

A Permanent Magnet Synchronous Motor

Field of the Invention

This invention relates to a permanent magnet synchronous motor and refers particularly, though not exclusively, to a permanent magnet synchronous motor with an axial magnetic field.

Background to the Invention

Figure 1 shows the structure of a known permanent magnet synchronous motor with an outer rotor. This form of motor is presently used in hard disk drives. It has a permanent magnet 101 on the inner surface 103 of the rotor yoke 102.

Figure 2 shows the structure of a known permanent magnet synchronous motor with an inner rotor. This form of motor is also presently used in hard disk drives. It has a permanent magnet 202 on the outer surface 203 of the rotor yoke.

For permanent magnet synchronous motors as shown in Figures 1 and 2, the electromagnetic field produced by the permanent magnet is distributed in a radial direction in the motor air gap. For such permanent magnet synchronous motors, besides the tangential force that forms the operational torque of the motor, the electromagnetic field in the air gap can also induce a force in the radial direction. Therefore, an unbalance-magnetic-pull in the radial direction is induced by problems during the assembly of the motor, and the quality of the components used in the motor. This quality aspect is especially so for the quality of the permanent magnet. An unbalance-magnetic-pull in the radial direction is not expected, nor desirable, as it induces noise and vibration during the operation of the motor.

The air gap of the permanent magnet synchronous motors as shown in Figures 1 and 2 is a ring band illustrated in Figure 3. Increasing the length L of the ring band can increase the effective surface area of the air gap, and this is important in increasing the ability of the motor to generate torque. For applications such as, for example, spindle motors used in hard disk drives, the thickness of the hard disk drive is limited so the axial length L of the motor must be short. Therefore the electromagnetic torque can only be produced in a short air gap as is shown in Figure 3. As such, a permanent magnet synchronous motor with a radial electromagnetic field is not suitable for small-form-factor spindle motors the diameter of which is small, and the height of which is short.

For obtaining a relatively high performance, permanent magnet synchronous motors use a permanent magnet with high magnetic energy. For permanent magnet synchronous motors with radial air gaps, only permanent magnets made of materials that have an homogeneous performance can be used. Only bonded NdFeB permanent magnets have been used in such spindle motors. Such a permanent magnet has a high energy product (8-12 MGOe), but is weak in mechanical strength. Sintered NdFeB magnets have an energy-product that may be 50 MGOe or higher. But they cannot produce the required electromagnetic field in the air gap in known permanent magnet synchronous motors as their performance is inhomogeneous. Therefore, it is difficult to use them in permanent magnet synchronous motors with the structures shown in Figure 1 and 2.

For the permanent magnet synchronous motor shown in Figure 1, besides its role in the electromagnetic field path, the rotor yoke 102 will protect the permanent magnet 101 (that may be bonded NdFeB) during the operation of the motor to thus provide mechanical support for, and thus strength to, the permanent magnet 101. Therefore, the motor can be used in hard disk drives with a big form factor, and may be operated at high speeds.

For the permanent magnet synchronous motor shown in Figure 2, the rotor yoke 203 cannot protect the permanent magnet 202 from eccentricity forces. Therefore, the motor can only be used in small form factor hard disk drives, and even then only at low speeds.

Summary of the Invention

In accordance with a first preferred aspect there is provided a permanent magnet synchronous motor comprising:

- (a) a rotor comprising a top yoke and a bottom yoke;
- (b) a permanent magnet mounted to at least one of: the top yoke and the bottom yoke;
- (c) an air gap between the permanent magnet and another of: the top yoke and the bottom yoke; and
- (d) armature windings in the air gap; wherein, in use,
- (e) an electromagnetic field in the air gap is distributed axially.

The permanent magnet may be mounted to the top yoke or the bottom yoke. The permanent magnet may comprise a top portion mounted to the top yoke and a bottom portion mounted to the bottom yoke, the air gap being between the top portion and the bottom portion. The top yoke and the bottom yoke may be joined by a web. The web may be at an inner end of each of the top yoke and the bottom yoke. The armature windings may be surrounded by the permanent magnet and the web.

The permanent magnet synchronous motor may further comprise at least one sealing sheet between the permanent magnet and the top yoke. The sealing sheet may be formed as at least one pair of layers. A first layer of the pair of layers may have a high relative permeability, and a second layer of the pair of layers may have a low relative permeability.

The permanent magnet may be made of a material selected from: sintered NdFeB, and bonded NdFeB. The permanent magnet may be formed from a plurality of fan-like segments.

The armature windings may be mounted to a base of the permanent magnet synchronous motor. The permanent magnet synchronous motor may be of a structure selected from: inside-surrounded, and outside-surrounded.

The permanent magnet may extend radially of the permanent magnet synchronous motor, as may the armature windings.

According to a second preferred aspect there is provided an armature winding for a permanent magnet synchronous motor, the armature winding comprising:

- (a) a plurality layers, each of the plurality of layers comprising a printed circuit board;
- (b) each of the plurality of printed circuit boards comprising a plurality of identical cycles of windings; and
- (c) each cycle of windings having a single via hole through the printed circuit board for connecting cycles of windings on different layers.

For both aspects, the single via hole may be at the centre of the cycle of windings. The cycles of windings may be: multi-phase concentrated, or multi-phase distributed. The armature winding may be for a structure selected from: inside-surrounded, and outside-surrounded.

Brief Description of the Drawings

In order that the present invention may be fully understood and readily put into practical effect, there shall now be described by way of non-limitative example only preferred embodiments of the present invention, the description being with reference to the accompanying illustrative drawings.

In the drawings:

Figure 1 illustrates the structure of a known permanent magnet synchronous motor;

Figure 2 illustrates the structure of another known permanent magnet synchronous motor;

Figure 3 illustrates the thickness and length of the air gap in a known permanent magnet synchronous motor;

Figure 4 illustrates the structure of a preferred embodiment of a permanent magnet synchronous motor;

Figure 5 is three illustrations of on an enlarged scale of different arrangements of the rotor yoke, permanent magnet and armature windings of Figure 4;

Figure 6 illustrates a preferred form of a permanent magnet for the embodiment of Figures 4 and 5;

Figure 7 illustrates a permanent magnet for the embodiment of Figures 4 and 5 that is formed by fan-like sintered segments;

Figure 8 illustrates a magnetic sealing sheet;

Figure 9 illustrates a one phase concentrated armature winding inside structure using a two layer printed circuit board;

Figure 10 illustrates a three phase concentrated armature winding inside structure using a two layer printed circuit board;

Figure 11 illustrates a one phase distributed armature winding inside structure using a two layer printed circuit board;

Figure 12 illustrates a one phase concentrated armature winding outside structure using a two layer printed circuit board;

Figure 13 illustrates a three phase concentrated armature winding outside structure using a two layer printed circuit board;

Figure 14 illustrates a one phase distributed armature winding outside structure using a two layer printed circuit board;

Figure 15 is a vertical cross-sectional view of the assembled armature windings of Figure 9; and

Figure 16 is an exploded perspective view of the rotor yoke assembly of Figure 4.

Detailed Description of the Preferred Embodiments

Figure 4 shows the structure of a preferred embodiment of a permanent magnet synchronous motor 400.

The motor 400 has a base 402, rotor shell 404, a motor shaft 406 and bearings 408. The rotor has a yoke generally shown as 410 and that is somewhat U-shaped. The yoke 410 has a top yoke 412 and a bottom yoke 414. The top yoke 412 and bottom yoke 414 are joined by a web 422. The permanent magnet has a top portion 416 mounted to top yoke 412 and a bottom portion 418 mounted to bottom yoke 414, with the armature windings 420 located between the permanent magnets 416, 418. The top portion 416, bottom portion 418 and web 422 define an air gap 424 therebetween in which the armature windings 420 are located.

As the armature windings 420 are mounted to base 402 and are surrounded on three sides by the permanent magnets 416, 418 and the web 422, the structure is an inside-surrounded structure. Similarly, the structure where the armature windings 420 are surrounded from the outside of the winding is an outside-surrounded structure. Both are possible with this embodiment.

As is shown in Figure 5(a), the permanent magnets 416, 418, and yoke 410, provide the path for the electromotive field. The electromagnetic field (illustrated by the dotted line) will extend over the area of overlap of the armature windings 420 with the permanent magnets 416, 418. The permanent magnets 416, 418 extend generally radially of the shaft 406, as do the

armature windings 420, and thus the permanent magnets 416, 418 have a relatively large surface area overlapping with the armature windings 420.

Figure 5(b) shows that the permanent magnet has only the top portion 416, and in Figure 5(c) there is only the bottom portion 418. Both will operate, but not as well as the form shown in Figure 5(a) with both the top permanent magnet 416 and the bottom permanent magnet 418.

The permanent magnets 416, 418 may extend over all, or the majority of, the inner surface areas 426, 428 of the top yoke 416 and bottom yoke 418, respectively. The structure illustrated allows the permanent magnets 416, 418 to be relatively thin in the axial direction thereby allowing the permanent magnet synchronous motor 400 to be relatively thin in the axial direction. By having the armature windings 420 also relatively thin in the axial direction, the thinness of the permanent magnet synchronous motor 400 in the axial direction is further enhanced. Similarly, by reducing the axial extent of the air gap 424, the axial length of the permanent magnet synchronous motor 400 may be further reduced. This is important in modern, portable devices such as, for example, mobile/cellular telephones, digital cameras, MP3 players, media players, portable memory devices, and so forth.

For the inside and outside permanent magnet synchronous motor structures of Figure 4, in the axial direction the electromagnetic parts of the motor are the top rotor yoke 412, top magnet 416, armature windings 420, bottom magnet 418, and the bottom rotor yoke 414.

The major difference of the embodiment having the structure illustrated in Figure 4 over the prior art structures illustrated in Figures 1 and 2 is that its electromagnetic field in the air gap 424 is distributed axially.

In Figure 4, the air gap 424 of the motor is discal. The effective area of the air gap 424 is thus not related to the thickness of the motor and is formed by the area of overlap of the permanent magnets 416, 418 and the armature windings 420. As such, this structure is able to be used in applications where low profile is important such as, for example, small form factor hard disk drives. The permanent magnets 416, 418 are also discal. As the electromagnetic field in the permanent magnet 410 is in the direction of the longitudinal axis of shaft 406 - between the armature windings 420 and the top magnet 416, and the armature windings 420 and the bottom magnet 418 - it will be generally perpendicular to the armature windings 420. As such, an homogeneous permanent magnet material such as, for example, bonded NdFeB, may be used.

As the electromagnetic field in air gap 424 is axial, inhomogeneous materials such as, for example, sintered NdFeB, may also be used. As the energy-product of a sintered-NdFeB permanent magnet is very high (>50 MGOe), the same volume of permanent magnet produces a stronger axial electromagnetic field. This is of assistance in increasing the energy density of the motor, which is of importance in applications such as small form factor hard disk drives. The permanent magnets 416, 418 are supported by the top yoke 412 and bottom yoke 414 respectively. This gives strength and mechanical support to the permanent magnets 416, 418.

As shown in Figure 7, a sintered NdFeB magnet may be formed by several fanlike segments 701. This may simplify the magnetization procedure, and enable the permanent magnets' 416, 418 "disk" to be able to produce a strong electromagnetic energy in the air gap 424.

For sealing against axial magnetic field leakage, a sealing sheet 801 may be used. The sheet 801 may be formed by a pair of layers 802, or multiple pairs of layers. One pair of layers 802 is formed by one magnetic layer whose relative permeability is high – for example, steel or amorphous alloy. The other is a layer whose relative permeability is low – for example, aluminum, copper or paper. The number of the layer pairs is determined by the requirements of the leakage field. The more layer pairs in each layer 802, the better the sealing effect.

The armature windings 420 may be distributed on a disc. Printed circuit board technology, or self-bonded wire, may be used.

Figures 9 and 15 show an example of a single phase concentrated winding formed by a two-layer printed circuit board 910 and 912. The first layer 910 is shown in Figure 9(a) and the second layer 912 in Figure 9(b). The winding is for an inside structure and is formed by three cycles 901 of windings, all identical. There are six fundamental magnetic poles for the single phase winding 900. For each winding cycle 901, only one via hole 902 is used to connect the windings of the different layers. Therefore, the space taken by the via hole 902 is very small. As the holes are in the center of the cycles 901, via holes 902 do not affect the electromagnetic torque generation. Different single phase winding cycles can be made for different numbers of fundamental magnetic poles. The winding cycles 901 are each on a top surface 914 of the printed circuit boards 910, 912. The bottom surface 916 of each printed circuit board 910, 912 is an insulating material. By placing the bottom surfaces 916 together to form a "sandwich" armature winding 420, and with the vias 902 aligned, the armature windings can be assembled. The vias 902 may be lined with a conductive material and may be connected using known techniques.

Figure 10 is similar to Figure 9 and shows an example of a three-phase winding. The winding structure shows that the three-phase winding can also use a two-layer printed circuit board 1010 and 1012. As shown, there are three cycles of three windings 1001, all identical. Vias 1002 are as before. Therefore, the armature windings 420 can be created by printed circuit board technology to form a thin disc. This is of assistance in low-profile permanent magnet synchronous motors. Different three-phase winding cycles for different numbers of fundamental magnetic poles may be produced in a similar manner.

Distributed windings have a higher winding coefficient than concentrated windings. Both single and three-phase distributed winding can use multi-layer printed circuit boards. Figure 11 shows a one-phase distributed winding, which can be formed by a two-layer printed circuit board 1110 and 1112. The windings in Figure 11 have three cycles. Therefore it has six fundamental magnetic poles. Different single-phase winding cycles for different numbers of fundamental magnetic poles can be formed in a similar manner. If three distributed printed circuit board windings are used and their phase difference is 120 electrical degrees, a three-phase distributed winding can be formed using printed circuit boards. Such a three phase winding can also be formed by a six-layer printed circuit board. Such a three-phase winding with a permanent magnet synchronous motor can possess improved electrical performance.

Figures 12 to Figure 14 show the single-phase concentrated winding, three-phase concentrated winding and single-phase distributed winding for the motor with outside structure. Similar reference numerals are used for the components, with the prefix number being the Figure number.

The permanent magnet synchronous motor can have a low profile, compact structure, and high power density. Therefore, the motor can operate with relatively low acoustic noise and relatively low vibration. The unbalance-magnetic-pull and cogging torque of the motor may be reduced.

Whilst there has been described in the foregoing description preferred embodiments of the present invention, it will be understood by those skilled in the technology concerned that many variations or modifications in details of design or construction may be made without departing from the present invention.

THE CLAIMS

1. A permanent magnet synchronous motor comprising:
 - (a) a rotor comprising a top yoke and a bottom yoke;
 - (b) a permanent magnet mounted to at least one of: the top yoke and the bottom yoke;
 - (c) an air gap between the permanent magnet and the other of: the top yoke and the bottom yoke; and
 - (d) armature windings in the air gap;wherein, in use,
 - (e) an electromagnetic field in the air gap is distributed axially.
2. A permanent magnet synchronous motor as claimed in claim 1, wherein the top yoke and the bottom yoke are joined by a web.
3. A permanent magnet synchronous motor as claimed in claim 2, wherein the web is at an inner end of each of the top yoke and the bottom yoke.
4. A permanent magnet synchronous motor as claimed in claim 2 or claim 3, wherein the permanent magnet is mounted to the top yoke, the armature windings being surrounded by the permanent magnet, the bottom yoke and the web.
5. A permanent magnet as claimed in claim 2 or claim 3, wherein the permanent magnet is mounted to the bottom yoke, the armature windings being surrounded by the permanent magnet, the top yoke and the web.
6. A permanent magnet synchronous motor as claimed in any one of claims 1 to 3, wherein the permanent magnet comprises a top portion mounted to the top yoke and a bottom portion mounted to the bottom yoke, the air gap being between the top portion and the bottom portion.

7. A permanent magnet synchronous motor as claimed claim 6, wherein the armature windings are surrounded by the top portion, the bottom portion and the web.
8. A permanent magnet synchronous motor as claimed in any one of claims 1 to 7 further comprising at least one sealing sheet between the permanent magnet and a shell of the rotor.
9. A permanent magnet synchronous motor as claimed in claim 8, wherein the sealing sheet is formed as at least one pair of layers, a first layer of the pair of layers having a high relative permeability, and a second layer of the pair of layers having a low relative permeability.
10. A permanent magnet synchronous motor as claimed in any one of claims 1 to 9, wherein the permanent magnet is made of a material selected from the group consisting of: homogeneous material, and inhomogeneous material.
11. A permanent magnet synchronous motor as claimed in any one of claims 1 to 10, wherein the permanent magnet is formed from a plurality of fan-like segments.
12. A permanent magnet synchronous motor as claimed in any one of claims 1 to 11, wherein the armature windings are mounted to a base of the permanent magnet synchronous motor.
13. A permanent magnet synchronous motor as claimed in any one of claims 1 to 12, wherein the armature windings comprise:
- (a) a plurality layers, each of the plurality of layers comprising a printed circuit board;
 - (b) each of the plurality of printed circuit boards comprising a plurality of identical cycles of windings; and
 - (c) each cycle of windings having a single via hole through the printed circuit board for connecting cycles of windings on the plurality of layers.
14. A permanent magnet synchronous motor as claimed in claim 13, wherein the via hole is at the centre of the cycle of windings.

15. A permanent magnet synchronous motor as claimed in claim 13 or claim 14, wherein the cycles of windings are selected from the group consisting of: multi-phase concentrated, and multi-phased distributed.
16. A permanent magnet synchronous motor as claimed in any one of claims 13 to 15, wherein the armature winding is for a structure selected from the group consisting of: inside-surrounded, and outside-surrounded.
17. A permanent magnet synchronous motor as claimed in any one of claims 1 to 16, wherein the permanent magnet extends radially of the permanent magnet synchronous motor.
18. A permanent magnet synchronous motor as claimed in any one of claims 1 to 17, wherein the armature windings extend radially of the permanent magnet synchronous motor.
19. An armature winding for a permanent magnet synchronous motor, the armature winding comprising:
- (a) a plurality layers, each of the plurality of layers comprising a printed circuit board;
 - (b) each of the plurality of printed circuit boards comprising a plurality of identical cycles of windings; and
 - (c) each cycle of windings having a single via hole through the printed circuit board for connecting cycles of windings on the plurality of layers.
20. An armature winding as claimed in claim 19, wherein the via hole is at the centre of the cycle of windings.
21. An armature winding as claimed in claim 19 or claim 20, wherein the cycles of windings are selected from the group consisting of: multi-phase concentrated, and multi-phase distributed.
22. An armature windings as claims in any one of claims 19 to 21, wherein the armature winding is for a structure selected from the group consisting of: inside-surrounded, and outside-surrounded.