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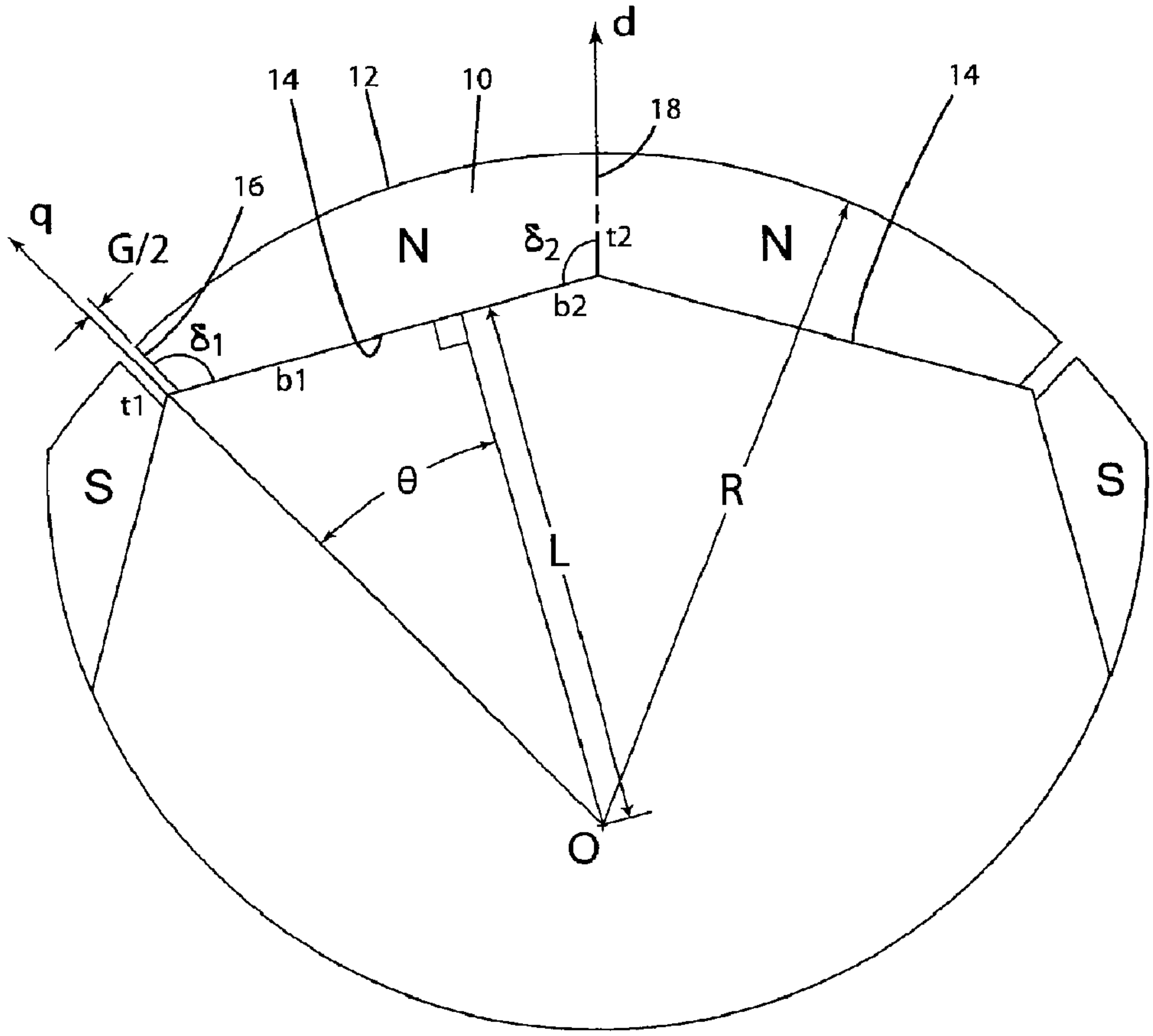
(54) Titre : FORMAGE D'AIMANTS DANS UNE MACHINE SYNCHRONE A AIMANTS PERMANENTS
(54) Title: MAGNET SHAPING IN PERMANENT MAGNET SYNCHRONOUS MACHINES




(57) Abrégé/Abstract:
A permanent magnet synchronous machine comprises a stator, a rotor and a plurality of permanent magnets mounted to the rotor. Each magnet has a shaped body characterized by an arcuate radially outer surface, a flat inner surface, a first side surface facing

(57) **Abrégé(suite)/Abstract(continued):**
an opposite pole, and a second side surface facing a like pole, wherein the first side surface and the flat inner surface subtend an angle $\delta_1$ that is greater than 90 degrees and wherein the second side surface and the flat inner surface subtend an angle $\delta_2$ that is also greater than 90 degrees. The permanent magnet synchronous machine may be used in a flywheel energy storage system or in other electromechanical systems.

## ABSTRACT

A permanent magnet synchronous machine comprises a stator, a rotor and a plurality of permanent magnets mounted to the rotor. Each magnet has a shaped body characterized by an arcuate radially outer surface, a flat inner surface, a first side surface facing an opposite pole, and a second side surface facing a like pole, wherein the first side surface and the flat inner surface subtend an angle $\delta_1$ that is greater than 90 degrees and wherein the second side surface and the flat inner surface subtend an angle $\delta_2$ that is also greater than 90 degrees. The permanent magnet synchronous machine may be used in a flywheel energy storage system or in other electromechanical systems.

# MAGNET SHAPING IN PERMANENT MAGNET SYNCHRONOUS MACHINES

## TECHNICAL FIELD

**[0001]** The present invention generally relates to a permanent magnet motor/generator and, more particularly, to shaping magnets in permanent magnet synchronous alternating current (AC) machines.

## BACKGROUND

**[0002]** Electric machines may be classified as direct current (DC) or alternating current (AC), the latter being categorized as either synchronous or induction. Synchronous AC electric machines may be further classified as brushless, sine wave, step, hysteresis and reluctance. In the sine wave category are those that use permanent magnets and those that use wound fields. The permanent magnets of permanent magnet synchronous AC machines are either surface-mounted, inset-mounted or interior-mounted.

**[0003]** Permanent magnet synchronous AC electric machines may be used for motors, generators and motor/generators. One particular application is a flywheel energy storage system.

**[0004]** In a flywheel energy storage system, it is often desirable to operate an electric machine at high rotational speeds in a vacuum environment. Frequently, a structural element is used to support the magnets in the electric machine to obtain higher speed operation. This structural element is variously called an overwrap, sleeve, bandage, or sheath and can be made of non-ferrous metallic or composite materials. It is desirable to have magnets that provide uniform loading of the sleeve. For operation in a vacuum environment, it is desirable to minimize rotor losses, since heat generated on the rotor cannot be rejected with convective means. Magnet shaping can be used to reduce heat generated in the magnets; however, magnet shaping can also provide undesired, non-uniform loading of the sleeve, and may incur significant manufacturing cost increases. Accordingly, there is a need for an electric machine that provides low rotor losses and good structural integrity without incurring excessive manufacturing costs.

**SUMMARY**

**[0005]** In general, the present invention provides a novel permanent magnet shape for a permanent magnet synchronous machine. The permanent magnet has a shaped body that is characterized by a radially outer surface that is arcuate, a flat inner surface, and first and second side surfaces. The first and second side surface face an opposite pole and a like pole, respectively. The first side surface and the flat inner surface subtend an angle $\delta_1$ whereas the second side surface and the flat inner surface subtend an angle $\delta_2$. Each of these angles is greater than 90 degrees. This shaped magnet exhibits low rotor losses, has good structural integrity, and is also easy to manufacture.

**[0006]** Accordingly, one aspect of the present invention is a permanent magnet for use in a permanent magnet synchronous machine, the permanent magnet comprising a shaped body, the shaped body having an arcuate radially outer surface, a flat inner surface, a first side surface facing an opposite pole, and a second side surface facing a like pole. The first side surface and the flat inner surface subtend an angle $\delta_1$ that is greater than 90 degrees and the second side surface and the flat inner surface subtend an angle $\delta_2$ that is also greater than 90 degrees.

**[0007]** Another aspect of the present invention is a permanent magnet synchronous machine comprising a stator, a rotor and a plurality of permanent magnets mounted to the rotor in which each magnet has a shaped body characterized by an arcuate radially outer surface, a flat inner surface, a first side surface facing an opposite pole, and a second side surface facing a like pole. The first side surface and the flat inner surface subtend an angle $\delta_1$ that is greater than 90 degrees and the second side surface and the flat inner surface subtend an angle $\delta_2$ that is also greater than 90 degrees.

**[0008]** Yet another aspect of the present invention is a flywheel energy storage system comprising a flywheel and a permanent magnet synchronous machine having a stator, a rotor and a plurality of permanent magnets mounted to the rotor, wherein each permanent magnet includes a shaped body characterized by an arcuate radially outer surface, a flat inner surface, a first side surface facing an opposite pole, and a second side surface facing a like pole. The first side surface and the flat inner surface subtend an angle $\delta_1$ that is greater than 90 degrees and the second side surface and the flat inner surface subtend an angle $\delta_2$ that is also greater than 90 degrees.

**[0009]** A further aspect of the present invention is a permanent magnet for use in a permanent magnet synchronous machine that includes two shaped magnet halves formed as an integral structure. This permanent magnet comprises a shaped body formed of two magnet halves or portions. The shaped body has an arcuate radially outer surface and an inner surface composed of two flat angled sections for each of the two magnet halves or portions.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0010]** Further features and advantages of the present technology will become apparent from the following detailed description, taken in combination with the appended drawings, in which:

**[0011]** FIG. 1 is a plan view of a permanent magnet for use in a four-pole magnet array in accordance with an embodiment of the present invention;

**[0012]** FIG. 2 is a plan view of a four-pole magnet array comprising eight magnets of the type depicted by way of example in FIG. 1;

**[0013]** FIG. 3 is a plan view of a six-pole magnet array comprising twelve magnets in accordance with another embodiment of the present invention;

**[0014]** FIG. 4 is a plan view of an eight-pole magnet array comprising sixteen magnets in accordance with another embodiment of the present invention;

**[0015]** FIG. 5 is a schematic depiction of a permanent magnet synchronous machine having permanent magnets in accordance with embodiments of the present invention; and

**[0016]** FIG. 6 is a schematic depiction of a flywheel energy storage system incorporating having shaped permanent magnets in accordance with embodiments of the present invention.

**[0017]** It will be noted that, throughout the appended drawings, like features are identified by like reference numerals.

## DETAILED DESCRIPTION

**[0018]** In general, the present invention is an electric machine comprising a permanent magnet having a novel shape that exhibits superior performance characteristics in terms of low rotor losses and good structural integrity while being easy to manufacture.

**[0019]** FIG. 1 illustrates an example of a shaped magnet generally designated by reference numeral 10 for use in a four-pole magnet array in an electric machine. This shaped magnet 10 is defined geometrically by an origin (O), a radius (R), a gap (G), a base length (L) and an angle (θ).

**[0020]** As illustrated in FIG. 1, the magnet 10 is characterized by an arcuate radially outer surface 12 (which may be of a constant radius R) as defined from the origin O. As depicted in FIG. 1, the radially inwardly facing surface comprises a flat inner surface 14 defining a base of the magnet. A centerline of base length L (which line is defined as being a line extending orthogonally from the origin O to the flat inner surface) divides the flat inner surface 14 (i.e. the base of the magnet) into first and second sections of length $b_1$ and $b_2$, respectively.

**[0021]** As illustrated in FIG. 1, the shape of the magnet body 10 is characterized further by a first side surface 16 facing an opposite pole (N-S, S-N) and a second side surface 18 facing a like pole (N-N, S-S). In the embodiment illustrated in FIG. 1, the magnet 10 is a North magnet. The first side surface 16 thus faces a South magnet whereas the second side surface 18 faces a North magnet. In the embodiment depicted in FIG. 1, the first side surface 16 is spaced apart by a gap G from the adjacent magnet of opposite polarity whereas the second side surface abuts the adjacent magnet of like polarity.

**[0022]** In embodiments of the invention, the first side surface 16 and the flat inner surface 14 subtend an angle $\delta_1$ that is greater than 90 degrees. The second side surface 18 and the flat inner surface 14 subtend an angle $\delta_2$ that is also greater than 90 degrees.

[0023] As illustrated in FIG. 1, the angle θ subtends the orthogonal centerline of length L and the quadrature axis (denoted "q axis"). The q axis is offset from the direct axis ("d axis") by a rotation of 90 degrees magnetic.

[0024] In the embodiment depicted in FIG. 1, the magnet angles are defined as follows:

[0025] θ is the angle subtended by the q-axis and a line orthogonal to an adjacent magnet base (i.e. flat inner surface) which line also passes through the origin O of the radius R of the arcuate radially outer surface.

[0026] $\delta_1$ is the angle subtended by the base and side of a magnet where the side of the magnet faces an opposite pole (S-N, N-S).

[0027] $\delta_2$ is the angle subtended by the base and side of a magnet where the side of the magnet faces a like pole (N-N, S-S).

[0028] As noted above, a characteristic of this shaped magnet is that $\delta_1$ and $\delta_2$ are each greater than 90 degrees. In most embodiments, $\delta_1$ is not equal to $\delta_2$. In some embodiments, $\delta_1$ is greater than $\delta_2$ as illustrated by way of example in FIG. 1. In the specific example presented in FIG. 1, $\delta_1$ is 120 degrees and $\delta_2$ is 105 degrees, although it should be understood that these angles will vary depending on the exact geometry and size of the magnets and rotor.

[0029] In a case in which the base of the magnet is arcuate, then δ is the angle subtended by the side of the magnet and the tangent of the base at the intersection of the side.

[0030] The angles $\delta_1$, $\delta_2$ and θ are defined as follows:

$$\delta_1 = 90 + \frac{360}{2n} \cdot x$$

$$\delta_2 = 90 + \frac{360}{2n} \cdot (1 - x)$$

$$\theta = \frac{360}{2n} \cdot x$$

where n is the number of magnetic poles and, preferably,

$$x = \frac{2}{3}$$

**[0031]** However, x may take any value in a range of

$$\frac{5}{9} \leq x \leq \frac{7}{9}$$

**[0032]** In some 4-pole embodiments of the magnet, the mechanical angle theta θ is between 25 and 35 degrees.

**[0033]** In the embodiment depicted in FIG. 1, the base dimension $b_1$ left of the centerline L (i.e. the length of the first section) is greater than the base dimension $b_2$ right of the centerline (length of the second section). In the same illustrated embodiment, the thickness $t_1$ of the first side facing the magnet of opposite polarity is less than the thickness $t_2$ of the second side facing the magnet of similar polarity. In other words, the surface area of the first side surface is less than that of the second side surface. This geometric asymmetry is one characteristic of the magnet. However, it should be appreciated that the shaped magnet may be asymmetrical or symmetrical about the direct axis.

**[0034]** The geometric asymmetry may also be expressed in terms of a ratio of asymmetrical length to total length, i.e. $(b_1-b_2)/(b_1+b_2)$. For a four pole magnet configured as shown by way of example in FIG. 1, the ratio of asymmetrical length to total length would be approximately +35% but, in other embodiments, this could range between, for example, 0% and 75%.

**[0035]** The electric machine comprising this novel magnet shape can be operated as a motor, as a generator or as a motor/generator. One application of this electric machine is in a flywheel energy storage system although it will be understood that the electric machine may be incorporated into any other suitable electromechanical system. The electric machine may be a high-speed electric machine or in a low-speed electric machine. When these shaped magnets are incorporated into an electric machine such as a flywheel energy storage system, they provide low rotor losses and good structural integrity by virtue of uniform distribution of centrifugal loading on the sleeve without incurring excessive manufacturing costs.

**[0036]** As will be readily appreciated by those of skill in the art, the geometry of the shaped body of the magnet may be varied, i.e. the R, L, G and θ parameters may be varied to achieve different effects. Tuning of the variables R, L, G and θ will thus enable the electric machine designer to adapt the performance characteristics for specific applications or uses.

**[0037]** The two adjoining magnets of like pole may be, in one embodiment, formed or manufactured as a single integral magnet. In such an embodiment, the magnet would be defined by a common arcuate radially outer surface, two inclined flat surfaces, and a pair of side surfaces. The magnets would thus define a line (or plane) of symmetry along the d-axis. The angle $\delta_1$ would be defined as before (i.e. the angle between the first side surface and the flat inner surface). The angle $\delta_1$ would be greater than 90 degrees as shown in FIG. 1. However, the angle $\delta_2$ would, in this particular embodiment, be re-defined as the angle subtended by the flat inner surface and the line of symmetry or d-axis. As shown in FIG. 1, the magnet body may be formed of two symmetrical halves (two symmetrical portions) that are symmetrical about the plane of symmetry defined by the d-axis. The thickness $t_2$ of the magnet along the plane of symmetry is greater than the thickness $t_1$ along each of the side surfaces. In an electric machine, these magnets are arranged with alternating poles with a gap between each adjacent magnet.

**[0038]** In another embodiment, each magnet may be segmented into magnet components or subcomponents to facilitate manufacturing or assembly operations. In other words, each magnet may comprise a plurality of components or subcomponents that are joined, attached, connected or otherwise assembled to form a single consolidated magnet.

**[0039]** The present invention may be applied to 2-pole, 4-pole, 6-pole or 2n-pole magnet arrays as shown by way of various examples depicted in FIGS. 2-4. For example, in a 2-pole (1 pole pair) magnet array, θ = 60°. In other words, each angled section of each permanent magnet defines an angle θ (where θ = 60 degrees in this particular configuration) between a quadrature axis and a line that is orthogonal to one of the flat angled sections and that intersects the origin O of the radius of curvature of the arcuate radially outer surface.

**[0040]** FIG. 2 is a plan view of a four-pole magnet array comprising eight magnets of the type depicted by way of example in FIG. 1. In the 4-pole (2-pole pair) magnet array depicted in FIG. 2, θ = 30°.

**[0041]** FIG. 3 is a plan view of a six-pole magnet array comprising twelve magnets in accordance with another embodiment of the present invention. In the 6-pole (3-pole pair) magnet array depicted in FIG. 3, θ = 20°.

**[0042]** FIG. 4 is a plan view of an eight-pole magnet array comprising sixteen magnets in accordance with another embodiment of the present invention. In the 8-pole (4-pole pair) magnet array depicted in FIG. 4, θ = 15°.

**[0043]** Any of the curved surfaces shown by way of example in FIG. 1 may be replaced by linear approximations of the curved surfaces. The arcuate radially outer surface may thus be replaced by a segmented surface composed of a plurality of segments that approximate an arc.

**[0044]** Likewise, a curved implementation of any of the linear surfaces may be possible in a variant. For example, the flat inner surface may be replaced by a slightly curved surface.

**[0045]** In another embodiment, the flat inner surface may be segmented into two or more flat sub-sections having slightly different angles.

**[0046]** The magnets disclosed in this specification and illustrated in the drawings may be used to construct a novel electric machine such as the one illustrated by way of example only in FIG. 5.

**[0047]** In the embodiment schematically depicted by way of example in FIG. 5, a permanent magnet synchronous machine comprises a stator, a rotor and a plurality of permanent magnets 10 mounted to the rotor. As described above, each permanent magnet has a shaped body characterized by an arcuate radially outer surface, a flat inner surface, a first side surface, and a second side surface such that that the angles $\delta_1$ and $\delta_2$ are both greater than 90 degrees, as described above. The machine may incorporate a 2-pole, 4-pole, 6-pole, 8-pole, or 2*n*-pole magnet array, where $n$ = any even integer.

**[0048]** As depicted in FIG. 5, the 4-pole machine includes a stator core 52, a motor shaft 54, a sleeve 56, a winding end turn 58 and eight permanent magnets 10 having the novel shape described above.

**[0049]** The permanent magnet synchronous machine may be part of a novel flywheel energy storage system such as the one illustrated by way of example only in FIG. 6.

**[0050]** In the embodiment schematically depicted by way of example in FIG. 6, a flywheel energy storage system 100 comprises a flywheel 110, a housing 112, and a permanent magnet synchronous machine having a stator, a rotor and a plurality of permanent magnets mounted to the rotor. Upper and lower bearing mounts 120, 130 are shown. Each permanent magnet includes a shaped body characterized by an arcuate radially outer surface, a flat inner surface, a first side surface, and a second side surface such that that the angles $\delta_1$ and $\delta_2$ are both greater than 90 degrees, as described above.

**[0051]** The electric machine incorporating the novel shaped magnets may itself have many variants. For example, the electric machine may have a sleeve or no sleeve, the magnets may be glued (bonded by adhesive) or not. It is noted that the magnets in low-speed sleeveless machines are bonded to the rotor. The permanent magnets may be plated or unplated, or they may be coated or uncoated. The magnets may be axially straight or skewed, i.e. stepped or with a continuously varying helical angle. The magnets may be surface-mounted to the rotor or inset-mounted or interior-mounted. The rotor may be constructed of a solid ferrous material or of a laminated material (e.g. laminated rotor iron). The rotor of the electric machine may be constructed as a straight cylinder or as a tapered cone. The stator of the electric machine may be constructed in any number of variants including air cored or laminated, with magnet wire or litz wire, or in any suitable design known in the art.

**[0052]** Although the shaped permanent magnets are primarily designed for use in a permanent magnet synchronous machine in a flywheel energy storage system, these shaped permanent magnets may also be used in many other different electromechanical systems, including motors, generators and motor/generators.

**[0053]** The embodiments of the invention described above are intended to be exemplary only. As will be appreciated by those of ordinary skill in the art, to whom this specification is addressed, many obvious variations, modifications, and refinements can be made to the embodiments presented herein without departing from the inventive concept(s) disclosed in this specification. The scope of the exclusive right sought by the applicant is therefore intended to be limited solely by the appended claims.

**CLAIMS:**

1. A permanent magnet for use in a permanent magnet synchronous machine, the permanent magnet comprising:

   a shaped body, the shaped body having:

   an arcuate radially outer surface;

   a flat inner surface;

   a first side surface facing an opposite pole;

   a second side surface facing a like pole;

   wherein the first side surface and the flat inner surface subtend an angle $\delta_1$ that is greater than 90 degrees and wherein the second side surface and the flat inner surface subtend an angle $\delta_2$ that is also greater than 90 degrees.

2. The permanent magnet as claimed in claim 1 wherein the angle $\delta_1$ is greater than the angle $\delta_2$.

3. The permanent magnet as claimed in claim 1 wherein $\theta$ ranges from 25 to 35 degrees, wherein $\theta$ is an angle that subtends a quadrature axis and a centerline orthogonal to the flat inner surface.

4. The permanent magnet as claimed in claim 1 wherein the first side surface has a lesser surface area than the second side surface.

5. The permanent magnet as claimed in claim 1 wherein a centerline orthogonal to the flat inner surface and extending through an origin of a radius of the arcuate radially outer surface divides the flat inner surface into a first section facing the opposite pole and a second section facing the like pole, wherein the first section is longer than the second section.

6. The permanent magnet as claimed in claim 4 wherein a centerline orthogonal to the flat inner surface and extending through an origin of a radius of the arcuate radially outer surface divides the flat inner surface into a first section facing the

opposite pole and a second section facing the like pole, wherein the first section is longer than the second section.

7. The permanent magnet as claimed in claim 1 wherein the arcuate outer surface has a constant radius of curvature.

8. The permanent magnet as claimed in claim 1 wherein the shaped body is axially skewed.

9. The permanent magnet as claimed in claim 1 wherein a ratio of asymmetrical length to total length $(b_1-b_2)/(b_1+b_2)$ ranges between 0% and 75%.

10. The permanent magnet as claimed in claim 1 wherein $\delta_1$, $\delta_2$ and $\theta$ are defined as follows:

$$\delta_1 = 90 + \frac{360}{2n} \cdot x$$

$$\delta_2 = 90 + \frac{360}{2n} \cdot (1 - x)$$

$$\theta = \frac{360}{2n} \cdot x$$

wherein n is a number of magnetic poles and wherein

$$\frac{5}{9} \leq x \leq \frac{7}{9}$$

11. The permanent magnet as claimed in claim 10 wherein x = 2/3.

12. A permanent magnet synchronous machine comprising:

a stator;

a rotor; and

a plurality of permanent magnets mounted to the rotor, each magnet having a shaped body characterized by:

an arcuate radially outer surface;

a flat inner surface;

a first side surface facing an opposite pole;

a second side surface facing a like pole;

wherein the first side surface and the flat inner surface subtend an angle $\delta_1$ that is greater than 90 degrees and wherein the second side surface and the flat inner surface subtend an angle $\delta_2$ that is also greater than 90 degrees.

13. The machine as claimed in claim 12 wherein the angle $\delta_1$ is greater than the angle $\delta_2$.

14. The machine as claimed in claim 12 wherein $\theta$ ranges from 25 to 35 degrees, wherein $\theta$ is an angle that subtends a quadrature axis and a centerline orthogonal to the flat inner surface.

15. The machine as claimed in claim 12 wherein the first side surface has a lesser surface area than the second side surface.

16. The machine as claimed in claim 12 wherein a centerline orthogonal to the flat inner surface and extending through an origin of a radius of the arcuate radially outer surface divides the flat inner surface into a first section facing the opposite pole and a second section facing the like pole, wherein the first section is longer than the second section.

17. The machine as claimed in claim 12 wherein the arcuate radially outer surface has a constant radius of curvature.

18. The machine as claimed in claim 12 wherein the permanent magnets are surface-mounted in pairs to the rotor such that each magnet abuts adjacent magnet of like pole and such that there is a gap between adjacent magnets of opposite pole.

19. A flywheel energy storage system comprising:

a flywheel; and

a permanent magnet synchronous machine having:

a stator;

a rotor; and

a plurality of permanent magnets mounted to the rotor, wherein each permanent magnet includes a shaped body characterized by:

an arcuate radially outer surface;

a flat inner surface;

a first side surface facing an opposite pole;

a second side surface facing a like pole;

wherein the first side surface and the flat inner surface subtend an angle $\delta_1$ that is greater than 90 degrees and wherein the second side surface and the flat inner surface subtend an angle $\delta_2$ that is also greater than 90 degrees.

20. The system as claimed in claim 19 wherein the angle $\delta_1$ is greater than the angle $\delta_2$.

21. The system as claimed in claim 19 wherein $\theta$ ranges from 25 to 35 degrees, wherein $\theta$ is an angle that subtends a quadrature axis and a centerline orthogonal to the flat inner surface.

22. The system as claimed in claim 19 wherein the first side surface has a lesser surface area than the second side surface.

23. The system as claimed in claim 19 wherein a centerline orthogonal to the flat inner surface and extending through an origin of a radius of the arcuate radially outer surface divides the flat inner surface into a first section facing the opposite

pole and a second section facing the like pole, wherein the first section is longer than the second section.

24. The system as claimed in claim 19 wherein the arcuate radially outer surface has a constant radius of curvature.

25. The system as claimed in claim 19 wherein the permanent magnets are surface-mounted in pairs to the rotor such that each magnet abuts adjacent magnet of like pole and such that there is a gap between adjacent magnets of opposite pole.

26. A permanent magnet for use in a permanent magnet synchronous machine, the permanent magnet comprising:

a shaped body, the shaped body having:

an arcuate radially outer surface; and

an inner surface composed of two flat angled sections that are symmetrical about a plane of symmetry defined by a d-axis.

27. The magnet as claimed in claim 26 wherein one of the flat angled sections and a respective side surface facing an adjacent magnet subtend an angle $\delta_1$ that is greater than 90 degrees.

28. The magnet as claimed in claim 27 wherein a thickness $t_1$ of the shaped body along the side surface is less than a thickness $t_2$ along a plane of symmetry of the magnet.

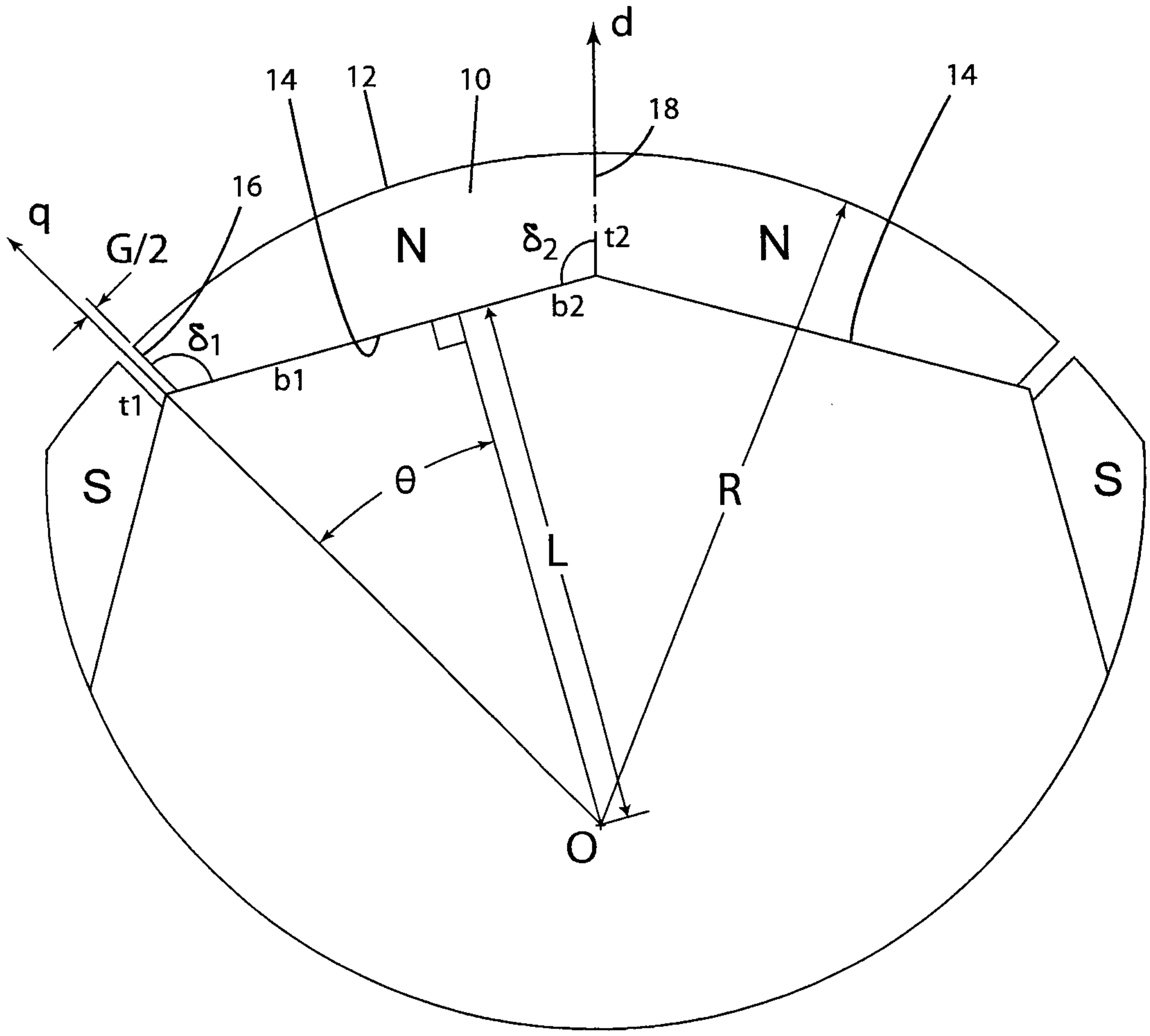



FIG. 1

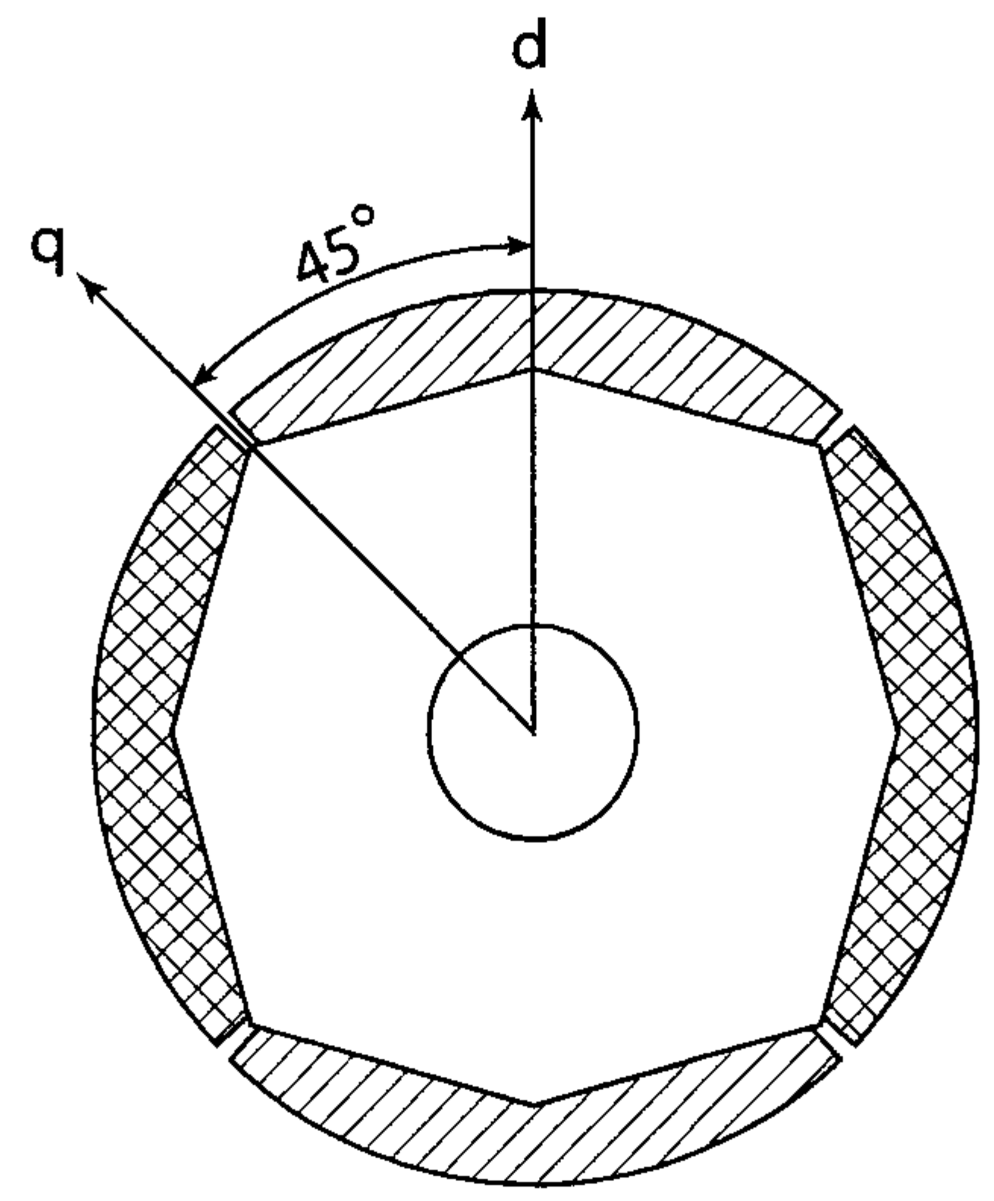



FIG. 2

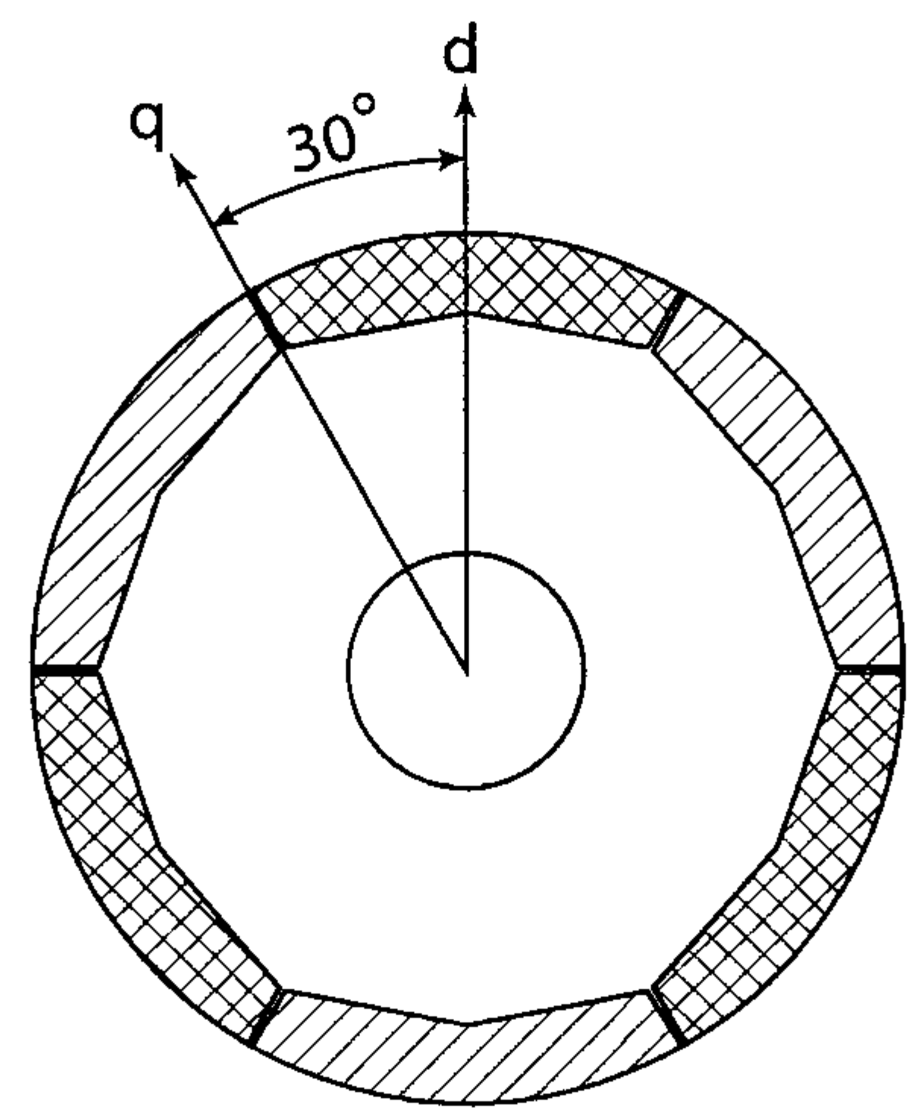



FIG. 3

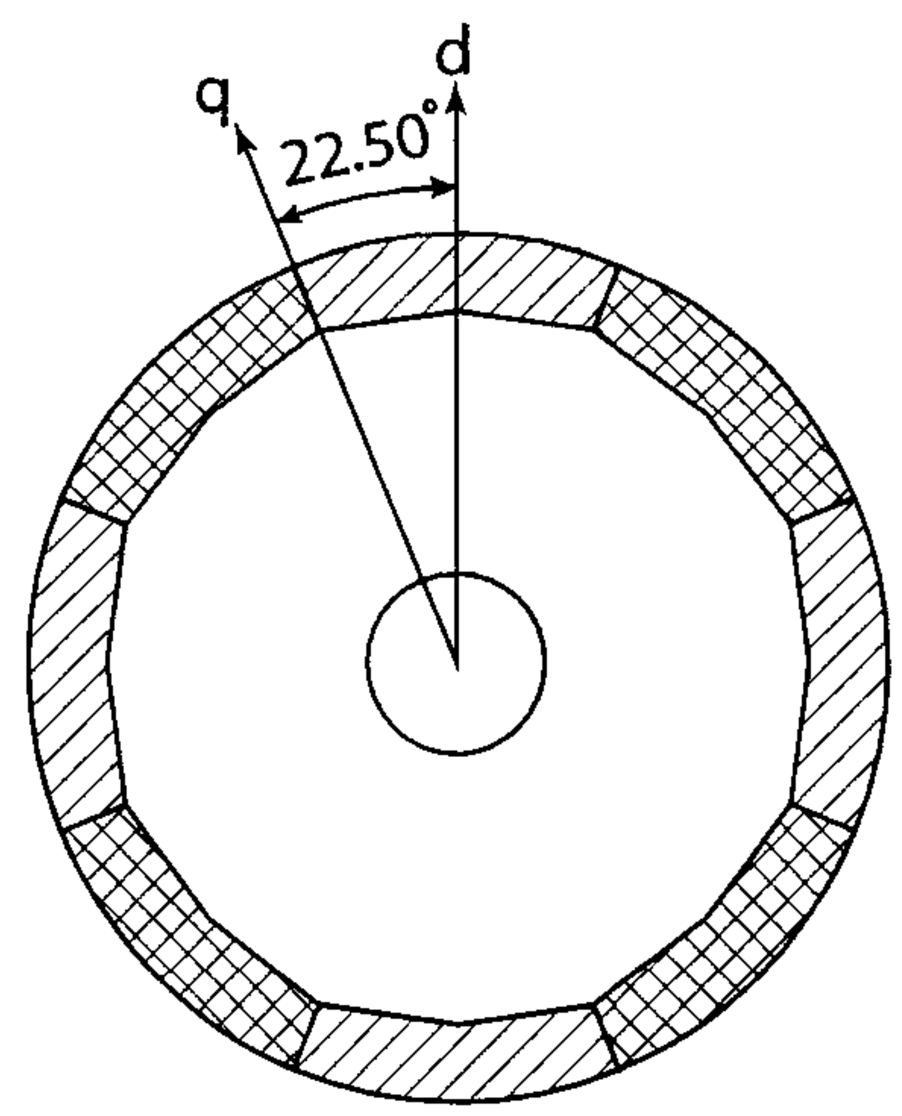



FIG. 4

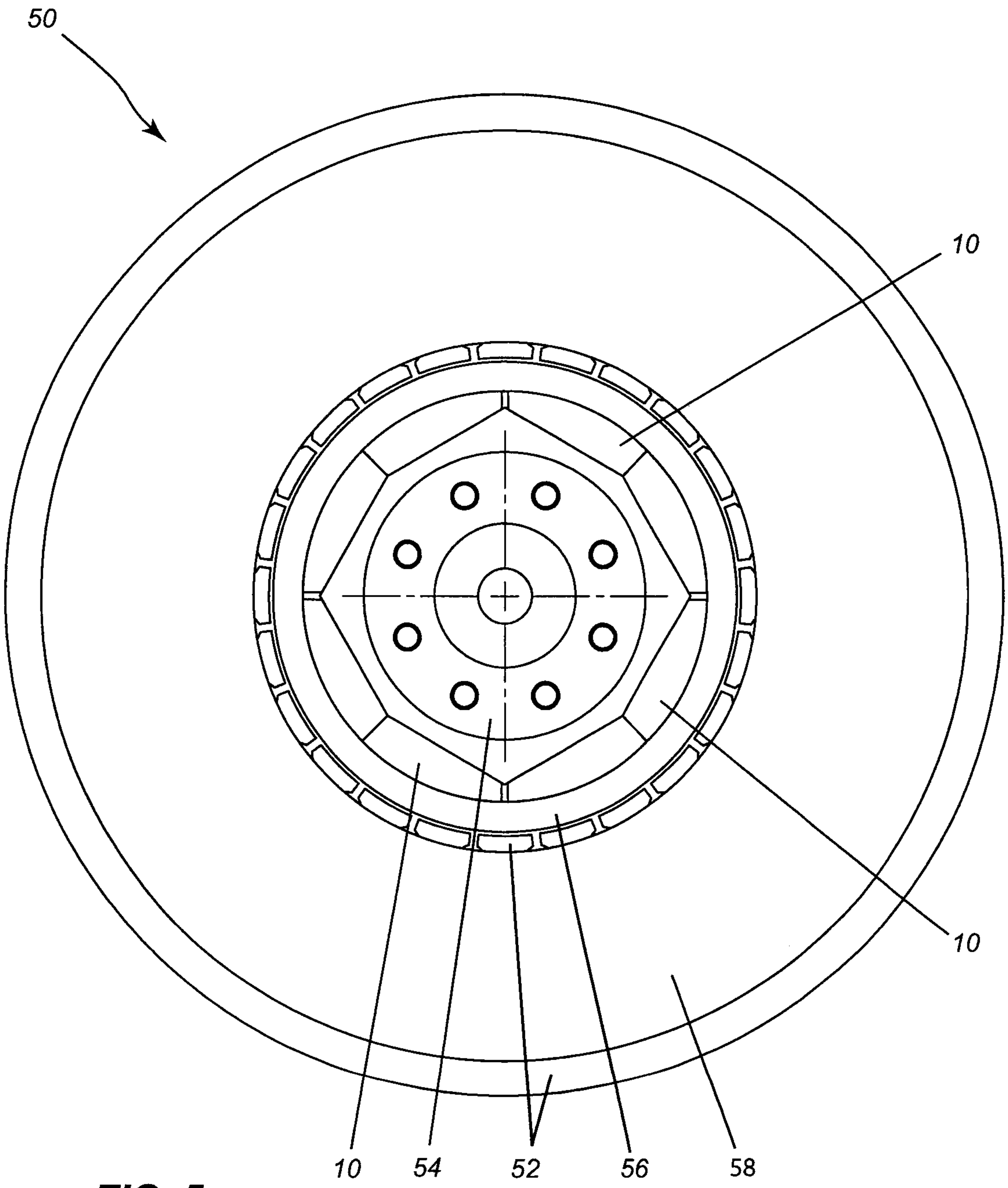



FIG. 5

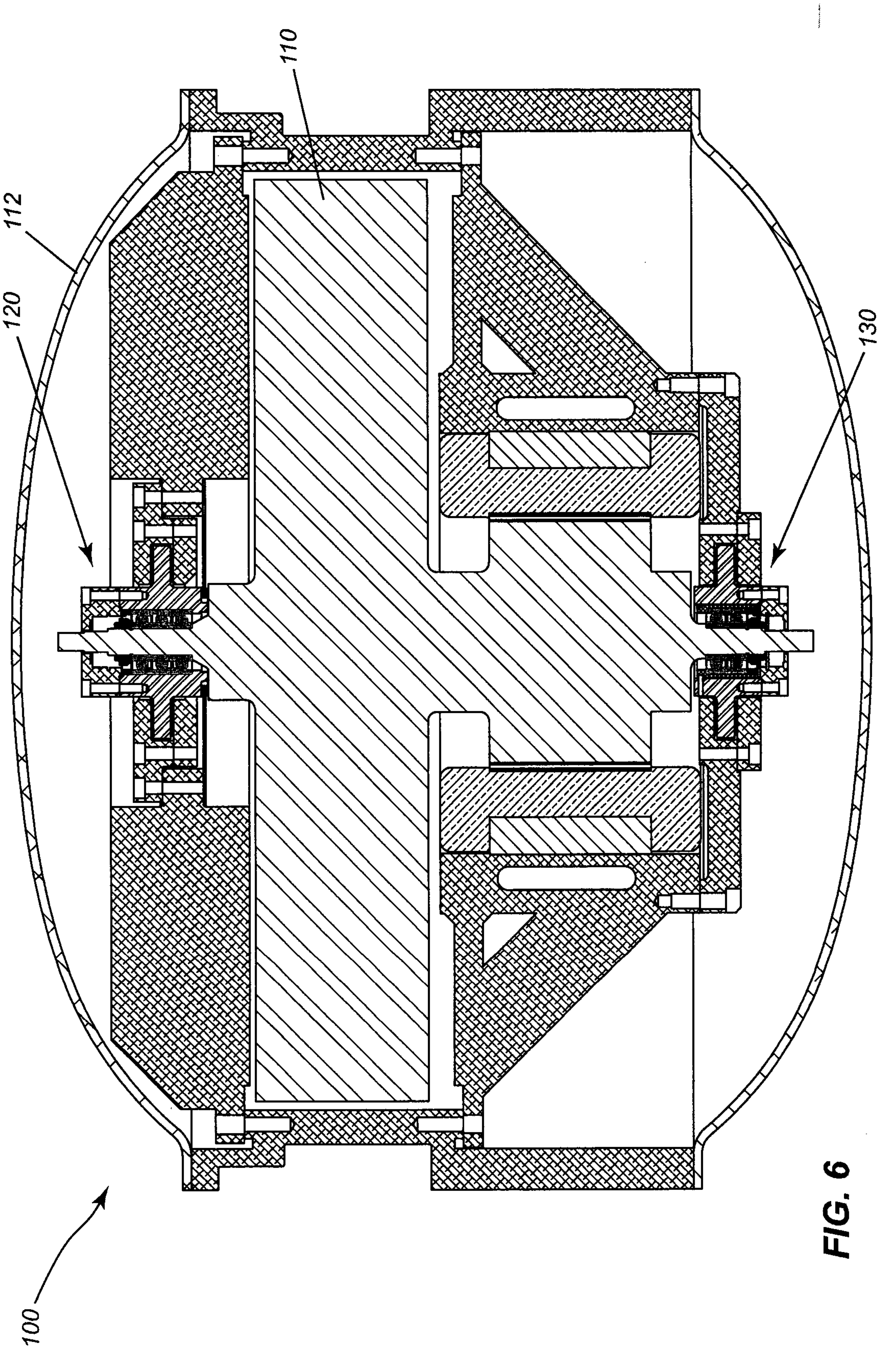
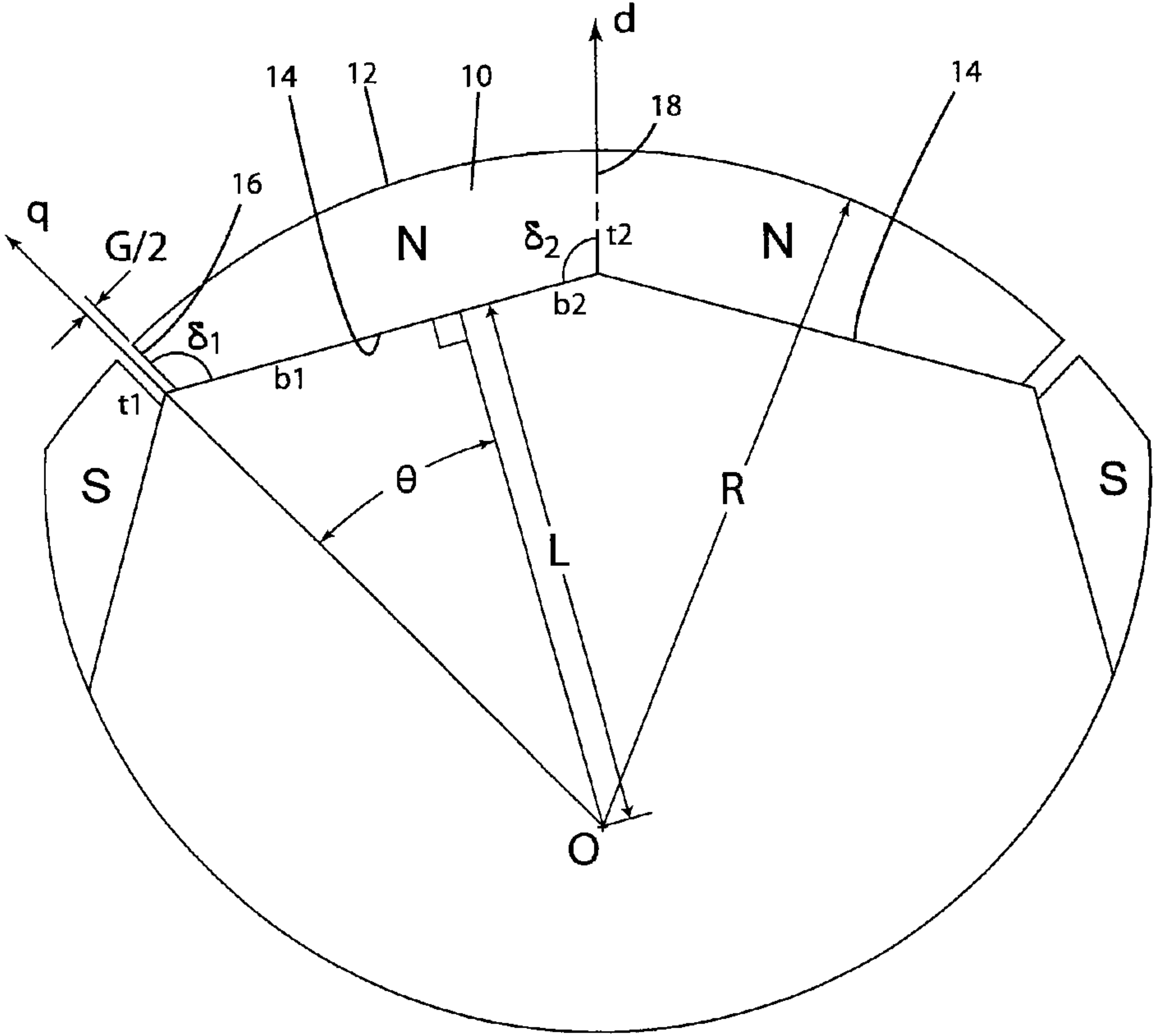



FIG. 6



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12
10
18
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16
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N
δ2
t2
N
δ1
b2
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t1
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R
S
L
O