Analytical Model and Optimal Design of Axial Flux PM Motor with Amorphous Core

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論文内容要旨

In recent years, high efficiency electric machines have been in high demand due to increased attention being placed on energy conservation and environmental concerns. Over the past 30 years, electrical machines, equipped with neodymium-iron-boron permanent magnets, have been used in a wide variety of industries. Given the increased costs and limited availability of rare earth metals, suitable replacements or alternative methods must be employed to increase motor efficiency. There are two main approaches to increase the efficiency of a permanent magnet motor: 1) increase the motor output; or 2) decrease the power losses. Since the coercive force of non-rare earth magnets, such as ferrite or ceramic permanent magnets, are typically 50% to 70% weaker than that of rare earth magnets, increasing the output of a motor using these weaker magnets is extremely difficult with conventional motor structures without increasing the size of the motor.

An electric motor can be constructed in two ways according to the direction of the main magnetic flux interacting between the rotor and stator. “Radial-flux machines” in Fig. 1 refers to a motor with a magnetic field in the radial direction and an air gap that is parallel to the rotational axis. “Axial-flux machines” in Fig. 2 refers to a motor with a magnetic field in the axial direction and an air gap that is perpendicular to the rotational axis. The general advantages of AFPM machines over RFPM machines include higher torque density, an adjustable air gap, and better heat removal. A larger output can be obtained without increasing a motor's size by employing a dual gap AFPM structure.

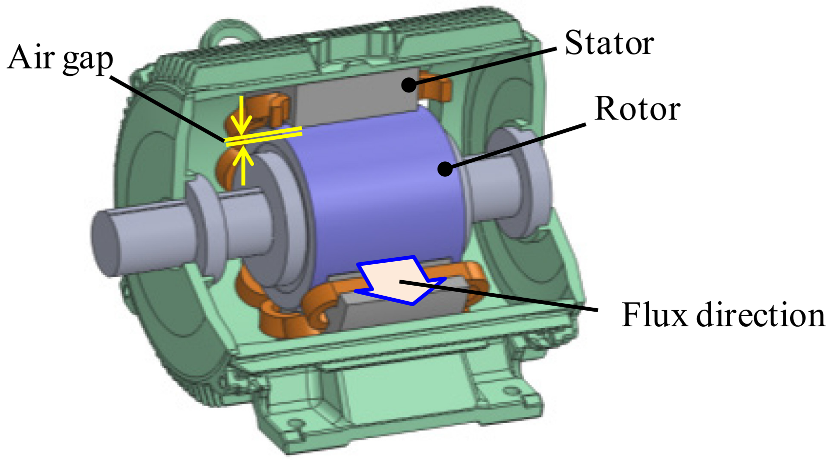

Fig. 1. Radial-flux permanent-magnet motor.

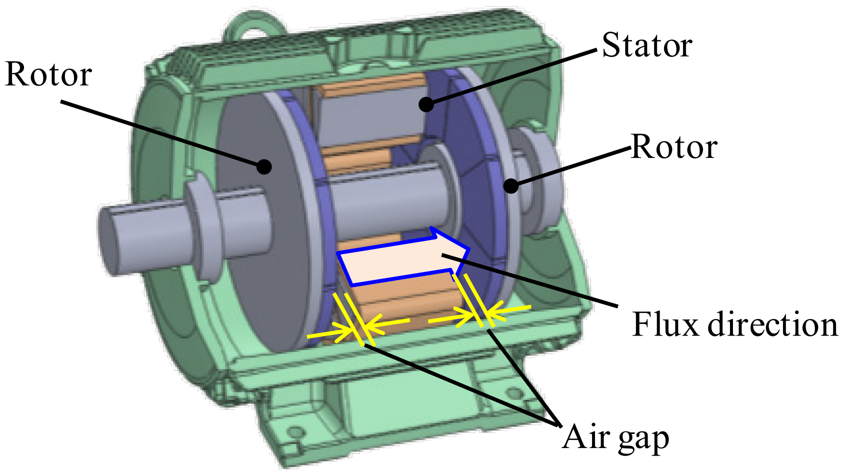

Fig. 2. Axial-flux permanent-magnet motor.

The iron-based amorphous magnetic alloy has features of extremely low iron losses, high magnetic permeability and high fracture toughness. Compared to the non-oriented magnetic steel, iron-base amorphous produces less eddy current loss when the material is subjected to an alternating magnetic field due to their high electric resistance. The amorphous magnetic alloy also produces low hysteresis loss due to their disordered atomic structure.

The objective of this work is to develop high efficient axial flux permanent magnet (AFPM) motors with amorphous stator cores and rare-earth free permanent magnets. The major bottlenecks that prevent the wide range application of AFPM motors are a well-established efficient design procedure and a reliable manufacturing process. Furthermore, amorphous magnetic alloy is a completely new material for electrical motors and the detailed electromagnetic properties are not well understood. This work provides the analytical modeling, optimal design of axial flux permanent magnet motors with prototype machine testing, and the research on amorphous magnetic alloy's motor application. The corresponding conclusions and possible further works are presented hereafter.

Chapter 1 introduces the research background, the purpose and the approach of the work. An introduction to axial flux permanent magnet motor and iron-based amorphous magnetic alloy is presented.

In Chapter 2, the 2D analytical electromagnetic models and the magnetic field calculations are presented. The 2D model was obtained by dividing the AFPM motor into several linear models in the axial direction while taking the 3D geometrical features into consideration. Then the 2D model was divided into three regions: the magnetized region (ferrite PMs), current carrying region (stator windings) and source-free region (air). The analytical calculation of electromagnetic fields was performed with the 2D models at no-load and load operations. The influences of slotting openings on the magnetic field distribution in the air gap must be taken into consideration for an accurate design. The traditional Carter's model for calculating slotting effect was proven to be less accurate for the targeted motor. Therefore, a new analytical model based on Weber's theory was proposed. The accuracy of the 2D analytical model was verified with 3D FEA in terms of magnetic field distribution, the induced voltage and the torque. The slotting effect calculation was also verified by comparing the waveforms of both the 2D analytical and 3D FEA calculations. Furthermore, the detailed analysis of the fractional slot windings was also provided. The analysis results showed that a considerable amount of space harmonics is produced, which can cause large eddy current in the rotor. Therefore, the wound core was applied to the rotor to reduce eddy current loss.

Since the magnetic field is a key factor in the iron loss calculation, and the iron loss is crucial for predicting thermal behavior in the motor, the iron losses of the motor were analyzed and calculated in Chapter 3. However, the amorphous core's magnetic properties needed to be investigated before creating the iron loss model for the AFPM motor. The thin amorphous magnetic ribbon was found to be very sensitive to mechanical stress such as punching and cutting. In Chapter 3, the measurement system developed for amorphous cores was provided. Using the developed system, the iron losses for amorphous cores and non-oriented magnetic steel cores were measured. The amorphous cores exhibited much lower iron losses in all frequency ranges. The iron losses of the AFPM motor produced under no-load and load operations were calculated while taking pulse width modulation (PWM) voltage and current harmonics into consideration. The analytical iron loss calculation showed positive agreement with the 3D FEA calculation results.

The lumped thermal models for the AFPM motor were provided in Chapter 4. The motor was divided into several lumped components and the heat flow paths of the motor's components were transformed into a thermal equivalent circuit. According to the calculation results in chapter 3, the rotor produced extremely low power loss due to the adoption of the wound core and ferrite magnets. Therefore, the heat production in the rotor was excluded. The detailed thermal models for the stator were also introduced. The thermal conductivity of amorphous cores were measured and applied to the thermal model. The slot windings and end windings were modeled separately and a thermal model of the copper wires with insulation and air were proposed for calculating the thermal transfer in the copper laminated direction. The temperature rise in the motor was less than 12K.

By using the developed analytical models, an AFPM motor was designed in Chapter 5 for package air-conditioner fan application. An optimal design of the motor's specifications was performed and low irons, easy to manufacture amorphous cores were applied to the motor. The no-load test, load test and heat-run test were performed on the prototype motor. The motor achieved 94% efficiency at full load and 90% efficiency at other operation speeds. The measured results are a good match with the calculation results in terms of induced voltage, torque-current relationship and temperature rise. The accuracy of the analytical calculation was verified and the research showed that the measurement method for amorphous magnetic properties provided a solution to estimate amorphous core behavior, which also improves the accuracy of the iron loss calculation. Designing optimal structures for different applications can be achieved using the investigated results for amorphous cores. Furthermore, this research shows that an optimal design of the AFPM motor can be completed within a relatively short period of time.

論文審査結果の要旨

一般に，高効率モータには回転子に希土類磁石を用いた永久磁石同期モータ（以下PMモータ）が使用されるが，磁石材料であるネオジムやジスプロシウムは，資源が特定の国に偏在するため，価格と供給が安定しないという問題が指摘される．本論文は，希土類磁石を用いない高効率モータの開発を目的として，アモルファス磁性合金が低鉄損で高透磁率という優れた磁気特性を有すること，およびアキシャルギャップモータが薄型で高出力に適した構造であることに着目し，固定子鉄心にアモルファス磁性合金，回転子にフェライト磁石を適用したアキシャルギャップ形のPMモータを開発したもので，全編6章から成る．

第1章は緒言であり，本論文の背景および目的を述べている．

第2章では，アキシャルギャップPMモータの解析手法を提案している．アキシャルギャップPMモータは3次元構造を有するため，有限要素法による磁界解析では計算時間が長大化する．ここでは，モータの回転運動を直線化して取り扱う2次元解析モデルに着目し，円周上に配置された固定子鉄心の内径，外径，およびその平均直径の3つの断面で得られる3種類の2次元解析モデルを基に，半径方向の磁束分布を考慮してアキシャルギャップPMモータの特性を算定する手法を提案している．本手法によるギャップ磁束密度，誘導起電力，およびトルクの計算値と，3次元有限要素法による計算値は良好な一致を示している．本手法は，3次元有限要素法解析の100倍程度の高速計算を可能にするもので，形状パラメータが多いアキシャルギャップPMモータの解析・設計に有用な手法として高く評価される．

第3章では，アモルファス磁性合金の磁気特性の評価方法と，モータ鉄心に適用した際の鉄損推定方法について述べている．一般に，磁性材料は機械的な加工によって磁気特性が劣化する．ここでは，モータ鉄心に適用した場合と同等の条件で，アモルファス磁性合金の鉄損および透磁率を測定する手法を考案している．さらに，これらの測定結果を用い，2章で提案した解析手法に基づいて，アモルファス磁性合金を固定子鉄心に適用した場合の鉄損を算定する手法を与えている．また，PWMインバータによる高周波パルス電圧で励磁した場合の鉄損の算定手法を導いている．これらの手法はアキシャルギャップPMモータの最適設計を行ううえで重要な成果である．

第4章では，3次元構造のアキシャルギャップPMモータの熱解析を行うために，モータにおける伝熱および放熱経路を分析し，固定子の鉄心と巻線，回転子の鉄心と磁石，ならびにケースを含むモータの熱等価回路を構築している．本熱等価回路によるアキシャルギャップPMモータの温度特性の計算時間は，3次元有限要素法による熱解析時間の1/60～1/70である．これは，アキシャルギャップPMモータの高速熱解析を可能にする実用的な手法として評価される．

第5章では，2章から4章で提案した解析手法を用いて，出力150Wのアキシャルギャップ PMモータの設計を行うとともに，これに基づいて試作したモータの性能評価を行っている．試作機における誘導起電力，トルク，および温度上昇の実測値は計算値と良好な一致を示し，本論文で提案した解析手法が妥当であることが明らかにされている．試作モータの効率は広い動作領域にわたって90%以上であり，希土類磁石と無方向性ケイ素鋼板を使用する通常のPMモータと同等以上の効率が得られている．これは極めて優れた成果である．

第6章は結言である．

以上要するに本論文は，アモルファス磁性合金とフェライト磁石を用いたアキシャルギャップPMモータの最適設計に必要な解析手法を提案し，実用に供し得る希土類フリーの高効率モータを開発したもので，電気機器工学およびパワーエレクトロニクスの発展に寄与するところが少なくない．

よって，本論文は博士（工学）の学位論文として合格と認める．