Analysis of Electromagnetic Force and Vibration Characteristics for Transverse Flux Permanent Magnet Motor

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Abstract: Electromagnetic noise of motor is determined by the electromagnetic force acting on stator system and motor vibration characteristics. In this article, three dimensional model of motor is established, air-gap field is calculated by finite element method, and the compositions of stator system electromagnetic force and vibration characteristics of motor are analyzed. Electromagnetic noise sources are found out by analyzing the calculation results, which provides theoretic support for suppressing electromagnetic noise for transverse flux permanent magnet motor.

Key Words: Transverse flux permanent magnet motor (TFPM), Electromagnetic force, Natural frequency, Vibration noise, Finite element method (FEM)

1 INTRODUCTION

In order to improve motor torque density, German professor Herbet Weh designed Transverse Flux Permanent Magnet Motor (TFPM) in 1986. The distribution of its three dimensional magnetic circuit can decouple magnetic circuit and electric circuit, and improves the density of motor torque fundamentally [1]. Meanwhile, TFPM has advantages of high free degree, high fault tolerant, saving raw materials, and so on. It is suitable for high torque, low speed drive application situation. The application prospect of TFPM is great. In recent years, scholars have done a lot of researches on TFPM, including some advanced technology [2-4], which perfects the theory of TFPM. At present, TFPM has some general problems, such as complex structure, big magnetic flux leakage, low power factor and electromagnetic vibration noise [5-7], which hinder its application. Among them, the study on electromagnetic vibration noise is less and further study is needed to suppress electromagnetic noise.

Electromagnetic noise comes from magnetic force vibration and the size of noise is decided by the electromagnetic force and motor vibration response characteristics. At present, the main method of suppressing motor electromagnetic noise is avoiding resonance. Analysis is divided into the following four stages, analyzing air gap magnetic field, calculating the amplitude and frequency of electromagnetic force, calculating the natural frequency of stator system, taking measures to make the electromagnetic excitation frequency away from natural frequency to avoid resonance phenomenon, or reducing the amplitude of electromagnetic force and then reducing vibration amplitude, so as to achieve the purpose of reducing electromagnetic noise [8-13].

In this paper, a 20kw TFPM is studied. Air gap magnetic field is calculated by using finite element method, constituent parts of electromagnetic force and vibration characteristics of the motor are analyzed, which has important significance to suppress the electromagnetic noise of TFPM and promote the application of this kind of motor in related fields.

2 STRUCTURE OF TFPM

TFPM is free in designing, and has many topologies. Among them, magnetic concentrating structure is widely used. The topology structure of TFPM in this paper is magnetic concentrating structure. The structure of the rotor and stator is shown in Figure 1.The motor is three-phase circular array, each phase sector occupies 120 degrees and they share a rotor [14]. Stator adopts bilateral structure, each phase has 5 pairs of internal and external teeth, each pair of internal and external tooth has 180° electrical angle difference. The stator teeth and back yoke is laminated by silicon steel sheet, the laminated direction are axial and circumferential direction, respectively. Then the stator teeth insert the back yoke hole and they constitute the stator magnetic circuit. In order to saving space, double winding is adopted for the motor. Each phase has inside and outside winding, and their direction of current are opposite. Rotor iron core is laminated by silicon steel sheet. Permanent magnets are evenly distributed in the circumference of rotor, the number is 34. Permanent magnet magnetization direction along Z axis, as Figure 2 shows. The magnetization direction of adjacent permanent magnet is opposite, and all permanent magnets constitute 17 poles. Table 1 shows main parameters of the motor.

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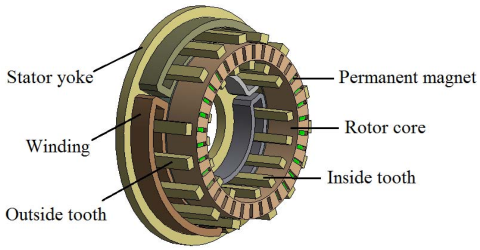


Fig 1. The structure of TFPM

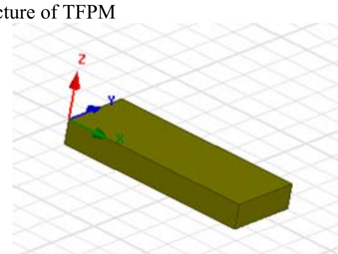


Fig 2. The magnetization direction of permanent magnet

Table1. Main Parameters of Motor

Phase Number	3
Voltage Rating	380 V
Rated Power	20 KW
Rated Speed	450 r/min

3 ANALYSIS FOR AIR GAP MAGNETIC FIELD AND ELECTROMAGNETIC FORCE

Electromagnetic vibration is the result of the alternating magnetic force caused by air gap magnetic field. To calculate the electromagnetic vibration noise, first of all, air gap magnetic field and electromagnetic force should be analyzed. The structure and magnetic circuit of TFPM is complex, meanwhile, the magnetic flux leakage is large. Traditional analytical method is no longer applicable for calculating magnetic field, because it should take many approximations and the calculation error is big. With the development of computer and related technologies, the numerical analysis method of magnetic field has been comparatively mature and become an important analysis method for magnetic field analysis. In this paper, 3D transient magnetic field and electromagnetic force of the motor is calculated by ANSYS Maxwell 2015.

Maxwell's equations are the basis of calculation for TFPM air gap magnetic field. For low frequency transient magnetic field, the equations can be written as the following form.

$$\left.\begin{aligned} &\nabla \times H = \sigma E \\ &\nabla \times H = \frac{\partial B}{\partial t} \\ &\nabla \cdot B = 0 \end{aligned}\right\} \tag{1}$$

The following two equations can be constructed by equation 1.

$$\left.\begin{aligned} &\nabla \times \frac{1}{\sigma} \nabla \times H + \frac{\partial B}{\partial t} = 0 \\ &\nabla \cdot B = 0 \end{aligned}\right\} \tag{2}$$

Where H is magnetic field strength, E is electric field intensity, B is magnetic flux density.

For calculating the three-dimensional transient magnetic field, T - Ω algorithm is adopted and local subdivision method can be used to calculate the effects of transient motion.

Calculation process is divided into the following steps. Firstly, create 3D model according to the motor structure. Secondly, import the model into Maxwell software and define material properties. Thirdly, set up excitation source and boundary condition. Fourthly, generate mesh and add solution setup. Finally, solve all [15]. The mesh generation of stator and rotor are shown in Figure 3.

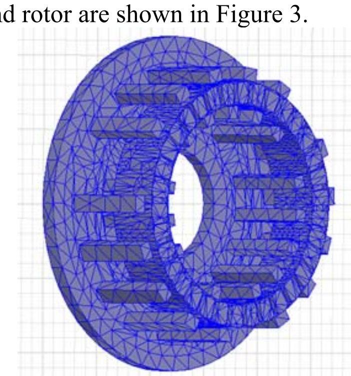


Fig 3. The mesh generation of stator and rotor

This kind of TFPM has three phases, each phase differs by 120 electrical degree from other two, so analysis of one phase magnetic field and electromagnetic force distribution can know the other two phases. At some point, the relative position of stator and rotor is shown in Figure 4. Figure 5 and 6 show the flux density cloud and chart vector diagram of stator.

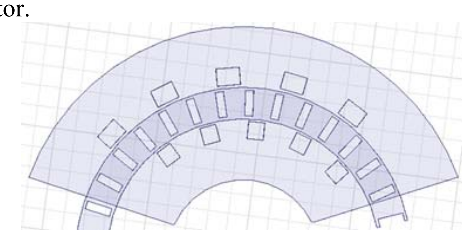


Fig 4. The relative position of stator and rotor

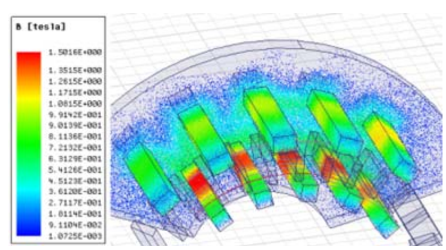


Fig 5. The flux density cloud chart of stator

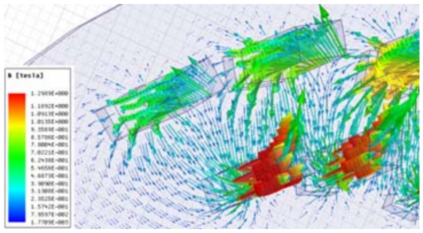


Fig 6. The flux density vector diagram of stator

From flux density vector diagram, the magnetic field generated by permanent magnet through stator core and air gap, then into the stator outside tooth, then into the stator yoke and out from the stator inside tooth, and then through the air gap and return to permanent magnet stator core. Three dimensional equivalent magnetic circuit is shown in Figure 7.

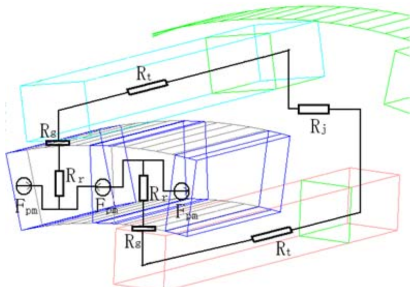
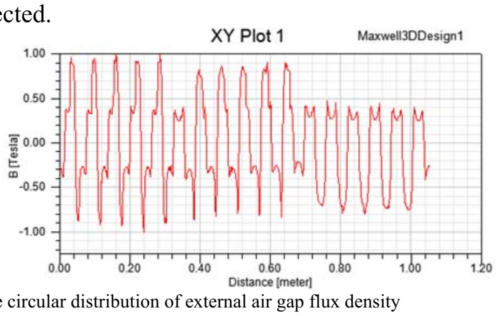


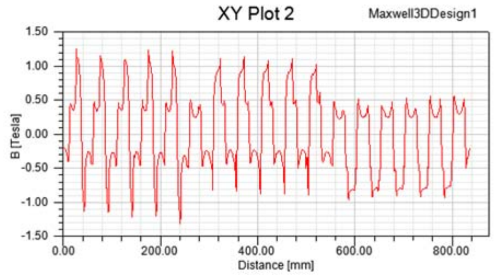
Fig 7. Three-dimensional equivalent magnetic circuit of TFPM

Where F_{pm} is magnetomotive force of permanent magnet, R_t , R_j , R_g , R_r is the stator tooth, stator yoke, air gap and reluctance rotor, respectively.

Figure 8 is the circumference distribution of the air gap flux density. The air gap flux density distribution shows that flux density distribution of five outside teeth (or inside teeth) of each phase are approximately the same. In other words, at the same time, each of the five outside teeth (or inside teeth) of one phase bear almost the same electromagnetic force. Among them, the flux density of inside teeth is slightly bigger than outside teeth, because the inside teeth width are slightly smaller than outside teeth. From Figure 8, the air gap magnetic field has an obvious distortion, which is caused by leakage magnetic flux. Magnetic flux leakage has a big influence on the electromagnetic force of inside and outside teeth, so its effects on electromagnetic vibration noise should not be neglected.



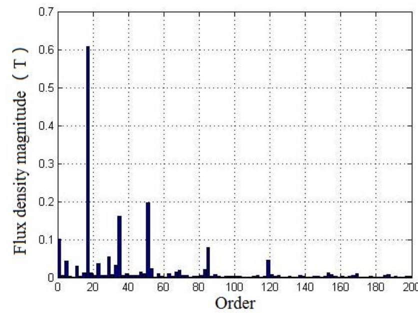
(a) The circular distribution of external air gap flux density



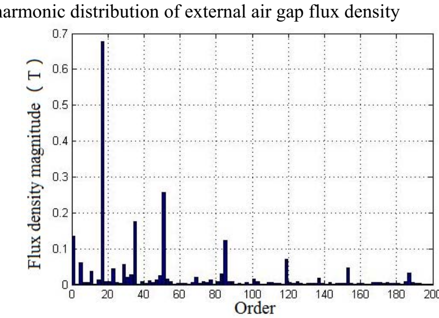
(b) The circular distribution of internal air gap flux density

Fig 8. The circular distribution of air gap flux density

Figure 9 shows the air gap flux density harmonic distribution. The fundamental wave amplitude of inside and outside air gap are 0.68T and 0.61T, and its frequency is 127.5 Hz. The harmonic of air gap magnetic field is rich. Especially the third harmonic, reaches 37% of the fundamental wave amplitude.



(a) The harmonic distribution of external air gap flux density



(b) The harmonic distribution of internal air gap flux density

Fig 9. The harmonic distribution of air gap flux density

When motor running, the electromagnetic force acting on stator and rotor change with the air gap flux density. Periodic electromagnetic force cause the stator and rotor vibration. The vibration of rotor is transmitted to motor shell by bearing, while the elasticity and damping of bearing can make the vibration attenuation [16]. For TFPM, electromagnetic noise mainly comes from the vibrations caused by the electromagnetic force acting on the stator teeth. The vibrations include teeth vibration and tooth end cover vibration. Figure 10 is the stator teeth electromagnetic force distribution at one point.

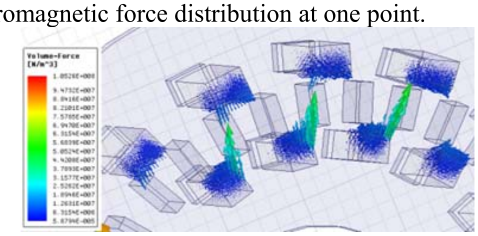
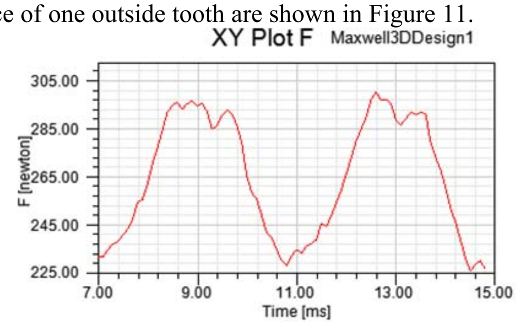
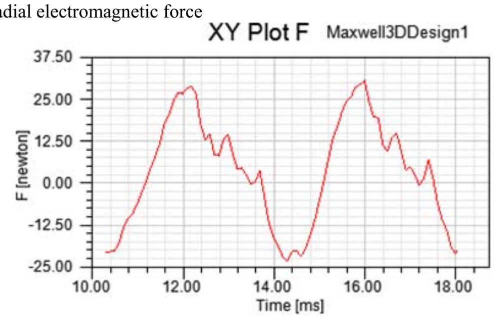


Fig 10. The electromagnetic force distribution of stator teeth

The stator tooth electromagnetic force can be decomposed into radial and tangential force. Among them, tangential electromagnetic provides torque. Different from traditional motor structure, the radial and tangential electromagnetic force of TFPM can all cause motor vibration and then produce electromagnetic noise. When motor turns 360 electrical degrees, the radial and tangential electromagnetic force of one outside tooth are shown in Figure 11.



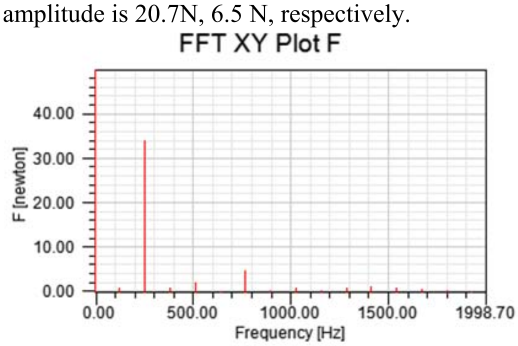
(a) Radial electromagnetic force



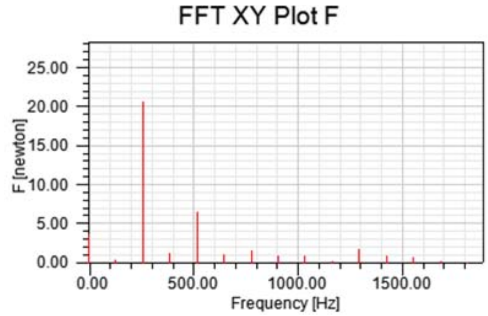
(b) Tangential electromagnetic force

Fig 11. The electromagnetic force of stator tooth

From the change of electromagnetic force, radial force electromagnetic force is composed of constant and alternating part, and the tangential electromagnetic force is mainly alternating part. Radial electromagnetic force constant part is 265N, and the direction along motor radius point to rotor. Main content of alternating part is shown in Figure 12 (a), as we can see, the frequency of 255Hz and 765Hz electromagnetic force is the main components of the radial alternating force, and the amplitude is 34.1N, 4.9 N, respectively. In tangential electromagnetic force, the frequency of 255Hz and 510Hz electromagnetic force are the main components of the tangential alternating force, and amplitude is 20.7N, 6.5 N, respectively.



(a) The FFT of radial electromagnetic force



(b) The FFT of tangential electromagnetic force

Fig 12. The FFT of stator tooth electromagnetic force

According to Maxwell electromagnetic force calculation formula, the normal electromagnetic force on unit area is proportional to the square of the magnetic flux density and its instantaneous value can be described by equation 3.

$$p(\theta,t) = b^2(\theta,t) / 2\mu_0 \tag{3}$$

Where $p(\theta,t)$ is electromagnetic transient value, $b(\theta,t)$ is air gap flux density, μ_0 is vacuum magnetic permeability, θ is position angle, t is time.

Contrast the electromagnetic force with the air gap flux density harmonic content, for radial force of stator teeth, the electromagnetic forces with frequency of 255Hz and 765Hz are produced by gap flux density fundamental wave and three times harmonic respectively. For tangential force of stator teeth, the electromagnetic forces with frequency of 255Hz and 510Hz are produced by the air gap flux density fundamental wave and second harmonic respectively. These forces may cause large electromagnetic noise when the motor inherent frequency is close to these frequencies.

4 ANALYSIS FOR MOTOR VIBRATION CHARACTERISTIC

Motor electromagnetic noise size is not only related to the electromagnetic force, but also closely related to the vibration characteristics of the motor. With the method of structural mechanics, the vibration characteristics of the motor can be described by natural frequencies, mode shapes, etc. Analysis methods include analytic method and numerical method, analytical method has limitation of a poor accuracy when calculating the modal of complex constructions, but the finite element method (FEM) can take into account the influence of the irregular structure of motor to obtain a more accurate inherent frequency [17-20]. In this paper, we use the finite element numerical method to analyze the vibration characteristics of TFPM.

The basis of finite element modal analysis is energy method, and the Lagrange's equation can be expressed as follows.

$$F_i = \frac{d}{dt}\left(\frac{\partial L}{\partial q_i}\right) - \frac{\partial L}{\partial q_i} \tag{4}$$

Where i represents positive integer, L is the Lagrange function, $L = T - U$, F_i is the generalized force, q_i is the generalized coordinates. The displacement vector of unit nodes expressed as follows.

$$T = \frac{1}{2}\dot{\delta}^{T}\int_{v} N^{T}\rho_{e} N dv\, \dot{\delta} \quad (5)$$

$$U = \frac{1}{2}\delta^{T}\int_{v} B^{T} D B dv \delta \quad (6)$$

Substitute equation 5 and 6 into equation 4, the value of the unit of mass matrix and stiffness matrix can be obtained.

$$M_{e} = \int_{v} N^{T}\rho_{e} N dv \quad (7)$$

$$K_{e} = \int_{v} B^{T} D B dv \quad (8)$$

By using the relationship between stress, strain and displacement and Hamilton theorem, we can obtain the discrete equation of structure units:

$$[M]\{\ddot{u}\}+[R]\{\dot{u}\}+[K]\{u\}=\{F\} \quad (9)$$

Where $[M]$, $[R]$ and $[K]$ are respective represent for mass, damping and stiffness matrix, $\{u\}$, $\{F\}$ are respective represent for displacement and force vector. When the motor is free vibrating, force vector is zero and ignore the damping, substituting $A\sin(\omega t)$ into u to calculate TFPM modal, and then, equation 9 can be expressed as:

$$([K]-\omega^{2}[M])\{u\}=0 \quad (10)$$

Where ω is natural vibration circular frequency. $f=\frac{\omega}{2\pi}$ is natural vibration frequency, and $\{u\}$ is the corresponding vibration model.

The actual structure of TFPM is relatively complicated, the simplify process of motor model is needed when proceeding the modal analysis. In this paper, we build the model of the stator iron core, permanent magnet, winding, rotor field spider, bearing, front and rear bearing cap, front and rear end cover and the frame of engine base. Assume all parts of motor are closely combined, and the influence of screws and holes are ignored, the TFPM modal is calculated by Ansys Workbench.

Figure 13 is the mesh generation model of the motor, Table 2 is the calculation result of natural frequency of the whole motor. Figure 14 is the corresponding vibration mode figure.

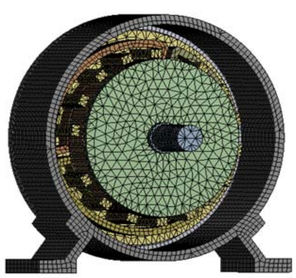
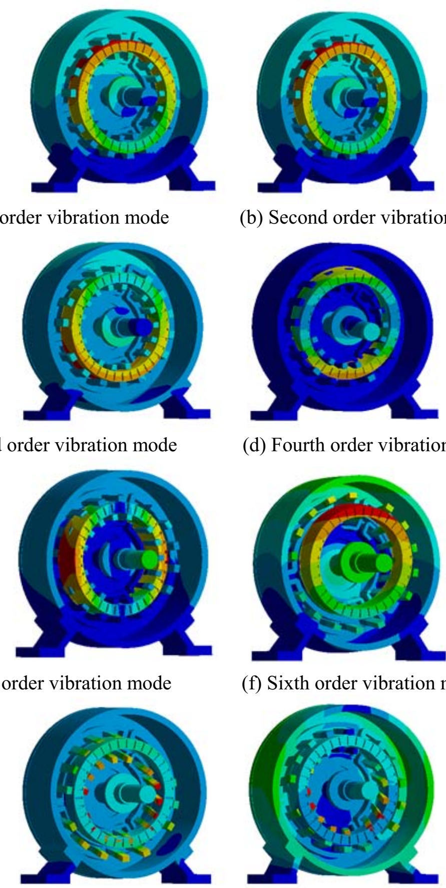


Fig 13. The mesh generation model of motor

Table2. The Natural Frequency of Motor

Vibration Model	Inherent Frequency	Vibration Model
1	249.95 Hz	Figure 14 (a)
2	422.03 Hz	Figure 14 (b)
3	460.14 Hz	Figure 14 (c)
4	516.76 Hz	Figure 14 (d)
5	540.29 Hz	Figure 14 (e)
6	581.13 Hz	Figure 14 (f)
7	762.36 Hz	Figure 14 (g)
8	774.95 Hz	Figure 14 (h)



(a) First order vibration mode (b) Second order vibration mode

(c) Third order vibration mode (d) Fourth order vibration mode

(e) Fifth order vibration mode (f) Sixth order vibration mode

(g) Seventh order vibration mode (h) Eighth order vibration mode

Fig 14. The first eight order vibration modes of motor

The TFPM is fixed on the ground by stand bracket, as we can see from the model diagram, in the first eight orders, the main vibration parts of motor are the upper half part of engine base, stator tooth and rotor iron core. Because of the uneasy shape change of rotor, as well as the certain amount of reducing vibration of bearing, the motor electromagnetic noise mainly derive from the upper half part of engine base and the vibration of the stator teeth. Through the analysis of electromagnetic force in previous chapter, the main part of radial and tangential force is the electromagnetic force with frequency of 255 Hz, it is nearly to the 1 order motor natural frequency of 249.95 Hz; secondly, the electromagnetic force of 765Hz in radial force is close to the 7 order motor natural frequency of 762.36Hz, the electromagnetic force of 510 Hz is close to the 4 order motor natural frequency of 516.76 Hz, these electromagnetic forces may cause motor to produce a large electromagnetic noise. We should improve the structure of motor, making the main frequency of electromagnetic force far from the motor natural frequency, so as to avoid producing large electromagnetic noise.

5 CONCLUSION

Transverse flux permanent magnet motor has an advantage of high torque density, which gives it a good application prospect. Researches on electromagnetic noise of this kind of motor have a great importance on promoting its application. A new kind of TFPM is introduced in this paper, the air gap magnetic field, electromagnetic force and the vibration characteristics of the motor are analyzed, by calculation and analysis, draw the following conclusions:

1) The vibrations of motor are mainly caused by the electromagnetic force acting on stator teeth, flux density distribution of five outside teeth (or inside teeth) of each phase are approximately the same.

2) Magnetic flux leakage has a large influence on TFPM air gap magnetic field, and makes the air gap magnetic field produce distortion, then influence the electromagnetic force on the stator teeth, so its effects on electromagnetic vibration noises cannot be neglected.

3) For EFPM, both radial and tangential electromagnetic forces acting on stator teeth can cause vibration of stator, and then produce the electromagnetic noises.

4) TFPM is fixed by motor base bracket, the electromagnetic vibration noises mainly come from the upper half part of motor base and the stator teeth. The force with a frequency of 255 Hz from the radial and tangential electromagnetic force on stator teeth is close to the first order natural frequency of 249.95 Hz, and this force is generated by gap flux density fundamental wave. We should improve the structure of motor, so as to make the main harmonic frequency of electromagnetic force far from the motor natural frequency, and then avoid producing large electromagnetic noise.

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