ANALYSIS OF ENERGY LOSSES OF A CERAMIC MOTORIZED SPINDLE

Ke ZHANG[1,2] , Zhipeng WU[1], Gheorghe OANCEA[2,3], Zinan WANG[1*], Xiaotian BAI[1,2]
[1]*School of Mechanical Engineering, Shenyang Jianzhu University, Shenyang110168, China;*
[2]*Joint International Research Laboratory of Modern Construction Engineering Equipment and Technology, Shenyang, Liaoning, 110168, China*
[3]*Department of Manufacturing Engineering, Transilvania University of Brasov, Brasov, 500036, Romania*
**E-mail:wzn1404589743@126.com*

ABSTRACT*: The application of ceramic motorized spindle in extreme environments such as ultra-high or ultra-low temperature. It is of great significance to reduce spindle loss and improve the processing efficiency of machine tools. Considering the effect of current harmonic effect about iron loss, a loss model of spindle is established by MATLAB/Siumlink. The effects of speed, current and load on loss and efficiency are analyzed by using electrical theory. Iron loss, copper loss and mechanical loss under different working conditions are calculated by constant coefficient trinomial method. The model of ceramic motorized spindle is highly consistent with the theoretical model through experimental verification. The average error between simulation and experiment is 2.88%. The prediction model of high spindle lays technical principle for the energy-saving improvement of high-speed motorized spindle system.*

KEYWORDS*: ceramic motorized spindle; energy loss; load; harmonic*

1 INTRODUCTION

As the core component of the high-speed machine tool the performance of high-speed motorized spindle has a direct impact on the quality and efficiency of machine tools. Loss is the most important aspect of evaluating the quality of high-speed motorized spindle(Hong et al.,2013; Durantay et al.,2017). The excessive loss of motorized spindle will directly harm the motor(Shi et al., 2020; Feng et al., 2016). On the one hand, motorized spindle will generate thermal energy during operation due to its high speed and high power, and the high temperature will directly affect its life. On the other hand, the output current of frequency converter contains high-order harmonics, which will cause additional harmonic loss to the motor, the excessive harmonic loss will affect its processing performance(Wang et al., 2019; Song et al., 2019). The loss is related to many factors, such as structural performance, material performance, load size and external environment etc(Ho et al.,2017; Chang G, 2019; Zhao et al., 2015; Jorge et al., 2019).

Ceramic motorized spindle is a kind of motorized spindle which replaces the material of shaft and bearing with ceramic. Ceramic motorized spindle can effectively avoid problems of axis which currently exist in metal motorized spindle, thereby reducing additional losses. Domestic and overseas scholars have carried out extensive researches on accurate calculation of the loss of motor system in motorized spindle. Aryza, S., et al (2018) established a 2D model by using finite element method, accurately got the iron loss and copper loss of induction motor by sinusoidal three-phase power supply. The model was verified by experiments, but the harmonic loss and mechanical loss in current were not considered in this model. Yan (2018), Boglietti, A., et al (2012) used the finite element method to analyze the loss of asynchronous motor in PWM power supply mode. By dividing the magnetic field distribution into several harmonic components, it had been found that the harmonic magnetic field was the main factor causing the rotor loss. In this analysis, only the influence of low-order harmonic magnetic field had been considered, but not the effect of high-order harmonic on the rotor loss. Ishigami , H., Yamazaki, K (2010) established the equivalent model of iron loss of induction motor under PWM power supply based on the principle of iron loss separation. The stator and rotor shape of the motor were optimized by the combination of optimization method and finite element method, the harmonic iron loss of the rotor was calculated by the parameter estimation method, but the calculation of the overall iron loss of the motor was lacking. Yamazaki, K., et al (2012) studied the wind resistance friction loss, the copper loss and the iron loss of three-phase sinusoidal and PWM wave-driven motors under no-load conditions. Based on the test results, a more accurate motor 2D model was established. However, the model established by this method can only be applied to three-phase power supply with sinusoidal power.

In this paper, the ceramic spindle system loss under various conditions are calculated accurately. Based on the MATLAB/Simulink motor model, constant coefficient trinomial method is applied to calculate the loss of ceramic motorized spindle system and the results are verified by experiments. The effects of different operating frequencies and loads on the loss and efficiency are analyzed. The influences of fundamental and harmonic on copper and iron loss are studied. The predicted results have a good similarity with the actual test, which provides an important reference value for reducing the loss of ceramic spindle system.

2 MODELING OF THE CERAMIC MOTOR SPINDLE

2.1 Mathematical model of the ceramic motorized spindle

The structure of spindle is mainly composed of stator and rotor. The frequency converter drives the rotating shaft to rotate at a high speed by controlling the rotating magnetic field. The high speed rotation will be accompanied by the loss, which is related to the core structure, flux density and other parameters(Handgruber, et al., 2015). Spindle iron loss mainly comes from stator iron loss, which is usually calculated by equivalent resistance. In the static α*β* coordinate system, the ceramic motorized spindle model adds two iron loss windings to the stator side besides the four windings of the stator and rotor. Fig.1 is an equivalent circuit of the motor model. The circuit diagram consists of α-axis and *β*-axis equivalent circuits, which are composed of three windings and one flux linkage respectively.

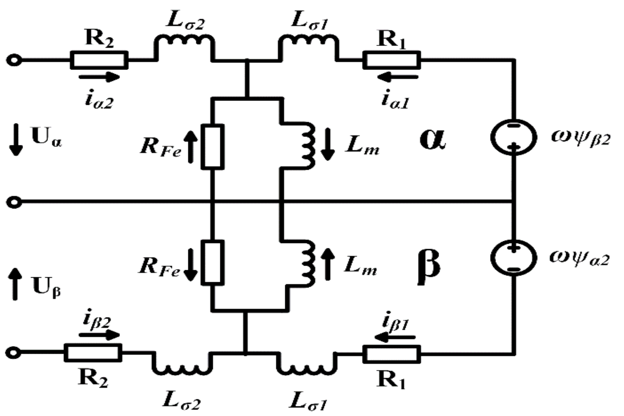


Fig.1 Dynamic equivalent circuit diagram

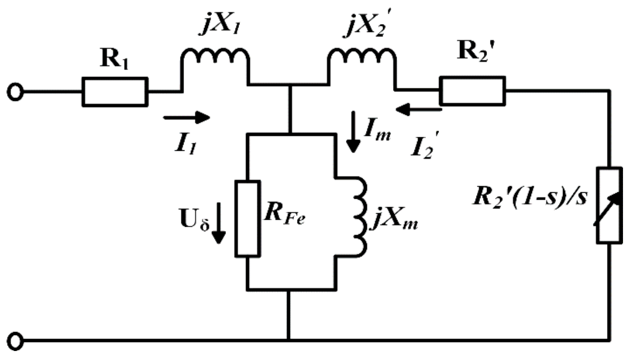


Fig.2 Steady equivalent circuit diagram

According to the state variables of equivalent circuit diagram of spindle, following the principle of rotating magnetic potential and the Park transformation equation, the relationship among current(Péter Stumpf, et al., 2013), inductance and flux linkage in electromagnetic parameters are obtained, as shown in Eq.1.

$$p\begin{pmatrix} I_{\alpha1} \\ I_{\beta1} \\ I_{\alpha2} \\ I_{\beta2} \end{pmatrix} = \frac{1}{L_{\sigma1}L_{\sigma2} - L_m^2}\left\{\begin{pmatrix} R_2L_m & -L_2L_m\omega & -R_1L_2 & -L_2L_1\omega \\ L_2L_m\omega & R_2L_m & L_2L_1\omega & -R_1L_2 \\ -R_2L_1 & L_m^2\omega & R_1L_m & L_1L_m\omega \\ -L_m^2\omega & -R_2L & -L_1L_m\omega & R_1L_m \end{pmatrix}\begin{pmatrix} I_{\alpha1} \\ I_{\beta1} \\ I_{\alpha2} \\ I_{\beta2} \end{pmatrix} + \begin{pmatrix} -L_mu_{\alpha2} \\ -L_mu_{\beta2} \\ L_1u_{\alpha1} \\ L_1u_{\beta1} \end{pmatrix}\right\} \quad (1)$$

where R_1 is stator resistance, R_2 is rotor resistance, R_{Fe} is iron loss equivalent resistance, $I_{\alpha1}$ is stator current of α axis, $I_{\beta1}$ is stator current of *β* axis, $I_{\alpha2}$ is rotor current of α axis, $I_{\beta2}$ is rotor current of *β* axis, $U_{\alpha1}$ is stator voltage of α axis, $U_{\beta1}$ is stator voltage of *β* axis, $U_{\alpha2}$ is rotor voltage of α axis e, $U_{\beta2}$ is rotor voltage of *β* axis, $L_{\sigma1}$ is stator leakage, $L_{\sigma2}$ is rotor leakage, L_m is stator-rotor mutual inductance, *p* is differential operator.

The equivalent resistance of iron loss is calculated according to the steady-state equivalent circuit of the ceramic motorized spindle. According to Fig.2, the equivalent iron loss resistance is calculated by Kirchhoff voltage law and Ohm's law, as shown in Eq.2.

$$R_{Fe} = \frac{3U_\delta^2}{P_{Fe}} = \frac{3(U_1 - I_1\sqrt{R_1^2 + (\omega_1L_1)^2})^2}{P_{Fe}} \quad (2)$$

where U_δ is air gap voltage,w$_1$ is stator angular frequency, P_{Fe} is the ceramic motorized spindle iron loss.

Building the motor model of the ceramic motorized spindle according to Eq.1 and using Siumlink input, output, gain, integral, product and other modules to build a simulation model.

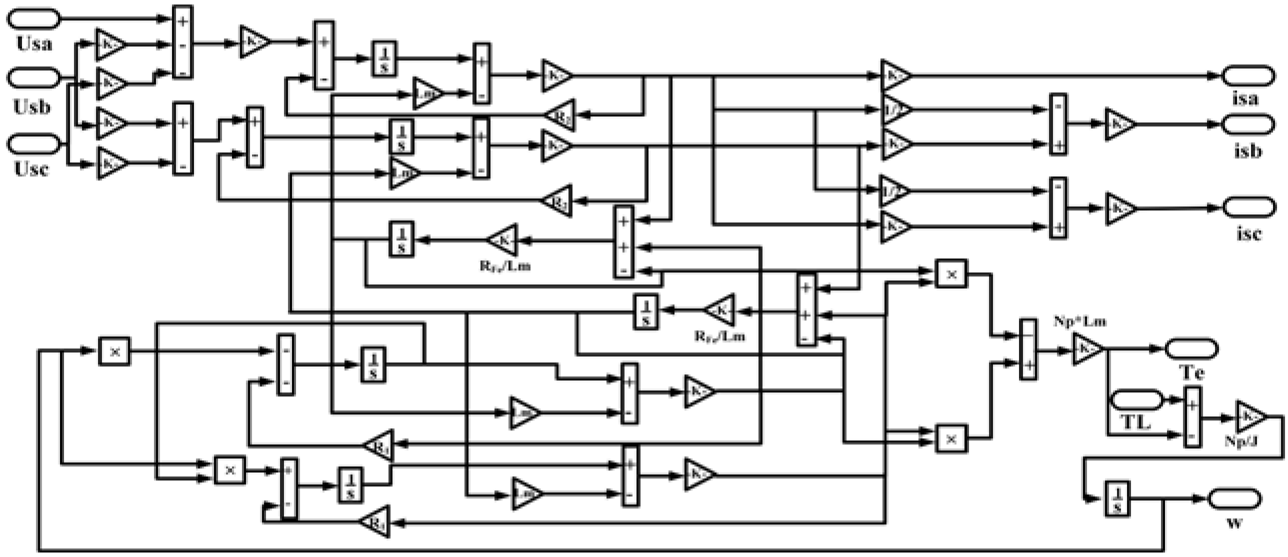


Fig.3 Simulation model of ceramic spindle motor

2.2 Theoretical model for the loss of ceramic motorized spindle

There are many factors affecting the loss of spindle, including material properties, load size, power supply frequency, winding form and so on. The main forms of loss are the electromagnetic loss and friction loss. The electromagnetic loss mainly includes the motor iron loss, rotor copper loss.

2.2.1 Iron loss calculation model

The iron loss of motor in ceramic motorized spindle mainly includes the hysteresis loss, eddy current loss and abnormal loss. In this paper, the calculation method of iron loss in motorized spindle adopts magnetic circuit analysis method(Yamazaki et al., 2006; Dong et al., 2015). The constant coefficient trinomial method combined with the voltage separation method to calculate the loss in each part. It is necessary to analyze the loss caused by harmonic magnetic field.

The iron loss in ceramic motorized spindle is shown in Eq.3

$$P_{Fe} = k_h \frac{U_{av}^2}{f} + k_e U_{rmn}^2 \qquad (3)$$

where U_{av} is average voltage of power supply, U_{maxs} is RMS of power supply, k_h is the constant term coefficient of hysteresis loss, $k_h = \frac{\sigma}{2\sqrt{2}N_c fl\tau}$,k_e is the constant term coefficient of eddy current loss, $k_e = \frac{\varepsilon}{4(N_c Sn\pi)^2} = \frac{\gamma}{24\rho\,(N_c nl)^2}$,N_c is coil turns of stator windings, l is the effective length of a conductor cutting magnetic line, γ is the conductivity.

2.2.2 Copper loss calculation model

During the rotating process of ceramic motorized spindle, current flows through both stator and rotor, the copper losses are produced at both stator and rotor. The copper loss is a kind of loss that converts electric energy into heat energy. It reduces the efficiency of the motorized spindle, which will affect the working state of motorized spindle. According to classical formula, the copper loss is equal to the product of the square of the current in the winding and the resistance. The stator windings of the motor in the ceramic motorized spindle are three-phase windings.

$$P_{cu1} = 3I_1^2 R_1 \qquad (4)$$

The stator fundamental copper loss is Eq.5.

$$P_{Cu1f} = 3I_{1f}^2 R_1 \qquad (5)$$

The stator harmonic copper loss is Eq.6.

$$P_{Cu1h} = P_{Cu1} - P_{Cu1f} \qquad (6)$$

According to the law of energy transfer inside the motor, the rotor copper loss is Eq.7.

$$P_{cu2} = sP_{em} \qquad (7)$$

where P_{cu2} is the rotor copper loss, s is slip rate, P_{em} is the electromagnetic power of motor, $P_{em} = \frac{P_m}{1-s}$, P_m is the total mechanical power of spindle.

The total copper loss of ceramic motorized spindle is Eq.8.

$$P_{cu} = P_{cu1} + P_{cu2} = 3I_1^2 R_1 + \frac{s}{1-s} P_m \qquad (8)$$

2.2.3 Mechanical loss calculation model

The mechanical loss is usually constant loss, which is related to the material of the ceramic motorized spindle, manufacturing process, structural design, rotational speed and other parameters. The mechanical loss includes the friction loss between rotor surface and cooling gas which caused by the rotor rotation and bearing friction loss. The empirical equation is used to calculate the wind friction loss as shown in Eq.9.

$$p_w = 2.4 n_p \tau^3 (N_v + 11) \times 10^3 \quad (9)$$

where N_v is the number of ventilation ducts.

The friction loss of the bearings is related to the pressure on the friction surface, the friction coefficient and the relative velocity between the friction surfaces. The friction loss of the bearings is shown in Eq.10.

$$p_f = 1.047 \times 10^{-4} nM \quad (10)$$

where n is speed, r/min, M is bearing friction torque, N.m.

The mechanical loss of the ceramic motorized spindle is Eq.11.

$$p_{fw} = p_f + p_w = 1.047 \times 10^{-4} nM + 2.4 n_p \tau^3 (N_v + 11) \times 10^3 \quad (11)$$

3 LOSS ANALYSIS OF THE CERAMIC MOTORIZED SPINDLE GENERAL RECOMMENDATIONS

In this paper, the type of ceramic motorized spindle is 170SD30SY. The effect of load, speed and current on various losses and efficiency are studied. The motorized spindle basic parameters are shown in Tab.1. According to motor model of the ceramic

motorized spindle which established above, an analysis model about loss of spindle system under PWM control is established. In order to verify that this model is closer to the actual situation, the traditional metal motorized spindle model and the ceramic motorized spindle model are compared. The comparison model is shown in Fig.4. A is three-phase voltage source, B is inverter rectifier, DC link and inverter, C is converter PWM signal generation module, D is ceramic motorized spindle motor module, E is oscilloscopes.

Under the conditions of no-load, half-load and full-load, changing the operating frequency of the spindle to obtain its voltage, current and rotational speed. Calculating the loss and efficiency of the system under different working conditions and draw the graphs according to the calculated loss. Fig. 5 shows the curves of three kinds of loss under various conditions. Fig.6 shows the stator fundamental copper loss and iron loss curves under various conditions. Fig.7 is the stator harmonic copper loss and iron loss curves under various conditions. According to the loss, the efficiencies of the system under various conditions are calculated and the drawing efficiency varies with the load rate and the operating frequency, as shown in Fig.8.

Table 1. Motorized spindle basic parameters

Technical parameters			
rated power /kW	**speed r/min**	**rated voltage /V**	**number of poles**
15	30000	350	4
Performance parameters			
stator resistance /Ω	**stator inductance /H**	**rotor resistance /Ω**	**rotor inductance /H**
0.253	0.0032	0.105	0.0032
stator-rotor mutual inductance /H	**rated torque /N.m**		
0.0364	4.8		

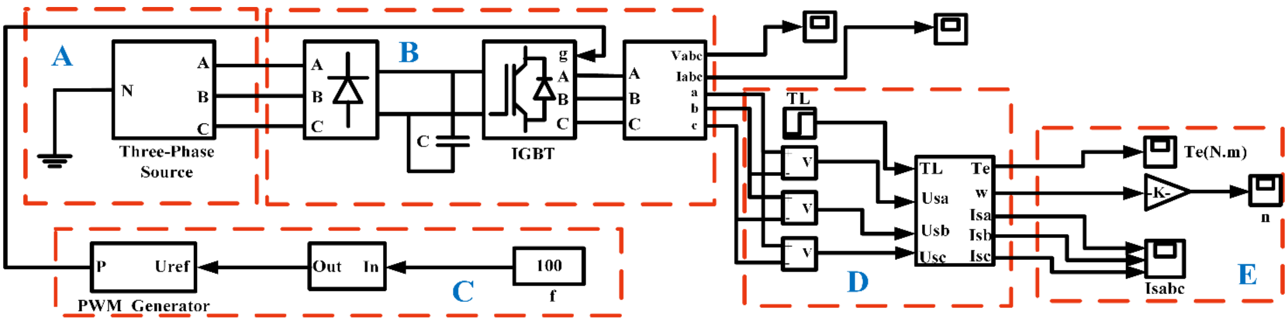


Fig.4 Energy loss analysis model of motorized spindle

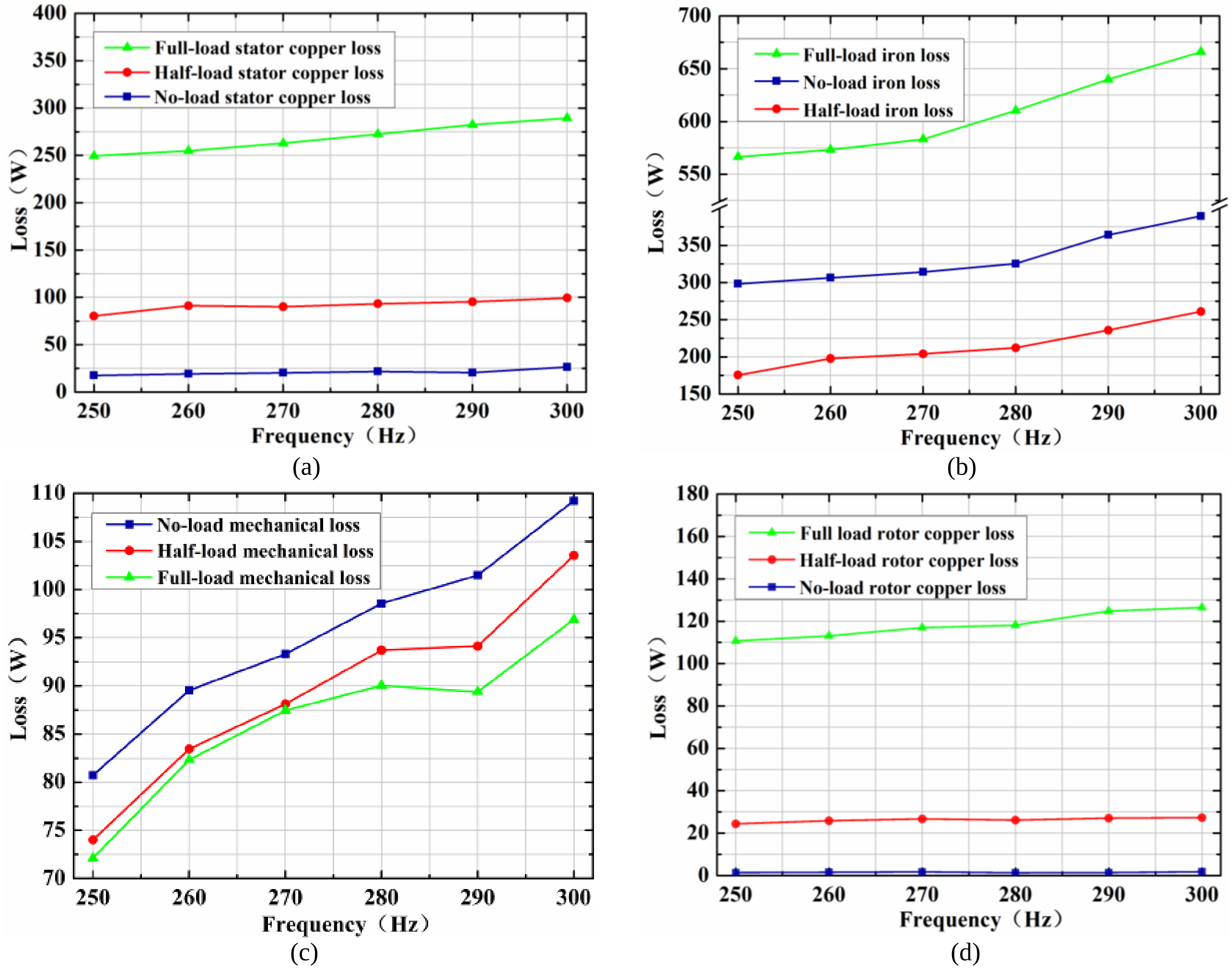
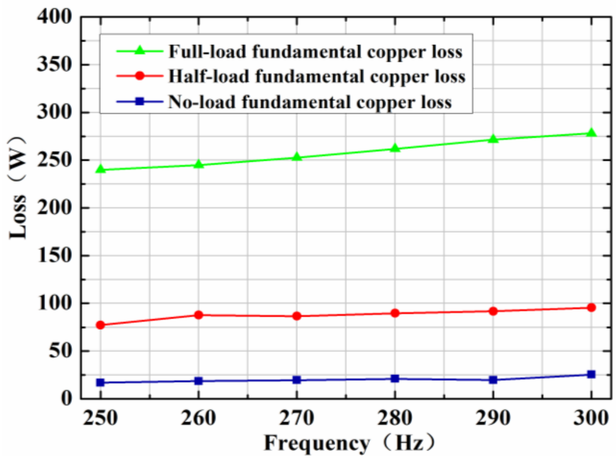


Fig.5 The variation of copper loss, iron loss and mechanical loss with frequency and load rate of ceramic motorized spindle, (a) stator copper loss, (b) iron loss, (c) mechanical loss, (d)rotor copper loss

From Fig.5 (a) and (d), the copper loss increases slowly under three kinds of loads. The copper loss at full load is 30 times higher than that at no load and 10 times higher than that at half load. The stator copper loss is about 2.5 times of the rotor copper loss and the maximum stator copper loss is 285W, the maximum rotor copper loss is 123W.

From Fig.5 (b), the total iron loss increases with the raise of the frequency, which has the minimum iron loss at half-load, the second at no-load and the maximum at full-load being 673W. The lowest iron loss at half-load indicates that the efficiency of the spindle is the highest and the performance effect is the best, the iron loss is the maximum of the ceramic spindle. According to Fig.5(c), the mechanical loss is related to the speed, so mechanical loss is proportional to the frequency. At the same operating frequency, the larger the load rate, the lower the rotation speed and the smaller the mechanical loss.



(a)

From Fig.6 (a) and (b), the fundamental iron loss is larger than the stator fundamental copper loss under three kinds of loads. The change trends of the two fundamental losses are basically consistent with each other and both of them increase gently. The stator fundamental copper loss accounts for more than 95% of the stator copper loss, and the fundamental iron loss accounts for 75% of iron loss.

The stator fundamental copper loss is the main loss source of stator copper loss.

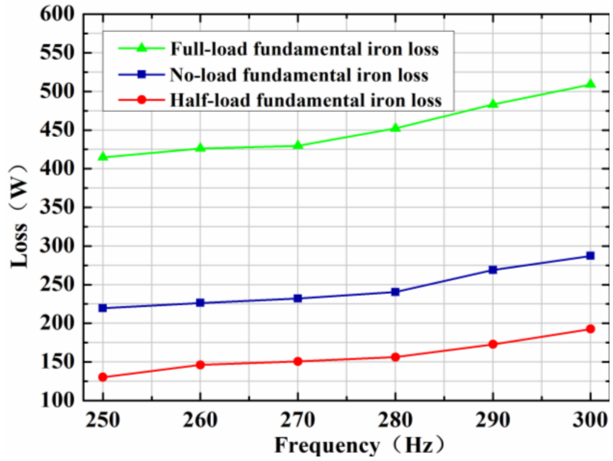


Fig.6 The variation of fundamental loss with frequency and load rate of ceramic motorized spindle, (a) stator fundamental copper loss under different load conditions, (b) fundamental iron loss under different load conditions.

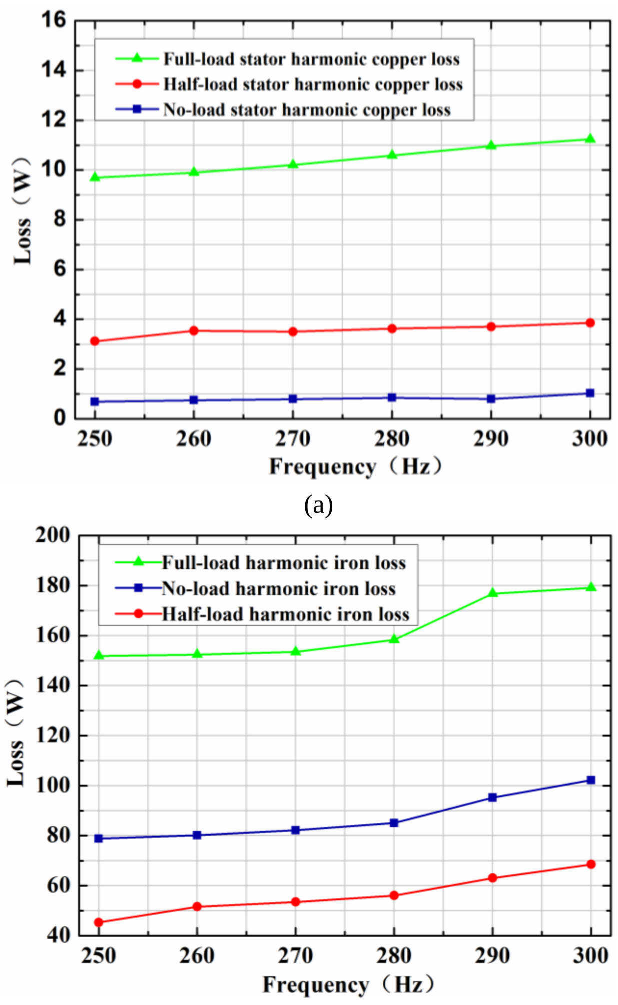


Fig.7 The variation of harmonic loss with frequency and load rate of ceramic motorized spindle, (a) stator harmonic copper loss, (b) harmonic iron loss

From Fig.7 (a) and (b), the stator harmonic copper loss accounts for only about 5% of the stator copper loss, the stator harmonic copper loss is basically in a flat state in the 250Hz-300Hz range, the maximum value is 11W under full load. The stator harmonic copper loss has little influence on the loss of the spindle. The harmonic copper loss is about 25% of the total copper loss, the maximum value is 180W under full load, which is 16 times of the harmonic copper loss. It shows that the harmonic iron loss is more than the harmonic copper loss.

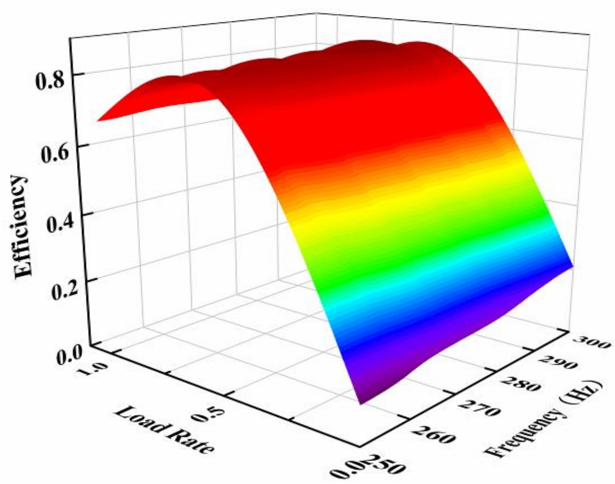


Fig.8 The variation of efficiency with frequency and load rate of ceramic motorized spindle

From Fig.8, spindle efficiency is proportional to the operating frequency, the relationship between the efficiency and the load rate reaches the maximum at half-load and the minimum at no-load. The motorized spindle system efficiency reaches a maximum of 82% at the frequency of 290 Hz at half-load, the efficiency of the spindle system is about 65% at full-load. This is because the ceramic motorized spindle has the best performance when the iron loss is minimum and the input and output power reach the optimal balance state in the case of half-load.

4 TESTING VERIFICATION OF CERAMIC MOTORIZED SPINDLE LOSS

The high-speed motorized spindle performance test platform was used to conduct the loss test on the ceramic motorized spindle 170SD30SY.The input current, voltage and power are tested by the Fluke5000 power analyzer and the load torque is tested by the Type4700A torque speed sensor. Power supply from 250Hz to 300Hz. Load is applied by towing with dynamometer, which can reduce the spindle speed to apply load.

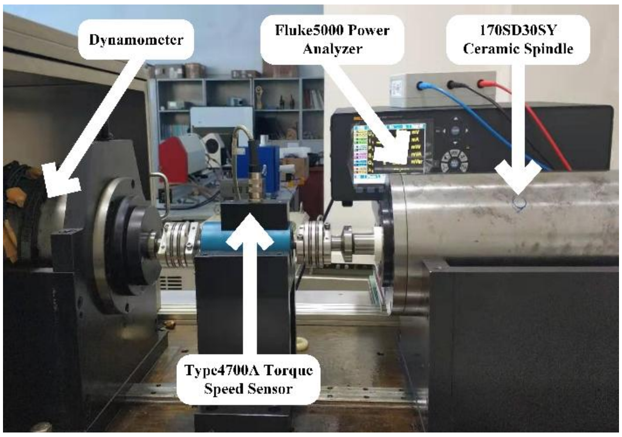


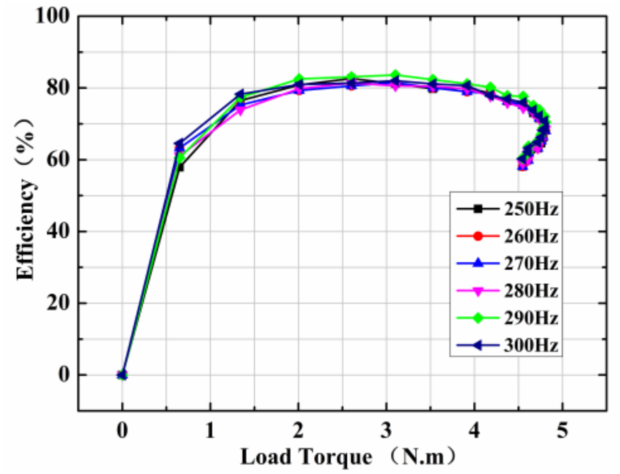
Fig.9 Testing platform for loss of the ceramic motorized spindle

Measuring six groups of loss data, including input current, input voltage, input power, load torque, speed, output power, efficiency and power factor. In order to accurately compare the simulation and measured values, the total loss in the system is compared and the corresponding errors are given, as shown in Tab.2 below. According to six groups of efficiency data, the operation characteristic curves of the ceramic motorized spindles under different loads and slip rates are drawn, as shown in Fig.10. Drawing the comparison figure of mechanical loss test and simulation under no-load condition, as shown in Fig.11.

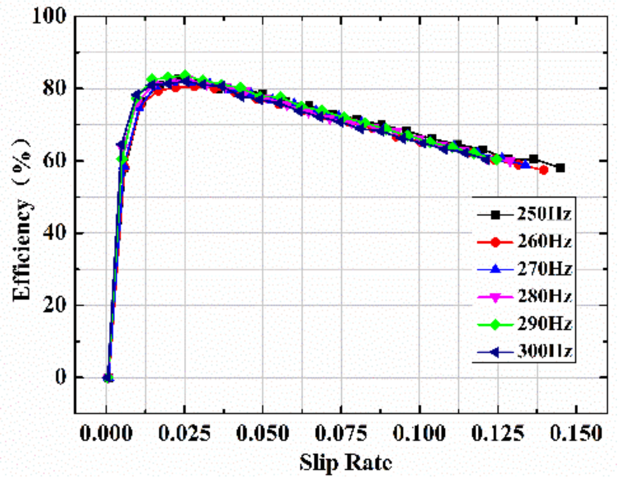
From the comparison of the test and simulation data in Tab.2, the error between the simulation value and the test value is small, the maximum error is less than 8% and the average error is 2.88%. The accuracy can meet the application of the actual energy efficiency evaluation. The change trend of the loss between the test value and the simulation value is basically consistent with the increase of the frequency, but the change trend is very gentle that the increase range is less than 10%. The average loss of 6 groups of test data is 421.74 W, the average loss of no load is 449.81 W, the maximum loss of full load is 1666.78 W. Through the comparison of Tab.2, it can be seen that the established loss calculation model can reflect the loss characteristics of spindle under specific working conditions.

Table2. Comparison of measured and simulated total loss of ceramic motorized spindle

Frequency（Hz）	Load	Measured Value（W）	Simulation Value（W）	Error（%）
250	No-load	391	397.992	-1.788
	Half-load	367.63	354.231	3.644
	Full-load	1586.88	1574.361	0.078
260	No-load	422	413.776	1.949
	Half-load	431.26	398.125	7.683
	Full-load	1599.88	1589.314	0.066
270	No-load	442	426.033	3.612
	Half-load	401.45	409.052	-1.893
	Full-load	1665.66	1615.478	3.012
280	No-load	450	446.827	0.705
	Half-load	406.52	425.362	-4.634
	Full-load	1697.27	1668.904	1.671
290	No-load	494	487.540	1.308
	Half-load	432.35	452.367	4.630
	Full-load	1839.50	1751.045	4.809
300	No-load	512	526.696	-2.870
	Half-load	465.38	491.304	-5.570
	Full-load	1837.69	1801.585	1.965



(a)



(b)

Fig. 10 Efficiency characteristic curve of ceramic motorized spindle, (a) efficiency characteristic curve with the load, (b) efficiency characteristic curve with the slip

From Fig.10(a), efficiency of motorized spindle increases rapidly with the load, reaching maximum when the load reaches half-load and then decreases with the increase of the load. When the load reaches the rated load, the test system automatically decreases the load and the efficiency decreases. The test data show that the maximum efficiency of 290 Hz is 83% in the range of 250 Hz-300 Hz under half load, which is basically consistent with simulation results. Fig.10 (b) is the relationship between slip rate and efficiency. The efficiency increases rapidly with the increase of slip rate before 0.025, reaching the maximum value of 85%, then the efficiency begins to decrease slowly after 0.025. As the load increases, the rotational speed of the ceramic motor spindle decreases by an amount and the slip rate increases. The trend of efficiency change with slip rate is consistent with the results of previous simulation.

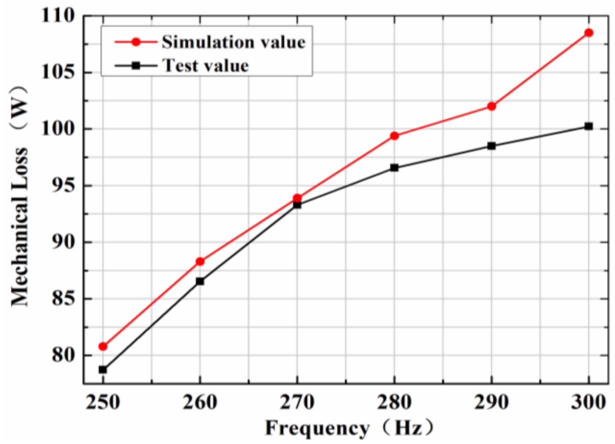


Fig. 11 Mechanical loss comparison of ceramic motorized spindle

By comparing the measured values in Fig.11 with the simulated calculated values shows that the error between the mechanical loss value simulated by the ceramic motorized spindle model and the measured loss value in the test are small, the maximum error is 5%. The increasing trend of the two kinds of data is basically the same, the operating frequency is positively related to the mechanical loss. According to the analysis of the experimental results, The loss model based on MATLAB/Siumlink can reflect the energy loss and efficiency characteristics.

5 CONCLUSION

In this paper, the energy loss model of the ceramic motorized spindle is established. The change trends of three kinds losses in the spindle. The simulation model of ceramic motorized spindle under PWM control is established, the loss change of spindle under various conditions are studied.

1. Based on MATLAB/Siumlink, the loss simulation model of spindle is established. The model considers the loss of iron, copper and machinery. A model is controlled through PWM frequency converter, which is suitable for energy loss analysis of the ceramic motorized spindle which supplied by frequency conversion.

2. Through analyzing the energy loss of the spindle under various conditions. It is concluded that the maximum loss of ceramic spindle is the total iron loss, which is three times and six times of the copper loss and the mechanical loss respectively. The change trend of each loss is increasing as the increase of speed and load. The efficiency of the ceramic motorized spindle system increases rapidly before half-load, reaches the maximum of 82% at half-load, eventually decreases to 65% after half-load.

3. Through the experiments on the test ceramic spindle under various conditions, the tested loss data are basically consistent with the simulation

data. The maximum error is 8% and the average error is about 2.88%, which indicates that the energy loss analysis model of the ceramic spindle can effectively simulate the actual operation ceramic spindle. The model has an important reference value for improving the efficiency of the ceramic motorized spindle and reducing energy loss.

6 ACKNOWLEDGMENTS

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