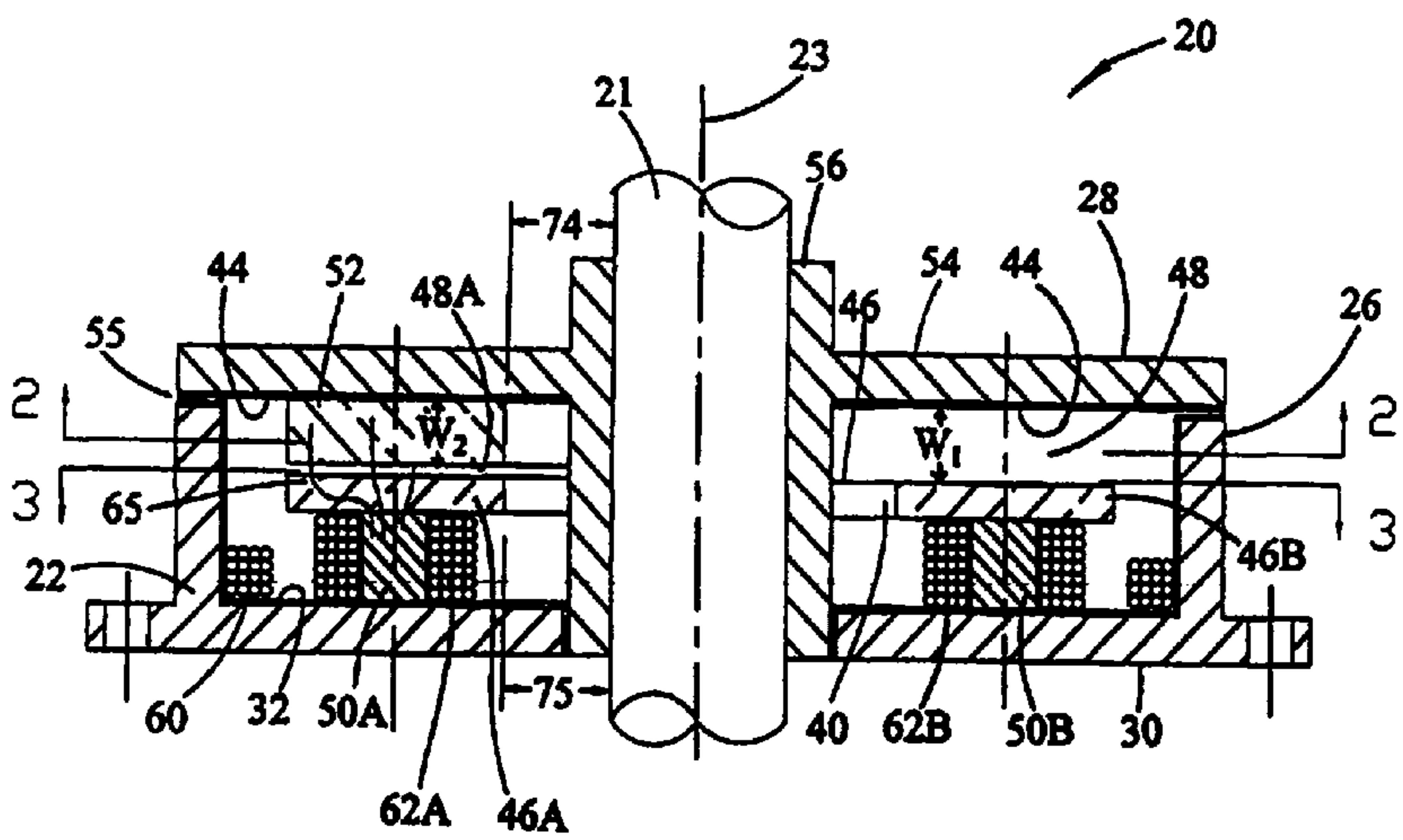
(54) **DETECTEUR DE DEPLACEMENT ANGULAIRE DOTE D'UNE CIBLE A PERMEABILITE MAGNETIQUE ET ORIENTANT LE FLUX D'UN CHAMP MAGNETIQUE**

(54) **ANGULAR DISPLACEMENT TRANSDUCER HAVING MAGNETICALLY PERMEABLE FLUX-DIRECTING TARGET**



(57) L'invention a trait à un détecteur de déplacement angulaire doté d'une cible à perméabilité magnétique élevée qui oriente de préférence le flux d'un champ magnétique fluctuant à travers un noyau sélectionné parmi deux noyaux ou d'avantage. Le champ magnétique fluctuant induit des tensions dans des bobines secondaires situées autour des noyaux. Des signaux de sortie, qui varient en fonction de l'angle formé par la cible tournant autour d'un axe, sont obtenus grâce à des connexions différentes de paires de bobines secondaires. Grâce au choix de cibles de différentes formes, on peut faire varier la tension de sortie en fonction de l'angle, c'est-à-dire, sous forme d'une onde sinusoïdale ou bien d'une onde triangulaire. Les détecteurs selon l'invention peuvent être robustes et précis tout en conservant une construction simple.

(57) An angular displacement transducer has a highly magnetically permeable target which preferentially directs the flux of a fluctuating magnetic field through one of two or more cores. The fluctuating magnetic field includes voltages in secondary windings around the cores. Output signals which vary with the angle of the target about an axis are obtained by connecting pairs of secondary windings differentially. By choosing targets of different shapes the output voltage can be made to vary with angle as a sine wave or as a triangular wave. Transducers according to the invention can be rugged and accurate while retaining a simple construction.

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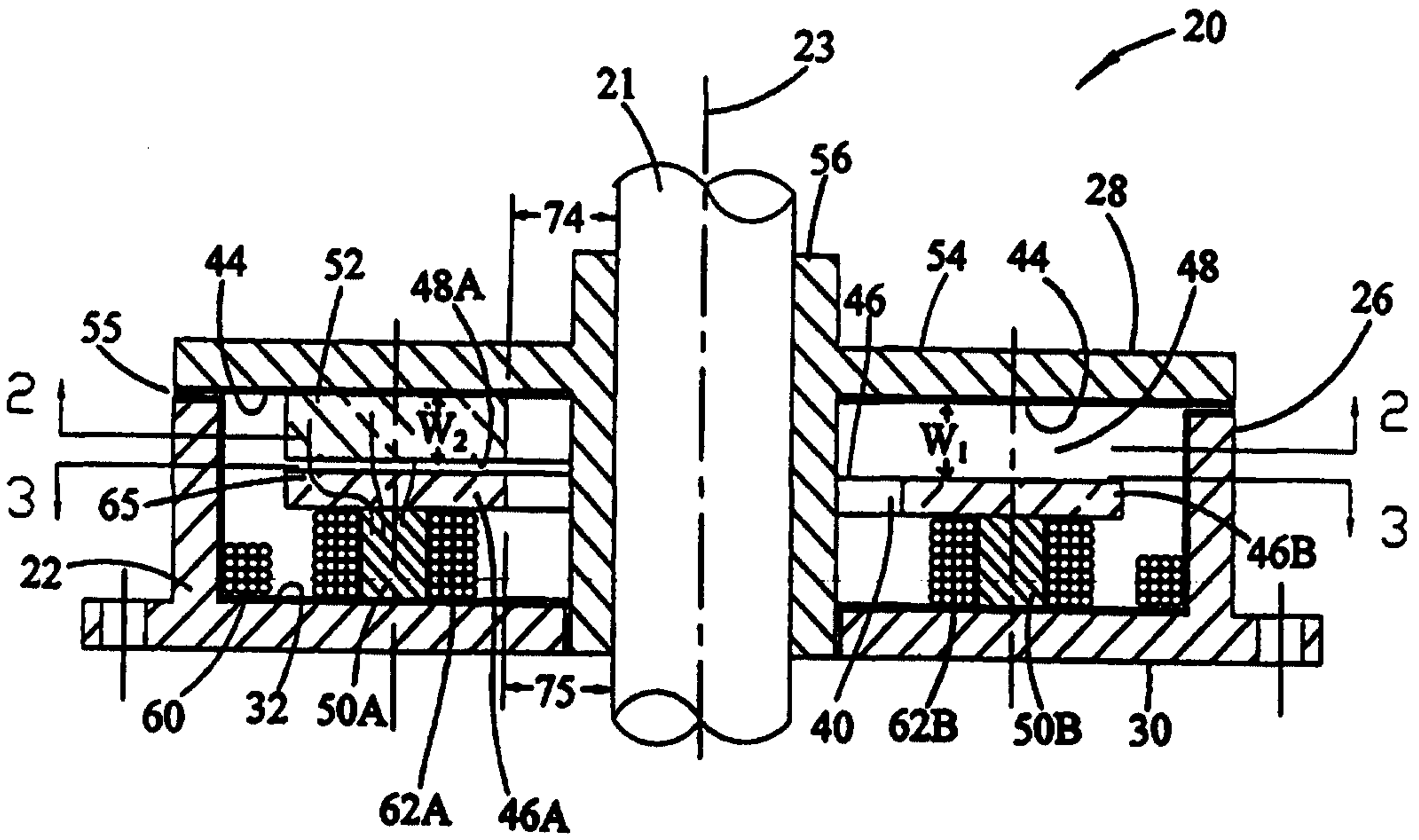

(57) Abstract

An angular displacement transducer has a highly magnetically permeable target which preferentially directs the flux of a fluctuating magnetic field through one of two or more cores. The fluctuating magnetic field includes voltages in secondary windings around the cores. Output signals which vary with the angle of the target about an axis are obtained by connecting pairs of secondary windings differentially. By choosing targets of different shapes the output voltage can be made to vary with angle as a sine wave or as a triangular wave. Transducers according to the invention can be rugged and accurate while retaining a simple construction.

ANGULAR DISPLACEMENT TRANSDUCER HAVING MAGNETICALLY PERMEABLE FLUX-DIRECTING TARGET

Technical Field

This invention relates to apparatus for determining the angular displacement of a part, such as a shaft about an axis.

Background

Angular displacement transducers, which produce an electrical signal indicative of the rotational angle of a part, such as a shaft, are widely used in industry. Various designs of incremental and absolute optical encoders as well as electromagnetic or inductive angle sensors, also known as "resolvers", are known. Optical encoders tend to be expensive, fragile and/or have low angular resolutions.

Some electromagnetic angular displacement transducer designs involve mounting a winding on the rotating part adjacent a stationary winding. As the rotating winding turns the electromagnetic coupling between the stationary and rotating windings changes. This, in turn, changes an electrical potential induced in one of the windings by a signal in the other winding. The geometry of these devices generally causes such devices to produce an electrical output which varies sinusoidally with angle.

There are several problems which prior art angular displacement transducers typically share in various combinations. One problem is that accurate transducers according to prior art designs are complicated and expensive to make. A second problem with some prior art angular displacement transducers is that they the relationship between the electrical output signal and the angle being measured can not be easily derived from simple calculations. Many such transducers cannot produce an analog output which varies linearly with angle. As noted above, most such analog transducers produce an output that varies sinusoidally with angle. A third problem is that the prior art does not provide a good selection of angular transducers that can be placed in the center of a shaft and are reasonable in both cost and accuracy. A fourth problem is that most prior art transducers are not easily capable of resolving the relative angular displacement of two shafts. A fifth problem is that many prior art angular displacement transducers are fragile and/or do not work well when wet. Such transducers are not readily usable in settings where there is significant vibration or moisture.

U.S. patent No. 5,402,096 to Harris shows a rotary displacement transducer in which a movable rotor causes changes to the inductance of coils. The two sets of coils are connected in a half-bridge differential configuration so that changes in their relative inductances can be measured. The Harris design only partially compensates for axial displacements of the rotor.

There is a need for simple, rugged, accurate angular displacement transducers. There is a particular need for simple accurate rugged angular displacement transducers which produce output signals which bear a linear relationship to the angle being measured. There is also a need for simple, rugged, accurate angular displacement transducers which produce output signals which bear sinusoidal or other relationships to the angles being measured.

Summary of the Invention

The invention provides an angular displacement transducer which avoids limitations of many prior art angular displacement transducers. A first aspect of the invention provides a transducer for measuring the angular displacement of a part. The transducer comprises an annular first pole piece comprising a material having a high magnetic permeability and centered on an axis, a second pole piece comprising a material having a high magnetic permeability spaced apart from the first pole piece by a gap; a primary coil for generating an alternating magnetic field having field lines extending through the first

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and second pole pieces and the gap; and, a target between the first and second pole pieces in the gap, the target mounted for rotation about the axis and comprising a material having a high magnetic permeability. The first pole piece comprises an annular cap portion comprising a plurality of separated sectors and a core connected to each of the sectors. A secondary winding is wrapped around each of the cores.

In one preferred embodiment of the invention the target is semi-annular. In another preferred embodiment of the invention, the target is crescent shaped.

Another aspect of the invention provides a transducer for measuring the angular displacement of a target about an axis. The transducer comprises: a housing having first and second annular end faces centered on an axis and a cylindrical side face all comprising a highly magnetically permeable material; a circular primary coil in the housing extending peripherally of the first end face adjacent the side face; a first pole piece in the housing, the first pole piece comprising a planar annular cap centered on the axis and comprising one or more pairs of opposed sectors, each sector connected to one of the end faces by a core, the cap and each core comprising a highly magnetically permeable material; an annular second pole piece in the housing connected to another one of the end faces and spaced apart from the first pole piece by a gap, the second pole piece comprising a highly magnetically permeable material; a secondary winding around each of the cores; a target comprising a semi-annular pad of highly magnetically permeable material mounted for rotation about the axis in the gap, the target having a thickness nearly equal to a width of the gap; and, an oscillator connected to the primary coil. The oscillator causes the primary coil to generate an alternating magnetic field in the housing. The alternating magnetic field passes through the first pole piece, the target and the second pole piece, and induces alternating voltages in the secondary windings. The magnitude of the alternating voltage in each secondary winding varies with the degree of overlap between the target and the sector associated with that secondary winding.

Yet another aspect of the invention provides a transducer for measuring the angular displacement of first and second shafts. The transducer comprises annular first and second pole pieces. Each of the pole pieces has an annular cap portion comprising a plurality of separated sectors each of high magnetic permeability and a core having a high magnetic permeability connected to each of the sectors. The transducer also comprises: a magnetically permeable member between the first and second pole pieces and separated from the first and second pole pieces by first and second gaps; a primary coil for generating an alternating magnetic field having field lines extending through said first and second pole pieces, the magnetically permeable member and the first and second gaps; a first target connected for rotation with the first shaft, the first target located in the first gap, the first target mounted for rotation about an axis of the first pole piece and comprising a material having a high magnetic permeability; a second target connected for rotation with the second shaft, the second target located in the second gap, the second target mounted for rotation about an axis of the second pole piece and comprising a material having a high magnetic permeability; a highly magnetically permeable path extending between said cores of said first pole piece and said cores of said second pole piece; and, a secondary winding around each of said cores of said first and second pole pieces.

Still another aspect of the invention comprises a method for measuring the angular displacement of a part around an axis. The method comprises the steps of: generating a fluctuating magnetic field; causing the fluctuating magnetic field to extend through a pair of pole pieces and a gap between the pole pieces, a first one of the pole pieces comprising a two or more sectors, each sector comprising a core passing through a secondary winding; moving a highly magnetically permeable target within the gap to direct substantially all of the magnetic field lines passing through the gap into the portions of the first and second pole pieces adjacent the target; and, measuring the difference in the magnitudes of voltages induced in pairs of the secondary windings.

Brief Description of the Drawings

In drawings which illustrate specific embodiments of the invention, but which should not be construed as restricting the spirit or scope of the invention in any way:

Figure 1 is a partially schematic section through an angular transducer according to the invention;

Figure 2 is a transverse sections thereof along the line 2-2;

Figure 3 is a transverse section thereof along the line 3-3;

Figure 4 is a schematic illustrating the electrical connection of windings in the transducer of Figure 1;

Figure 5 is a plot of the output voltage of the transducer of Figure 1 as a function of angle;

Figure 6 is a schematic view of the magnetic paths in the transducer of Figure 1;

Figure 7A is a plan view of a semi-annular target superimposed on a pole piece;

Figure 7B is a plan view of an alternative target for use with the invention superimposed on a pole piece;

Figure 8 is a plot of the output voltage of the transducer of Figure 1 as a function of angle with the target of Figure 7B;

Figure 9A is a plan view of a first pole piece having four sectors for use with the invention;

Figure 9B is a plan view of a first pole piece having six sectors for use with the invention;

Figure 10A is a plot of the output voltage of a transducer equipped with the first pole piece of Figure 9A as a function of angle with the target of Figure 7B;

Figure 10B is a plot of the output voltage of a transducer equipped with the first pole piece of Figure 9B as a function of angle with the target of Figure 7B;

Figure 11 is a transverse section through a transducer according to the invention having two first pole pieces shifted relative to each other; and,

Figure 12 is a transverse section through an embodiment of the invention adapted to measure the relative angle between two shafts.

Detailed Description

This invention provides angular displacement transducers in which the output voltage depends on the relative magnetic flux from a fluctuating magnetic field passing through each of two or more secondary coils. A highly magnetically permeable target which is connected to the part whose angle is to be measured directs the magnetic field preferentially into one or more of the secondary coils so that the relative flux passing through the secondary coils varies with the angular position of the target.

Figure 1 shows a section through a basic embodiment of a transducer **20** according to the invention for measuring the angular rotation of a shaft **21** about an axis **23**. Transducer **20** comprises a housing **22** having a generally cylindrical side face **26** and generally annular end faces **28** and **30**. Housing **22** is lined with, incorporates, or is made of a highly magnetically permeable material. The material may be, for example, permalloy or supermalloy. In the embodiment of Figure 1, the highly permeable material is provided in the form of a coating **32** on the inner surface of housing **22**.

In this application, "highly magnetically permeable" means a magnetic permeability of at least about 500 and preferably well in excess of about 2,500. For example, modern permalloy materials have magnetic permeabilities in excess of 20,000. In general, it is preferred that those parts which are stated to have high magnetic permeabilities have magnetic permeabilities as high as possible.

Inside housing **22** are a first pole piece **40** and a second pole piece **44** separated by a gap **48**. Gap **48** has a width W_1. First and second pole pieces **40** and **44** preferably have planar surfaces facing gap **48**. Most preferably the facing surfaces of first and second pole pieces **40**, **44** are perpendicular to axis **23**. It is not absolutely necessary that the surfaces of pole pieces **40** and **44** be planar, however, pole pieces **40** and **44** should be circularly symmetrical in respect of axis **23**.

Second pole piece **44** may be a portion of end **28** of housing **22**, as shown. In the alternative, second pole piece **44** may project inwardly from end **28** of housing **22**. First and second pole pieces **40**, **44** are preferably both formed from highly magnetically permeable material.

First pole piece **40** comprises an annular cap **46** which is divided into two C-shaped sectors **46A** and **46B** (Fig. 3). Sectors **46A** and **46B** are preferably semi-annular. Sectors **46A** and **46B** do not contact each other. Sectors **46A** and **46B** are each connected to end surface **30** of housing **22** by one of cores **50A**, **50B**. The magnetic permeability of the spaces **47** between sectors **46A** and **46B** is much smaller than the magnetic permeability of cores **50**. The material in spaces **47** may be air or some other material having a low magnetic permeability. In general, spaces **47** should be as narrow as possible while maintaining a magnetic reluctance across spaces **47** which is much greater than the magnetic reluctance of a path extending from any point on the surface of the sector **46A** or **46B** through the associated core **50A** or **50B**.

A target **52** is mounted to shaft **21** in gap **48** between poles **40** and **44**. Target **52** comprises a highly magnetically permeable material. Target **52** is preferably in the form of a pad of material and preferably has parallel faces having shapes defined by a peripheral edge of target **52**. Target **52** preferably has a thickness W_2 which is nearly equal to W_1. Target **52** is separated from first pole piece **40** by a narrow gap **48A**. The surfaces of target **52** and first pole piece **40** which define gap **48A** are preferably parallel.

As shown in Figure 2, in one preferred embodiment of the invention, target **52** is semi-annular. Target **52** may be secured to, mounted on or embedded in, a disk **54** which extends flange-like from a collar **56** mounted to shaft **21**. In the embodiment of Figure 1, disk **54** also forms end wall **28** of housing **22**. Disk **54** is spaced slightly away from the side wall **26** by a narrow circular gap **55** so that disk **54** can rotate freely with respect to the rest of housing **22**. Gap **55** is typically an air gap. While air is not highly magnetically permeable, gap **55** can be made narrow so that it has a reasonably low magnetic reluctance. Further, gap **55** is circularly symmetrical so that its magnetic reluctance does not change appreciably with the angle of rotation of disc **54**.

A primary coil **60**, or some other means for generating a fluctuating magnetic field, is located inside housing **22**. Preferably primary coil **60** is located at the junction between side face **26** and one of end faces **28**, **30**. A secondary winding (indicated generally by **62**) wraps around each of cores **50**. Secondary winding **62A** wraps around core **50A** connected to sector **46A**. Secondary winding **62B** wraps around core **50B** connected to sector **46B**. Secondary winding **62A** is connected differentially with secondary winding **62B** as shown in Figure 4. As shown in Figure 4, an oscillator **70** is connected to primary coil **60**.

The transducer of Figure 1 operates as follows. Oscillator **70** generates a alternating current in primary coil **60**. The frequency of oscillator **70** is not critical but is typically in the range of about 50 Hertz to 1600 Hertz or so. Frequencies beyond this range may also be used.

The alternating current in primary coil **60** generates an alternating magnetic field in housing **22**. The alternating magnetic field extends in a circuit around primary coil **60** as indicated by field lines **65** and as illustrated in Figure 6. Because magnetic field lines **65** tend to concentrate in material which is highly magnetically permeable, the magnetic field lines **65** generated by primary coil **60** primarily lie in the highly magnetically permeable coating **32** on the inner faces of housing **22**. The magnetic field lines extend in loops extending along side wall **26**, through gap **55**, through second pole piece **44**, through gap **48A** by way of target **52**, and through first pole piece **40**. The magnetic reluctance of gap **55** is typically much smaller than that of gap **48A**. Gap **48A** has a uniform distribution of magnetic flux which passes from target **52** into cap portion **46** of first pole piece **40**. Gaps **48A** and **55** are preferably small to minimize the magnetic reluctance provided by gaps **48A** and **55** and to minimize leakage of magnetic flux from housing **22**. Due to the symmetries of the structure shown in Figure 1, most leakage of magnetic flux will be balanced and will not influence the accuracy of transducer **20** very much.

Magnetic field lines **65** generated by coil **60** which pass through target **52** also pass into and through annular cap **46** of the first pole piece **40**. Substantially all of the magnetic field lines which enter annular cap **46** pass through one of cores **50** because cores **50** provide a much more highly magnetically permeable route to coating **32** on end face **30** than any alternative route.

The fluctuating magnetic field passing through cores **50** induces an alternating voltage in secondary windings **62**. The voltage induced in any particular secondary winding **62** relative to the other one(s) of secondary windings **62** depends upon the relative amounts of magnetic flux travelling through the cores **50** on which those secondary windings **62** are mounted. This, in turn, depends upon the position of target **52** about axis **23**.

The magnetic field in gap **48A**, which is the portion of gap **48** between target **52** and cap portion **46**, will be reasonably constant over the entire surface of target **52** assuming that gap **48A** is small compared to the dimensions of target **52** and the width of gap **48**. In practice, this is easily accomplished. Consequently, to a very good first approximation, the amount of magnetic flux directed by target **52** into each of sectors **46A** and **46B** (and the voltages thereby induced in coils **62A** and **62B**) depends upon the relative areas of overlap between target **52** and each of sectors **46A** and **46B**. If extreme accuracy is required then it is necessary to take into account the fact that the magnetic field in the space between target **52** and first pole piece **40** is not completely uniform over the surface of target **52** but varies slightly, particularly in narrow regions along the edges of target **52**.

When target **52** is exactly overlapping sector **46A** then substantially all of the flux generated by primary coil **60** will travel through core **50A** and secondary winding **62A** so that a relatively large voltage will be induced in secondary winding **62A**. By contrast, substantially no flux will be directed through core **50B** and secondary winding **62B** will not have any significant voltage induced in it. For example, if target **52** is rotated until it overlaps both of sectors **46A** and **46B** by the same amount, then the same amount of magnetic flux will travel through each of cores **50A** and **50B** and secondary windings **62A** and **62B** will have equal voltages induced in them.

Those skilled in the art will recognize that a transducer generally as shown in Figure 1 can be made to be rugged. A further advantage of the transducer of Figure 1 is that it does not require any electrical connections to any moving parts.

Figure 6 shows a schematic view of the magnetic circuit **72** formed in the apparatus of Figure 1. The main path **73** followed by magnetic flux lines **65** is indicated by solid lines. The main possible undesirable leakage paths are indicated by dotted lines. Magnetic circuit **72** can be viewed as a series of elements connected in a series-parallel configuration. Each element has a magnetic reluctance which depends upon its geometry and is inversely proportional to the magnetic permeability of the material(s) from which it is made.

One possible leakage path **76** extends from end **28** of housing **22**, through gap **74** (Fig. 1) to shaft **21**, and through gap **75** (Fig. 1) to end **30** of housing **22**. The magnetic reluctance of path **76** can be made to be much higher than the magnetic reluctance of main path **73** by ensuring that gaps **74** and **75** are significantly larger than gaps **55** and **48A**.

Second leakage paths **77A** and **77B** extend from second pole piece **44** across gap **48** to sectors **46A** and **46B** of first pole piece **40** respectively. These leakage paths are also undesirable because, for optimum operation, substantially all of the magnetic flux passing through sectors **46A** and **46B** of first pole piece **40** should be directed through target **52**. Leakage through paths **77A** and **77B** can be substantially eliminated by making gap **48A** much smaller than gap **48**. If this is done then substantially all of the magnetic flux will pass through target **52** and gap **48A** rather than passing through gap **48** between first and second pole pieces **40**, **44** in their portions away from target **52**. Target **52** is much more magnetically permeable than air (or any portions of disk **54** which might project into gap **48**).

Third leakage paths **78** extend between sectors **46A** and **46B** through gap **47**. Leakage through paths **78** can be substantially eliminated by ensuring that gaps **47** are wide enough that the magnetic reluctance between sectors **46A**, **46B** and housing **28** through cores **50** is much lower than the magnetic reluctance offered by spaces **47**.

As shown in Figure 4, it is convenient to connect windings **62A** and **62B** differentially. The output of transducer **20** is then the magnitude of the voltage V_{out}. Figure 5 shows the variation in the magnitude of V_{out}. with angle θ. It can be seen that V_{out} varies linearly with θ. It will be understood that where the magnitude of V_{out} is shown as having a negative value, V_{out} is out of phase with the signal produced by oscillator **70**. Where V_{out} is shown as having a positive value, V_{out} is in phase with the signal produced by oscillator **70**.

It is apparent that a transducer **20** according to the invention may be hollow along axis **23** so that transducer **20** may be mounted anywhere along a shaft **21**. It is not necessary for transducer **20** to be at one end of shaft **21** (although there is no reason why transducer **20** could not be mounted at one end of shaft **21**).

In some circumstances it can be desirable to vary the shape of the curve relating V_{out}. and θ. For example, in some circumstances it may be desirable to have V_{out}. and θ related by a sinusoidal curve.

The shape of the curve relating V_{out} and θ may be changed by changing the shape of target **52**. This changes the way in which the overlap between the target and the sectors on first pole piece **40** varies with the angle of the target relative to the first pole piece. One advantage of a transducer according to the invention is that it is relatively easy to design a target **52** which will produce a desired output.

When target **52** is at a given angle θ, as shown in Figure 7A, then V_{out} is given to a good approximation by:

$$V_{out} = (A_1 - A_2) \times K \tag{1}$$

where: A_1 is the area of overlap between target **52** and sector **46A** of first pole piece **40**; A_2 is the area of overlap between target **52** and sector **46B** of first pole piece **40**; and K is a constant. The change in V_{out} for small changes in θ is given by:

$$\Delta V_{out} \cong K \times (R_2^2 - R_1^2) \times \Delta\theta \qquad (2)$$

where: ΔV_{out} is the change in V_{out}; R_2 is the radius of the outermost portion of target **52** along space **47**; R_1 is the radius of the innermost portion of target **52** along space **47**; and $\Delta\theta$ is the small change in θ. More exact calculations of the changes in areas A_1 and A_2 with changes in θ, and the resulting changes in V_{out} can be made in ways which will be clear to those skilled in the art in light of this disclosure. Corrections for edge effects and the like may be made by slightly changing the shape of target **52**.

For example, Figure 7B shows an alternative crescent shaped target **52A** which, when used in the transducer of Figure 1 in place of semi-annular target **52**, produces a sinusoidal output curve, as shown in Figure 8.

The invention is not limited to the use of first pole pieces which include only two sectors. For example, Figure 9A shows a top plan view of a first pole piece comprising four sectors **46A**, **46B**, **46C**, and **46D**, four corresponding cores **50A** through **50D**, and four secondary windings **62A** through **62D**. Figure 9B shows a top plan view of a first pole piece comprising six sectors, six cores **50** and six secondary windings **62**. The pole pieces of Figures 9A and 9B may be used with targets **52** of various shapes. For example, the pole pieces of Figures 9A and 9B may be used with semi-annular targets or crescent shaped targets as described above. The preferred form for a pole piece **40** for use with a semi-annular target has two semi-annular sectors **46A** and **46B**.

The pole pieces of Figures 9A and 9B may be used to provide transducers which provide several outputs which are phase shifted relative to one another. Preferably in such embodiments, the outputs are each provided by connecting secondary coils **62** in opposed sectors in differential relationship to one another. For example, in the embodiment of Figure 9A, a first output can be derived by connecting secondary windings **62A** and **62C** differentially and a second output may be derived by connecting windings **62B** and **62D** differentially. In the embodiment of Figure 9B, three outputs may be provided by connecting the secondary windings differentially in the pairs **62A-62D**; **62B-62E**; and **62C- 62F**. If this is done and a target **52A** is used as shown in Figure 7 then the three output voltages produced by the pole pieces of Figures 9A and 9B used in the apparatus of Figure 1 will be generally as shown in Figures 10A and 10B respectively.

In the embodiments described above, second pole piece **44** has only been used to direct magnetic flux generated by primary coil **60** into target **52**. The embodiment of the invention shown in Figure 11, is a transducer **100** having two pole pieces, **40'** and **40"**, both of which are constructed generally in the manner of the first pole piece **40** of Figure 1. Pole piece **40'** is shifted angularly relative to pole piece **40"** by an angle ϕ. Preferably ϕ is a multiple of 15 degrees. A disc **54** containing an embedded target **52** is located in the gap **48** between the pole pieces.

Transducer **100** uses a single primary coil **60** and a single target **52**. However, it provides two sets of output voltages, one from pole piece **40'** and one from pole piece **40"**. The pole pieces **40'** and **40"** each yield a separate output signal (or set of output signals). The two output signals (or sets of output signals) may be used independently and/or used in combination to increase the accuracy of transducer **100** or to resolve any ambiguity as to the angle of shaft **21** that may be present in one of the sets of output signals.

In transducer **100**, pole pieces **40'** and **40"** may each have 2, 4, 6, or more sectors. It is not necessary for both of pole pieces **40'** and **40"** to have the same number of sectors. Target **52** may be semi-annular, as shown in Figure 2, crescent-shaped, or some other shape.

Figure 12 shows a transducer **200** according to a further alternative embodiment of the invention for simultaneously measuring the angles of rotation of two shafts **21A** and **21B** which are coaxial along an axis **23**. Transducer **200** has two pole pieces **40'** and **40"**; two targets **52'** and **52"** respectively adjacent pole pieces **40'** and **40"**; and a central member **90** of a highly magnetically permeable material. Targets **52"** and **52'** are respectively connected to shafts **21A** and **21B**. Transducer **200** is essentially a pair of transducers **20** (as shown in Figure 1) connected back-to-back and sharing a single coil **60**.

The magnetic field generated by coil **60** passes through housing **22**, through one or more sectors of pole piece **40'**, through target **52'**, through central member **90**, through target **52"**, and through pole piece **40"** back to housing **22**. Outputs from the coils **62** in pole pieces **40'** and **40"** vary respectively with the angle of rotation of shafts **21A** and **21B** about axis **23** as described above. Central member **90** is symmetrical with respect to axes **23** and is highly magnetically permeable so that the output derived from pole piece **40'** is independent of the output derived from pole piece **40"** and vice versa.

In transducer **200**, pole pieces **40'** and **40"** may each have 2, 4, 6, or more sectors. It is not necessary for both of pole pieces **40'** and **40"** to have the same number of sectors. Targets **52'** and **52"** may be semi-annular, as shown in Figure 2, crescent-shaped, or some other shape.

As will be apparent to those skilled in the art in the light of the foregoing disclosure, many alterations and modifications are possible in the practice of this invention without departing from the spirit or scope thereof. Accordingly, the scope of the invention is to be construed in accordance with the substance defined by the following claims.

WHAT IS CLAIMED IS:

1. A transducer for measuring the angular displacement of a part, the transducer comprising:
   (a) an annular first pole piece (40) comprising a material having a high magnetic permeability and centered on an axis(23), the first pole piece (40) comprising an annular cap portion (46) comprising a plurality of separated sectors (46A, 46B) and a plurality of cores (50A, 50B), each one of said sectors (46A, 46B) connected to a corresponding one of said cores (50A, 50B);
   (b) an annular second pole piece (44) comprising a material having a high magnetic permeability spaced apart from the first pole piece by a gap (48);
   (c) a primary coil (60) extending around said axis (23) for generating an alternating magnetic field having field lines extending through said first and second pole pieces (40, 44) and said gap (48);
   (d) a target (52) between said first and second pole pieces (40, 44) in said gap (48), the target (52) mounted for rotation about said axis (23) and comprising a material having a high magnetic permeability; and,
   (e) a secondary winding (62A, 62B) around each of said cores (50A, 50B).

2. The transducer of claim 1 wherein said target (52) is semi-annular.

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3. The transducer of claim 2 wherein said first pole piece (40) comprises two substantially identical semi-annular sectors (46A 46B), each sector extending through an arc of approximately 180 degrees relative to said axis (23) as measured in a plane perpendicular to said axis (23).

4. The transducer of claim 2 wherein said first pole piece (40) comprises four substantially identical sectors (46A, 46B, 46C, 46D), each sector extending through an arc of approximately 90 degrees relative to said axis (23) as measured in a plane perpendicular to said axis (23).

5. The transducer of claim 2 wherein the first pole piece (40) comprises an annular cap portion (46) having 6 symmetrical sectors (46A, 46B, 46C, 46D, 46E, 46F).

6. The transducer of claim 2 wherein the first pole piece (40) comprises an annular cap portion (46) comprising a plurality of pairs of opposed symmetrical sectors (46A, 46B, 46C, 46D).

7. The transducer of claim 1 wherein said target (52) is crescent shaped and said target (52) extends through an angle of about 180 degrees relative to said axis (23)as measured in a plane perpendicular to said axis (23).

8. The transducer of claim 7 wherein said first pole piece (40) comprises two substantially identical semi-annular sectors (46A, 46B), each sector (46A, 46B) extending through an arc of

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approximately 180 degrees relative to said axis (23)as measured in a plane perpendicular to said axis (23).

9. The transducer of claim 7 wherein said first pole piece (40) comprises four substantially identical sectors (46A, 46B, 46C, 46D), each sector (46A, 46B, 46C, 46D) extending through an arc of approximately 90 degrees relative to said axis (23)as measured in a plane perpendicular to said axis (23).

10. The transducer of claim 7 wherein the first pole piece (40) comprises an annular cap portion (46) having 6 symmetrical sectors (46A, 46B, 46C, 46D, 46E, 46F).

11. The transducer of claim 7 wherein the first pole piece (40) comprises an annular cap portion (46) comprising a plurality of pairs of opposed symmetrical sectors (46A, 46B, 46C, 46D, 46E, 46F).

12. The transducer of claim 1 wherein said target (52) is embedded in a disc (54) of material, the material having a low magnetic permeability.

13. The transducer of claim 12 wherein said disc (54) of material comprises a flange projecting from a hub.

14. The transducer of claim 1 wherein said target (52) comprises a permalloy material.

15. The transducer of claim 1 wherein the first pole piece (40) comprises 2 semi-annular sectors (46A, 46B).

16. The transducer of claim 1 wherein the first pole piece (40) comprises 6 symmetrical sectors (46A, 46B, 46C, 46D, 46E, 46F).

17. The transducer of claim 1 wherein the first pole piece (40) comprises a plurality of pairs of opposed symmetrical sectors (46A, 46B, 46C, 46D, 46E, 46F).

18. The transducer of claim 1 wherein said second pole piece (40'') comprises an annular cap portion comprising a plurality of separated sectors and a core (50) connected to each of said sectors wherein boundaries of said sectors of said second pole piece (40'') lie in a plane parallel to a plane of said first pole piece (40') and are offset through an offset angle about said axis (23) relative to boundaries of said sectors on said first pole piece.

19. The transducer of claim 18 wherein each of the first and second pole pieces (40', 40'') comprise two semi-annular sectors.

20. The transducer of claim 18 wherein said offset angle is a multiple of 15 degrees.

21. The transducer of claim 1 wherein a flux density over an entire surface of said target (52) adjacent said first pole piece (40) is substantially uniform.

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22. The transducer of claim 1 wherein surfaces of said first and second pole pieces (40, 44) facing said gap are planar.

23. A transducer (20) for measuring the angular displacement of a target (52) about an axis (23), the transducer (20) comprising:
    (a) a housing (22) having first and second annular end faces (28, 30) centered on an axis (23) and a cylindrical side face (26) all comprising a highly magnetically permeable material;
    (b) a primary coil (60) in said housing (22) extending circumferentially to said first end face (28) its length parallel and adjacent to said side face (26);
    (c) a first pole piece (40) in said housing (22), the first pole piece (40) comprising a planar annular cap (46) centered on the axis (23) and comprising one or more pairs of opposed sectors (46A, 46B), each sector (46A, 46B) connected to one of said end faces (28, 30) by one of a plurality of cores (50), the cap (46) and each core (50) comprising a highly magnetically permeable material;
    (d) an annular second pole piece (44) in said housing (22) connected to another one of the end faces (28,30) and spaced apart from said first pole piece by a gap (48), the second pole piece (44) comprising a highly magnetically permeable material;
    (e) a secondary winding (62) around each of said cores (50);
    (f) a target (52) comprising a semi-annular pad of highly magnetically permeable material mounted for rotation about said axis (23) in said gap (48), said target (52) having

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a thickness (W_2) nearly equal to a width (W_1) of said gap (48); and,

(g) an oscillator (70) connected to said primary coil so as to cause said primary coil (60) to generate an alternating magnetic field in said housing (22), the alternating magnetic field passing through said first pole piece (40), said target (52) and said second pole piece (44);

wherein said windings (62) are disposed so that the magnetic field induces alternating voltages in said secondary windings (62), the magnitude of the alternating voltage in each secondary winding (62) varying with the degree of overlap between the target (52) and the sector (46A, 46B) associated with that secondary winding (62).

24. A transducer (200) for measuring the angular displacement of first and second shafts (21A, 21B), the transducer (200) comprising:

(a) annular first and second pole pieces (40', 40''), each of the pole pieces having an annular cap portion comprising a plurality of separated sectors each of high magnetic permeability and a plurality of cores (50) having a high magnetic permeability, each of said sectors connected to a corresponding one of said cores (50);

(b) a magnetically permeable member (90) between the first and second pole pieces and separated from the first and second pole pieces (40', 40'') by first and second gaps;

(c) a primary coil (60) extending around said axis (23) for generating an alternating magnetic field having field lines second pole pieces, the magnetically permeable member (90) and the first and second gaps;

(d) a first target (52') connected for rotation with a first shaft (21B), the first target (52') located in the first gap the first target (52')mounted for rotation about an axis (23) of the first pole piece (40'') and comprising a material having a high magnetic permeability;

(e) a second target (52'') connected for rotation with a second shaft (21A), the second target (52'') located in the second gap the second target (52'') mounted for rotation about an axis (23) of the second pole piece (40') and comprising a material having a high magnetic permeability;

(f) a highly magnetically permeable path extending between said cores of said first pole piece and said cores of said second pole piece; and,

(g) a secondary winding (62) around each of said cores (50) of said first and second pole pieces (40', 40'').

25. A method for measuring the angular displacement of a part around an axis, the method comprising the steps of:

(a) generating a fluctuating magnetic field;

(b) causing the fluctuating magnetic field to extend through a pair of annular pole pieces (40,44) and a gap (48) between the pole pieces (40, 44), a first one of the pole pieces (40) comprising a two or more sectors (46A, 46B), each sector comprising a core (50) passing through a secondary winding (62);

(c) moving a highly magnetically permeable target (52) within the gap (48) to direct substantially all of the magnetic field lines passing through the gap (48) into the portions of the first and second pole pieces (40, 44)adjacent the target (52); and,

(d) measuring the difference (V_{out}) in the magnitudes of voltages induced in pairs of the secondary windings (62).

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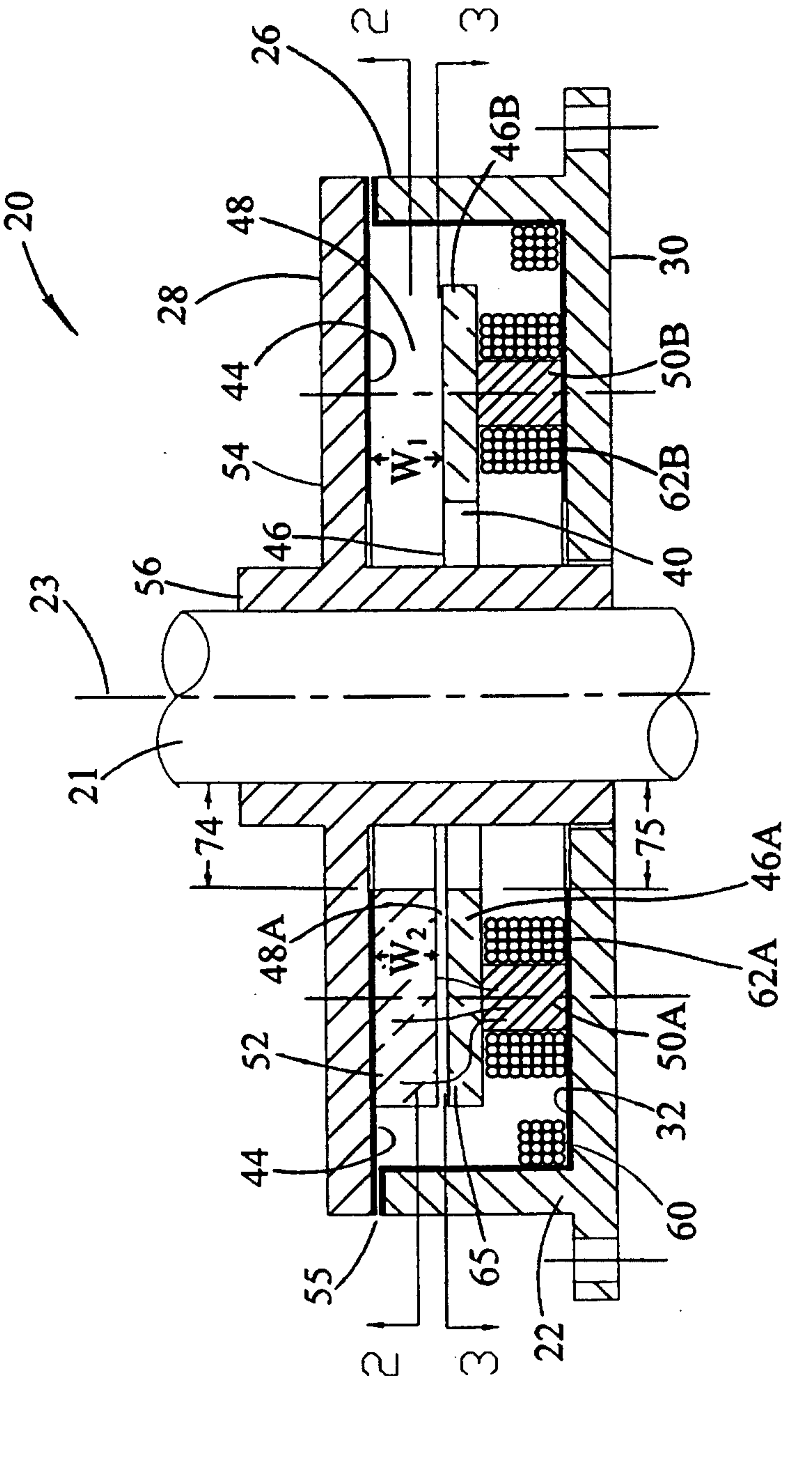
20
26
2
3
46B
48
28
30
44
50B
54
W_1
62B
46
40
56
23
21
74
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46A
48A
W_2
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32
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55
65
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2
3

FIG 1

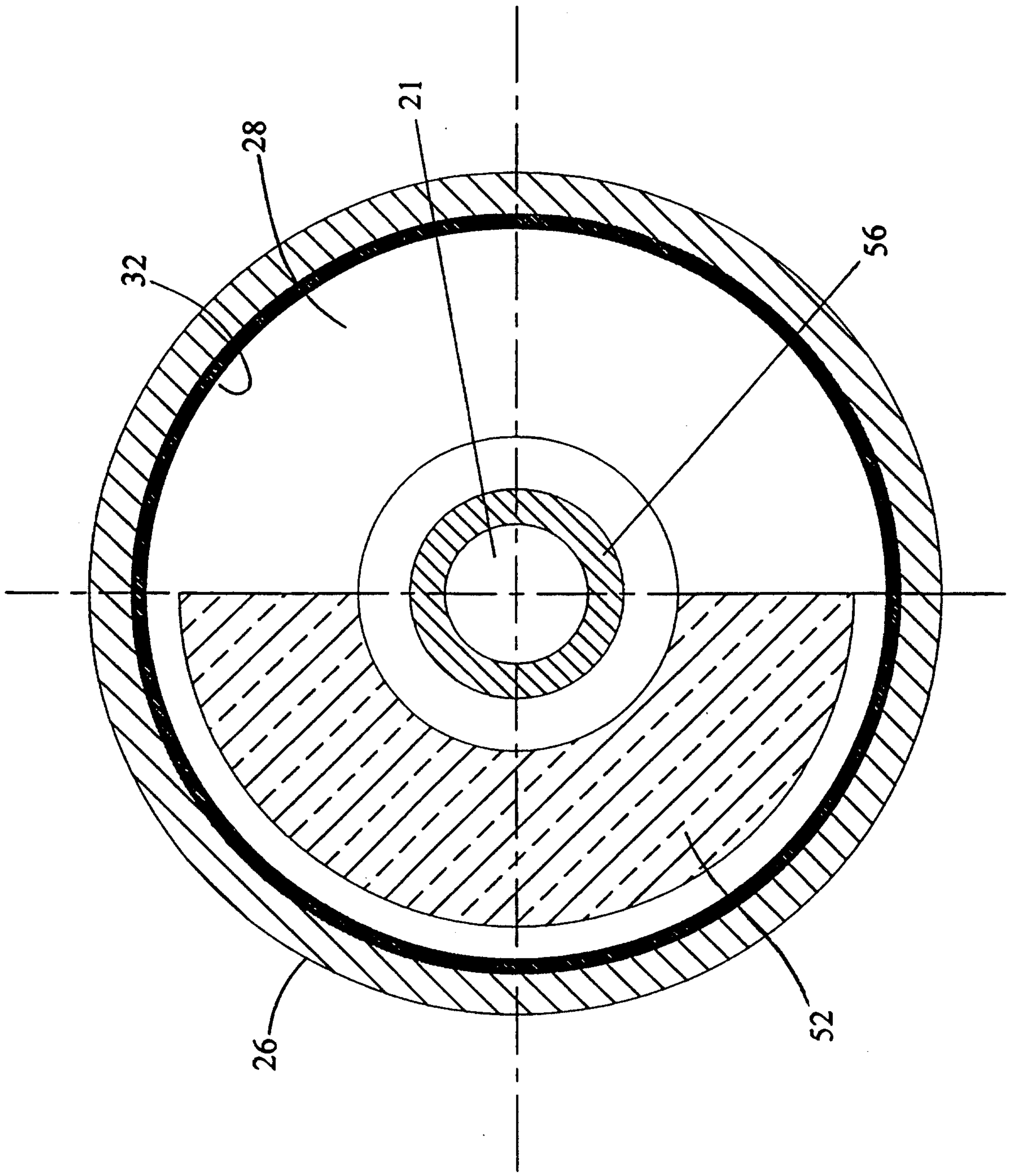


FIG 2

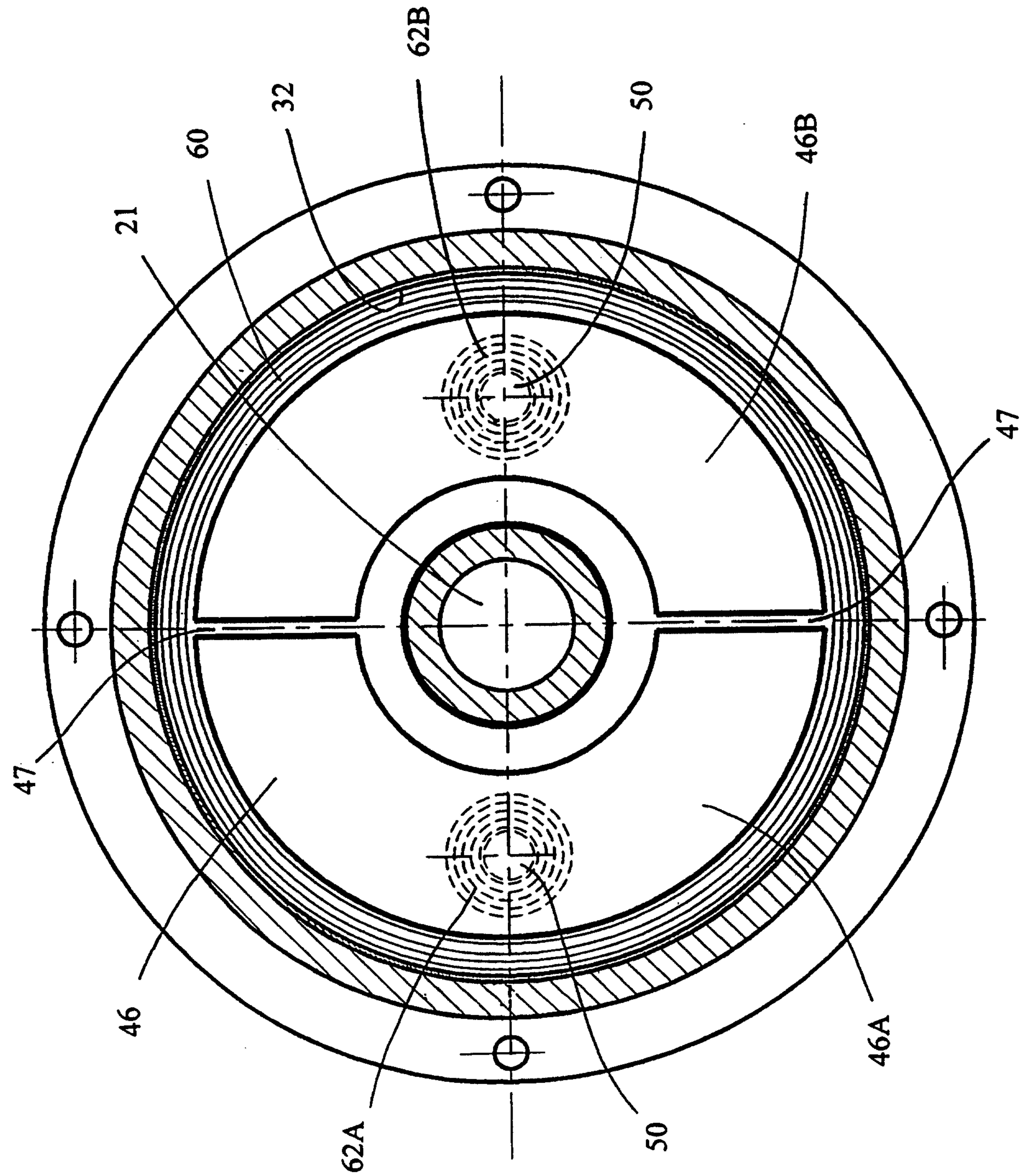


FIG 3

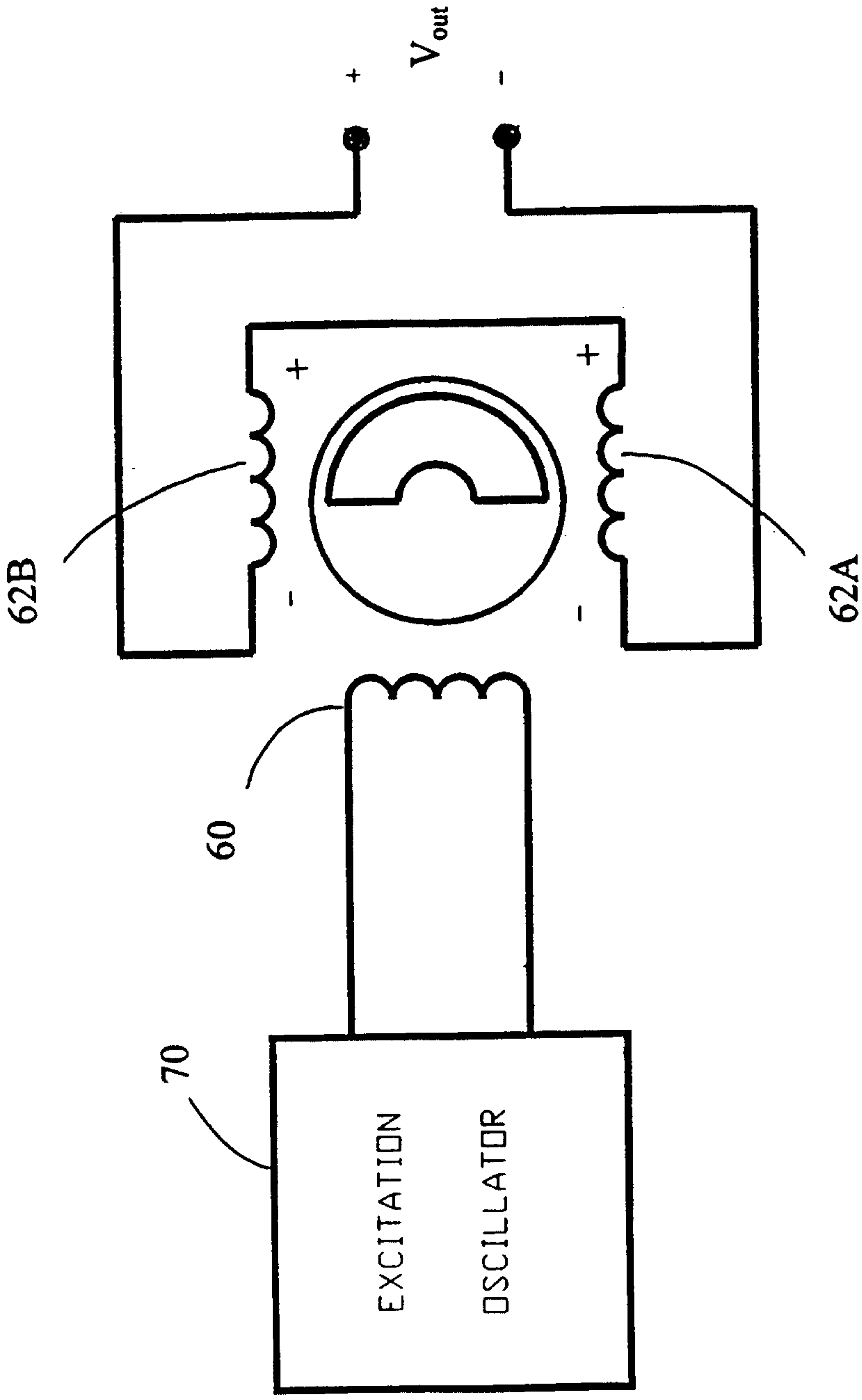


FIG 4

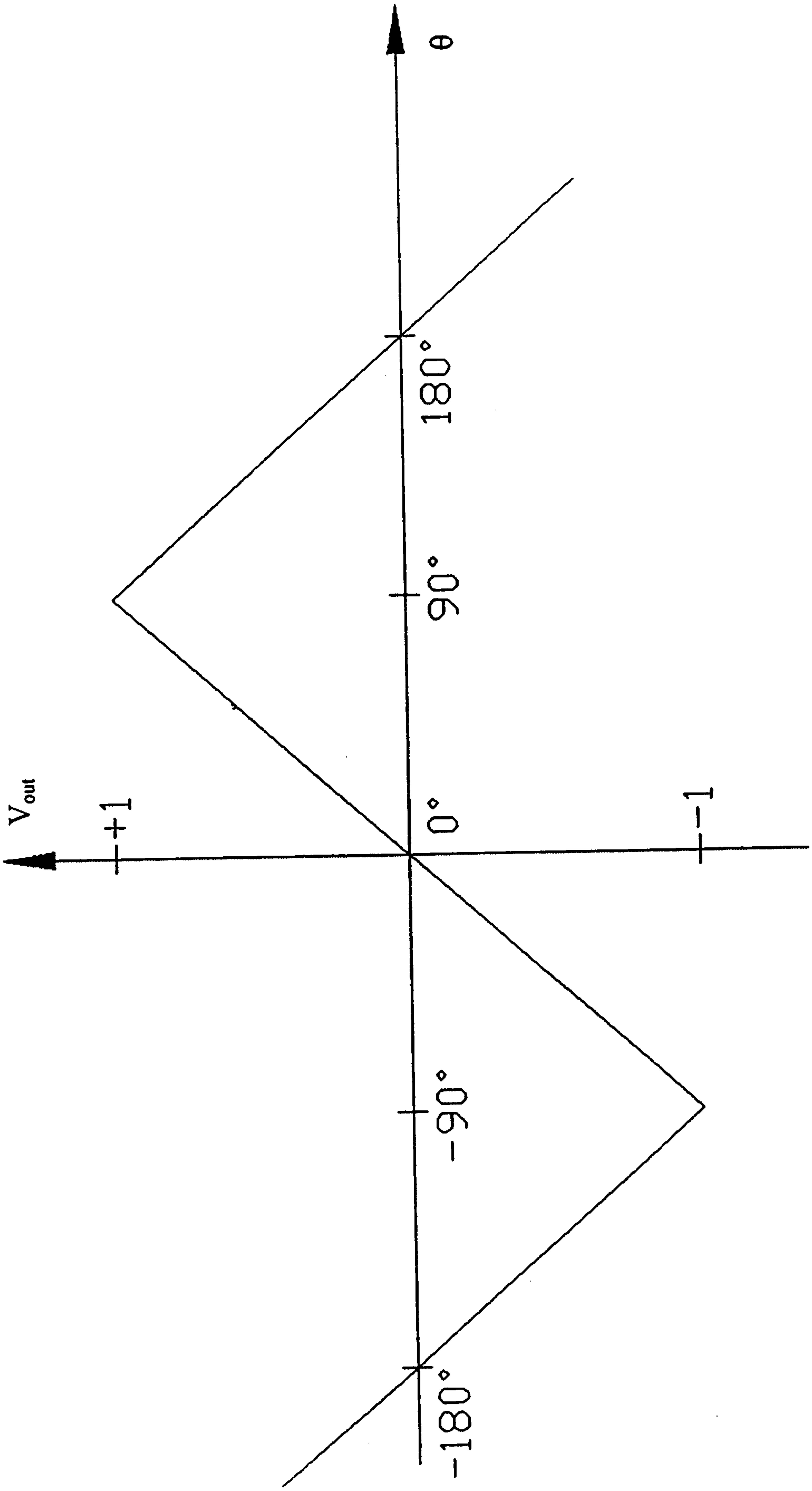
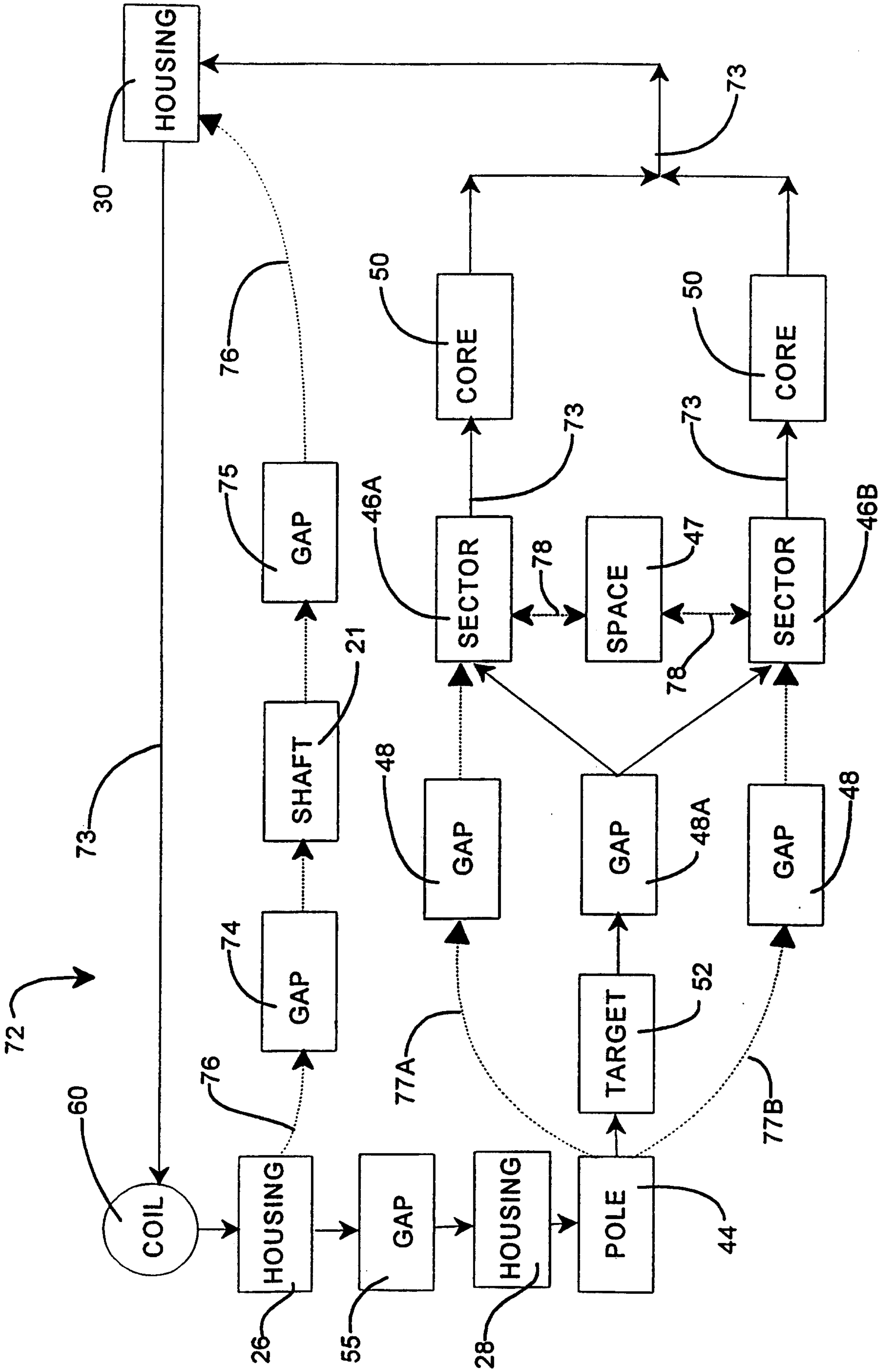


FIG 5


HOUSING
30
73
50
CORE
50
CORE
76
75
GAP
73
73
46A
SECTOR
78
SPACE
47
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78
21
SHAFT
73
48
GAP
GAP
48A
GAP
48
74
GAP
72
77A
TARGET
52
77B
60
76
COIL
HOUSING
GAP
HOUSING
POLE
44
26
55
28

FIG 6

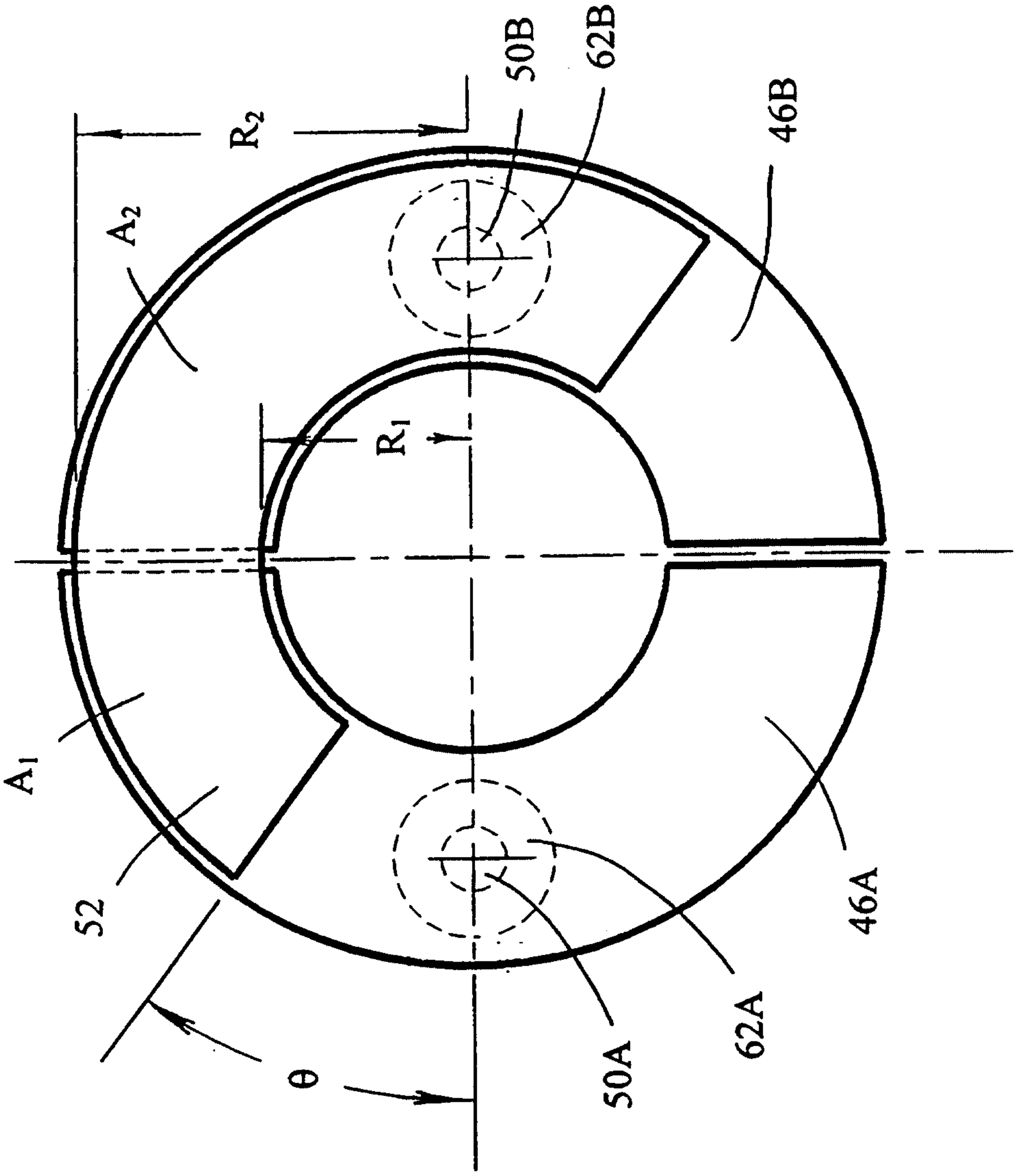


FIG 7A

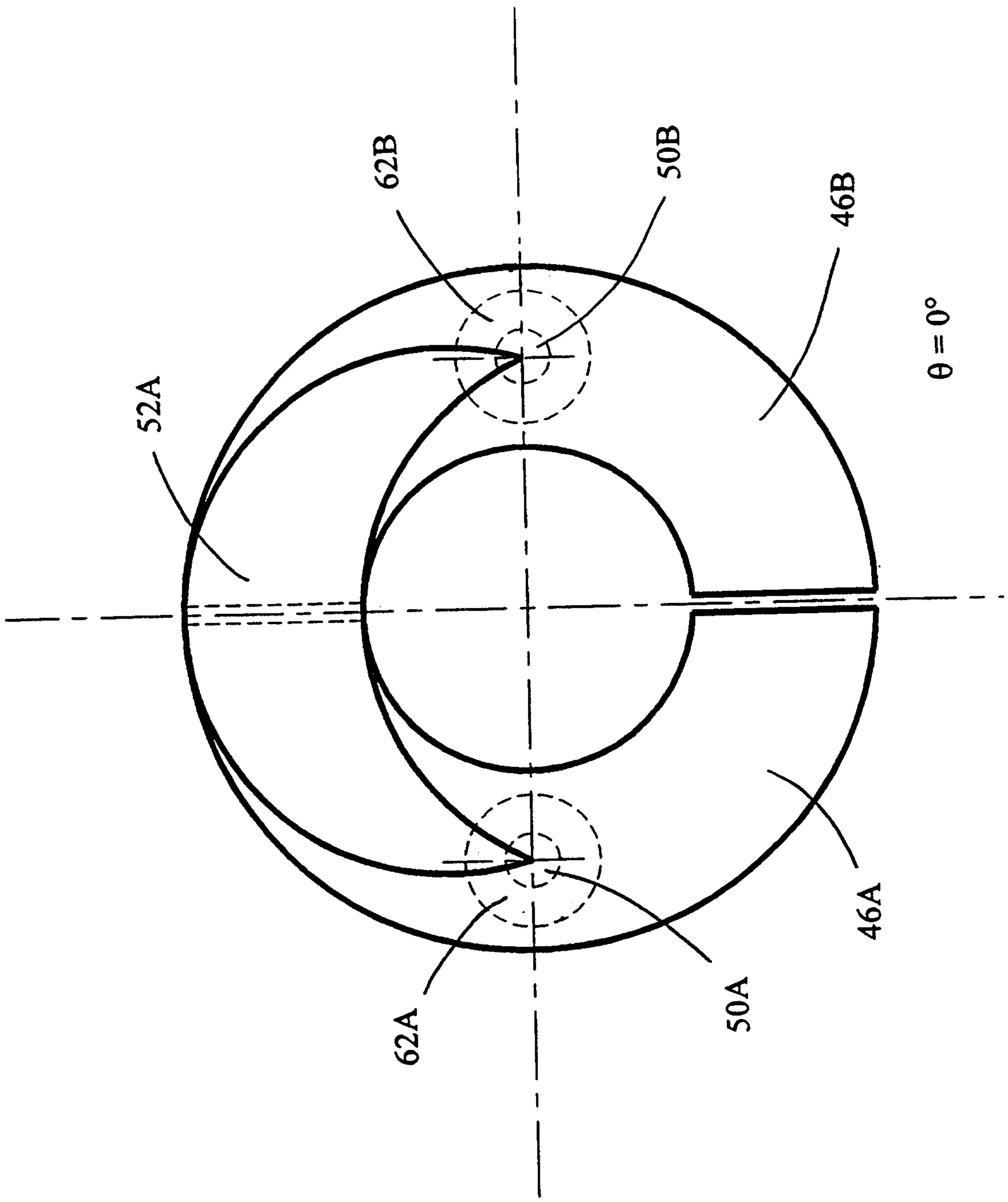


FIG 7B

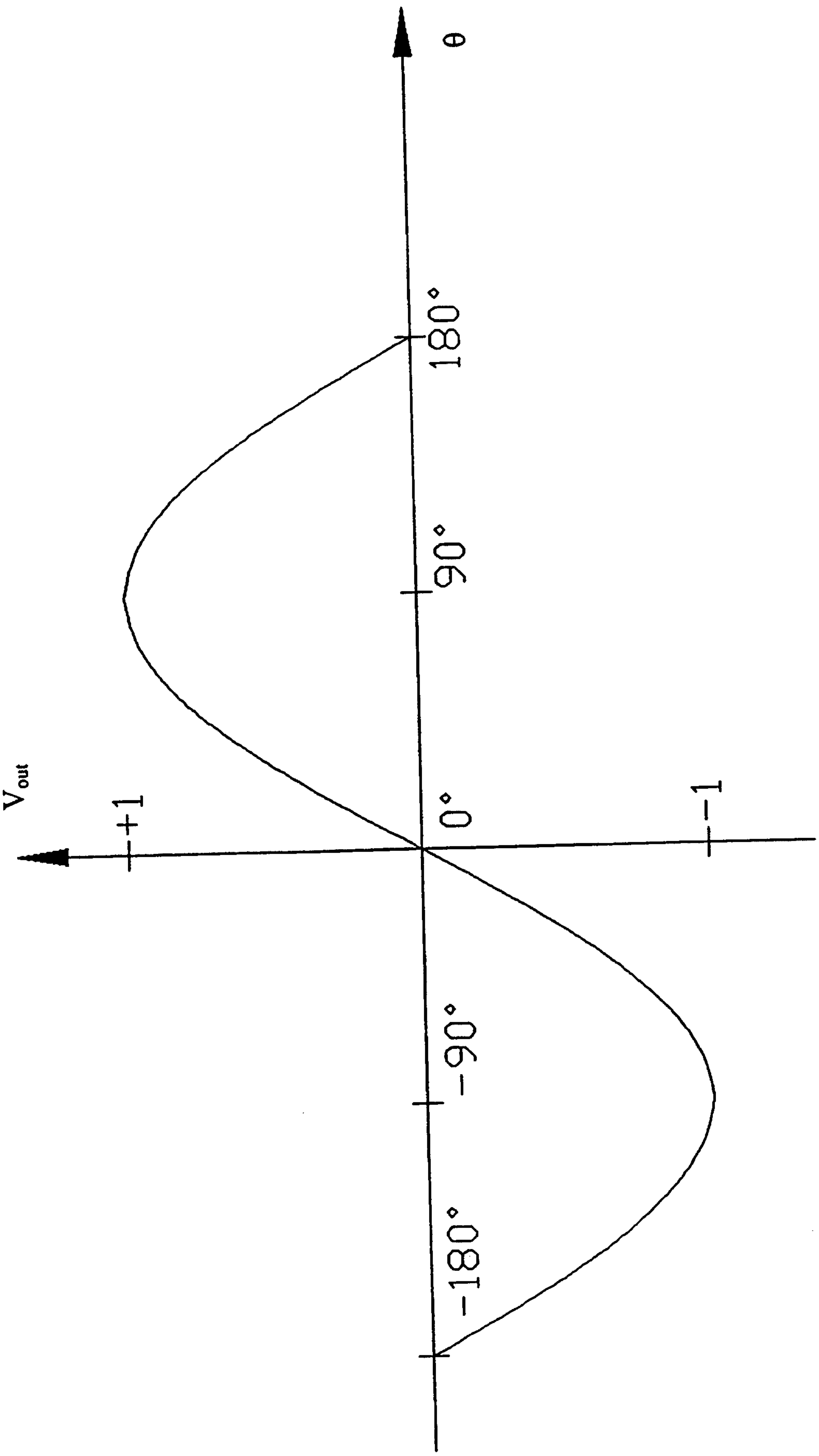


FIG 8

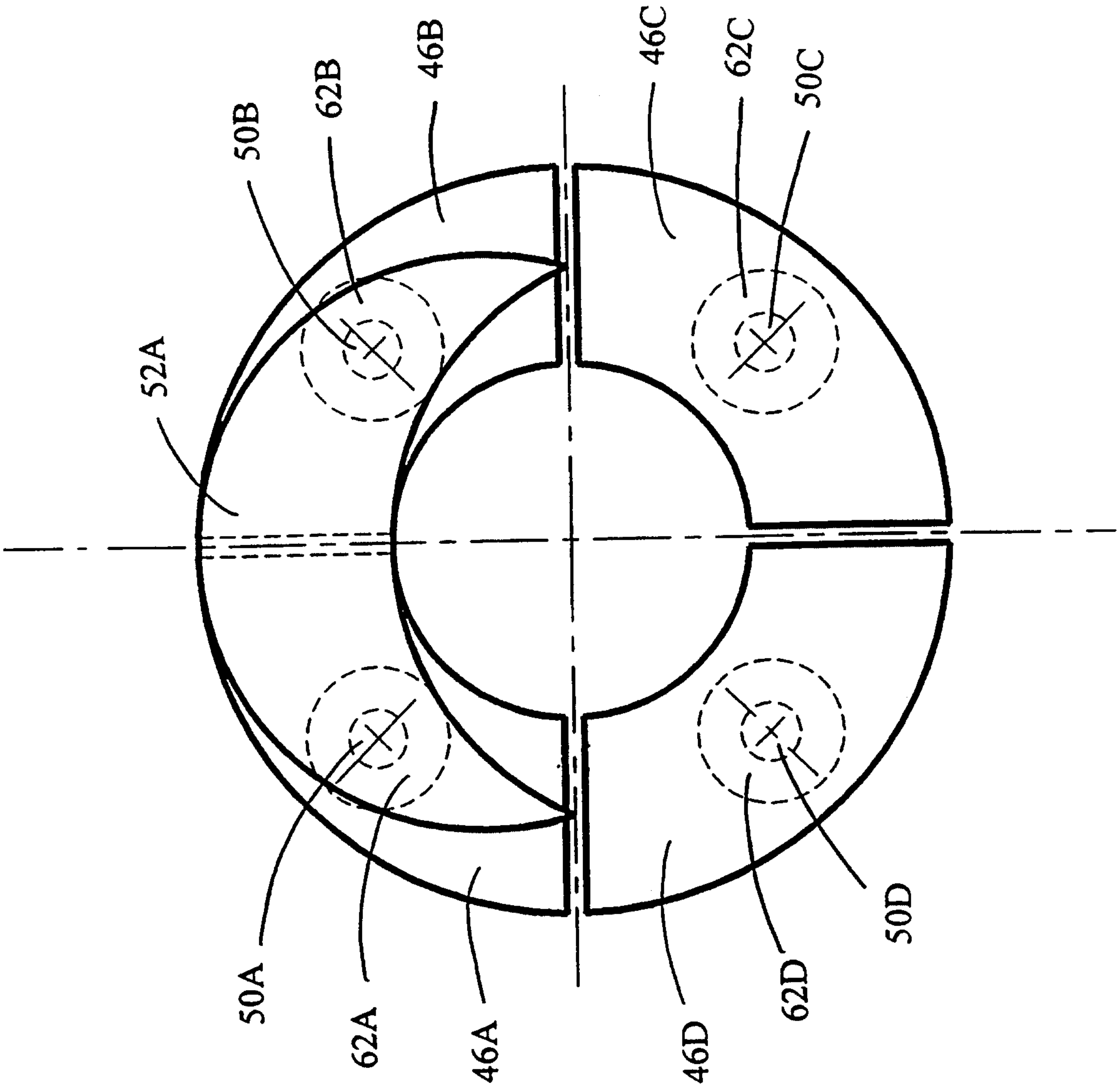
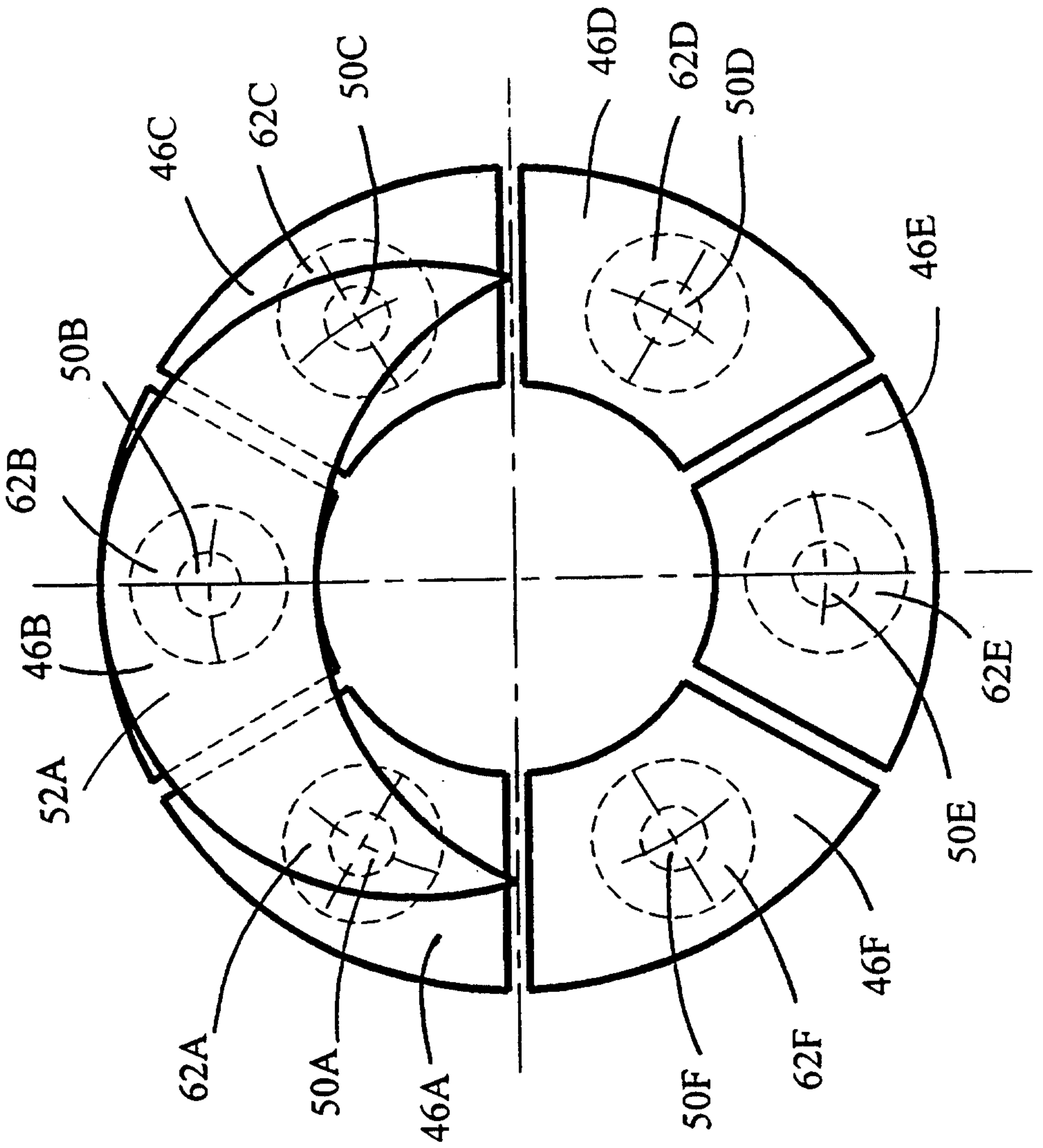


FIG 9A


46D
62D
50D
50C
62C
46C
46E
50B
62B
46B
52A
62E
50E
62A
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46A
50F
62F
46F

FIG 9B

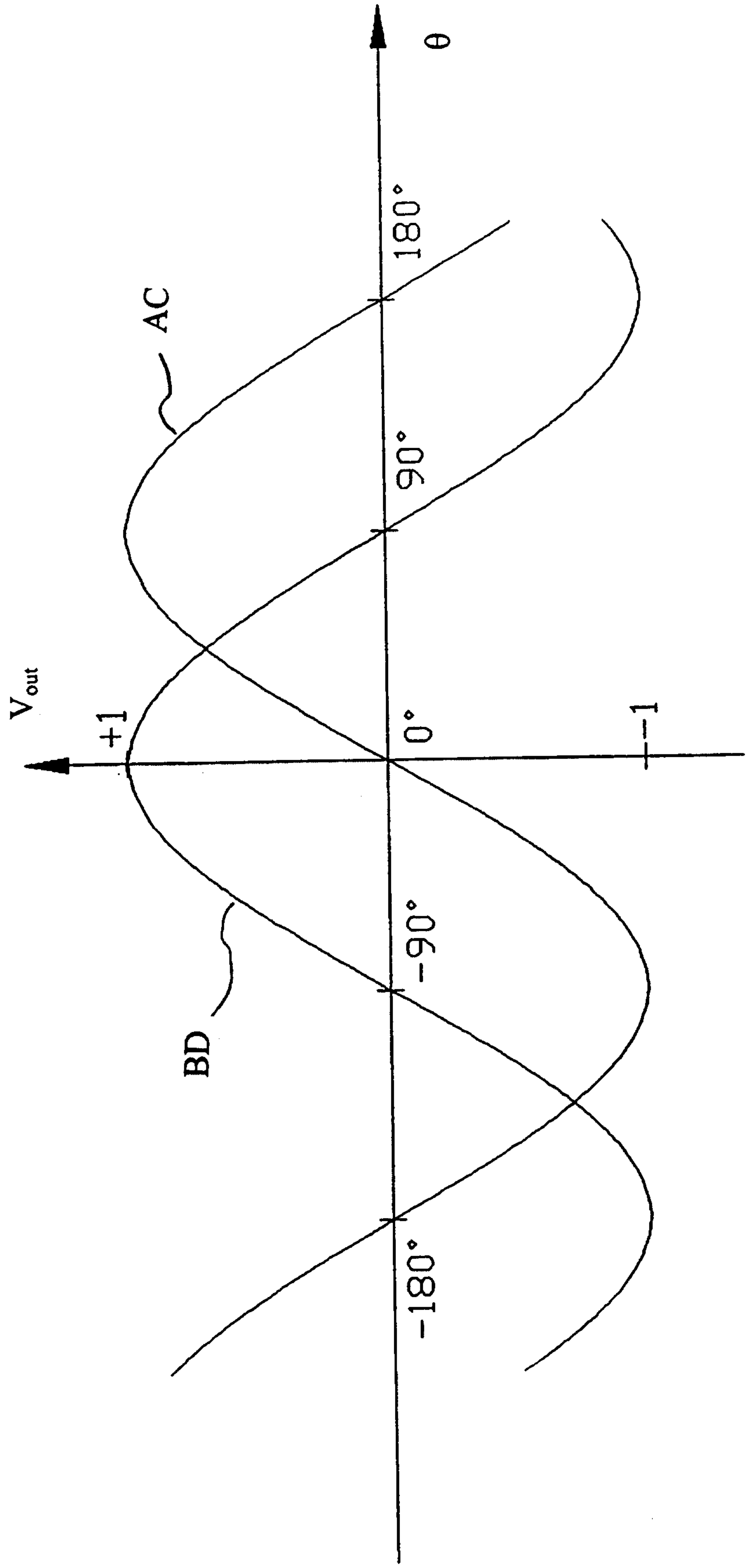

FIG 10A

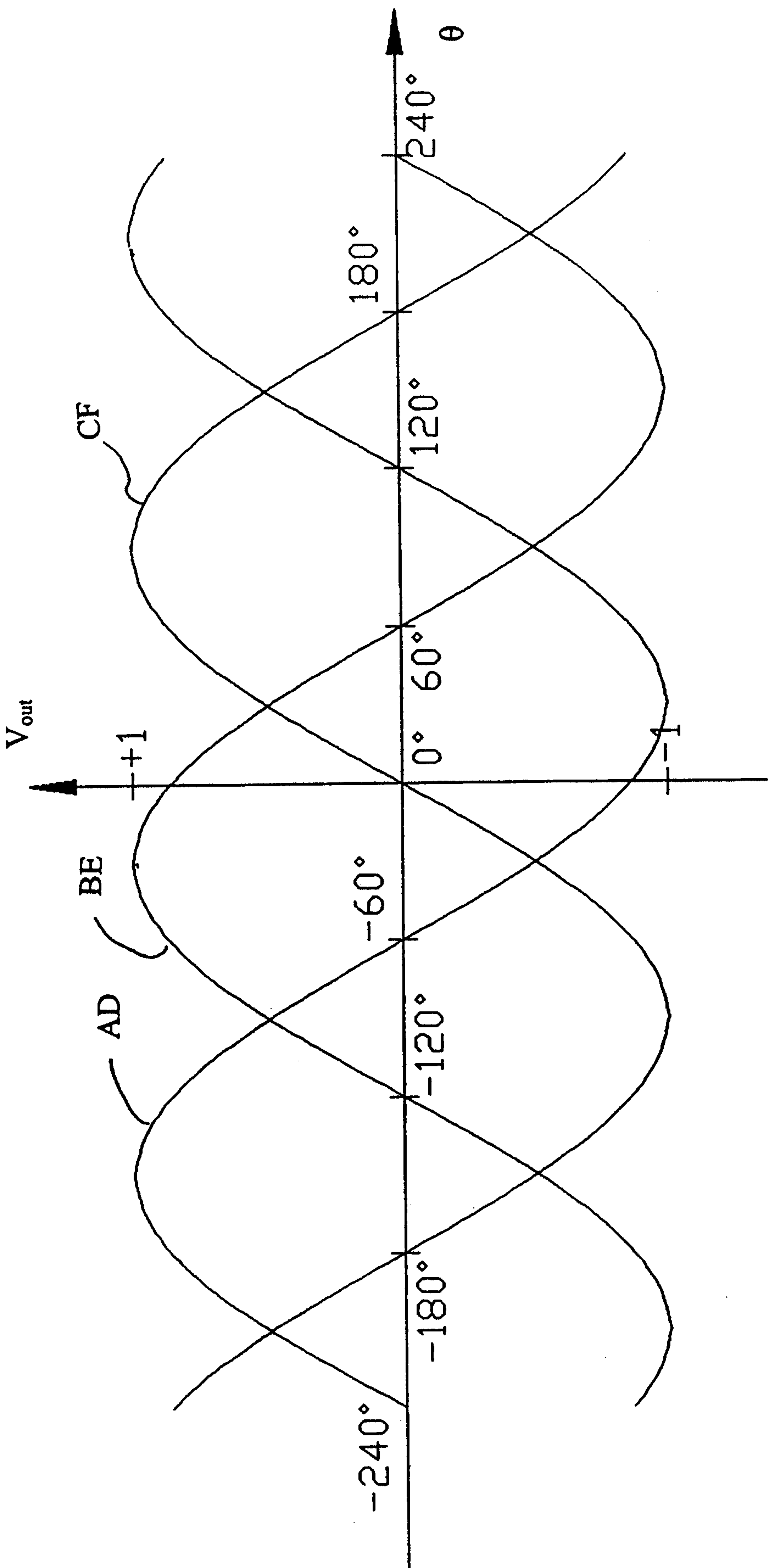

FIG 10B

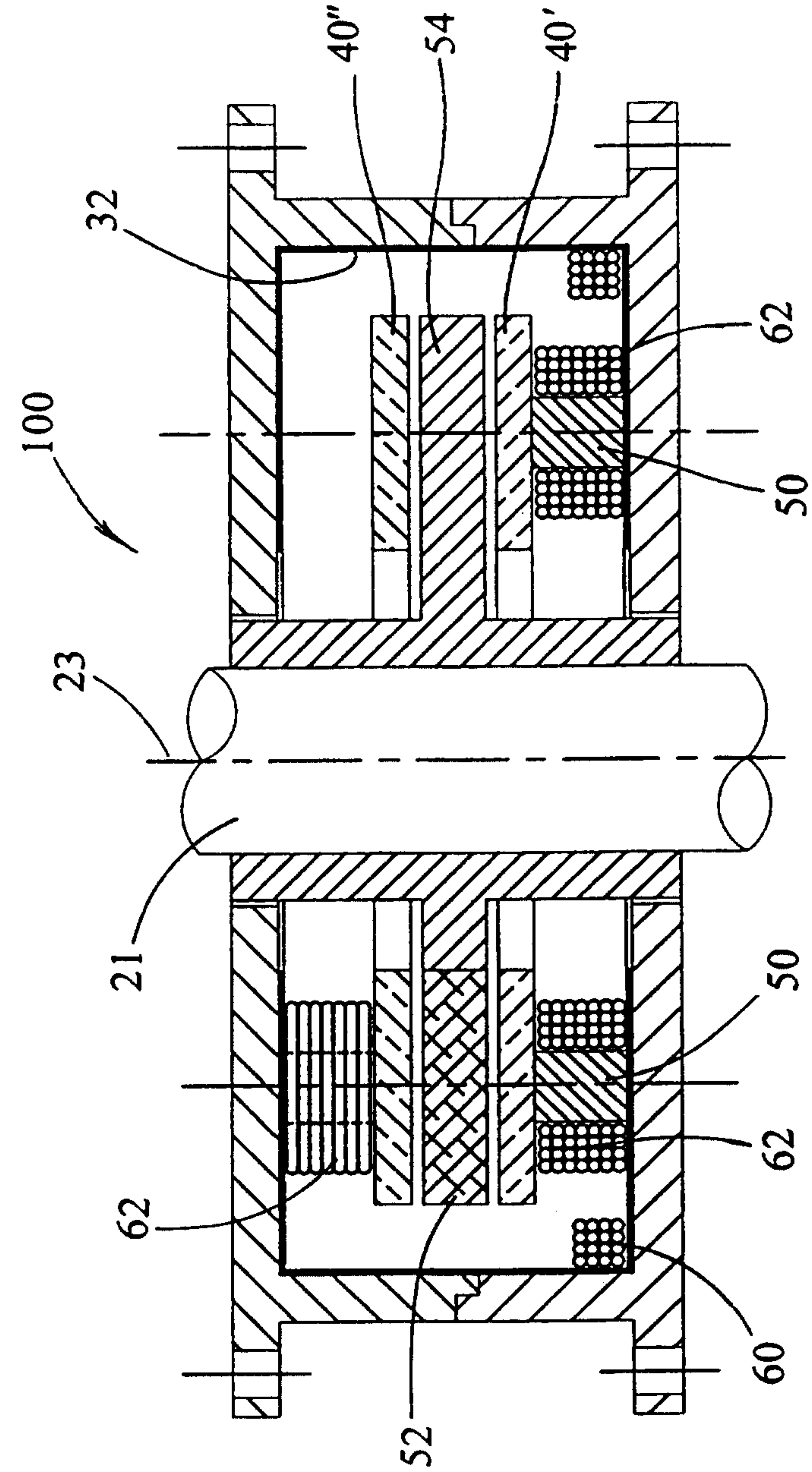

FIG 11

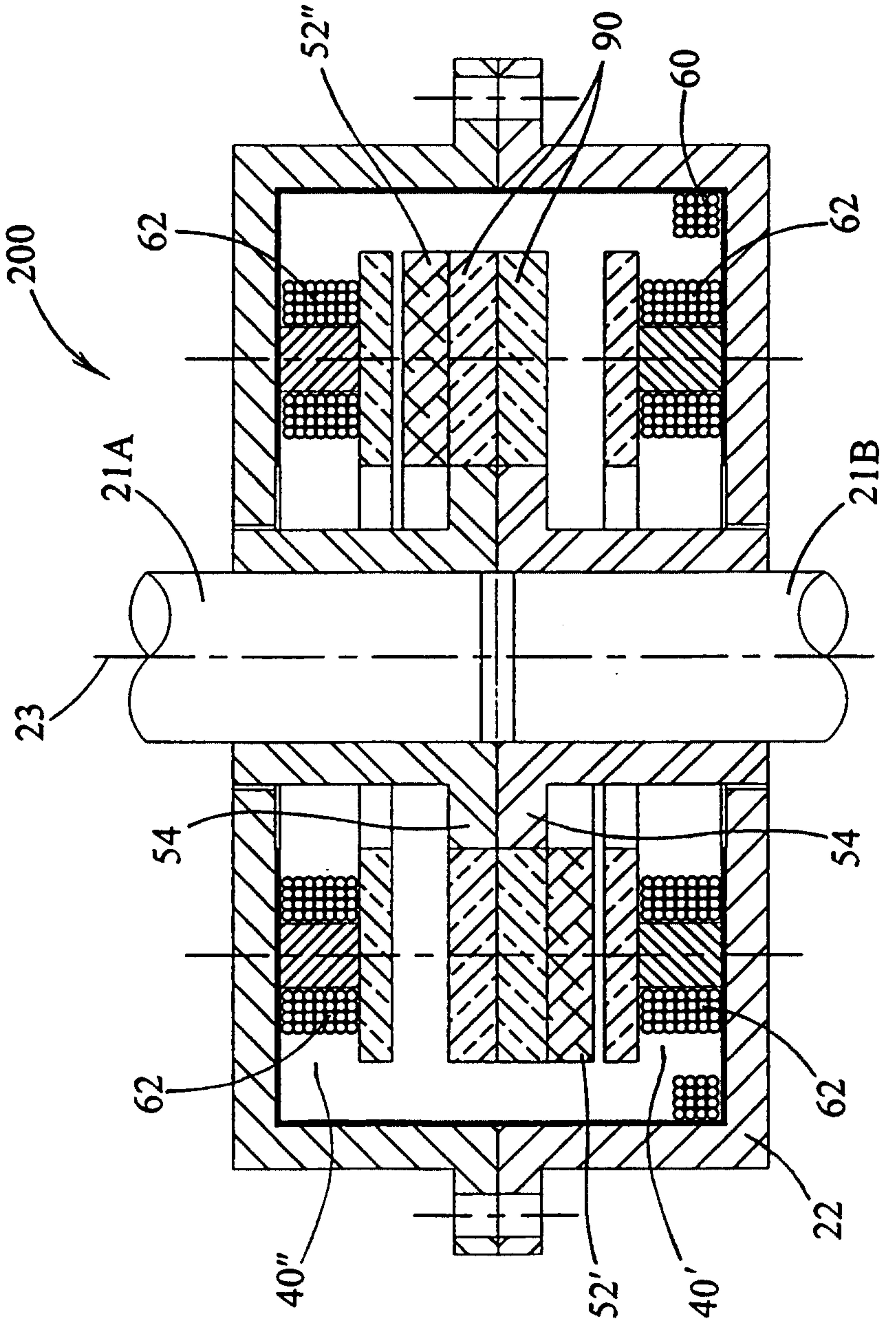

FIG 12