Development of an Axial Gap motor with Amorphous Metal Cores

Z. Wang*, Y. Enomoto*, M. Ito*, R. Masaki**, S. Morinaga**, H. Itabashi*** and S. Tanigawa***
* Hitachi Research Laboratory, Hitachi, Ltd., Ibaraki, Japan
** Hitachi Industrial Equipment Systems Co.,Ltd., Tokyo, Japan
*** Hitachi Metals, Ltd., Japan

Abstract—**This paper presents a noble motor design concept that utilizes amorphous cut cores in the stator to obtain a high efficiency motor. This motor employs 6-pole, 9-slot axial gap construction and aims to provide high efficiency with small size and low cogging torque for fan motor applications. Amorphous cut cores are applied to the stator to decrease iron loss and save motor space. The magnets with distinct shapes are employed to decrease cogging torque. 3D finite element analysis was used to model and analyze motor performance. In order to verify the design concept, a trial motor was constructed and a large range experiments were conducted to measure motor characteristics.**

Index Terms— **Amorphous core, axial gap motor, high efficiency, cogging torque.**

I. Introduction

With the increasing attention on energy crisis and environmental problems, high efficiency of electric machines has been strongly demanded. Motors consume more than 60% of all power consumed by industrial machines, therefore high efficiency motors can make an outstanding contribution to energy conservation. There are two major sources of loss in an electric motor, copper loss in stator coils and iron loss in magnetic cores. Optimal circuit design and advanced winding techniques can reduce copper loss dramatically. However, iron loss is affected by many factors such as the rotating speed of the motor, the field that penetrates magnetic cores and the resistance of magnetic cores. The techniques on decreasing iron loss of motors with conventional magnetic material already reached a breaking point. With the development of motor design techniques and material technology, employing low loss magnetic or conductive materials instead of the traditional counterpart becomes a feasible way to improve motor efficiency.

Amorphous magnetic metal (AMM) has features of extremely low losses, high magnetic permeability and high fracture toughness. Compared to silicon steel sheet, AMM produces less eddy current loss when the metal is subjected to an alternating magnetic field because of its high resistance. AMM also produce low hysteresis loss due to its disordered atomic structure. The excellent properties offer great possibilities to increase motor efficiency with using AMM. There are a few reports [1][2] that discussed different design concepts to construct motors with AMM cores. In ref [1], an axial gap motor with tape-wound AMM cores was introduced and lower iron loss of AMM cores than conventional magnetic materials in motor applications was demonstrated. In ref [2], the concept of employing cut AMM cores in a motor at 6000r/min rotating speed was introduced. Because of its high resistivity and thickness of laminations, AMM cores can improve motor efficiency specifically at high rotating speed. These initial studies were mainly aimed at motors in a high rotating speed field to demonstrate the application possibilities of motors using amorphous material.

We have developed and reported an axial gap motor with wound AMM cores that obtained 86% efficiency with a size of Φ100mm×L60mm [3]. This motor was designed for air conditioner application and obtained the same efficiency with the current motors at 3000r/min rotating speed. The successful application of AMM to motors gave rise to possibility that proper motor design could yield an increase in the efficiency of motors and application fields of AMM cores.

With the coming of global energy crisis and the exhaustion of natural resources, motor designs require not only high efficiency but also small dimension. In order to construct a high efficiency motor with decreased dimensions, we designed and tested a new motor with AMM cores targeting applications in fan motors. This motor utilizes AMM cut cores in the stator and aims to offer high efficiency at relatively low speeds. In addition, cut cores can contribute to a decrease in the overall size of a motor. For fan motor applications, low noise and low cogging torque are also required. In this motor, we applied permanent magnets that with distinct shapes to decrease cogging torque.

This paper introduces motor designs with AMM cores and presents the applicable three dimensional (3D) calculations derived with finite element analysis (FEA). Furthermore, a large range of testing results conducted on the trial motor are provided to verify the 3D FEA calculation and evaluate motor characteristics.

II. Motor Design

A. Target of motor design

As we mentioned before, an axial gap motor with tape-wound AMM cores was designed and tested [3]. This motor obtained comparable performances utilizing sintered ferrite magnets with the current motors which utilized rare earth permanent magnets. Based on the results of the developed motor, this research aims to construct a motor which utilizes sintered ferrite magnets to obtain higher efficiency and smaller size than current fan motors [4][5]. The target motor design specifications are shown in table.1

TABLE 1. THE SPECIFICATIONS OF TARGET MOTOR DESIGN

Phase number	3
Motor size	Φ100mm×L50mm
Voltage	Maximum AC200V (DC280V)
Rated speed	2000r/min
Rated power	200W
Efficiency	90%
Magnet type	Sintered ferrite
Stator core	Amorphous magnetic material (METGLAS® 2605SA1)

B. Motor design

In various types of motor, the axial gap structure is proven to be the most efficient way to construct a motor in a limited axial space because the output torque depends on the space in the radial direction [6][7]. Therefore, it is possible to obtain a high output axial gap motor with a short axial length. In addition, the axial gap structure is suited to utilize AMM cores because it is difficult to connect AMM to iron yoke due to its unique mechanical properties. Therefore, axial gap structure was employed to design a 200W motor at 2000r/min within a 50mm axial length.

Concerning axial gap structure motor, there can be more than one working face from the combinations of two rotors with one stator or one rotor with two stators. The combination of two rotors with one stator contributes to lower copper loss and smaller size in the axial direction. The combination of two stators with one rotor can lower cost of magnets and yield lower iron loss on the back yoke. In this design, the combination of two rotors with one stator was employed because that combination can save axial space. The number of poles and slots was decided by taking into consideration space for stator coils, the leakage flux from pole to pole inside the rotor and cogging torque. In this motor, 6-pole, 9-slot configuration was chosen to balance those three factors.

1) Design of stator

The geometry of a core made from AMM is considered one of the most difficult challenges when applying AMM to a motor. AMM is mainly in the form of 0.025mm thinness ribbon and has the special mechanic characteristics that make it difficult to stamp or press, which is dissimilar to the conventional silicon magnetic sheet. From this form, the most efficient way to use the material is to make a wound core from wrapping AMM ribbon. However, due to the difficulty of insulating the laminated layers, eddy current is produced even though the laminated layers are perpendicular to the flux produced by the rotors. In addition, a tape-wound core needs the hollow space in the middle to keep its shape, which takes more space in a motor. In order to increase motor efficiency, a cross section of the stator core needs to be removed to cut off the current loop. The removal of the cross section spawned the idea of using the removed cross section as a core.

In this design, cut AMM cores are utilized and arrange to be perpendicular to the field that produced by rotors to decrease iron loss. The three-dimensional (3D) core model is shown in Fig 1(a). Concentrate coil is arranged in the outside of the core. The assembly of a coil and a core is shown in Fig.1 (b). There are three slots in each phase and three phases are designed to be in a Y connection with the circuit of three coils connected in series to increase the induced voltage.

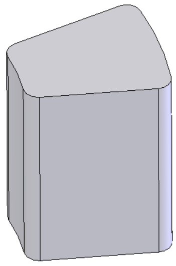

Fig.1. Cut AMM core.

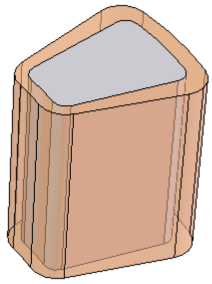

Fig.2. Assembly of a coil and a cut AMM core

2) Design of rotor

The geometric shape of the magnets is given more consideration when designing the rotors because this motor requires low cogging torque. Due to the processing difficulty of amorphous metals, variations are limited when choosing the shape of the amorphous stator cores. Therefore, the magnet shape is designed to decrease cogging torque. Generally, a large number of poles are used to produce smooth torque at low speed. However, in this motor, 6 poles are selected to guarantee ampere-conductors per pole. Therefore, skewed magnets are selected to decrease cogging torque.

First, we calculated cogging torque produced by a motor using conventional 60 degree flat magnets shown in Fig.3 (a). The 60 degree flat magnets caused low order harmonics which lead to cogging torque larger than 200mN·m. In order to eliminate low order harmonics, skewed magnets, shown in Fig.3 (b), was designed. The left-right asymmetric model added magnet with skewed edges, which can reduced cogging torque to 50mN·m level.

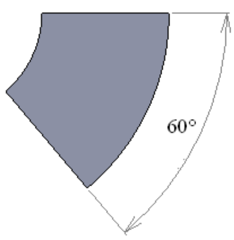

Fig.3(a).60 degree flat magnet

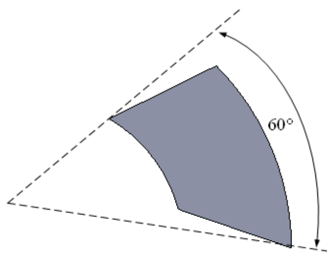

Fig.3 (b) Skewed magnet.

3) Finite element analysis

In order to obtain accurate motor design, the Finite

Element Method (FEM) was used to calculate motor performance in different operations. The 3D calculation model is shown in Fig4. The performance when the motor was operated with no load was carried out at varieties rotating speeds. Fig.5 shows the flux density of stator core that produced by the rotors when the rotating speed is 2000r/min. In spite of the low field produced by sintered ferrite magnets, the maximum flux density of the stator core is about 0.7T due to the high permeability of amorphous cores. The induced voltage when the motor is operated at 2000r/min was shown in Fig.6. The root mean square (RMS) value of every phase voltage is 102.2V. It should be noted here the back yokes of permanent magnets motors generate eddy current if they are not laminated due to the effect of a changing magnetic field. The no load FEM analysis is carried out while taking eddy current into consideration.

4) Iron loss calculation

In this motor, two parts generate iron loss: AMM stator cores and Iron rotor yokes. AMM core losses can be divided into eddy current loss and hysteresis loss. No load iron losses that produced at different rotating speed were calculated according to equation (1). The first part of the right side of the equation represents hysteresis loss and the second part represents eddy current loss.

$$W_i = k_h \times B^{1.6} \times f + k_e \times B^2 \times f^2 \qquad (1)$$

Where W_i is the total iron loss,

k_h is hysteresis loss coefficient,

k_e is eddy current loss coefficient

B is flux density,

f is the frequency of magnetic field

Fig.7 shows the calculated results of iron loss in terms of rotating speed. At 2000r/min, 9 amorphous cut cores produces less than 0.3W iron loss.

Eddy current is created in the rotor yoke because a moving magnetic field, caused by change of rotor and stator positions, penetrates the rotor. Eddy current loss was calculated when motor is rotated at various speeds without load. The eddy current loss density distribution of a rotor yoke is shown in Fig.8. According to the calculation, rotor yokes produce 2.6W iron loss at 2000r/min. The total iron loss of the motor at 2000r/min is 2.9W.

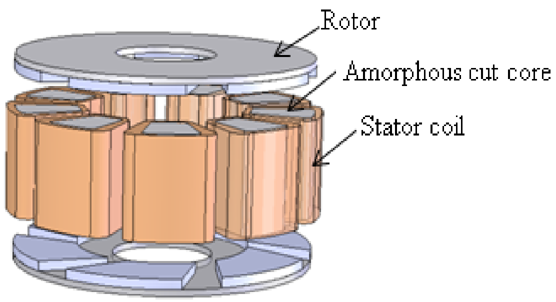

Fig.4. 3D model of designed motor.

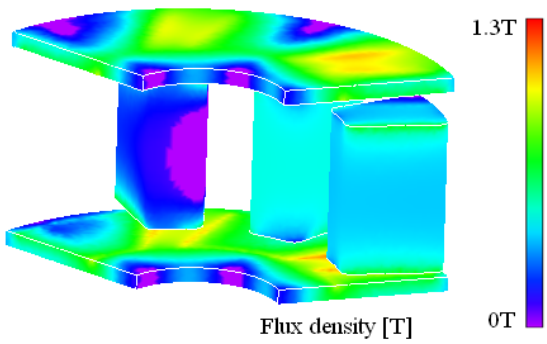

Fig.5 Motor flux distribution (n=2000r/min).

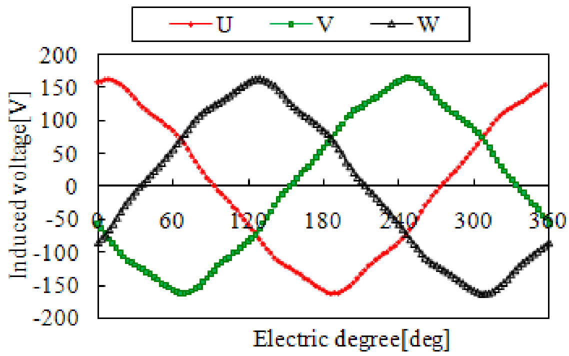

Fig.6. Waveforms of induced voltages (n=2000r/min).

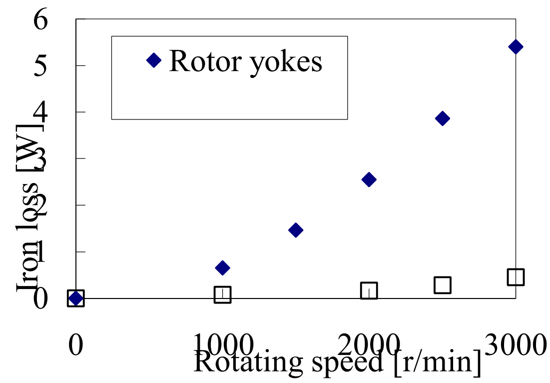

Fig.7. Calculated iron loss of amorphous cores and rotor yokes

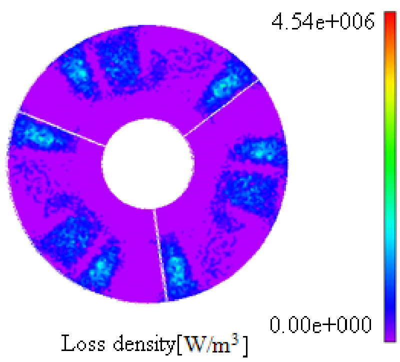

Fig.8. Eddy current loss density distribution. (n=2000r/min)

C. Trial motor

In order to verify the design ideas and demonstrate the feasibility of constructing a high efficiency motor with cut AMM cores at low rotating speeds, we manufactured a trial motor based on the design and conducted a large range of experiments on the trial motor.

1) Structure of trial motor

The motor employs two rotors with one stator in the middle. Each rotor utilizes six skewed magnets fixed on an iron back yoke. The magnets were made of sintered ferrite and magnetized parallel to produce a field in axial direction. The rotor of trial motor is shown in Fig9.

The stator cores were made by wrapping thin AMM ribbons (METGLAS ® 2605SA1) into a core, then encapsulated in resin to increase the strength of the core. The molded AMM core was cut into several separate cores with trapezoidal surfaces and fixed sizes. The cut core is shown in Fig.10 (a). Compared to the wound core, the cut core can reduce a motor's size because the cut core is not hollow in the middle, allowing for the same area to be used with a reduction on the total space occupied by the core. Since the cut core is smaller in size than the tape-wound core, it can leave more space for stator coils, which can reduce resistance of copper coils when the same volume of coil is employed. The high density stator coil is shown in Fig.10 (b).

In addition, the cut can be reproduced to specifications with more accuracy than the wound core, which can eliminate extra cogging torque. The assembly of a motor with an aluminum case is shown in Fig.11. The outer diameter of the motor is less than 100mm and the length of the motor is less than 50mm, which meet the target design size.

Fig.9. Rotor of the trial motor.

Fig.10 (a). Cut AMM core.

Fig.10 (b). Stator coil.

Fig.11. Dimension of the trial motor.

2) Motor tests

Motor evaluation experiments were carried out to verify three categories of performance which include no load performance, load performance and efficiency characteristics that demonstrate the concept of using AMM cut cores to obtain high efficiency motor at low speeds.

a) No load performance

The no load test is performed by unloading the motor and monitoring three phases of induced voltage. The measured three phases induced voltages are shown in Fig.12. The RMS value of the phase voltage is 99.4Vrms at 2000r/min. The small discrepancy between the measured value and the calculated 102.2Vrms is only about 2.7%, which proves the accuracy of the 3D FEM calculation.

The cogging torque is measured and one electric cycle of cogging torque is shown in Fig.13. The measured cogging torque is 48mN・m, which corresponded with the calculated value and proves the effectiveness of left-right asymmetric skewed magnets are effective at decreasing cogging torque.

b) Load performance

In the load tests, torque characteristics were measured in terms of current at different rotating speeds. Fig.14 shows torque versus current characteristics at rated speed 2000r/min. The calculated value is added in this figure to compare with the measured value. As can be observed in the figure two series of load characteristics corresponded with each other. The 3D FEM provided accurate calculation on motor's load tests.

c) Efficiency characteristics

In order to determine efficiency characteristics, no load losses were measured at different rotating speeds. The measure curve is shown in Fig.15. No load loss includes mechanical loss and iron loss, which are shown in Fig.16. According to the measured results, the motor produces 3.1W iron loss at 2000r/min, which has a good correlation with the calculated value. The copper loss as a function of torque can be calculated using the stator resistance and the measured current. Fig.17 shows the efficiency distribution at different torque and speed range. According to this plot, it is proven that this motor can obtain high efficiency in both high speed field (>3000r/min) and low speed field (1000r/min~3000r/min).

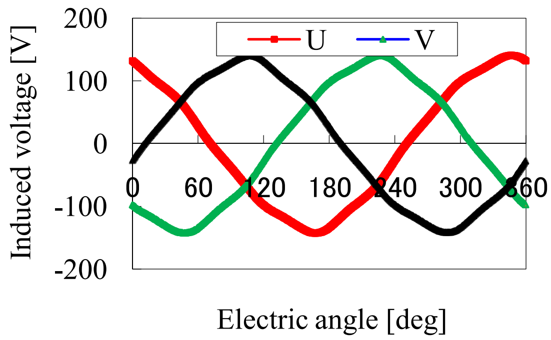

Fig.12. Measured three phases induced current at 2000r/min.

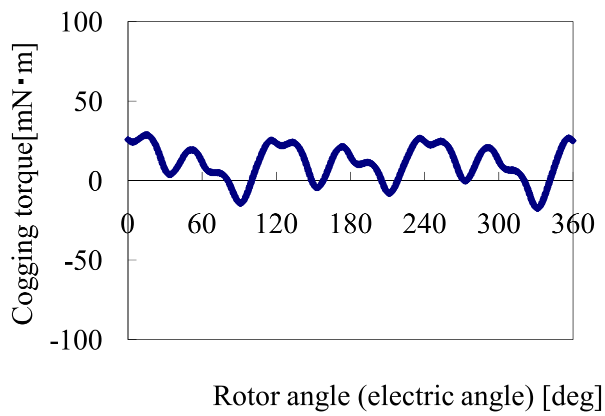

Fig.13. Measured cogging torque.

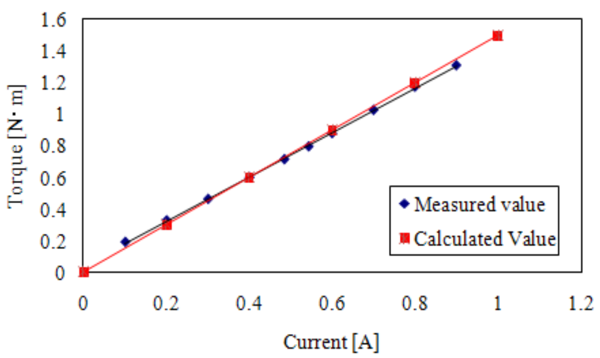

Fig.14. Torque vs. current characteristics. (n=2000r/min).

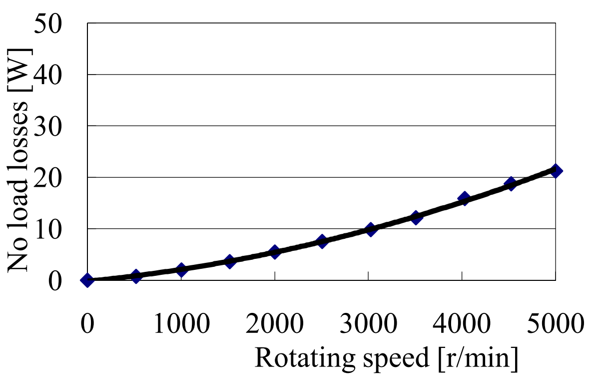

Fig.15. No load losses at different rotating speed.

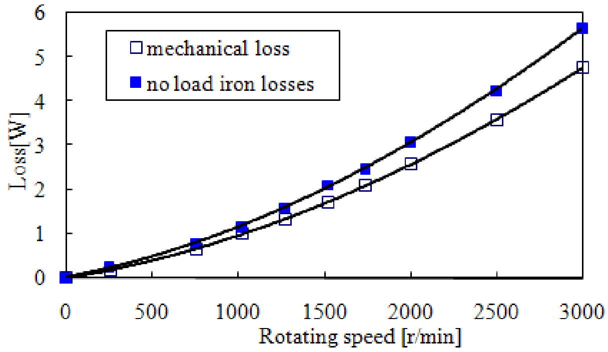

Fig.16. Measured mechanical loss and no load iron losses.

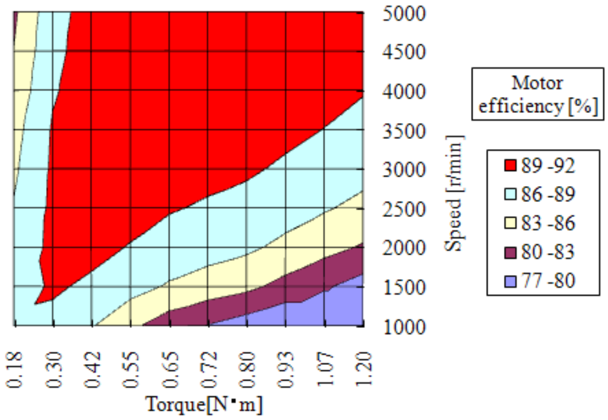

FIg.17. Motor efficiency distribution.

III. Conclusion

This paper presented a novel axial gap structure motor that employs an amorphous cut core's stator and two rotors with left-right asymmetric sintered ferrite magnets. Amorphous cut cores are employed to reduced iron loss and skewed magnets are employed to decrease motor cogging torque.

The motor design was analyzed by FEM and verified by the tests on a trial motor. The key points and results are described as follows:

(1) According to the FEM calculation and motor evaluation tests, amorphous cut cores can contribute to extremely low iron losses in a motor, which demonstrates the feasibility of the design concept of utilizing cut cores in a motor and makes high efficiency motors at low speed ranges possible. Compared to tape-wound cores, cut cores are beneficial for efficient using of motor space, which can reduce motor size. Furthermore, the high permeability of amorphous material allows high efficiency with sintered ferrite magnets. It can be estimated that with rare earth magnets, a motor with higher efficiency and smaller size is possible.

(2) The magnets with Left-right asymmetric skewed shapes are effective at eliminating harmonics and can provide motors with less than 50mN・m cogging torque.

(3) The calculated results from 3D finite element analysis, which include no load performance, load

performance and iron losses, showed a good correlation with the measured characteristics of the motor. Therefore, the accuracy of 3D FEM calculations is demonstrated.

REFERENCES

[1] C.C. Jensen, F. Profumo and T.A.Lipo, "A Low-Loss Permanent-Magnet Brushless dc Motor Utilizing Tape Wound Amorphous Iron," IEEE transactions on industry applications, vol.28, NO.3, May/June 1992.

[2] G. S. Liew, N. Ertugrul, W. L. Soong and J. Gayler, " Investigation of axial field permanent magnet motor utilizing amorphous magnetic material," Australasian Universities Power Engineering Conference (AUPEC), 2005.

[3] H.Amano, H. Itabashi, S. Tanigawa, Y. Enomoto, M.Ito, and R. Masaki, " Examination of Applying Amorphous Rolled Core to Permanent Magnet Synchronous Motors," Institute of Electrical Engineers of Japan(IEEJ), RM-05-109, pp.7-12,2005.

[4] http://www.fujitsu-general.com/jp/news/2004/12/04-N07-20/index.html.

[5] http://www.mitsubishielectric.co.jp/news/2006/0215-h.htm

[6] K. Sitapati and R. Krishnan, "Performance Comparisons of radial and axial field, permanent-magnet, brushless machines", IEEE transactions on industry applications, vol. 37, no.5, Sep/Oct 2001.

[7] A. Cavagnino, M. Lazzari, F. Profumo and A. Tenconi, " A comparison between the axial flux and the radial flux structures for PM synchronous motors", IEEE transactions on industry applications, vol. 38, no.6, Nov/Dec 2002.