Performance diagnosis of the drive unit for high speed motorized spindle based on hidden state mapping model

Z W Jia¹, L T Fan¹*, C X Zhu¹, Z P Si¹ and J Z Liu¹
¹School of Mechanical Engineering, Shenyang Jianzhu University, Shenyang 110168

Abstract. As the key component of the motorized spindle system, the performance of drive unit will directly affect the processing quality of CNC machine tools. This paper proposed a performance diagnosis method of hidden state mapping model to prevent the motorized spindle from failure. The hidden state model was obtained by feature extraction of the parameter vectors identified from the dynamic responses to test input signals. The thresholds of performance degradation were determined by the hidden state to evaluate the performance of the drive unit in the motorized spindle system. The feasibility and effectiveness of the model can be verified by taking IGBT degradation failure as an example. The results showed that the model parameters extracted from different degradation degrees of IGBT devices can be mapped to hidden state characteristics and used for performance evaluation of the drive unit. The proposed hidden state mapping model can be used in the framework of monitoring the safety and reliability of the drive unit, and lay the foundation for the prognostic and health management of the motorized spindle system.

1. Introduction
High-end CNC machine tools provide guarantee for the manufacture of high-tech products in my country, it is a processing equipment commonly used in my country's manufacturing industry, basic equipment for manufacturing, automotive and power generation equipment manufacturing industries. The performance of the system is used to describe the ability of the entire system to maintain a certain degree of reliability and continue to achieve predetermined goals. Health monitoring is a kind of periodic detection of a certain part of the system parameters or characteristics failure. During the long-term use of the equipment, the phenomenon of aging and wear inside the equipment, the performance of the equipment is degraded. With long-term performance degradation, the device is malfunctioning. In large mission-critical systems, an advanced detection system can continuously assess the health of the system. Production equipment should be regularly evaluated for performance to avoid downtime maintenance.

There are many ways to evaluate performance, the evaluation method introduced in the reference [1] to determine the evaluation weight, this method can provide a reference for mechanical system performance evaluation and similar problems, but the scale workload is too large, it should cause disgust and confusing judgment experts. Reference [2] describes the method of fuzzy comprehensive evaluation, aiming at the problem of many uncertain factors in the diagnosis process of industrial equipment, it realizes the simplicity of the equipment diagnosis process and the accuracy of the evaluation results through the conversion of qualitative analysis to quantitative analysis, but it has strong subjective certainty to the index weight vector; this article uses the method of system identification performance evaluation, determine the parameters of the system model by performing system
identification on the system in the normal state, identify systems at different stages of degradation. Study the mapping relationship between the geometric distance of the parameter vector and the performance degradation, and evaluate the performance of the current drive system [3]. Through IGBT performance degradation simulation examples to verify, the result shows: as the degree of performance degradation continues to intensify, the geometric distance of the system parameter vector gradually increases. Confirm the feasibility of this performance evaluation method.

2. High-speed motorized spindle drive system simulation design and system identification

2.1. Drive system simulation design
The high-speed motorized spindle drive system is a closed-loop system composed of a frequency converter and spindle motor. The spindle motor has synchronous motor and asynchronous motor, this design selects asynchronous motor for design analysis. The closed-loop drive system is built according to the idea of rotor orientation control, which converts the alternating current in the system into direct current for control, so as to realize the separation control of the electric spindle torque and speed, and achieve the equivalent effect of DC power control [4]. In the process of simulation design, combined with the equation expression of asynchronous motor.

\[
\begin{bmatrix}
u_{sd} \\ u_{sq} \\ u_{rd} \\ u_{rq}
\end{bmatrix} =
\begin{bmatrix}
R_i + L_m P & -\omega L_r & L_m P & -\omega L_m \\
\omega L_r & R_i + L_r P & \omega L_m & L_m P \\
L_m P & -\omega L_m & R_i + L_r P & -\omega L_r \\
\omega L_m & L_m P & \omega L_r & R_i + L_r P
\end{bmatrix}
\begin{bmatrix}
i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq}
\end{bmatrix}
\tag{1}
\]

\[
\begin{bmatrix}
\psi_{sd} \\ \psi_{sq} \\ \psi_{rd} \\ \psi_{rq}
\end{bmatrix} =
\begin{bmatrix}
L_i & 0 & L_m & 0 \\
0 & L_i & 0 & L_m \\
L_m & 0 & L_r & 0 \\
0 & L_m & 0 & L_r
\end{bmatrix}
\begin{bmatrix}
i_{sd} \\ i_{sq} \\ i_{rd} \\ i_{rq}
\end{bmatrix}
\tag{2}
\]

\[
T_e = n_p L_m (i_{sq} i_{rd} - i_{sd} i_{rq})
\tag{3}
\]

In two-phase rotating coordinate system, \(\psi_{rd} = \psi_r, \psi_{rq} = 0\);

\[
T_e = n_p \frac{L_m}{L_r} i_{sq} \psi_r
\tag{4}
\]

\[
i_{sd} = \frac{1 + T_e P}{L_m} \psi_r
\tag{5}
\]

\[
\psi_r = \frac{L_m}{1 + T_e P} i_{sd}
\tag{6}
\]

\[
\omega_s = \frac{L_m}{T_r \psi_r} i_{sq}
\tag{7}
\]

In the equations: \(\omega_s\) is the synchronous speed; \(\omega_r\) is the rotor speed; \(\omega_s\) is slip angular velocity; \(\psi\) is flux linkage; \(i\) is the current; \(R\) is the resistance; \(L\) is the inductance; \(n_p\) is polar logarithm; \(T_r\) is the rotor
time constant; \( P = d/dt \) is the differential factor; \( s \) is stator; \( r \) is the rotor; \( d \) is d-axis; \( q \) represents q-axis; \( m \) is the mutual inductance.

2.1.1. Transformation from 3 phases to 2 phases of stationary coordinate system. When the asynchronous motor is connected with three-phase alternating current, it will generate a rotating magnetic field inside the motor. Under the condition of ensuring a certain power, the rotating magnetic field generated by the three-phase alternating current can be equivalent to the rotating magnetic field generated by the two phases, and the process is realized. The equivalent transformation of the static coordinate system from three phases to two terms. Under the premise that the magnetomotive force remains unchanged, determine the relationship between the voltage, current and magnetomotive force of the three-phase winding and the two-phase winding. Set the current of two symmetrical windings, current of three-phase symmetrical winding, the transformation equation between them is:

\[
\begin{bmatrix}
i_d \\
i_q
\end{bmatrix}
= \begin{bmatrix}
1 & -1 & -1/2 \\
-2/2 & -2/2 & -2/2 \\
\sqrt{2} & \sqrt{2} & \sqrt{2}
\end{bmatrix}
\begin{bmatrix}
i_A \\
i_B \\
i_C
\end{bmatrix}
= C_{3/2} \begin{bmatrix}
i_A \\
i_B \\
i_C
\end{bmatrix}
\] (8)

In equation (8), it is a one-phase zero-sequence component added for inverse transformation.

2.1.2. Transformation between two-phase stationary coordinate system and two-phase rotating coordinate system. The two-phase static winding is connected with a two-phase balanced alternating current to generate a rotating magnetomotive force. According to the analysis of the relative relationship between static and motion, assuming that the fixed current is direct current, the winding becomes rotating, and the angular velocity of rotation is consistent, then the two-phase windings are connected with direct current to produce space rotating magnetomotive force. This transformation process is called two-phase rotation-two-phase static transformation. The transformation equation is:

\[
\begin{bmatrix}
i_d \\
i_q
\end{bmatrix}
= \begin{bmatrix}
\cos \varphi & -\sin \varphi \\
\sin \varphi & \cos \varphi
\end{bmatrix}
\begin{bmatrix}
i_d \\
i_q
\end{bmatrix}
= C_{2r/2s} \begin{bmatrix}
i_d \\
i_q
\end{bmatrix}
\] (9)

In equation (9), \( \varphi \) is the angle between the d axis of the d-q coordinate system and the axis of the coordinate system, \( \omega (\varphi = \omega t) \) is the rotational angular velocity of the d-q rotating coordinate system. \( C_{2r/2s} \) is the transformation matrix from two-phase rotation to two-phase stationary coordinate system.

\[
C_{2r/2s} = \begin{bmatrix}
\cos \varphi & -\sin \varphi \\
\sin \varphi & \cos \varphi
\end{bmatrix}
\] (10)

Inverse transformation of equation (10) can get the conversion from static to rotating coordinate system.

\[
C_{2s/2r} = C_{2r/2s}^{-1} = \begin{bmatrix}
\cos \varphi & \sin \varphi \\
-\sin \varphi & \cos \varphi
\end{bmatrix}
\] (11)

2.1.3. Transformation between three-phase stationary coordinate system and two-phase rotating coordinate system. Through equations (8)-(11) in section 2.1.2, comprehensive analysis of the formulas can derive the matrix relationship between the three-phase stationary to the two-phase rotating coordinate system. The conversion relation is as follows:
The transformation matrix from the three-phase stationary coordinate system to the two-phase arbitrary rotating coordinate system is:

\[
\begin{bmatrix}
i_a \\
i_\beta \\
i_0
\end{bmatrix} = C_{2s/\beta}^{2/2r} \begin{bmatrix}
i_a \\
i_\beta \\
i_0
\end{bmatrix} = C_{2s/\beta}^{2/2r} C_{3s/2s}^{3/2s} \begin{bmatrix}
i_A \\
i_B \\
i_C
\end{bmatrix}
\]

(12)

The transformation matrix from the two-phase arbitrary rotating coordinate system to the three-phase stationary coordinate system is:

\[
C_{2s/\beta}^{2/2r} = C_{3s/2s}^{2/2r} = \sqrt{\frac{2}{3}} \begin{bmatrix}
\cos \varphi & \cos(\varphi - 120^\circ) & \cos(\varphi + 120^\circ) \\
-\sin \varphi & -\sin(\varphi - 120^\circ) & -\sin(\varphi + 120^\circ) \\
\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}
\end{bmatrix}
\]

(13)

2.1.4. Under the d-q coordinate system, the motor model. In the d-q coordinate system, the basic formula of asynchronous motor can be obtained.

\[
Te = n_p \frac{L_m}{L_r} (i_{sq} \psi_{rd} - i_{sd} \psi_{rq})
\]

(15)

\[
Te - T_L = J \frac{dw_r}{dt}
\]

(16)

\[
i_{sd} = \frac{U_{sd}}{L_{sc}s + R_s} - \psi_{rd} \frac{1}{L_r} \frac{L_m s}{L_{sc}s + R_s}
\]

(17)

\[
i_{sq} = \frac{U_{sq}}{L_{sc}s + R_s} - \psi_{rq} \frac{1}{L_r} \frac{L_m s}{L_{sc}s + R_s}
\]

(18)

\[
\psi_{rd} = \frac{1}{R_r + L_r s} (i_{sd} L_m R_r - w_r L_s \psi_{rq})
\]

(19)

\[
\psi_{rq} = \frac{1}{R_r + L_r s} (i_{sq} L_m R_r + w_r L_s \psi_{rd})
\]

(20)

From (15) to (20), the following motor models can be built.
Figure 1. Asynchronous motor simulation model.

Figure 1 is a model simulation diagram of an asynchronous motor, the motor model under ideal conditions is established to eliminate the influence of motor performance degradation on the IGBT degradation case study.

2.1.5. Establish the entire system simulation model. Figure 2 is the simulation model of the motorized spindle frequency conversion speed regulation system. Use the from workspace and to workspace of the simulink module to transfer input and output data to and from the workspace, use this model for the following identification steps.

Figure 2. System simulation model.
2.2. Drive system identification

2.2.1. Principles of system identification. System identification is widely used in control systems. The input and output signals of the system are collected through experiments, the system model is identified using the identification toolbox, and the system model can be determined by further verification [5]. It can get a description of the system through the processing and calculation of input-output signals. For manual control in industrial processes, the process operator needs to know how the process output responds to different control behaviours. System identification is to study how to obtain the mathematical model of the system from the measured values.

![Figure 3. Expressions to identify problems.](image)

The system identification method is to identify the transfer function. The process equation is:

\[ y^n(t) + a_1y^{(n-1)}(t) + \cdots + a_ny(t) = b_0u^m(t) + b_1u^{(m-1)}(t) + \cdots + b_mu(t) \]  \hspace{1cm} (21)

Among them, \( y(t), u(t) \) are the output and input signal in the time domain, \( n, m \) are the system order of the model, \( a_1, \ldots, a_n, b_0, \ldots, b_m \) are constant, the above formula is transformed by Laplace, we can get a general expression in the time domain of the transfer function [6].

\[ G(s) = \frac{Y(s)}{U(s)} = \frac{b_0s^n + b_1s^{n-1} + \cdots + b_ms^0}{s^n + a_1s^{n-1} + \cdots + a_n} \]  \hspace{1cm} (22)

\( Y(s), U(s) \) are the output input signals. In the study, we introduce unit forward operator and unit delay operator, get a description of the discrete process of the system

\[ y(t) = G(q)u(t) \]  \hspace{1cm} (23)

Pass operator \( G(q) \) expression is

\[ G(q) = \frac{b_0q^{-1} + \cdots + b_nq^{-m}}{1 + a_1q^{-1} + \cdots + a_nq^{-n}} \]  \hspace{1cm} (24)

2.2.2. System identification steps. Generally speaking, the system identification process includes the following basic steps:

Step 1 - identification experiment.

Reference [7] uses Chirp signal as excitation signal to study the identification of electro-hydraulic servo system. Select the generalized binary noise (GBN) signal [8] as the input signal, the selection of sampling time should refer to the response speed of the system. This article selects GBN signal as the
excitation signal, the GBN signal is a randomly generated noise signal, suitable for control identification experiments related to industrial processes, the generation rule of this signal is that the value of $u(t)$ is switched back and forth between the constant $\pm a$, and switch at a certain conversion moment, meet the following formula with the conversion time $t$.

\[
P[u(t)=-u(t-1)]=P_{sw}
\]

\[
P[u(t)=u(t-1)]=1-P_{sw}
\]

$P_{sw}$ is the conversion probability that is the probability of the signal switching at each conversion time, each time is distributed independently. Therefore, the expectation of the GBN signal is zero.

**Step 2 - model order/Structure selection.**

Choose the optimal model order, the finalized model can best describe the system under test. In the system identification research, different transfer function models are selected for different measured objects to carry out experimental design. Generally speaking, the models commonly used in system identification are the most commonly used ARX (auto regression model) models, ARMAX (noisy autoregressive moving average) models, GLS (generalized least squares) models, etc. These models are selected for different system structures, the ARX and ARMAX models are used in common systems. In this paper, the ARX model is selected as the system identification model.

**Step 3 - parameter estimation.**

Use the optimization algorithm to get the best parameter estimate.

**Step 4 - model checking.**

For different recognition situations, determine different accuracy standards, perform accuracy test on the obtained model, if the accuracy does not meet the requirements, then optimize the previous experimental steps, do the model test again, until it meets the standard. The test method adopted in this article is 0.3 precision test method, That is, 0.3 times the size of the performance degradation evaluation interval is greater than or equal to the identification parameter error.

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**Figure 4.** Identification process block diagram.
2.2.3. Determination of system performance evaluation level. According to the literature [9], we can know that the operation performance of the motorized spindle will decrease, the overall performance gradually decreases. In order to make the different results obtained by the system identification have different measurement standards, we need to rank the evaluation results in advance, determine the status of different levels.

![High-speed electric spindle drive system block diagram](image)

Figure 5. High-speed electric spindle drive system block diagram.

This paper determines the degree of performance degradation based on the geometric distance between the parameters identified by the system and the identification parameters of the normal system, the geometric distance \( g \) reflects the degree of deviation of the values [10, 11], the evaluation value is obtained by normalizing the calculated distance.

\[
g = \sqrt{(a_1 - b_1)^2 + (a_2 - b_2)^2 + \ldots + (a_n - b_n)^2} = \sqrt{\sum_{i=1}^{n} (a_i - b_i)^2}
\]  
\[x = \frac{g - g_{\text{min}}}{g_{\text{max}} - g_{\text{min}}}
\]

where \( a_1, a_2, \ldots, a_n \) are the transfer function parameters identified by the normal system, \( b_1, b_2, \ldots, b_n \) are the transfer function parameters identified during operation, \( g \) is the Euclidean distance of the parameter vector, \( x \) is the normalized value of geometric distance.

Establish four performance evaluation levels between normal and faulty systems, on the basis of summarizing the current classification, this article, this paper proposes a model table 1 for the evaluation of the high-speed motorized spindle drive system [12].

| Evaluation level | Evaluation value | Recommended measures          |
|------------------|------------------|-------------------------------|
| excellent        | \(0 \leq x < 0.25\) | Excellent performance         |
| good             | \(0.25 \leq x < 0.5\) | Normal maintenance            |
| average          | \(0.5 \leq x < 0.75\) | Strengthen maintenance and local repair |
| poor             | \(0.75 \leq x \leq 1\) | Overhaul                      |
3. IGBT degradation performance evaluation example analysis

3.1. IGBT performance degradation principle

The performance of IGBT is degraded, the literature [13] analyse the degradation process from its internal chip and external package. In terms of internal chips, one is the aging of the solder layer, the solder layer is used to fix the IGBT chip and the package shell, the shell temperature cycle rises and falls, it causes electron-thermal shock to the solder layer, leads to fatigue degradation of the solder layer, reduces the heat dissipation capacity of IGBT, causes the junction temperature to rise continuously as the degree of degradation deepens, eventually fails and a short circuit or open circuit fault occurs. The second is that the bonding wire falls off, the IGBT module continuously withstands the impact of temperature fluctuations during the work process, resulting in the accumulation of plastic strain at the connection point between the bonding wire and the silicon chip, and the cracks at the edge of the connection point between the bonding wire and the silicon initially appear. Under the repeated impact of temperature fluctuations, the crack gradually expands, accelerating the fall of the bonding wire, at the same time, the aluminium substrate of the emitter is restructured, which leads to the degradation of IGBT performance. Literature [14] through temperature cycle experiments, after the device failed, the phenomenon of bond wire shedding, cracking and metal reconstruction was observed through scanning electron microscope pictures. After the performance of the IGBT chip is degraded, the results of bond wire drop and metal reconstruction are shown in figure 7: (a) bond wire off, (b) bond wire cracks, (c) the surface of the aluminium substrate without reconstruction before use, (d) after the performance degradation and reconstruction, the surface of the aluminium substrate.

Figure 6. Picture of IGBT device structure degradation.

Figure 7. IGBT structure diagram.
In terms of the material composition of the package, there are various materials in the packaged IGBT. From table 2, the material will expand and contract due to temperature changes, under equal pressure (P-fixed) conditions, measured by the change in volume of the material caused by the change in unit temperature, this change can be called the coefficient of thermal expansion (CTE) [15].

| Name                  | Material used | Thermal expansion coefficient (ppm/℃) |
|-----------------------|---------------|--------------------------------------|
| Aluminium bonding wire| aluminium     | 22                                   |
| IGBT chip             | silicon       | 3                                    |
| Welding layer         | solder        | 28                                   |
| Ceramics              | ceramics      | 7                                    |
| Substrate             | copper        | 17.5                                 |

The connection between the IGBT chip and the diode chip is made of aluminium metal layer and bonding wire, moreover, the chip material silicon and the metal layer and the material of the bonding wire have a large difference in thermal expansion coefficient, resulting in the thermal cycling process, repetitive mechanical stresses caused by different degrees of expansion on the contact surface, this will lead to continuous fatigue degradation of the lead metal layer, and the bonding wire subjected to this repeated stress impact.

There are two forms of failure caused by this degradation. One form of failure is to cause reconstruction of the surface of the lead metal layer, On the other hand, the resistance of this part and the power generated is increased, and the junction temperature is further increased. On the other hand, reducing the heat dissipation capability also makes the junction temperature further increase. When the junction temperature is greater than a certain threshold, the parasitic crystal tube in the IGBT is turned on, the gate loses control, and a collector-emitter short circuit occurs; another type of failure is to cause the bonding wire to break, and an open collector-emitter circuit will occur. The breaking of the bonding wire will also cause the resistance of this part to increase. In summary, both the lead metal layer and the bonding wire will increase the resistance of this part, both resistances are part of the resistance of the IGBT collector-emitter channel. Therefore, online monitoring of the resistance of the IGBT collector-emitter channel enables monitoring of the degree of degradation of the IGBT lead metal layer and bonding wire.

3.2. Performance evaluation of IGBT performance degradation process

3.2.1. IGBT performance degradation simulation design. According to the analysis of the degradation mechanism of IGBT, there are two types of IGBT degradation, bond wire breakage and aluminium metal layer damage. The two forms of degradation eventually lead to an increase in the internal resistance \( R_{on} \), and the internal resistance of the IGBT varies from 0.105 to 0.115 [16]. The resistance change inside the IGBT can characterize the degradation degree of the aluminium metal layer and the bonding wire inside the IGBT, and not affected by changes in load current \( I_c \). Through this part of the analysis, simulation experiments of performance degradation can be established, in the simulation, the value of internal resistance \( R_{on} \) is continuously increased to simulate the degradation process of IGBT performance. Set the \( R_{on} \) value to 0.110 to evaluate the performance of the current state.

3.2.2. Performance evaluation. The parameters of the asynchronous motor model are set as: rated power \( P_N=20kW \), rated voltage \( U_N=350V \), rated frequency \( f_N=500Hz \), stator resistance \( R_s=0.11\Omega \), rotor resistance \( R_r=0.21\Omega \), stator leakage inductance \( L_s=0.00030239H \), rotor inductance \( L_r=0.00030876H \),
stator and rotor mutual inductance $L_r=0.0086 \, H$, number of pole pairs $p_n=2$, moment of inertia $J=0.01 \, kg \cdot m^2$.

The system identification method is used to gain the transfer function, it contains the dynamic and static characteristics of many models. Under the guidance of practical industrial process experience and knowledge, by comparing and analysing some parameter information of these system transfer functions, in order to obtain some changes in key information, data information with reference value for system testing personnel, make corresponding judgments and repair work.

![Figure 8. Performance evaluation method based on system identification.](image)

The basics model in the figure is the transfer function parameter identified by the normal system $a_1, a_2, ..., a_n$, new model is the system transfer function parameter identified during detection. This figure describes the overall idea of using the system identification method to evaluate the performance of the system proposed in this article. From the framework, it can be seen as a research method based on model discrimination. Identify the system during the period of normal operation of the system and the period of being tested, compare the transfer function information obtained at different times, if some key variables and information in the industry have serious deviations from normal operating conditions, it is necessary to carry out troubleshooting or troubleshooting in advance.

When the internal resistance of the IGBT is set to 0.110, according to the theoretical analysis, the evaluation grade of IGBT is good. Follow the system identification steps in chapter 2 to perform identification under $R_{on}=0.105$ and $R_{on}=0.110$ states, as shown figure 9.

![Figure 9. System identification output.](image)
The transfer function can be obtained through the identification method as shown in table 3.

**Table 3. Identification transfer function table.**

| Transfer Function | Transfer Function Equation |
|-------------------|-----------------------------|
| $G_{normal}$      | $-0.7136z^{-1} - 0.1279z^{-2}$ \[1+0.3247z^{-1} + 0.2312z^{-2}\] |
| $G_{K_m=0.110}$   | $-0.7113z^{-1} - 0.1051z^{-2}$ \[1+0.3035z^{-1} + 0.2335z^{-2}\] |
| $G_{fault}$       | $-0.6712z^{-1} - 0.0763z^{-2}$ \[1+0.2521z^{-1} + 0.2310z^{-2}\] |

The above examples of IGBT degradation confirm the correctness of the established model and system identification performance evaluation method, using the system identification parameter mapping mechanism to diagnose the system performance, it provides a great help to the system performance evaluation.

**4. Conclusion**

In this paper, the geometric distance between the identification parameters of the high-speed motorized spindle drive system and the normal working system in the actual working process is obtained. Determine the degree of system performance degradation through the geometric distance, the corresponding evaluation level is given to the current system performance. Using this method, an example of IGBT device performance degradation is analysed. The result shows, the method can evaluate the performance of IGBT degradation process well, the degree of degradation is mapped through the identification parameters. There are few studies using this method to evaluate system performance. The system performance evaluation method based on system identification parameter changes and geometric distance determination lays the foundation for future system performance evaluation research.

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