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Research paper

Characteristic Analysis of High-Speed Permanent Magnet Synchronous Motor

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Abstract

Background/Objectives: This paper presents characteristic analysis of High-SpeedPermanent Magnet Synchronous Machine (High-Speed PMSM) by using FEM (Finite Element Method) tools. The High-Speed PMSM need the protective tube with non-magnetic materials that protect the scattering of permanent magnet, it is necessary that analyzed about mechanical analysis.
Methods/Statistical analysis: For preventing and improving, the fracture of the rotor of High-Speed PMSM, it is important that analyzed characteristic of mechanical stress, it should not be analyzed that occurred the fracture and decreased the performance, since the structure of rotor. However, structure analysis is usually performed by using FEM, which need the big amount of time consuming. Therefore, in this paper is derived the mechanical stress of rotor by using analytical method of stress.
Findings: The results of the stress analysis are compared with the results of FEM analysis that validated the analytical method of stress analysis. Based on the results of the analysis, an analytical model was fabricated. Through the experiments, the presence of rotor breakage was examined and the performance was measured.
Improvements/Applications: It can be applied to stress analysis and characterization of superhigh speed machine through the analysis methods presented in this paper.

Keywords: *mechanical stress analysis, interference fit, analytical method, high-speed PMSM, electromagnetic analysis, characteristic analysis*

1. Introduction

In order to build a high-performance pump and blower system, it is essential to increase the precision of electrical equipment and increase the speed. In addition to increase the efficiency of the system, high power and high efficiency of the electric device are required, so that the technology and researches on the high speed motor using the permanent magnet are developing. The permanent magnet synchronous motor (PMSM) is adopted as a permanent magnet motor for high-speed operation. The PMSM can be divided into two types depending on the shape of the rotor: surface-mounted permanent magnet (SPM) and interior permanent magnet (IPM) motors.TheIPM motors could prevent the scattering of permanent magnets during high-speed operation because the permanent magnet is embedded in the rotor [1]-[14]. The IPM motor is not only difficult to control due to the generation of reluctance torque, but also has a disadvantage that it is complicated in structure and difficult to manufacture because a permanent magnet is embedded in the rotor. On the other hand, SPM has the disadvantage that it is very easy to manufacture and control but the performance of the weak field is very poor. Moreover, it is necessary to fabricate a non-magnetic-material tube for preventing the magnet from scattering during high-speed operation[1], [14]. However, the structure is simple and suitable for high-speed machines. Prior to design the machines, mechanical analysis should be considered, the rotor of high-speed machine is made of shrink fit of sleeve and PM that generate mechanical stress and broke the structure of rotor according to interference[2]-[11]. Thus, the design of sleeve thickness is affected by shrink fit and the materials. In this paper, for the design of a high - speed permanent magnet motor, the base size was derived through the TRV method and to consider the mechanical size of sleeve, stress analysis performed by using analytical method and FEM tools. In addition,the magnetic characteristics of the high - speed permanent magnet motor were analyzed by using FEM tools.

2. The Characteristic Analysis of High Speed PMSM

2.1. Selection of Rotor Size

In order to choose the rotor size of machines, typical method is adapted by using TRV value. TRV means torque per rotor volumes that is related tangential stress on the machines surface, thus, TRV equation is constructed by employing stress or rotor volumes. In this paper, using the rotor volumes, it is constructed the TRV equation and it is derived rotor and axial stack length by using TRV equation as follow equation (1)[7].

$$TRV = \frac{Torque}{\pi \cdot D_{ro}^2 \cdot L_{stk}} \tag{1}$$

Here, the $D_{ro}$is the diameter of the rotor, $L_{stk}$is the axial stack length of the rotor.

The typical range of TRV values are shown as table 1. The analysis model of high speed machine choose the type of the Rare-Earth permanent magnet Sm2Co17 and it is necessary that need the high-output power for using air blower in factory, the range of the TRV value is chosen the 30-75.

Table 1: The TRV range of Machines type[7]

Machine Type	TRV (kNm/m^3)
Small totally-enclosed motors (Ferrite)	7 – 14
Totally-enclosed motors (Sintered Rare Earth or NdFeB)	14 – 42
Totally-enclosed motors (Bonded NdFeB)	21
Integral-hp industrial motors	7-30
High-performance servomotors	15 – 50
Aerospace machines	30 – 75
Large liquid-cooled machines	100 - 250

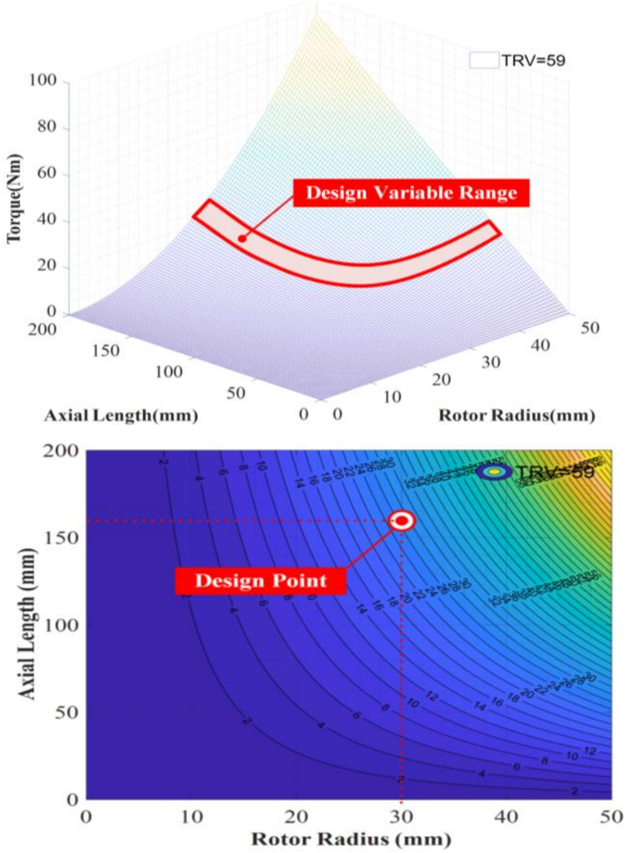


Figure 1: The Design Variable Range according to the following Design Specifications: (a) the design variable range (b) design point

Fig 1. is shown the graph of the rotor and axial stack length size based on TRV value. In the graph, design range is selected according to the following design specification. The table 2. is shown as the design specification of the high speed machines.

Table 2: The Design Specification

Parameter	Value	Parameter	Value
MaxPower	130 [kW]	Rotor Diameter Limits	70[mm]
Rated Torque	26 [Nm]	Axial Length Limits	180 [mm]
MaxSpeed	40000 [rpm]	Permanent Magnet	Sm_2Co_{17}

2.2. Mechanical Stressanalysis of Rotor

Operating the high speed motor safely at maximum speed, mechanical stress should be considered that varies with the rotor and sleeve radius by interference of shrink fit. If the mechanical stress is not considered in initial design stage, mechanical stress occur over the yield strength that makes break the machines,therefore, it is importantthat choose the suitable design parameter for operating safely with operation range, in order that choose the design parameter, it is necessary that mechanical stress is derived by using analytical method [2].

The equation of the mechanical stressis described as follow equation (2) – (5). The stress of the rotor is affected by occurring the interference force (compressive force) due to the interference length, thus, it should be derived by depending on interference length.The compressive force should be derived by using equation (2) [2],[3].

$$p = \frac{\delta}{b\left[\frac{1}{E_o}\left(\frac{c^2+b_o^2}{c^2-b_o^2}+v_o\right)+\frac{1}{E_i}\left(\frac{b_i^2}{b_i^2}\right)+v_i\right]} \quad (2)$$

Here, δ is the interference length, c is the diameter of the rotor, b_o is the diameter of the sleeve by interference force, b_i is the diameter of the PM by interference force, $E_o$is the young's modulus of the sleeve, E_i is the young's modulus of the PM, v_o is the poisson's ratio of sleeve, v_i is the poisson's ratio of PM, p is the compressive pressure on PM.

Derived the interference force, it used the equation of the mechanical stress as follow [2], [11]

$$\sigma_{iw} = \frac{3+v_i}{8}\rho\omega^2[b^2 - r^2] \quad (3)$$

$$\sigma_{ow} = \frac{3+v_i}{8}\rho\omega^2\left[b^2 - \frac{1+3v_i}{3+v_i}r^2\right] \quad (4)$$

$$\sigma_{von-mises} = \sqrt{\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2} \quad (5)$$

Here, ρ is the density of the each materials, ω is angular speed of the machines, r is the radius of the rotor, σ_1,$\sigma_2$are the each stress of the rotor.

The table 3. is shownas the material parameter of the rotor for analytical method, since, the yield strength of PM and sleeve is 35 and 1100 MPa, the maximum stress point should be designed to be lower than the yield strength to prevent fracture [2], [11].

Table 3: The material parameter of the rotor

Parameter	PM	Parameter	Sleeve
Poisson's ratio	0.24	Poisson's ratio	0.284
Young's modulus	120 [MPa]	Young's modulus	205 [MPa]
Density	8300 [kg/m^3]	Density	8190 [kg/m^3]
Yield Strength	35 [MPa]	Yield Strength	1100 [MPa]

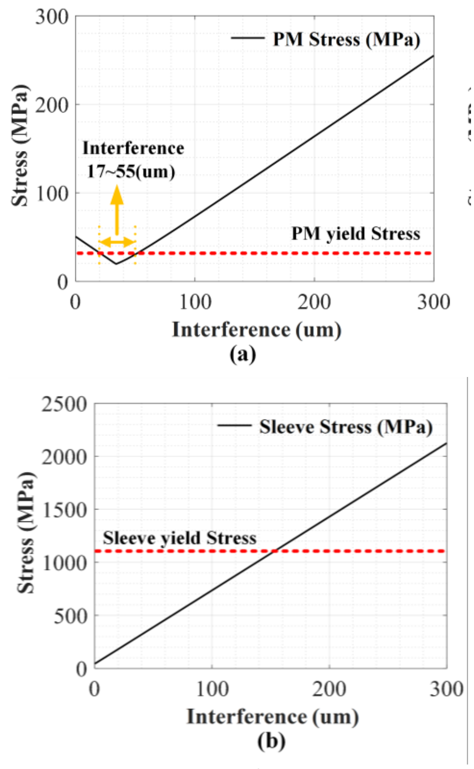


Figure 2: The analytical results of von-mises stress according to interference length: (a) PM stress (b) Sleeve stress

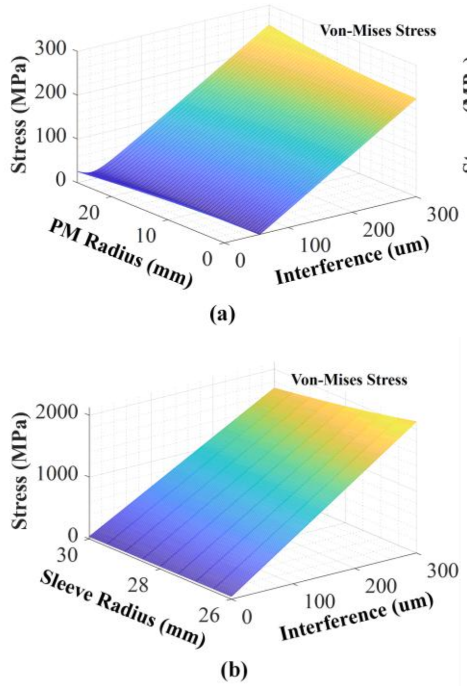


Figure 3: The analytical results of von-mises stress according to interference length and rotor Radius: (a) PM stress (b) Sleeve stress

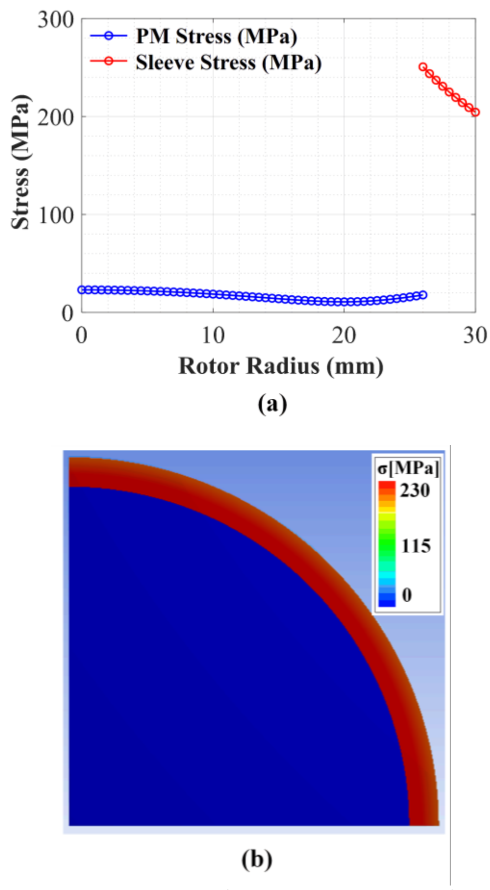


Figure 4. The analytical results of von-mises stress at interference length 30um: (a) PM stress (b) Sleeve stress

The analytical method results of the mechanical stress according to the interference length are shown as Fig. 2. and Fig. 3.. According to analysis results, the range of PM and sleeve interference length are derived between 17 and 55um by comparing materials data. Therefore, for considering the results of mechanical stress, the interference length is chosen 30um. Employing the interference length, the results of the analytical method are shown as Fig. 4(a)..The comparison of Fig.4 (a) and (b) is shown that validity of analytical method. The maximum stress point of PM and Sleeve radius is 22Mpa and 235MPa thus, it is considered that there is no the problem of the strength due to the stress of rotor.

2.3. Characteristics Analysis of High Speed PMSM

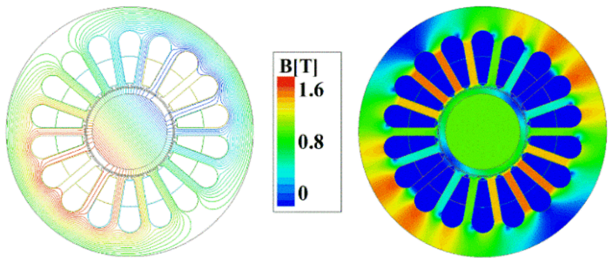
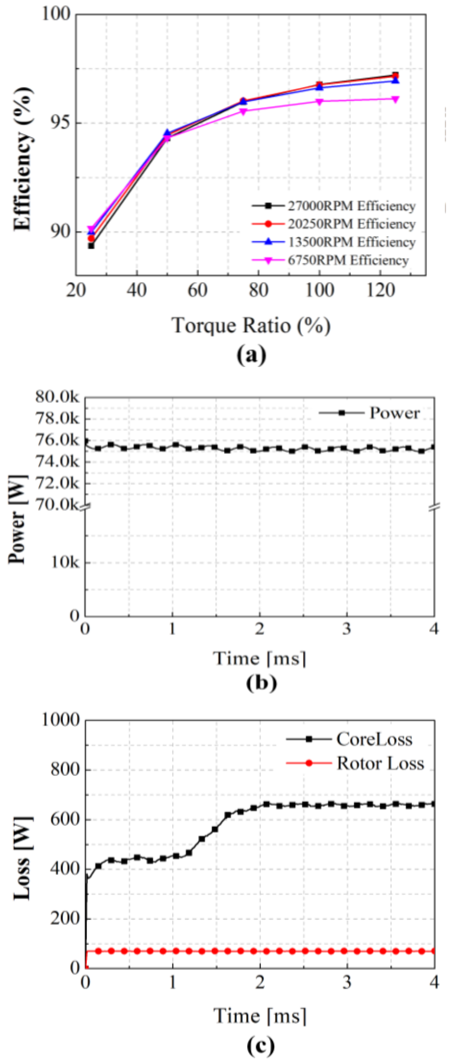
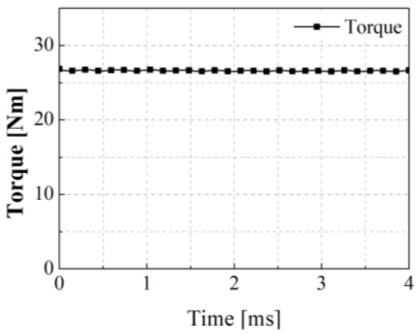


Figure 5: The analysis model of high speed PMSM

The analysis model of high speed PMSM designed through the derived parameter is shown as Fig. 5.. The stator has not magnetic saturation, flux path is formed that the flux flows smoothly. The characteristic analysis result of rated point is shown as table 3. The details results of characteristic is shown as Fig. 6.. The torque ripple satisfied the requirements with 6%. The characteristic satisfied the requirements design point. The rated torque is 26Nm, the efficiency of electromagnetic is 96.8%. The current density is less than 7, it is considered that there is no the problem of the thermal of machines.





(d)

Figure 6: The characteristics analysis results of high speed PMSM: (a) efficiency (b) power (c) loss (d) torque

Table 3: The characteristic results of the high speed PMSM at rated point

Parameter	**Value**	**Parameter**	**Value**
Torque	26.52 [Nm]	Input Current	183 [A_{rms}]
Back-EMF	280 [V_{rms}]	Core Loss	718.85 [W]
Cogging Torque	425 [mNm]	PM Loss	67.62 [W]
Current density	5.42 [A/mm^2]	Copper Loss	295.72 [W]

3. Results and Discussion

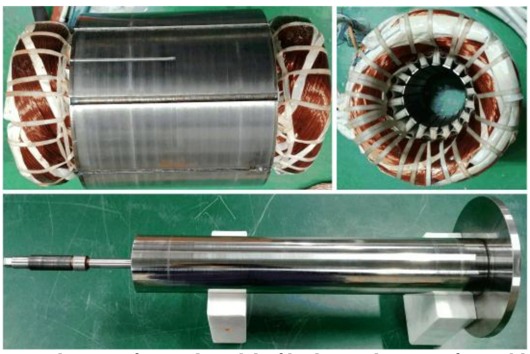
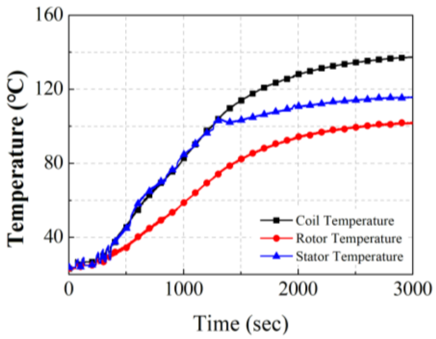
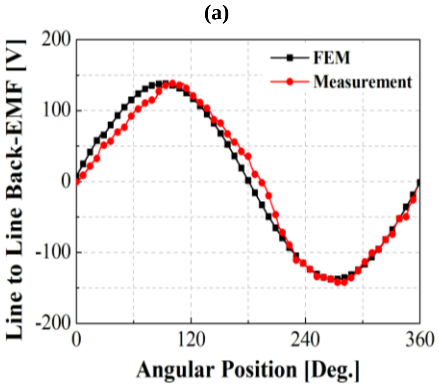


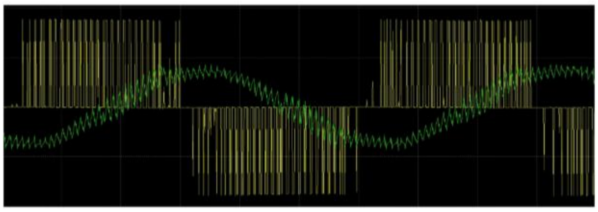
Figure 7: The manufactured model of high speed PMSM for air blower



(a)



(b)



(c)

Figure 8: The measurement results of manufactured model: **(a)** Thermal **(b)** back-EMF **(c)** PWM current waveform at rated point

Fig. 7. is shown as the manufactured model of high speed PMSM based on analysis model shape and results. The rotor of PMSM is made of shrink fit with interference length 30um. Fig. 8. is shownas the results of a no-load back EMF, thermal, input current waveform measurement.The measurement results of back EMF agree well with the analysis results. In addition, as a results of mechanical stress analysis, the rotor of PMSM has not fracture. The temperature of PMSM appear to be high, however, the ambient temperature of operation environment is 100degree Celcius.Therefore, it is considered that the increase rate of temperature due to heat generation is not too large.

4.Conclusion

This paper deals with the characteristic analysis of a high-speed PMSMfor air blower using the analytical method and finite element analysis. By usingthe analytical method, the stress of the rotor is analyzed, then designed the motor by comparing the results and analyzed the electromagnetic characteristics. Based on this, a model was constructed and the model was verified through experiments.

Acknowledgment

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References

[1] K. C. Kim, D. H. Koo, J. P. Hong, and J. Lee A Study on the Characteristics Due to Pole-Arc to Pole-Pitch Ratio and Saliency to Improve Torque Performance of IPMSM, IEEE Trans. Magn., 2007 June, 43(6), pp. 2516-2518

[2] J. H. Ahn, C. Han, C. W. Kim, and J. Y. Choi, Rotor Design of High-Speed Permanent Magnet Synchronous Motors Considering Rotor Magnet and Sleeve Materials,IEEE Trans. Super Conduct., 2018April, 28(3), ID 5201504.

[3] J. H. Ahn, J. Y. Choi, C. H. Park, C. Han, C. W. Kim, and T. G. Yoon, Correlation Between Rotor Vibration and Mechanical Stress in Ultra-High Speed Permanent Magnet Synchronous Motors,IEEE Trans. Magn., 2017 Nov., 53(11), ID 8209906.

[4] Z. Huang. and J. Fang, Multiphysics Design and Optimization of High-Speed Permanent Magnet Electrical Machines for Air Blower Applications, IEEE Trans. Ind. Electro., 2015 May., 63(5), pp. 2766-2774.

[5] J. D. Ede, Z. Q. Zhu, and D. Howe, Rotor resonances of high-speed permanent magnet brushless machines, IEEE Trans. Ind. Appl., 38(6), 2002 Nov/Dec., pp. 967–972.

[6] D. K. Hong, B. C. Woo, and D. H. Koo, Rotordynamics of 120000 r/min 15 kW Ultra High Speed Motor, IEEE Trans. Magn., 45(6), 2009 Jun., pp. 2831–2834.

[7] D. Hanselman, Brushless Motors : Magnetic Design, Performance and Control of Brushless DC and Permanent Magnet Synchronous Motors, E-Man Press LLC, 2012.

[8] D. H. Lee, J. H. Lee, and J. W. Ahn, Mechanical vibration reduction control of two-mass permanent magnet synchronous motor using adaptive notch filter with fast Fourier transform analysis, IET Electr. Power Appl., 6(7), 2012 Aug., pp. 455–461.

[9] Tuysuz, C. Zwyssig, and W. Kolar, A novel motor topology for highspeed micro-machinig applications, IEEE Trans. Ind. Appl., 61(6), 2014 Jun., pp. 2960–2968.

[10] M. S. Lim, S.-H. Chai, J.S. Yang, and J.P. Hong, Design and verification of 150-krpm PMSM based on experiment results of prototype, IEEE Trans. Ind. Electron., 62(12), 2015 Dec.,pp. 7827–7836.

[11] C. H. Park, S. K. Choi, D. E. Hong, T. G. Yoon, and S. H. Lee, Note: Radial-thrust combo metal mesh foil bearing for microturbomachinery, Rev. Sci. Instrum., 84(10), 2013 Oct., p106102

[12] K. Yamazaki, and A. Abe, Loss Investigation of Interior Permanent-Magnet Motors Considering Carrier Harmonics and Magnet Eddy Current," IEEE Trans. Ind. Appl., 2009 March/April,45(2), pp. 659-665.

[13] K. Yamazaki, and N. Fukushima, Iron-Loss Modeling for Rotating Machines Comparison Between Bertotti's Three-Term Expression and 3-D Eddy-Current Analysis, IEEE Trans. Magn., 2010, August, 46 (8), pp. 3121-3124

[14] S. I. Kim, J. Y. Lee, Y. K. Kim, J. P. Hong, Y. Hur, and Y. H. Jung, Optimization for Reduction of Torque Ripple in Interior Permanent Magnet Motor by Using the Taguchi Method, IEEE Trans. Magn., 2005 May, 41(5), pp. 1796-1799