IEEE Access
Multidisciplinary Rapid Review Open Access Journal

Received April 21, 2019, accepted May 4, 2019, date of publication May 14, 2019, date of current version May 30, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2916428

Research on Equivalent Material Properties and Modal Analysis Method of Stator System of Permanent Magnet Motor With Concentrated Winding

HONGBIN YIN[1], FANGWU MA[1], XUEYI ZHANG[2], CANSONG GU[1,3], HUI GAO[3], AND YONGCHAO WANG[3]

[1]State Key Laboratory of Automotive Simulation and Control, Jilin University, Changchun 130000, China
[2]School of Transportation and Vehicle Engineering, Shandong University of Technology, Zibo 255000, China
[3]China Automotive Technology and Research Center Co. Ltd., Tianjin 300300, China

Corresponding author: Fangwu Ma (mikema@sdut.edu.cn)

This work was supported in part by the National Science Foundation of China under Grant 51875327, and in part by the Science and Technology Development Plan of Jilin Province, China, under Grant 20190103056JH.

ABSTRACT Establishing an accurate stator system modal analysis model is of great significance for the vibration and noise analysis of the motor, scholars still have some controversy about how to set the material properties of the stator core and winding in modal analysis. First, the equivalent models of the stator core and winding was analyzed, the initial value of equivalent material parameters was determined. Second, the finite element models were used to analyze the influence of the equivalent material parameters on the natural frequency, a correction method of equivalent material parameters was proposed. Third, the modal of the stator core and the stator core with winding were tested by the moving force method. The finite element analysis results are consistent with the modal test results. Some influence laws of equivalent material parameters on natural frequency are obtained. The proposed correction method of equivalent material parameters helps to quickly determine the equivalent material properties of the stator core and windings. Setting the properties of the stator core and the winding material to the orthotropic materials can ensure the accuracy of the modal analysis.

INDEX TERMS Correction method of equivalent material parameters, winding, stator core, modal analysis.

I. INTRODUCTION

Electric motors manufacturers are highly concerned with low noise and vibration emissions in vehicle or home applications where motors are close to the end-user [1]–[5]. According to [6], in PM machines with concentrated windings, the low modals of vibration can be excited which have higher deformation amplitudes. In addition, the resonant vibration is more likely to occur in this case. Accurate determination of natural frequencies is thus one of the key issues to design low noise and vibrations motors [1], [7].

The calculation of the natural frequency of the stator system is very important during the vibration analysis of the motor. The stator system includes stator core, winding, frame, etc. The stator core is formed by stacking laminations axially into a pack. Paper [8] investigates the accurate modeling and the modal natural frequencies of the stator system of a permanent magnet synchronous motor with concentrated winding used in the in-wheel motor system of the electric vehicle. The effects of laminated core on the rotor modal shapes is investigate in paper [9]. Paper [10] proposes a reformative simulation method of motor pole core vibration characteristics. The pole core was considered as a homogeneous orthotropic laminates structure material, and material property parameters were obtained by fitting curve recommended. A novel approach of equivalent material identification is developed for multi-layered orthotropic structures in paper [11]. According to [12], the generally accepted value of Young's modulus is not valid for a machine with laminations and no frame. It introduces a simple and

The associate editor coordinating the review of this manuscript and approving it for publication was Hassan Ouakad.

nondestructive method for the measurement of Young's modulus. In paper [6], a method to identify the physical parameters of laminated core and windings is proposed based on the modal testing of the motor stators with different conditions, however, the equivalent Young's modulus of laminated stator core and the windings is the isotropy.

The impact of stator winding and end-bells on resonant frequencies and modal shape of switched reluctance motors was studied in paper [1]. According to [1], for conventional motors, the contact between pole and winding assembly is tight enough to allow the windings to move with the pole, but cannot add an extra stiffness due to the existence of the insulation. Although the windings may contribute to stiffness if the slot fill factor is high, the increase in the stiffness is low when compared to the mass added by windings to the stator assembly. Therefore, the effect of the windings is equated to an increase of the pole mass. In [8], the winding is equivalent to an integral structure without considering the insulating materials and contact between each wire. The turns are assumed to be contacted closely with teeth and the effect of varnish is equivalent to the change in the material properties of winding. In [13], six kinds of finite element models for winding are built, and compared with test results to elect the model consistent with the actual stator winding. In [14], the influence of winding dipping paint on the stator core model is studied. The research shows that before the immersion, the winding structure is loose, and it does not contribute to the stiffness of the stator structure. The contribution is mainly the quality improvement, which causes the natural frequency of the stator core with winding to be lower than the natural frequency of the stator core. After the varnishing, the gap between the windings in the slot is reduced, and the winding contributes significantly to the stiffness of the core. The natural frequency of the stator core with the winding is higher than the natural frequency of the stator core. According to [15], the coil in the slot consists of wire scattered at random in the varnish. Therefore, the equivalent Young's modulus is not greatly dependent on the size of wire. Its value is $1/100^{\text{th}}$ of Young's modulus of copper wire. The influence of laminated core and winding on the natural frequencies and modal shapes of the stator are investigated in [16], winding material property is set to orthotropic, which shows that the Young's modulus of the winding is much lower than that of the solid copper. A material model of the complete stator bar is developed to calculate the material properties of the stator bar in [17].

Both a smooth frame and a ribbed framed are examined in [18], [19]. The resonant frequencies of the low-order modals decrease due to the existence of the frame ribs and keys. This means that the ribs and keys mainly add extra mass to the stator vibration system for the low-order modals. However, an increase occurs in the higher order resonant frequencies. This means that the effects of ribs and keys mainly contribute extra stiffness to the high-order modal shapes of the stator vibration system. The length of frame has less of an effect than thickness. In [20], the models of the stator was analyzed by the 3D finite element software called Workbench. The influence of the yoke thickness, tooth depth, tooth width, the stator coils, the stator rind and the end caps on the natural frequencies and the modal shapes are taken into consideration. The effects of different lamination shapes on vibration were researched in [21].

In summary, scholars have some controversy about how to set the material properties of the stator core and winding. In some literatures, the stator core is set to an isotropic material while the stator core is set to an orthotropic material in other literatures. At the same time, the Young's modulus values and Poisson's ratio of the stator core are mostly determined by experiment and experience. There are many equivalent models of stator windings. The main reason is that the structure of the motor windings is different and the machining process is different, resulting in different stiffness of the windings. Take a stator system of a concentrated winding permanent magnet brushless DC motor for electric vehicles as an example, the equivalent material parameters and modal analysis methods of stator core and winding are studied in this paper. In section 2, the equivalent model of stator core and winding is analyzed, the initial value of equivalent material parameters is determined. In section 3, the finite element model is used to analyze the influence of the equivalent material parameters on the natural frequency, a correction method of equivalent material parameters is proposed. In section 4, the modal of stator core and the stator core with winding are tested by the moving force method. The correction method of equivalent material parameters and finite element analysis results are validated. In section 5, some conclusions are drawn.

II. THEORETICAL ANALYSIS

A. EQUIVALENT MODEL OF STATOR CORE

The stator core is formed by stacking laminations axially into a pack. This means that the cell (halt-thick steel sheet; varnish sheet; half-thick steel sheet) is repeated regularly through the stator's length, with the same thicknesses everywhere [11]. Equivalent model of the stator core are shown in Fig.1. According to [8], the laminated stator core is assumed to be modeled as a continuous solid with composite material, of which the equivalent Young's modulus is calculated by the Voigt-Reuss formula.

B. EQUIVALENT MODEL OF WINDING

Stator coils put together a number of components (conductors, conductor coating, insulation, etc.), basically it is conform to an anisotropic material. To simplify the calculation, we make the following assumptions [17].

(a) The dimensions of all conductors are constant and parallel.
(b) The conductors are regularly packed.
(c) Bonded contact between conductors and matrix, that means no relative movement between the conductors is possible.
(d) Small deformation and linear ideal elastic characteristic of conductors and matrix.

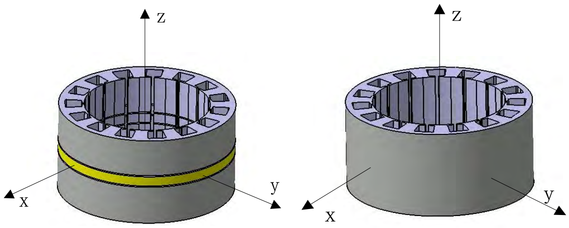

FIGURE 1. Equivalent model of stator core.

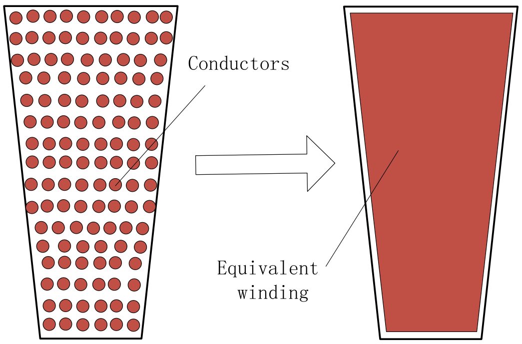

FIGURE 2. Equivalent model of winding.

TABLE 1. Symbol and definition of material properties.

Symbol	Definition	Unit
ρ	Mass density	kg/m^3
E_x	Young's modules in x axis direction.	MPa
E_y	Young's modules in y axis direction.	MPa
E_z	Young's modules in z axis direction.	MPa
ν_{xy}	Poisson's ratio in direction of xy.	-
ν_{yz}	Poisson's ratio in direction of yz.	-
ν_{zx}	Poisson's ratio in direction of zx.	-
G_{xy}	Shear modulus in direction of xy.	MPa
G_{yz}	Shear modulus in direction of yz.	
G_{zx}	Shear modulus in direction of zx.	

Then the coils can be simplified to a bar in the slot, the properties of the bar is defined as orthotropic. The simplified models of coils are illustrated in fig.2.

C. EQUIVALENT MATERICAL PROPERTIES OF STATOR CORE AND WINDING

According to the equivalent model of stator core and winding in section 2.1 and section 2.2, the material of stator core and winding is set as orthotropic material. As shown in table 1, ten parameters of material properties need to be determined in business analysis software JMAG-Designer.

For stator cores and windings, the following relationships exist between material parameters.

$$E_x = E_y \tag{1}$$

$$\nu_{yz} = \nu_{xz} \tag{2}$$

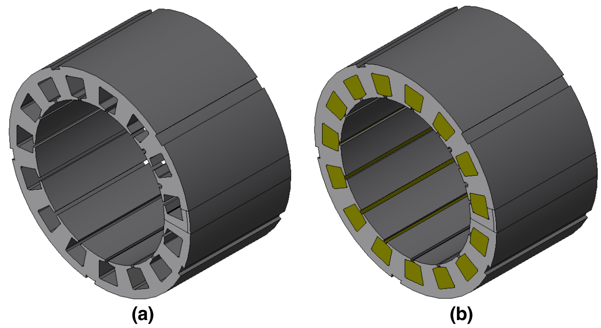

FIGURE 3. Finite element model of stator system. (a) Stator core. (b) Stator core with winding.

TABLE 2. Initial equivalent material properties of stator core.

Symbol	Value of stator core	Value of winding
ρ	7500	7000
E_x	195000	200
E_z	10000	400
ν_{xy}	0.3	0.25
ν_{yz}	0.3	0.25

According to [22], some parameters are automatically calculated from the set material parameter internally.

$$\nu_{zx} = \nu_{xz}\frac{E_z}{E_x} \tag{3}$$

$$G_{xy} = \frac{E_x}{2(1+\nu_{xy})} \tag{4}$$

$$G_{yz} = \frac{E_y}{2(1+\nu_{yz})} \tag{5}$$

$$G_{zx} = \frac{E_y}{2(1+\nu_{zx})} \tag{6}$$

In this paper, initial value of five parameters in table 1 are given in table 2 referring to Voigt-Reuss formula [8], [10]. Other material properties are calculated according to (1)-(6).

III. MODELING AND MODAL ANALYSIS

Taking a 2.2kW concentrated winding permanent magnet brushless DC motor for electric vehicle as an example, the finite element analysis model of the stator system is established. The basic dimensions of the permanent magnet brushless DC motor are shown in Table 3, Figure 3(a) is stator core finite element model, and Figure 3(b) is finite element model of a stator core with windings.

A. MODAL ANALYSIS OF STATOR CORE WITHOUT WINDING

The stator core is laminated by silicon steel sheets. In the cylindrical coordinate system, the radial and axial material properties are inconsistent. In order to observe the influence of the material properties of the stator core on the stator core modal, natural frequency stator core with different equivalent material properties were calculated. The equivalent material

TABLE 3. Basic dimensions of 10-pole 15-slot permanent magnet brushless DC motor.

Quantity	Unit	Value
Stator outer diameter	mm	140
Stator inner diameter	mm	99.6
Rotor outer diameter	mm	98.6
Permanent magnet thickness	mm	3
Pole embrace	/	0.9
Permanent magnet code	/	N35H
Iron core code	/	50A1000
Winding	/	Concentrated winding
Coil turns	/	3

TABLE 4. Equivalent material properties of stator core.

Condition	ρ	E_x	E_z	ν_{xy}	ν_{yz}
1-1	7500	**200000**	10000	0.3	0.3
1-2	7500	**195000**	10000	0.3	0.3
1-3	7500	**190000**	10000	0.3	0.3
1-4	7500	**185000**	10000	0.3	0.3
1-5	7500	**180000**	10000	0.3	0.3
2-1	7500	195000	**5000**	0.3	0.3
2-2	7500	195000	**10000**	0.3	0.3
2-3	7500	195000	**15000**	0.3	0.3
2-4	7500	195000	**20000**	0.3	0.3
2-5	7500	195000	**25000**	0.3	0.3
3-1	7500	195000	10000	0.3	**0.1**
3-2	7500	195000	10000	0.3	**0.2**
3-3	7500	195000	10000	0.3	**0.3**
3-4	7500	195000	10000	0.3	**0.4**
3-5	7500	195000	10000	0.3	**0.5**

properties of stator core are listed in table.4. The Young's modules in direction x are different, the other equivalent material properties are the same from condition 1-1 to condition 1-5. The Young's modules in direction z are different, the other equivalent material properties are the same from condition 2-1 to condition 2-5. The Poisson's ratio in direction yz are different, the other equivalent material properties are the same from condition 3-1 to condition3-5.

Natural frequencies of stator core with different Young's modules in direction x are shown in Figure 4. For the modal shape (m, n), the m is the circumferential modal order and the n is the axial modal order. It can be seen that the natural frequencies of stator core are proportional to the Young's modules in direction x. The natural frequencies of modal shape (m, 1) are higher than the modal shape (m, 0). Natural frequency change rate of modal shape (m, 1) is close to modal shape (m, 0).

Figure 5 shows the natural frequencies of stator core with different Young's modules in direction z. The natural frequencies of stator core in modal shape (m, 1) are proportional to the Young's modules in direction z, the change rates of stator core natural frequencies are large. However, the natural

TABLE 5. Equivalent material properties of winding.

Condition	ρ	E_x	E_z	ν_{xy}	ν_{yz}
1-1	7000	**100**	400	0.25	0.25
1-2	7000	**150**	400	0.25	0.25
1-3	7000	**200**	400	0.25	0.25
1-4	7000	**250**	400	0.25	0.25
1-5	7000	**300**	400	0.25	0.25
2-1	7000	200	**300**	0.25	0.25
2-2	7000	200	**350**	0.25	0.25
2-3	7000	200	**400**	0.25	0.25
2-4	7000	200	**450**	0.25	0.25
2-5	7000	200	**500**	0.25	0.25
3-1	7000	200	400	0.3	**0.1**
3-2	7000	200	400	0.3	**0.2**
3-3	7000	200	400	0.3	**0.3**
3-4	7000	200	400	0.3	**0.4**
3-5	7000	200	400	0.3	**0.5**

frequencies of stator core in modal shape (m, 0) are almost constant in different Young's modules in direction z.

Natural frequencies of stator core with different Poisson's ratio in direction yz are illustrated in Figure 6. It can be seen from Figure 6 that the natural frequencies of stator core in modal shape (m, 0) are proportional to Poisson's ratio in direction yz, the natural frequencies of stator core in modal shape (m, 1) are inversely proportional to Poisson's ratio in direction yz. The natural frequencies change rates in modal shape (m, 0) and modal shape (m, 1) are both small.

B. MODAL ANALYSIS OF STATOR CORE WITH WINDING

In order to investigate the impacts of winding on stator core, the natural frequency of stator core with winding of different equivalent material properties were calculated. The equivalent material properties of winding are listed in table 5. The equivalent material properties of stator core are same in all conditions. The Young's modules of winding in direction x are different while other parameters are same from condition 1_1 to condition 1_5. The Young's modules of winding in direction z are different while other parameters are same from condition 2_1 to condition 2_5. The Poisson's ratio of winding in direction yz are different while other parameters are same from condition 3_1 to condition 3_5.

As shown in Figure 7, the natural frequencies of stator core with winding are proportional to Young's modules in direction x. The natural frequencies of modal shape (m, 1) are higher than the natural frequencies of modal shape (m, 0). The natural frequency change rates of modal shape (m, 0) are close to modal shape (m, 1) in most conditions. The natural frequency change rates of modal shape (4, 0) are smaller than modal shape (4, 1) from condition 1-4 to condition 1-5.

Natural frequencies of stator core with winding of different Young's modules in direction z are shown in Figure 8. It illustrates that the natural frequencies of stator core with winding are proportional to the Young's modules of winding

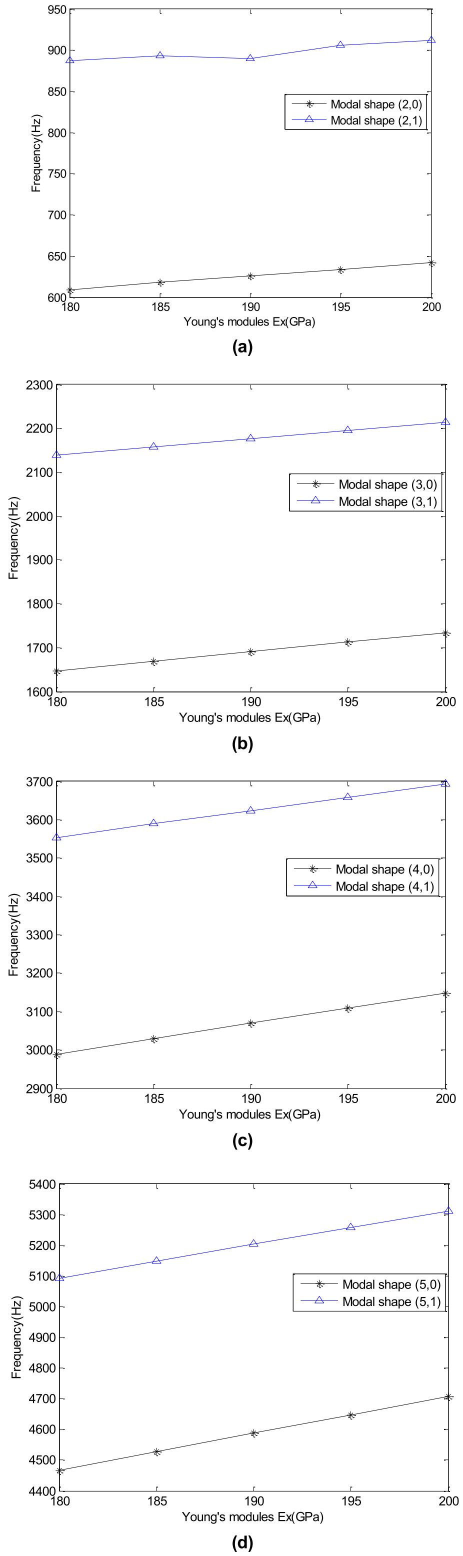

FIGURE 4. **Natural frequencies of stator core with different Young's modules in direction x. (a) Modal shape (2, n). (b) Modal shape (3, n). (c) Modal shape (4, n). (d) Modal shape(5, n).**

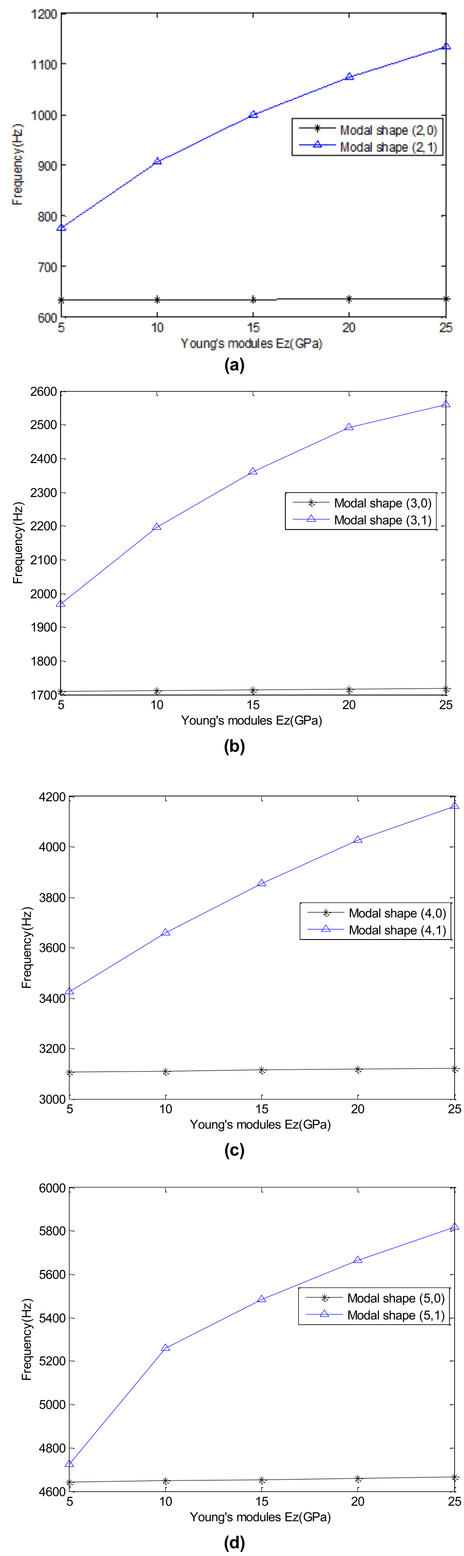

FIGURE 5. **Natural frequencies of stator core with different Young's modules in direction z. (a) Modal shape (2, n). (b) Modal shape (3, n). (c) Modal shape (4, n). (d) Modal shape (5, n).**

in direction z while the equivalent material properties of stator core are unchanged. The natural frequencies change rates are small.

Figure 9 illustrates the natural frequencies of stator core with winding of different Poisson's ratio in direction yz. It can be seen that the natural frequencies of

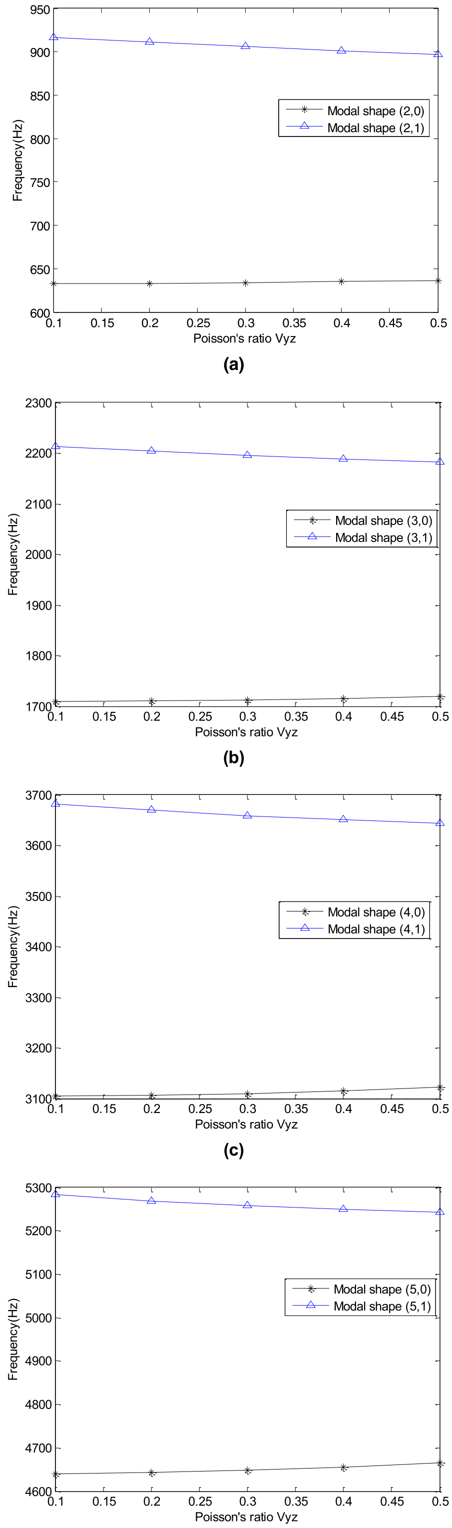

FIGURE 6. **Natural frequencies of stator core with different Young's modules in direction z. (a) Modal shape (2, n). (b) Modal shape (3, n). (c) Modal shape (4, n). (d) Modal shape (5, n).**

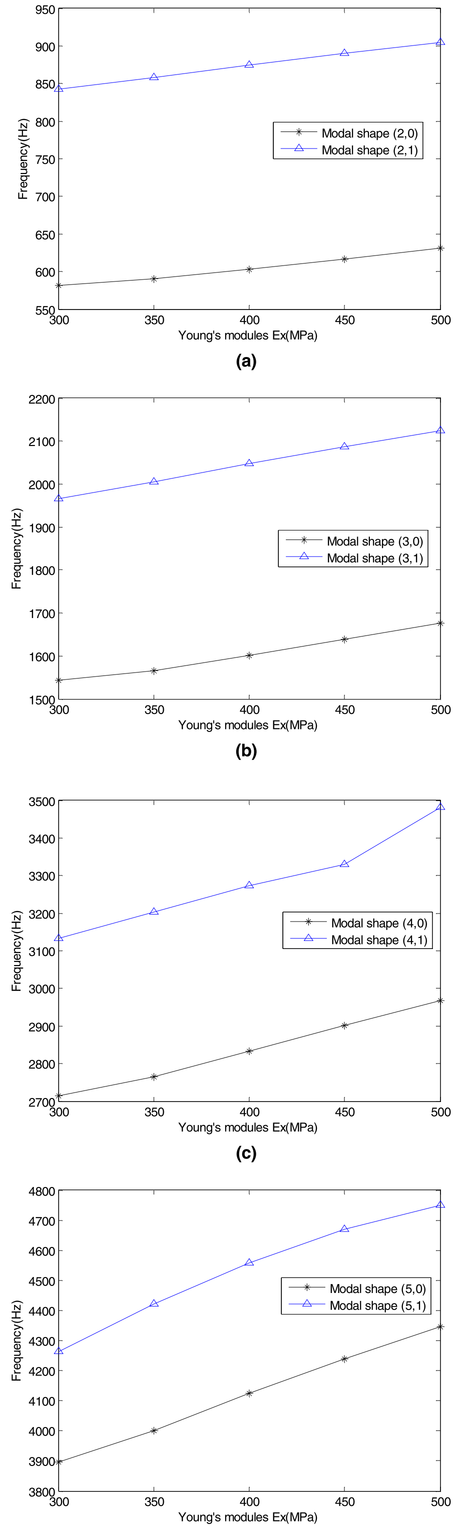

FIGURE 7. **Natural frequencies of stator core with winding of different Young's modules in direction x. (a) Modal shape (2, n). (b) Modal shape (3, n). (c) Modal shape (4, n). (d) Modal shape (5, n).**

stator core with winding are proportional to the Poisson's ratio. The natural frequencies change rate of modal shape (m, 0) are larger than modal (m, 1). As the Poisson's ratio increases, the difference of natural frequencies between modal shape (m, 0) and modal shape (m, 1) becomes smaller.

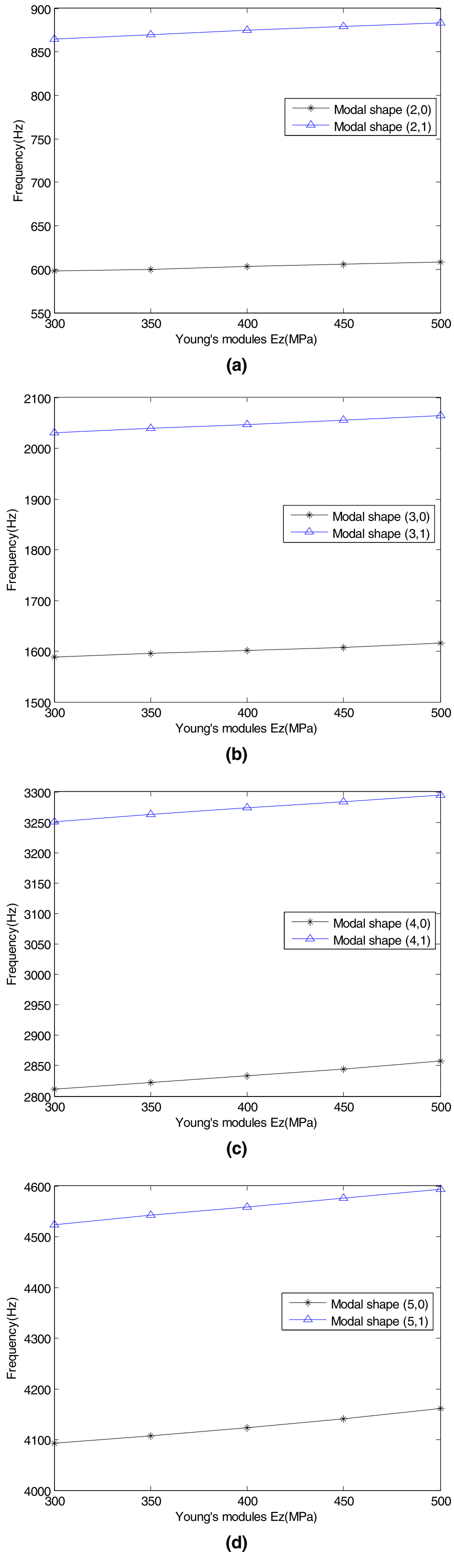

FIGURE 8. **Natural frequencies of stator core with winding of different Young's modules in direction z. (a) Modal shape (2, n). (b) Modal shape (3, n). (c) Modal shape (4, n). (d) Modal shape (5, n).**

C. CORRECTION METHOD OF EQUIVALENT MATERIAL PROPERTIES IN FINITE ELEMENT MODEL

Under normal circumstances, the initial material properties of the stator core and the winding can be initially predicted based on the empirical formula. However, the predicted values are difficult to be very accurate. In the process of establishing the finite element model, the equivalent material properties of the stator core and windings need to be adjusted, so that the analysis results of the finite element model are consistent with the experimental results. A general method for adjusting the parameters of equivalent materials is proposed in this paper. The correction method of the stator core equivalent material parameters is shown in Figure 10. The correction method for the equivalent material of the winding is shown in Figure 11.

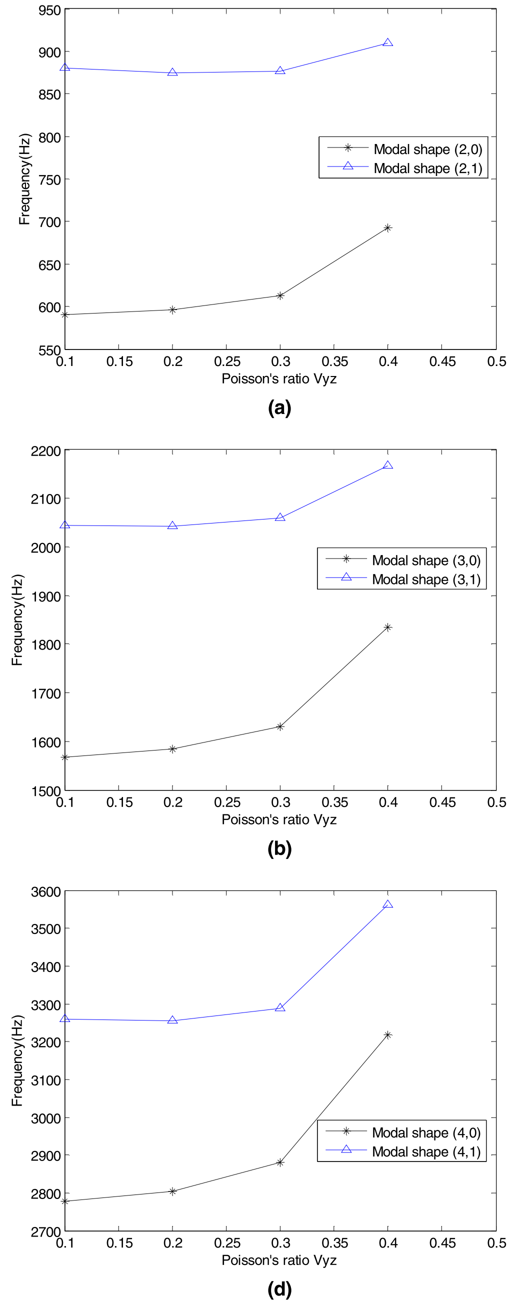

FIGURE 9. **Natural frequencies of stator core with winding of different Poisson's ratio in direction yz. (a) Modal shape (2, n). (b) Modal shape (3, n). (c) Modal shape (4, n).**

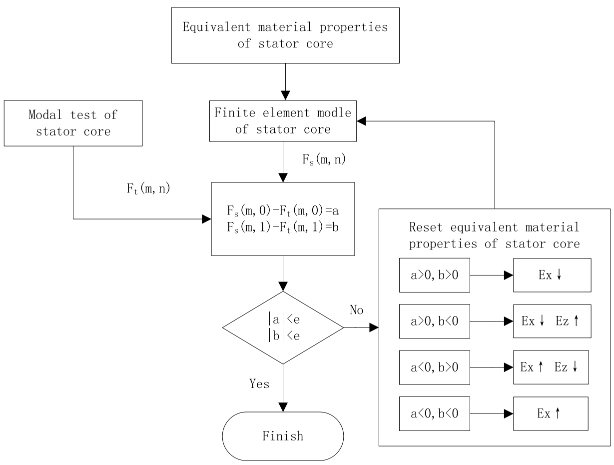

FIGURE 10. Correction method of the stator core equivalent material parameters.

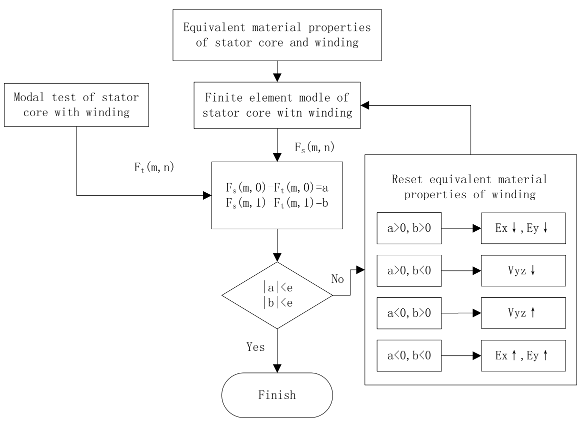

FIGURE 11. Correction method for the equivalent material of the winding.

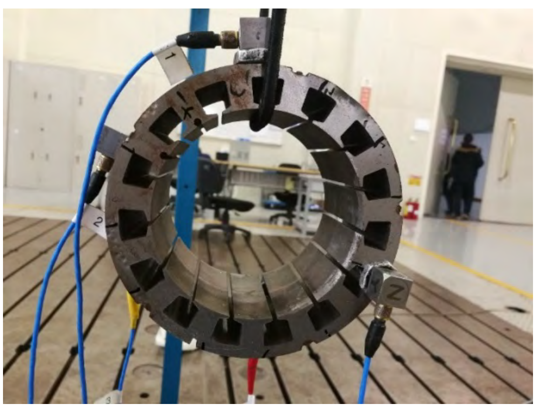

FIGURE 12. Stator core modal test.

IV. EXPERIMENT

A. MODAL TEST AND ANALYSIS OF STATOR CORE WITHOUT WINDING

In order to verify the validity of the finite element analysis, the modal test of the stator core was carried out by the moving force hammer method. The test arrangement is shown in Figure 12. The modal shape and frequency of the stator core obtained by the test are shown in Figure 13.

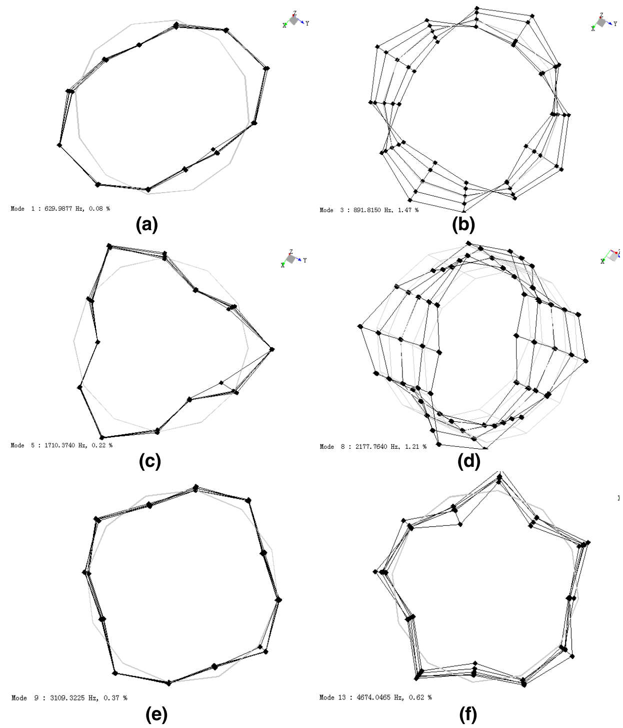

FIGURE 13. Stator core modal shape and frequency. (a) Modal shape (2, 0). (b) Modal shape (2,1). (c) Modal shape (3, 0). (d) Modal shape (3, 1). (e) Modal shape (4, 0). (f) Modal shape (5, 0).

TABLE 6. Comparison of finite element analysis results of stator core with test results.

Modal shape	Test result (Hz)	Finite element analysis result (Hz)	Error（%）
(2,0)	630	630	0
(2,1)	891	885	-0.7
(3,0)	1710	1700	-0.6
(3,1)	2156	2153	-0.1
(4,0)	3109	3091	-0.6
(4,1)	3565	3593	0.8
(5,0)	4674	4679	0.1

As can be seen from Figure 13, mode and frequency of five modals (2,0), (2,1), (3,0), (3,1), (4,0), (5, 0) are obtained by the stator core modal test. The equivalent material properties of the stator core are corrected according to the method described in figure 10. The final set material properties are $E_x = E_y = 190$GPa, $E_z = 9$GPa, $V_{xy} = 0.3$, $V_{yz} = 0.3$. The finite element analysis results and the test results are shown in Table 6. It can be seen that the maximum error of each modal frequency is 0.8%. It shows that the finite element method can accurately predict the modal shape and frequency of each modal of the stator core when using anisotropic material properties.

B. MODAL TEST AND ANALYSIS OF STATOR CORE WITH WINDING

In order to verify the validity of the finite element analysis model, the modal test of the stator core with winding was

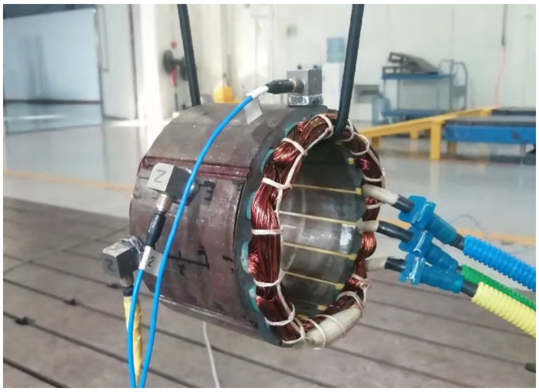

FIGURE 14. Modal test analysis of stator core with winding.

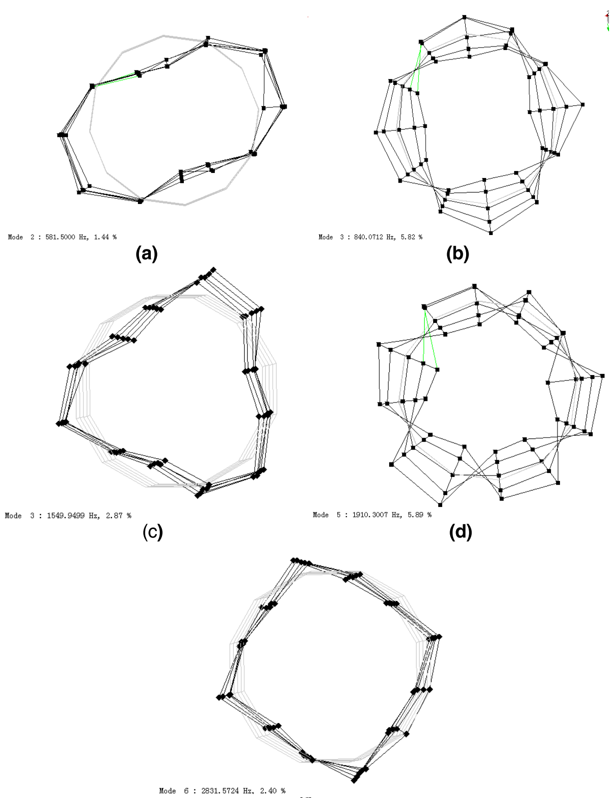

FIGURE 15. Modal shape and frequency of stator core with winding. (a) Modal shape (2, 0). (b) Modal shape (2,1). (c) Modal shape (3, 0). (d) Modal shape (4, 0). (f) Modal shape (5, 0).

carried out. The test method is the mobile hammer method, and the test sensor arrangement is shown in Figure 14. The test results of the modal shape and frequency of each modal are shown in Figure 15.

It can be seen from Fig. 12 that modal and frequency of five modals of (2, 0), (2, 1), (3, 0), (3, 1), (4, 0) are obtained by the modal test of the stator core with windings.

The equivalent material properties of the stator core are corrected according to the method described in figure 10. The final set material properties are $E_x = E_y = 135$MPa,

TABLE 7. Comparison of finite element analysis results with test results of stator core with winding.

Modal shape	Test results (Hz)	Finite element analysis result (Hz)	Error（%）
(2,0)	576	580	0.7
(2,1)	840	833	-0.8
(3,0)	1550	1541	-0.6
(3,1)	1910	1964	2.8
(4,0)	2818	2746	-2.6

$E_z = 200$ MPa, $V_{xy} = 0.3$, $V_{yz} = 0.2$. The comparison between test results and simulation results of stator core with winding is shown in Table 7. It can be seen from the table that the maximum error of each modal frequency is 2.8%, and the correction method of equivalent material parameters in the finite element simulation model is verified by the experimental results. Studies have shown that it is reasonable to simplify the stator windings into mutually independent columnar bodies that are embedded in the stator slots and that are in good contact with the stator core. Stator winding material properties should be set to anisotropy.

V. CONCLUSION

Firstly, the equivalent model of stator core and winding is analyzed, the initial value of equivalent material parameters is determined. Secondly, the finite element model is used to analyze the influence of the equivalent material parameters on the natural frequency, a correction method of equivalent material parameters is proposed. Thirdly, the modal of stator core and the stator core with winding are tested by the moving force method. The finite element analysis results are consistent with the modal test results. Some conclusions can be drawn as follows:

(1) The natural frequencies of stator core in modal shape (m, 0) and modal shape (m, 1) are both proportional to the Young's modules in direction x and y, the change rates are close. The natural frequencies of stator core in modal shape (m, 1) are proportional to the Young's modules in direction z, the change rates of stator core natural frequencies are large. However, the natural frequencies of stator core in modal shape (m, 0) are almost constant in different Young's modules in direction z. The natural frequencies of stator core in modal shape (m, 0) are proportional to Poisson's ratio in direction yz, the natural frequencies of stator core in modal shape (m, 1) are inversely proportional to Poisson's ratio in direction yz. The natural frequencies change rates of modal shape (m, 0) and modal shape (m, 1) are both small while Poisson's ratio of windings in direction yz increases.

(2) The natural frequencies of stator core with winding are proportional to Young's modules in direction x, z and Posson's ration in direction yz. The natural frequencies change rate of modal shape (m, 0) are larger than

modal (m, 1) while Poisson's ratio of windings in direction yz increases.

(3) Setting the properties of the stator core and the winding material to the orthotropic materials can ensure the accuracy of the modal analysis. The proposed correction method of equivalent material parameters helps to quickly determine the equivalent material properties of the stator core and windings.

ACKNOWLEDGMENT

The authors' would like to thank Hongli Zhang, Peng Zhao, Lulu Wei, and Zeyu Zhang for their support and the fruitful technical discussions.

REFERENCES

[1] G. Verez and C. Espanet, "Natural frequencies analytical modeling of small industrial radial flux permanent magnet motors," in *Proc. 18th Int. Conf. Elect. Mach. Syst. (ICEMS)*, Oct. 2015, pp. 1963–1969.

[2] F. Ma, H. Yin, L. Wei, G. Tian, and H. Gao, "Design and optimization of IPM motor considering flux weakening capability and vibration for electric vehicle applications," *Sustainability*, vol. 10, no. 5, p. 1533, May 2018.

[3] F. Ma, H. Yin, L. Wei, L. Wu, and C. Gu, "Analytical calculation of armature reaction field of the interior permanent magnet motor," *Energies*, vol. 11, no. 9, p. 2375, Jul. 2018.

[4] J. Sun, H. Feng, and C. Zhu, "Identification of laminated core and winding's physical parameters by stator's modal testings," in *Proc. 17th Int. Conf. Elect. Mach. Syst. (ICEMS)*, Oct. 2014, pp. 1488–1492.

[5] H. J. Shin, J. Y. Choi, H. I. Park, and S. M. Jang, "Vibration analysis and measurements through prediction of electromagnetic vibration sources of permanent magnet synchronous motor based on analytical magnetic field calculations," *IEEE Trans. Magn.*, vol. 48, no. 11, pp. 4216–4219, Nov. 2012.

[6] M. Valavi, A. Nysveen, and R. Nilssen, "Magnetic forces and vibration in permanent magnet machines with non-overlapping concentrated windings: A review," in *Proc. IEEE Int. Conf. Ind. Technol.*, Mar. 2012, pp. 977–984.

[7] I. C. Rosca, M. Filip, and E. Helerea, "Three-phase squirrel-cage induction motor modal analyses. Theoretical and experimental aspects," in *Proc. 13th Int. Conf. Optim. Elect. Electron. Equip. (OPTIM)*, May 2012, pp. 606–611.

[8] F. Chai, Y. Li, Y. Pei, and Z. Li, "Accurate modelling and modal analysis of stator system in permanent magnet synchronous motor with concentrated winding for vibration prediction," *IET Electr. Power Appl.*, vol. 12, no. 8, pp. 1225–1232, Sep. 2018.

[9] S. Singhal, K. V. Singh, and A. Hyder, "Effect of laminated core on rotor mode shape of large high speed induction motor," in *Proc. IEEE Int. Electr. Mach. Drives Conf. (IEMDC)*, May 2011, pp. 1557–1562.

[10] Y.-H. Chen, T.-H. Ding, and L. Tian, "Research on calculation method of motor lamination core vibration characteristics," *Electr. Mach. Control*, vol. 18, no. 1, pp. 71–76, Jan. 2014.

[11] P. Millithaler, É. Sadoulet-Reboul, M. Ouisse, J.-B. Dupont, and N. Bouhaddi, "Structural dynamics of electric machine stators: Modelling guidelines and identification of three-dimensional equivalent material properties for multi-layered orthotropic laminates," *J. Sound Vib.*, vol. 348, pp. 185–205, Jul. 2015.

[12] Z. Tang, P. Pillay, A. M. Omekanda, C. Li, and C. Cetinkaya, "Young's modulus for laminated machine structures with particular reference to switched reluctance motor vibrations," *IEEE Trans. Ind. Appl.*, vol. 40, no. 3, pp. 748–754, May 2004.

[13] R. Chen, S. Zuo, R. He, and L. He, "Stator FEM modeling of permanent magnet synchronous motor for electric vehicle driving based on structural vibration analysis," in *Proc. 2nd Int. Conf. Inf. Sci. Eng.*, Dec. 2010, pp. 5407–5411.

[14] L. Xiaohua, H. Surong, and Q. Zhang, "Analysis of natural frequencies of stator structure of permanent magnet synchronous motors for electric vehicles," *Proc. CSEE*, vol. 37, no. 8, pp. 2383–2390, 2017.

[15] S. Noda, S. Mori, F. Ishibashi, and K. Itomi, "Effect of coils on natural frequencies of stator cores in small induction motors," *IEEE Trans. Energy Convers.*, vol. EC-1, no. 1, pp. 93–99, Mar. 1987.

[16] T. Y. Wang and F. X. Wang, "Vibration and modal analysis of stator of large induction motors," *Proc. Chin. Soc. Elect. Eng.*, vol. 27, no. 12, pp. 41–45, Nov. 2007.

[17] B. Schlegl, F. Schönleitner, A. Marn, F. Neumayer, and F. Heitmeir, "Analytical determination of the orthotropic material behavior of stator bars in the range of the end windings and determination of the material characteristics of the orthotropic composite space brackets via experimental modal analysis and FE-calculation," in *Proc. Int. Conf. Elect. Mach.*, Sep. 2012, pp. 1948–1956.

[18] P. Pillay and W. Cai, "An investigation into vibration in switched reluctance motors," *IEEE Trans. Ind. Appl.*, vol. 35, no. 3, pp. 589–596, Jun. 1999.

[19] W. Cai and P. Pillay, "Resonant frequencies and mode shapes of switched reluctance motors," *IEEE Trans. Energy Convers.*, vol. 16, no. 1, pp. 43–48, Mar. 2001.

[20] Z. Li, Q. Chen, F. Yue, and Y. Zhang, "Modal analysis of electromagnetic resonance for multi-degree-of-freedom spherical motor," in *Proc. 21st Int. Conf. Elect. Mach. Syst. (ICEMS)*, Oct. 2018, pp. 1847–1852.

[21] W. Cai, P. Pillay, Z. Tang, and A. M. Omekanda, "Low-vibration design of switched reluctance motors for automotive applications using modal analysis," *IEEE Trans. Ind. Appl.*, vol. 39, no. 4, pp. 971–977, Aug. 2003.

[22] *JMAG-Designer 16.0. Help, Home, Functions of Analysis, Materials, Mechanical Properties*, JSOL, Tokyo, Japan, 2019.

HONGBIN YIN was born in Shandong, China, in 1986. He received the M.S. degree in power machinery and engineering from the Shandong University of Technology, Zibo, China, in 2012. He is currently pursuing the Ph.D. degree with Jilin University, Changchun, China.

Since 2015, he has been with the College of Automotive Engineering, Jilin University, Changchun, China, where he was involved in various research projects. He is also with the China Automotive Technology and Research Center Co., Ltd., as Intern Engineer. His research interests include control and modeling of electrical drives, design of electric machines, and automotive applications of electric motor drives.

FANGWU MA received the B.S. and M.S. degrees in automotive engineering from Jilin University (former Jilin University of Technology), Changchun, China, in 1982 and 1988, respectively, and the Ph.D. degree in mechanical engineering from the Imperial College London, London, U.K., in 1999.

He was a Research Fellow in transportation design with Wolverhampton University, U.K., in late 90s. He was with Chrysler LLC, as a Senior Engineer, taken charge of the vehicle research and development programs, including Jeep Liberty, Dodge Ram, and Caravan. Then, he was the Chief Engineer and Vice President of the Geely R&D Centre, in charge of developing GC7, GX7, and GX9, as well as the negotiation and recruitment training of IP and DDR during Geely Auto's Acquisition of Volvo. He is currently a National Thousand Talents Plan Distinguished Professor with Jilin University, China, and is also an Executive Dean of the Qingdao Automotive Research Institute, Jilin University. He has published numerous technical papers, reviewed technical papers for SAE and other journals to enhance quality of publication, and invented patents related to automotive engineering.

Dr. Ma is a fellow of SAE. He has actively participated, organized, and contributed to many automotive related important conferences, e.g., SAE World Congress, Automotive Design Conference in Interior Motive, International Forum on Chinese Automobile Recycling, FISITA World Automotive Congress & Exhibition, International Conference on Globalization of Development and Innovation, International AVL Conference on Engine & Environment, JSAE Annual Spring Congress, and International Conference on NVH Technology He serves as an Editor-in-Chief of *Automotive Innovation* - an international journal on Automotive Engineering.

XUEYI ZHANG born in 1963. He received the Ph.D. degree in mechanical and electronic engineering from the Shandong University of Science and Technology University, Qindao, China, in 2011. He is currently a Professor with the School of Transportation and Vehicle Engineering, Shandong University of Technology, China, a specially appointed expert of Taishan Scholars and a national candidate of Millions of Talents, who received special allowances from the State Council Government. He holds 53 authorized patents, and has published 142 papers and five monographs. His research interests include vehicle electrical and control technology, electric vehicle driving systems, and control technology. He received four first prizes from provincial and ministerial level and the second prize for technological invention (ranking 1), in 2006.

CANSONG GU received the B.S. degree in mechanical engineering from the Hebei University of Engineering, in 2004, and the M.S. degree in mechanical engineering from the Shijiazhuang Railway Institute, in 2007. He is currently pursuing the Ph.D. degree in automotive engineering with Jilin University, China.

Since 2007, he has been an Engineer with the China Automotive Technology and Research Center Co. Ltd. His research interest includes the noise vibration and harshness (NVH) development of combustion engine, the vehicle NVH refinement and development using CAE analysis, and prototype testing methods.

Mr. GU's awards and honors the deputy secretary of NVH committee of China-SAE.

HUI GAO received the M.S. degree in mechanical engineering from the Hebei University of Technology, Tianjin, China, in 2010. Since 2010, he has been an Engineer with the China Automotive Technology and Research Center Co., Ltd. He has been involved in the infrastructure and application of drivetrain NVH facilities, including engine, hybrid drivetrain, and electric power systems, and is engaged in the research of NVH testing and evaluation techniques of the above systems, and their NVH development. He was also invited to host and participate in three national automotive industry standards for noise measurement in transmissions and electric drive systems. He is currently a Senior Engineer.

YONGCHAO WANG received the B.S. degree in vehicle engineering from the Agricultural University of Hebei Province, in 2013, and the M.S. degree in mechanical engineering from Hebei University of Technology, in 2016.

Since 2016, he has been a NVH Test Engineer with China Automotive Technology and Research Center Co. Ltd., Tianjin, China. His research focuses on NVH for automotive new energy motor and transmission.