Vibration Analysis of Hub Motor Based on ANSYS

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Abstract. The hub motor is designed with multidirectional excitation and Halbach Array, which includes inner rotor, left and right stator, outer stator, encoder and rotary transformer. The rotor consists of an axial disk and a top ring. The rotor’s permanent magnets are affixed to the left and right sides of the disk and to the outside of the top ring. The permanent magnets on the rotor adopt a Halbach Array. The three stators have not the iron core and they are arranged outside the rotor to form a three-way closed loop. The motor has high power density, high torque density, low heating, strong adaptability and no cogging effect. It is suitable for electric car control. On this basis, the dynamic equation of the hub motor is established, the vibration mode of the rotor system is analysed, when the inner rotor’s speed is 18000rpm. By use of the solid model, the hub-rotor’s accurate dynamics solution can be obtained. In the future, the effect of vertical coupling vibration will be investigated for its ride comfort and safety.

Keywords. Electric vehicle, permanent magnet motor, Hub motor, vibration characteristics.

1. Introduction

Compared with the traditional car, wheel type electric car has the advantages of flexible control, simple structure and high controllability. It has always been the important development direction of the electric car industry. Because the electric wheel integrates with the motor, hub and brake system, the unsprung mass is increased, so that the vibration inertia of the electric wheel is greater when driving. The inertia load will have an impact on the hub motor vibration and car’s safety. The vibration of hub motor reduces the service life and lets its operation unstable, the reliability of hub motor is lowered. Therefore, it has great engineering significance to study the vibration characteristics of hub motor. Zuo [1] showed that the hub motor rotor-system’s coupling vibration problem was researched, and thinking of electromechanical coupling effect, by use of experiment, the vibration modes were analyzed to verify the accuracy of the calculated results. Xia [2] stated that the passive suspension model and the active suspension models were established, the vertical negative in fluences induced by high unsprung mass of in-wheel motor wheel were analyzed extensively, the validity of solving the problem by means of active suspension was discussed. Ma Conggan [3] indicated that a non-linear dynamical model for torsional vibration of a permanent magnet synchronous motor was established with the lumped parameter method, the non-linear differential equations were solved by means of the state variable technique and the effectiveness of the model was tested and verified. The electromagnetic force can excite vibration. K.H.Yim [4] calculated the radial and tangential electromagnetic forces in the air gap of the motor, and studied the forced vibration characteristics of the inner rotor of the permanent magnet synchronous motor. Xiao [5] designed a new type of wheel motor damping system, to solve the problem of large unsprung mass of distributed drive vehicles and provides a new method to improve the ride comfort of distributed drive electric vehicles. Qin [6] used
a new dynamic vibration absorption system to improve the dynamic performance of the vehicle and the simulation results show that vehicle vertical dynamic performance is enhanced. Hu [7] analyzed the encourage of electromagnetic force and suppression methods, an integrated model considering the electromagnetic force, including the suspension system, the driving system, and the IWM system, is established and developed. Liu [8] used Simulink, the dynamic model of the in-wheel motor is established, by defining the interface between the vehicle and the motor drive system, a joint simulation platform for in-wheel motor electric vehicles is established, and simulation verification is performed on it. The rotor’s stiffness and damping characteristics have a great influence on the coupling vibration of the rotor. Because the bending and torsional vibration of the hub motor directly affects the handling stability and driving smoothness of the electric car, and causes the low-speed jitter of the electric car. It is necessary to establish the coupling vibration model of hub motor with sliding bearing, and the bending and torsional vibration responses of the rotor are solved and analyzed.

Currently, the lower speed outer rotor motor and higher speed inner rotor motor used in electric wheels are radial flux permanent magnet motors. The structure of the high-speed inner rotor motor is basically the same as that of traditional permanent magnet synchronous motor or brushless DC motor. The maximum speed of the inner rotor can reach 10000 rpm. Planetary gear reduction device is adopted, and the transmission ratio is about 10:1. With the development of permanent magnet hub motor to high efficiency, high speed, high power density and miniaturization, the traditional motor also shows some limitations. For example, during high-speed operation, the rotor eddy current loss is large and the efficiency cannot be maintained at a high level, the air gap magnetic density is difficult to meet the pulsating torque is relatively large, etc. The new Halbach array has great advantages in the application of permanent magnet motor: (1) The distribution of air gap magnetic field is sine wave. (2) It generates the strongest magnetic field to use a small amount of magnets. (3) The arrangement of special magnet units is used to enhance the field strength of unilateral magnetic field. (4) High power density can reduce the motor volume and improve the motor power density. According to the requirements of electric car, the permanent magnet synchronous motor is accurately designed, the rotor structure is optimized, and its performance is analyzed by finite element software to meet the excellent performance of electric car drive.

2. Mode of a Multi-Directional Excitation Hub Motor
A Halbach hub motor is designed with the multi-directional excitation, including its left stator, right stator, outer stator, inner rotor and so on. The left stator and right stator are arranged on the left and right sides of the axial direction of the rotor, and the outer stator is arranged on the radial top side of the rotor without silicon steel sheet, and the three stators are fixedly sealed by their coils and iron cores (figure 1). The rotor is composed of its yoke and permanent magnet (figure 2), the rotor’s yoke is composed of an axial disc and a top ring, and the rotor permanent magnets are pasted on the sides of the left and right discs of the yoke and the outside of the top ring. The permanent magnets on the rotor adopts Halbach array (figure 3), and the mixed magnetic flux of the three stators is distributed sinusoidally to form the three-way closed loop. The disc hub motor with three stators and more rotor permanent magnets has the advantages of simple mechanical structure, small volume, high power density, high efficiency, low heating, high control accuracy, strong adaptability, no cogging effect and low vibration noise. It is suitable for the control of the electric cars.
Figure 1. A multi-directional excitation hub motor.
(1. Left end cap; 2. Left stator; 3. Rotor; 4. Shaft; 5. Flat key 1; 6. Left bearing; 7. Flat key 2; 8. Outer stator; 9. Right end cover; 10. Right stator; 11. Left bearing; 12. Encoder resolver.)

Figure 2. Hub motor rotor structure.
(1. Rotor radial permanent magnets, 16 pieces in total; 2. Rotor’s yoke; 3. Rotor axial permanent magnet, 16 pieces on the left and 16 pieces on the right.)

Figure 3. Rotor permanent magnet array.

Figure 4. Axial stator.
The permanent magnets marked in figures 3-4 are misaligned by 45 degrees in turn. The axial stator excitation winding is composed of independent coils (figure 4), which is sealed by EPT904 epoxy sealant or PUT120 polyurethane sealant, without iron core.

The hub motor is an inner rotor structure. The permanent magnets on the inner rotor adopts Halbach array, which has the unidirectional magnetic gathering ability and the high sinusoidal distribution of its air gap magnetic field. It is especially suitable for the occasion of the direct drive with a strong torque. The stator armature has no iron core and is directly injection molded from the winding. The stator armature forms the two-way magnetic field closed loop of the axial magnetic field and the radial magnetic field, which greatly improves the magnetic field strength, resulting in high torque density and high power density of hub motor. Further, the stator excitation winding and resin are fixedly sealed into a disk, and the permanent magnets on the rotor’s yoke is fixedly sealed into the disk. The rotor adopts axial disk and top ring structure, which has high strength, large bearing capacity and stable dynamics. It is suitable for electric cars.

3. Vibration Mode of Inner Rotor
The hub motor with the gear reduction device adopts an inner rotor motor, which is suitable for the operation requirements of the electric car. This electric wheel allows the motor to run at high speed, which can be design at 4000–20000 rpm. Its purpose is to obtain high specific power. The planetary gear reducer is adopted, so that the electric car has a large speed regulation range and output torque. In order to meet the hub motor’s size and the cost requirements, it takes rotor dynamics as an important part of the internal rotor design of the hub motor [9]. It includes the axial and radial magnetic flux, unsprung weight, electromagnetic torque, inertia moment, shaft structure, support mode, rotor structure, permanent magnet array, stator core or coreless structure design and so on. The vibration of the rotor system is the main vibration source of vehicle body order vibration and vehicle interior noise for the permanent magnet synchronous motor, and the influence on the longitudinal vibration of the vehicle under transient impact is particularly significant. Therefore, the calculation of various vibration modes of hub motor rotor system is one of the most important tasks. In the rotor dynamics analysis, the inner rotor of the hub motor is the inclusion of centrifugal force, unsprung moment of inertia, mass and stiffness, etc. In addition, the accurate prediction to the transient excitations such as its electromagnetic interference, are required.

The torsional vibration equation is [10]:

$$[J_r][\ddot{\theta}]+[K_r][\theta]=[T]$$  
$$\{\theta\}=[\theta_1, \theta_2, \ldots, \theta_i, \ldots, \theta_n] \quad (1)$$

$$[J_r]=\begin{bmatrix} J & 0 & 0 \cdots & 0 \\ 0 & J & 0 \cdots & 0 \\ 0 & 0 & J \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 \cdots & J_{mn} \end{bmatrix}$$

$$[K_r]=\begin{bmatrix} k_1 & -k_1 & 0 \cdots & 0 \\ -k_1 & k_1+k_2 & -k_2 \cdots & 0 \\ 0 & -k_2 & k_2+k_3 \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 \cdots & k_{n-1}+k_n \end{bmatrix}$$

The bending vibration equation is:

$$[K]-\omega^2M-\omega^2[M]+i\omega[G]=0 \quad (2)$$

where $[G]$ gyroscopic matrix, where $[K]$ is stiffness matrix, $[M]$ is the mass matrix.

The hub motor is of inner rotor structure, and the main performance parameters are shown in table 1. The main dimensions of the inner rotor for the hub motor are: Rotor’s outer diameter 300mm, Axial length 100 mm, Sliding bearing span 300 mm. The solid element model of ANSYS software is used for calculation. When the inner rotor’s speed is 18000 rpm, the vibration mode is shown in table 2.
| Parameter               | Data     |
|-------------------------|----------|
| Maximum torque(Nm)      | 1500     |
| Peak power(KW)          | 80       |
| Maximum speed(rpm)      | 20000    |
| Rated power(KW)         | 50       |
| Rated speed(rpm)        | 10000    |
| Bus voltage(V)          | <800     |

Table 2. Vibration modes of rotor in hub motor.

| Mode | Frequency(Hz) | Shape         |
|------|---------------|---------------|
| 1    | 299.52        | First torsion |
| 2    | 312.36        | First bend    |
| 3    | 618.28        | Second bend   |
| 4    | 1247.31       | Axial vibration |

Only part of the vibration modes of the inner rotor of the hub motor are calculated above, and the further calculation is also related to the transmission chain such as planetary gear transmission, etc. The actual car model can be simulated by using the finite element solid element model, and the calculation results are more reliable. The above work is only preliminary.

4. Result Analysis

(1) A Halbach hub motor with multi-directional excitation is designed. The main structure includes inner rotor, left stator, right stator and outer stator. The left stator and the right stator are arranged on both axial sides of the rotor, and the outer stator is arranged on the radial top side of the rotor without silicon steel sheet. The rotor is composed of yoke and permanent magnet. The permanent magnet is pasted on the side of the left and right discs of the yoke and the outside of the top ring. The permanent magnet on the rotor adopts Halbach array, and the mixed magnetic flux of the three stators is distributed sinusoidally to form a three-way closed loop. The hub motor has the advantages of high torque density and high power density.

(2) The vibration modes of the inner rotor are calculated by using the solid element model of ANSYS software. An advantage of the solid model is that all structural parameters of bearing support, unbalanced magnetic tension and rotor system structure optimization can be considered in one analysis. The dynamic analysis model of the whole vehicle can be established to analyze the collision impact and safe driving and riding characteristics. On this basis, the hub motor with high power density, high torque density, low heating, strong adaptability and no cogging effect can be designed, which is suitable for the control of electric vehicles.

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