Electromagnetic Vibration Analysis of High Speed Motorized Spindle Considering Length Reduction of Air Gap

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Abstract: In order to reveal the influence of air gap variation on dynamic characteristics of high speed motorized spindle, mathematic models of centrifugal expansion and thermal expansion are established based on elastic mechanics, results show air gap was remarkably reduced by the expansions of stator and rotor. Change rules of radical magnetic flux density and radical electromagnetic force of air gap were calculated with FEA software based on electromagnetic vibration theory, results show the magnetic density and electromagnetic force increased with air gap decreasing, fundamental and harmonic waves of the two parameters increased obviously as well, which lead to a further vibration of the stator, dynamic characteristics was dropt either.

Key words: High speed motorized spindle, air gap, expansion, electromagnetic vibration.

1. Introduction

High speed motorized spindle (HSS) is a key component to machine tool for high machining speed and machining accuracy, but inertial force and friction heat caused by high rotation velocity are two main factors for dynamic error. Centrifugal force is one of the main reasons, it not only leads to a series of shaft damage of spindle, but also acting on other components, such as centrifugal expansion of shaft/rotor, expansion of inner ring on bearing. Hence, support stiffness of interference between shaft and inner ring, contact angle of bearing will variate obviously [1]. Of course, the expansion caused by thermal expansion should not be ignored either.During high rotation speed process, the temperature of HSS will rise sharply. Although water cooling system can reduce spindle shell and stator temperature to some extent, however, due to the complexity of spindle structure, especially the contact resistance and air gap, heat generated by motor rotor cannot exchange to cooling system smoothly, which will cause heat concentration and lead to thermal deformation and thermal expansion.

HSS is a highly coupled electromechanical system, the vibration of spindle system is not only attributed to spindle-bearing system, but also the interaction between electromagnetic field and spindle structure [2]. Chen [3] has pointed out the air gap length can be altered by radial expansion of spindle rotor, and spindle vibration and nonlinear heat transfer can also affected by these changes. Ignoring thermodynamic properties, the variation of air gap will change air gap flux density and radial electromagnetic force [2], [4], [5]. In addition to the unbalanced magnetic force acting on the rotor, radial electromagnetic force is another main source of electromagnetic noise and stator. Wang [6] has analyzed air gap variation degree of a certain type of motorized spindle by finite element method (FEM), pointed out the radial expansion of rotor has great influence on air gap at high speed, and cannot be ignored. However, the electromagnetic vibration characteristics caused by this change have not been studied deeply. The influence of unbalanced magnetic force on the dynamic characteristics of spindle system has been studied by Chen [7], the influence mainly caused by doubling frequency, but radical electromagnetic force has not been included in the study. Zhang [8] studied the influence of air gap growth on spindle vibration characteristics by reducing rotor diameter, and determined the optimal air gap length, but air gap length decreases with the increase of speed in actual use, moreover, the study also did not explain the dynamic change law and the impact on the dynamic error.

In this paper, the centrifugal force and thermal expansion were calculated, and the variation of radical electromagnetic force caused by above effects were taken into consideration in order to study such influence on the electromagnetic vibration and dynamic characteristics of high speed spindle.

2. Mathematical Model

Variation of air gap is determined by two factors: Centrifugal force acting on rotor and thermal load acting on both stator and rotor. Stator has only thermal expansion, rotor has both expansions, the variation is determined by difference between initial design value and the total expansion of stator and rotor.

The rotor of HSS and the rotor of motor are connected under interference fit, assume the two material properties are the samefor simplicity, thus the two rotors can be regard as one. Therefore, the rotor can be equivalent to thick wall cylinder, and solving process is similar as axisymmetric plane strain problem.

2.1. Air Gap Variation

Based on assumptions above, thermal expansion formula of the two components can be written as [9]:

$$u(r)=\frac{1+\upsilon}{1-\upsilon}\frac{a}{r}\left[\int_{r_i}^{r}Trdr+(r_i^2+\frac{1-3\upsilon}{1+\upsilon}r^2)\frac{1}{r_e^2-r_i^2}\int_{r}^{r_e}Trdr\right]. \tag{1}$$

In above formulas, r_e and r_i are the outer diameter and inner diameter of the cylinder respectively. Thermal displacements u_{st} and u_{rt} of stator and rotor are obtained by fill corresponding upper limit and lower limit into equation (for example, $r_{stator.i}$ and $r_{stator.e}$ are inside radius and external radius of stator respectively, and the same naming method for $r_{rotor.i}$ and $r_{rotor.e}$). Meanwhile the centrifugal expansion u_{re} of rotor is obtained using the same method [10]:

$$u_{rc}=\frac{\rho\cdot 4\pi^2\cdot f_{rotor}^2(1-\upsilon)\cdot r_{rotor.e}^3}{4\cdot E}. \tag{2}$$

where, ρ is material density. f_{rotor} is rotating frequency of rotor.

Hence the final variation of air gap is obtained:

$$\Delta\delta=\delta_0-\left[u_{st}(r)+u_{rc}(r)+u_{rt}(r)\right]. \tag{3}$$

where, δ_0 is initial air gap length.

2.2. Electromagnetic Force under the Change of Air Gap

When radial electromagnetic force wave is close to structural mode of the HSS, stator resonance and large electromagnetic noise will be generated [11]. Compared with the time harmonics of nonsinusoidal waveforms, the spatial harmonics produced by the stator and rotor structures have greater influence on the HSS [8].Since only structural changes and the effects of spatial harmonics are considered in this paper.

FEM is more accurate than analytic method especially for complex motor structure [11]. Therefore, the FEM is used in this paper. The calculation of radial component is based on Maxwell stress tensor theory:

$$\sigma_r = \frac{b_r^2(\theta,t) - b_t^2(\theta,t)}{2\mu_0} \tag{4}$$

Flux density is a function of air gap permeance, and air gap permeance depends on air gap length, hence:

$$b(\theta,t) = f(\theta,t)\lambda(\theta,t) \tag{5}$$

$$\lambda(\theta,t) = \Lambda = \mu_0 / k_\delta \delta \tag{6}$$

where, $f(\theta,t)$ is agneto-motive force in the air gap, $\lambda(\theta,t)$ is gnetic conductivity of air gap, k_δ is air gap coefficient， δ is air gap length.

3. Finite Element Model

3.1. 3D Model of HSS

Spindle parameters are shown in Table 1. Geometric features such as taper shank are ignored for simplify, rotor surface is supposed smooth, inner hole is through hole and motor without eccentricity.

Table 1. Main Structural Parameters of HSS

Structural parameters	value	Structural parameters	value
Inner hole diameter of rotor d_0 / mm	36	Air gap length δ / mm	0.3
Outside diameter of rotor d_1 / mm	82	Top speed ω / (r/ min)	24000
Inner diameter of rotor d_2 / mm	54	Rated power P / kW	30
Inner diameter of stator d_3 / mm	82.6	Front bearing	NSK7012C
Outside diameter of stator d_4 / mm	132	Rear bearing	NSK7010C

3.2. Centrifugal Expansion, Thermal Expansion and Air Gap Reduction of HSS

Spindle expansion caused by centrifugal and thermal load, hence the centrifugal and thermal deformation are calculated separately in order to get precise results. Displacement of centrifugal expansion can be obtained by applying rotation speed on spindle axial after the spindle model was imported in Ansys®, as shown in Fig. 1. The radical expansion displacement raise as rotation speed increase and will achieve maximum when the speed reach to its top value.

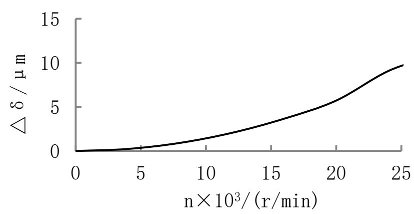


Fig. 1. Rotor expansion curve under rotation speed effect.

Unlike centrifugal expansion, thermal expansion occurs in spindle rotor as well as housing under thermal load. During rotating, heat production, heat transfer, heat convection and heat dissipation are dynamic process, thereby the thermal expansion is hard to measure. According to the change rule of centrifugal displacement, the deformation reaches to its maximum with rotation speed simultaneously, therefore take thermal displacement under 20 000 r/min as a research target for simplicity. Under this condition temperature of inner surface and outer surface of rotor are 118℃ and 113℃ separately, inner surface of spindle rotor is 115℃, 70℃ and 35℃ for inner surface of housing and outer surface of rotor separately. Thereout, thermal expansion displacements of the two surface are 25.2μm and 82.2μm respectively, total displacement is 107.4μm, while centrifugal expansion displacement is 5.7μm, total reduction of air gap length is 113.1μm, so it is clearly the reduction extent of air gap is mainly depend on thermal expansion of housing and rotor. The reduction accounts for 3.25% of total length when only centrifugal exists, this ratio raises to 35.8% when there is only thermal load; under the two effects the ratio finally achieved 37.7%.

HSS is the core of machine tool, For the technical secrecy and commercial competition, it is hard to obtain the structure details. In order to verify above theoretical hypothesis, a general asynchronous AC motoris used and the change of air gap length is obtained by modifying the diameter of rotor during modeling.

4. Example

Simulation process is shown in Fig. 2.

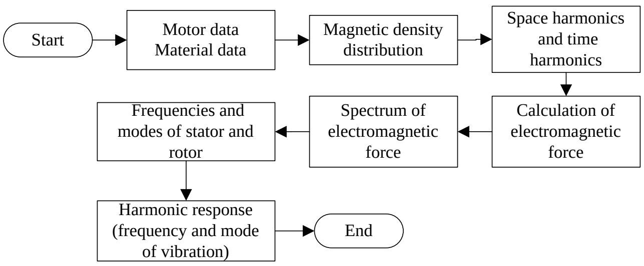


Fig. 2. Calculation flow of electromagnetic vibration.

4.1. 2D Model of Motor

Y160M-4 asynchronous AC motor is selected and the structural parameters are shown in Table 2. The air gap length of the motor is 1mm according to the Table 2, then another motor model can be obtained by increasing the rotor diameter 0.3mm.

Table 2. Structure Parameters of Y160M-4 Asynchronous AC Motor

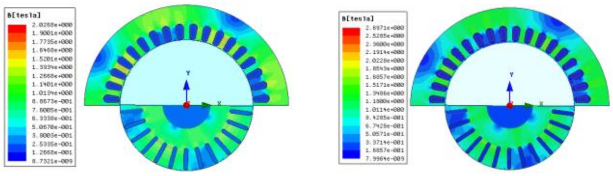
Structural parameters	Value	Structural parameters	Value
pole-pair numbers	4	Slot number of rotor	26
Phase number	3	Outer diameter of rotor	169mm
Rated speed	1500r/min	Inner diameter of rotor	60mm
Rated power	11kW	Inner diameter of stator	170mm
Frequency	50Hz	Outer diameter of stator	260mm
Air gap length	1mm	Core length of stator	155mm
Slot number of stator	36		

4.2. Air Gap Magnetic Flux Density and Radial Electromagnetic Force

4.2.1 Characteristics of magnetic field in electric machine

The analysis of radial electromagnetic force and its harmonics are the key to electromagnetic vibration.

Fig. 3 shows the size and distribution of flux density in the motor under different rotor diameters. It can be seen by compare 3a with3b that the magnetic flux densitytends to rise everywhere in addition to the outer tooth of rotor, where the magnetic flux density is decrease after the rotor expansion. For instance, the maximum value increased by 33% from 2.026T to 2.697T. It can be inferred the radial electromagnetic force will increase greatly after the rotor expands.For more intuitive analysis of air gap magnetic density and electromagnetic force changes, the spatial variation waveforms of magnetic density and electromagnetic force with rotor rotation are plotted respectively, along with the corresponding Fourier transform.



a. Unchanged b. Changed

Fig. 3. Flux density of motor in a certain.

4.2.2 Air-gap magnetic density

The distribution of air gap magnetic flux density is the key factor affecting motor vibration and noise, the air gap magnetic flux density changes with the variation of air gap length. Fig. 4 to Fig. 7 show the variation of the radial magnetic flux density and corresponding Fourier decompositionwith the electrical angle under the no-load condition of the high speed spindle.

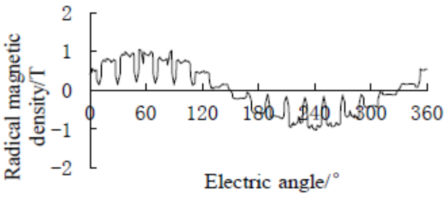


Fig. 4. Air gap magnetic density at a certain time (Rotor diameter unchanged).

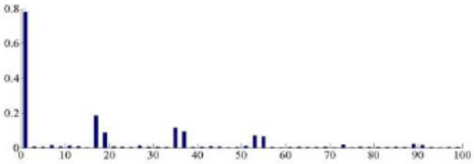


Fig. 5. Magnetic density FFT(Fast Fourier Transform) (Rotor diameter unchanged).

Results can be obtained by contrasting Fig. 4 and Fig. 6 that both waveforms are similar and change in the sine law with the rotation of motor, when diameter of the rotor increases, its waveform show more "sawtooth" and the amplitude are slightly increased. For instance, when the electric angle is 55°, radial magnetic flux increased by 9.1% from 1.018T to1.109T, which is verified by the FFT images respectively.

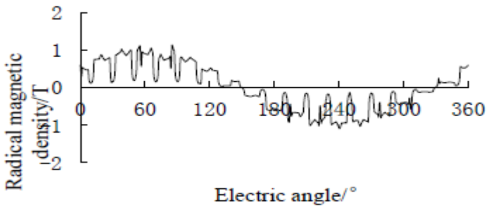


Fig. 6. Air gap magnetic density at a certain time (Rotor diameter changed).

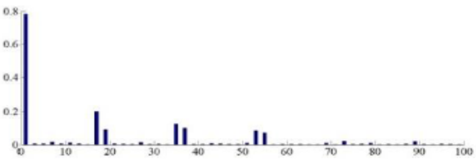


Fig. 7. Magnetic density FFT (Rotor diameter changed).

It shows the fundamental change of air gap magnetic density is small with the expansion deformation of the rotor by comparing Fig. 6 and Fig. 7, but the amplitude of each harmonic amplitude increased obviously.The results show that the amplitude of magnetic flux density increases with the decrease of air gap length.

4.2.3 Radial electromagnetic force

A similar variation curve and corresponding Fourier transform are also drawn for the radial electromagnetic force, as shown in Fig. 8 and Fig. 9.

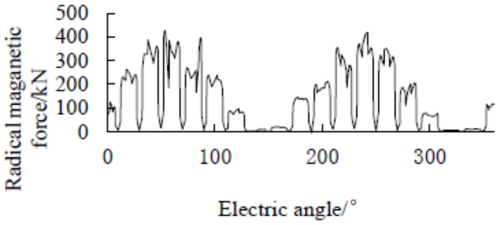


Fig. 8. Radial electromagnetic force (Rotor diameter unchanged).

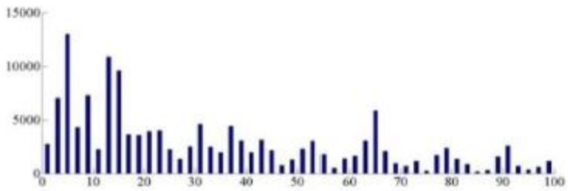


Fig. 9. Radial electromagnetic force FFT (Rotor diameter unchanged).

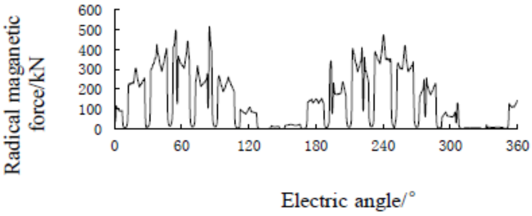


Fig. 10. Radial electromagnetic force (Rotor diameter changed).

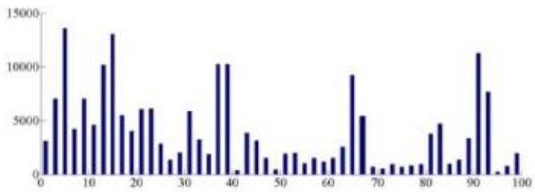


Fig. 11. Radial electromagnetic force FFT (Rotor diameter changed).

The variation of radial electromagnetic force is sine wave,it is similar to the air gap magnetic flux density.It can be conclude by comparing Fig. 9 with Fig. 11 the amplitude of radical electromagnetic force is obvious increase after the rotor expansion. When the electric angle is 55°, the radial electromagnetic forces are increased by 16.7% from 418.012kN and 487.864kN under the two conditions. Furthermore, it can be concluded that not only fundamental and harmonic amplitudes increase significantly, but also the amplitude variation of each harmonic. Hence, it is deducedthe air-gap induced radial electromagnetic force has a great influence on motor vibration.

Fig. 12 to Fig. 15 show the time history curve of air gap to electromagnetic force and its Fourier transform. From Fig. 12, it shows the electromagnetic force reaches steady state gradually after 60ms, the frequency of each harmonic can be obtained after decomposed as shown in Fig. 13. The same treatment is done for Fig. 14 and Fig. 15. In contrast Fig. 14 with Fig. 12, the frequency of air gap harmonics of motor are mostly between 0-2500Hz, and it is more obvious in the low-frequency region of 0-1000Hz. Compare Fig. 13 with Fig. 15, it can be seen the harmonics increase with the increase of rotor diameter, which means the change of the rotor geometry has an important influence on the radial electromagnetic force.

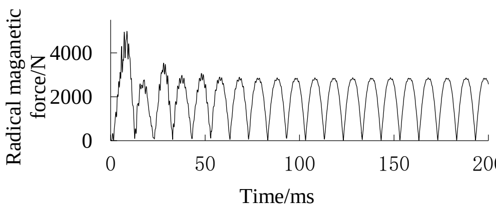


Fig. 12. Time-history curve of radial electromagnetic force(Rotor diameter unchanged)electromagnetic.

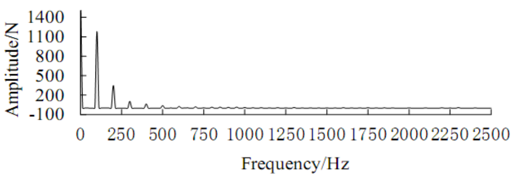


Fig. 13. Frequency-amplitude curve of radial force(Rotor diameter unchanged).

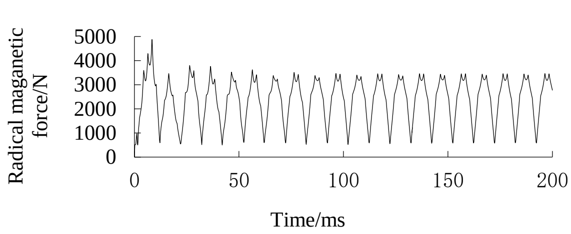


Fig. 14. Time-history curve of radial electromagnetic force (Rotor diameter changed).

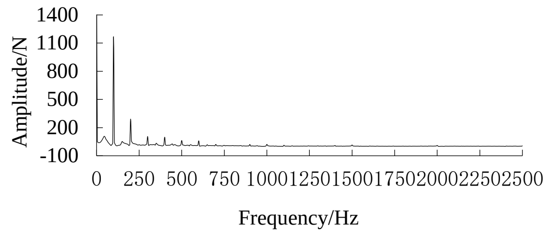


Fig.15. Time-history curve of radial electromagnetic force (Rotor diameter changed).

5. Dynamic Response Analysis of Stator and Rotor

The coupling condition is regarded as magnetic-solid weak coupling and the stator and rotor are analyzed separately.

5.1. Modal Analysis

Create 3D model of stator and rotor according to parameters in Table 2, Perform free modal analysis on the stator and rotor after meshed and boundary conditions is addedinANSYS®.Taking seventh order mode as the new first order mode after removing the first six rigid motion modes, the others are named in turn.

The frequencies of the new first six modes of stator are shown in Table 3. The natural frequency range of the stator coincides with the frequency range of the electromagnetic force wave. Therefore, the influence of electromagnetic force as excitation force on stator vibration cannot be ignored.

Table 3. First Six Order Frequency of Stator

Order	1	2	3	4	5	6
Frequency/Hz	967.3	967.6	1539.7	1540.6	2587.8	2588.3

The first six order frequency of rotor is shown in Table 4. Compare Table 4 with Fig. 14, the rotor frequencies are not within the main frequency range of the electromagnetic force, which means the direct effect of electromagnetic force has a tiny influence on the rotor and the effect of electromagnetic force on stator vibration should be mainly analyzed.

Table 4. First Six Order Frequency of Rotor

Order	1	2	3	4	5	6
Frequency/Hz	4637.1	5072.6	5076.2	5177.1	5177.5	5977.2

5.2. Harmonic Response Analysis

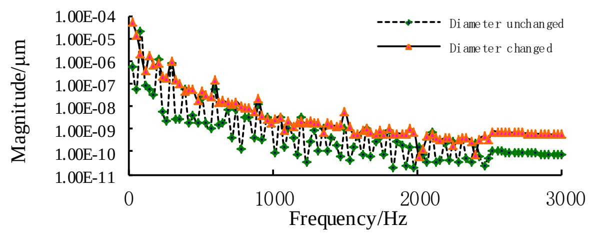


Fig. 16. Response of stator under two kinds of force waves.

Fig. 16 is the response curves of the stator under the two exciting forces. On the one hand, stator vibratesobviously at frequencies of 960Hz and 2582Hz, this indicates the two frequencies coincide with the electromagnetic force frequency. Meanwhile, electromagnetic force also arouses more resonance, especially at low order frequency. With the increase of excitation frequency, the vibration shows a downward trend, which shows the electromagnetic vibration of the motor is mainly affected by the lower harmonics. On the other hand, the amplitude of stator vibration increases obviously when the air gap changes, which means the expansion phenomenon in high speed spindle surely cause additional electromagnetic vibration.

Based on above analysis, these results prove the vibration of motorized spindle increases with the decrease of air gap, and the decreases of air gap comes from the centrifugal expansion and thermal expansion of the rotor system, this indicates increase the gap length of motor will restrain the vibration of highspeed motorized spindle, but the determination of the length should take into account the influence of motor efficiency, because the increase of air gap will reduce the motor efficiency of motorized spindle.

6. Conclusion

The electromagnetic vibration of spindle motor can be increasedwith the rise of radial electromagnetic force when the air gap changes. As the rotational speed increases, the air gap decreases gradually while the radial magnetic density and radial electromagnetic force increase. It shows that this is the inherent phenomenon of the HSS and the vibrationincreases with the increase of the $D_m N$ value. Vibration of motor stator decreases with the increase of electromagnetic force frequency, that means the influence of electromagnetic force with low frequency is higher than the higher order frequency. Therefore, the influence of low order force on the dynamic characteristics of HSS should be emphasized.

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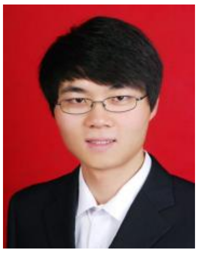

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