Composite Structures 204 (2018) 525–535

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Filament-wound composite sleeves of permanent magnet motor rotors with ultra-high fiber tension

Lei Zu, Hui Xu, Bing Zhang, Debao Li*, Huabi Wang, Bin Zi

School of Mechanical Engineering, Hefei University of Technology, Hefei 230009, China

ARTICLE INFO

Keywords:
Composite material
Filament winding
Permanent-magnet motor rotors
Sleeve
Ultra-high tension

ABSTRACT

Ultra-high fiber tension can provide sufficient compressive stresses to retain the permanet magnets mounted on the surface of the spindle. Therefore, a filament-wound sleeve with ultra-high fiber tension is designed to provide the radial compressive stress on the permanent magnet. Based on the elasticity theory, an approach for calculating the fiber stress distributions of composite layers and the radial compressive stresses on permanent magnets under different winding tensions are presented. The maximum winding tension of carbon fibers and the radial compressive stresses of composite layers are obtained by experiments. The fiber stresses of winding layers at the end of winding process under various winding tensions are calculated using the analytical method and finite element method, respectively. The results indicate that the analytical method can accurately predict the fiber stress distribution of the sleeve at the end of winding process and the radial compressive stresses on permanent magnets. The results obtained using the analytical method and the ones using the finite element method have a good agreement. The comparison between the analytical and experimental results is within the acceptable error. Therefore, filament-wound sleeves with ultra-high fiber tensions can satisfy the design requirements of high-speed permanent magnet rotors.

1. Introduction

Permanent magnet motors with high speed generally refer to the machines with typical operational speeds in excess of 10,000 r/min and r/min √KW in excess of 1×10^5 [1]. Surface-mounted high-speed permanent magnet motors have widely been used in various high-speed machine fields due to their advantages such as simple construction, high power density, smaller radius, high efficiency and reliability. The rotor of a surface-mounted high-speed permanent magnet motor must be protected with a sleeve to compensate large centrifugal forces generated by high rotational speed [2]. Nowadays, rotor sleeve materials mainly include non-magnetic high-strength alloys, pre-molded graphite composite and carbon or glass fiber [3]. The permanent magnet has the characteristic that the compressive strength is higher than tensile strength. The tensile strength cannot withstand the tensile stress generated by centrifugal forces when the rotor rotates at high speed. Therefore, rotor sleeves are required to provide enough compressive stresses to protect the permanent magnets from being damaged at high rotational speed and to ensure no looseness between the permanent magnet and the mandrel, the permanent magnet and the sleeve.

At present, many investigations on metallic sleeves of high-speed permanent magnet motor rotors have been carried out. Nevertheless, there are high eddy current losses in a metallic sleeve design [4–7]. Compared with metallic sleeves, carbon fiber sleeves have smaller thickness, lighter weight and the highest strength. Moreover, the high-frequency eddy current loss are typically eliminated by selection of a carbon fiber sleeve. However, the thermal conductivity of a carbon fiber sleeve is comparably lower, which is not beneficial for the permanent magnet rotor to cool [8]. In spite of this, carbon fiber sleeves remain the focus of many researches. Aglen [9] covered the rotor of a surface-mounted permanent magnet synchronous generator with a carbon fiber bandage to retain rotational speed of 70,000 rpm. In order to counteract the large centrifugal forces, Paulides et al. [10] selected the high-strength carbon fiber sleeve to protect the rotor magnets. Owing to the carbon fiber sleeve, the high-power electrical machines has a comparatively low airgap flux density. Arkkio [11] designed a surface-mounted permanent magnet synchronous motor. The permanent magnets are mounted with a carbon fiber sleeve to support against the centrifugal forces. In addition, the dimensions of the permanent magnets and aluminum screen were taking into account when designing the carbon fiber sleeve in order to keep the maximum stress of the sleeve below 800 MPa. Kolondzovski et al. [12] presented the thermal analysis of different rotors with the titanium alloy sleeve and carbon fiber sleeve. The result shows that compared with the rotors

---

* Corresponding author.
E-mail address: lidebao@hfut.edu.cn (D. Li).

https://doi.org/10.1016/j.compstruct.2018.07.119
Received 2 July 2018; Received in revised form 17 July 2018; Accepted 30 July 2018

protected by titanium alloy sleeves made of Ti–6%Al–6%V–2%Sn and Ti–2.5%Cu, respectively, the rotor with a carbon fiber sleeve and aluminium shield generates the lowest eddy-currents losses. Bailey et al. [13] designed a viable medium-voltage, high-speed permanent magnet machine with rotor protected by a carbon fiber sleeve. Nevertheless, the investigation on strength of the sleeve is not proposed in the paper. In order to investigate the influence of various rotor constructions depending on the type of the retaining sleeve on the rotordynamic properties, Kolondzovski et al. [14] chose the carbon-fiber composite sleeve and the titanium-alloy sleeve as the research objects. The analysis shows the rotordynamic properties of rotors with a titanium alloy Ti–6%Al–6%V–2%Sn sleeve are the best and superior to that of rotors with a carbon fiber sleeve. Luise et al. [15] investigated the physical properties of the carbon fiber sleeve by experiment. Fernando et al. [16] optimized the thickness of the sleeve and rotor diameter to minimize the stack-length of a high speed permanent magnet machine. The stress models of a carbon fiber sleeve and an Inconel sleeve are established using the finite element method and are chosen for a qualitative comparison of the stack-lengths. Reddy et al. [17] employed a carbon fiber sleeve and an Inconel sleeve to study the performance of synchronous reluctance machines. Fang et al. [18] analyzed the performances of three commonly used sleeves respectively made of Inconel 718, titanium alloy Ti6Al4V and carbon fiber composite when designing the rotor of a high-speed high-power permanent-magnet synchronous machine. The results show that carbon fiber composite sleeve is not applicable due to shrinkage fit between the permanent magnets and the carbon fiber composite sleeve is too small to provide enough pressure on the permanent magnets. Ahn et al. [19] investigated the influence of four different sleeves and two different permanent magnets on the mechanical stress of a high-speed permanent magnet rotor. Finally, Inconel718 is selected for the experiment due to the highest safety factor by comparing the distribution of von Mises stress of the four sleeves.

The aforementioned literatures illustrate that the majority of carbon fiber rotor sleeves are fabricated by conventional winding tension, which is difficult to provide enough radial compressive stress to compensate the high centrifugal force if the permanent magnet motor wants to achieve higher speed and power level. Furthermore, the compressive stresses of conventional sleeves are resulting from interference fits between the permanent magnets and sleeve [3,20,21]. However, this method has the disadvantages that the assembly is complicated and the magnitude of interference is not easily implemented. Carbon fibers are brittle material with low toughness and easy to generate damage cracks in the process of interference fits; therefore, interference fits are more suitable for metallic sleeves. In present paper, a method suitable for carbon fiber material is proposed. A filament-wound carbon-fiber sleeve of surface-mounted high-speed permanent magnet motor rotor with ultra-high fiber tension is designed in order to provide enough compressive stress to counteract the large centrifugal force and to ensure permanent magnets retained on the rotor spindle. Based on the elasticity theory, the relationships between the fiber stresses of fiber layers at the end of winding process and the winding tension are deduced. The maximum tension of carbon fibers is obtained by experiments with different winding tensions. Furthermore, the fiber stress distribution of fiber layers at the end of winding process and the radial compressive stresses generated by fiber layers are investigated under different winding tensions. The results of finite element simulations and experiments confirm the validity of the analytical calculations proposed in present paper.

2. Elasticity solution for filament-wound composite rotors

In order to analyze the deformation and stress of the rotor protected by the filament-wound carbon-fiber sleeve with ultra-high fiber tension, the assumptions are simplified as follows:

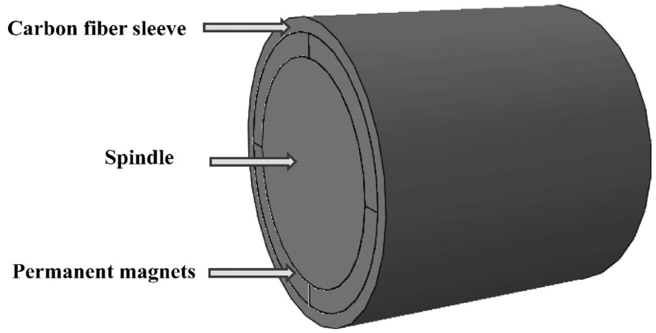

Fig. 1. Structure of the surface-mounted high-speed permanent magnet motor rotor.

(1) The size, shape and material properties of the surface-mounted permanent magnets are identical and the permanent magnets have no interaction among each other.
(2) Fibers are wound layer by layer from inside to outside.
(3) No slippage exists between two adjacent layers and the friction effect is not taken into account during filament winding process.
(4) The rotor is only subjected to the uniform external pressure resulting from ultra-high fiber tension without considering the influence of the magnetic force, gravity, temperature and axial force.
(5) During filament winding process the spindle and permanent magnets pertain to the elastic deformation.

The cross section of the surface-mounted permanent magnet motor rotor with high rotational speed is shown in Fig. 1, which is mainly composed of a spindle, permanent magnets and carbon-fiber winding layers. The rotor spindle is a cylinder on which the permanent magnets are mounted.

The cross section of the permanent magnet motor rotor is depicted in Fig. 2. A and b represent the radius of the spindle and the outer radius of the permanent magnet, respectively. F_j(N/m) represents the tension force per unit band width when the jth layer is wound. P_j is the compressive stress between the jth layer and the j-1th layer. P_1 represents the compressive stress between the winding layer and the permanent magnet. P_2 denotes the compressive stress between the permanent magnet and rotor spindle.

2.1. Elasticity solution of the permanent magnets and spindle

Due to the effect of winding tension, the inner fibers and the outer surfaces of the permanent magnets, the inner surfaces of the permanent magnets and the spindle are closely fit together. According to the elasticity theory, the microelements of fibers, the permanent magnets and spindle satisfy the balance equation [22]:

$$\frac{d\sigma_r}{dr}+\frac{\sigma_r-\sigma_\theta}{r}=0 \tag{1}$$

where the subscripts r and θ represent the physical quantities along the radial and circumferential directions, respectively.

The permanent magnets and spindle approximately satisfy isotropic three-dimensional constitutive relations and the stress components are related to the strain components as:

$$\begin{Bmatrix}\varepsilon_\theta^i\\ \varepsilon_r^i\\ \varepsilon_z^i\end{Bmatrix}=\frac{1}{E_i}\begin{bmatrix}1 & -\mu_i & -\mu_i\\ -\mu_i & 1 & -\mu_i\\ -\mu_i & -\mu_i & 1\end{bmatrix}\begin{Bmatrix}\sigma_\theta^i\\ \sigma_r^i\\ \sigma_z^i\end{Bmatrix},\ (i=m,z) \tag{2}$$

where m and z represent the variables of the permanent magnets and spindle, respectively. When the influence of the axial stress and strain is not taken into account, according to the small deformation theory, the stress-displacement relation of the permanent magnets and spindle can be expressed as: