Research on vibration control of bearingless motorized spindle

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Abstract—Bearingless motorized spindle is a new type of motorized spindle composed of bearingless motor and motorized spindle. With the increasing speed, the spindle will produce obvious gyro effect and vibration interference, so it is of practical significance to study the vibration control of bearingless motorized spindle. In this paper, the principle of minimum rotor vibration displacement is introduced, and a compensation controller based on adaptive feedback is designed and verified by simulation.

1. Introduction
During the operation of bearingless motorized spindle, the unbalanced vibration caused by its rotor has a great influence on its machining quality. And the current research results show that in the process of high-speed operation of bearingless motorized spindle, it is easy to cause faults due to the excessive vibration of the rotor. Therefore, it is necessary to compensate the vibration of bearingless motorized spindle. In this paper, based on the principle of minimum rotor vibration displacement, a bearingless motorized spindle controller is designed to compensate rotor vibration, which is simulated and verified by Matlab/Simulink.

2. Principle of minimum rotor vibration displacement
The principle of minimum rotor vibration displacement is to minimize the amplitude of vibration displacement of unbalanced rotor. In the control system, the compensation scheme can use the controller to generate a vibration compensation force with the same magnitude and opposite direction as the unbalanced excitation centrifugal force, so as to weaken the influence of the unbalanced excitation centrifugal force on the rotor\textsuperscript{[1]}. Due to the high rotation accuracy of the rotor, the control system needs to apply a certain compensation force to the rotor. According to the principle of force interaction, there will be a reaction force acting on the stator core and base of bearingless motorized spindle, which will cause the vibration of the stator and the base. At the same time, the corresponding compensation current will also increase the control energy of the system\textsuperscript{[2]}. Therefore, this compensation principle is generally used in situations where high rotation accuracy is required. Fig.1 shows the control block diagram of the compensation principle.
3. Rotor vibration unbalance displacement extraction algorithm

The unbalanced displacement adaptive filtering algorithm based on LMS is adopted. After adjusting the input signal parameters, the output signal generated by the LMS adaptive filter is compared with the expected signal to form an error signal. Then the filter parameters are adjusted through the adaptive algorithm to minimize the mean square of the error signal and obtain the expected useful signal[3].

3.1 LMS adaptive filtering principle

The reference input signals $x_1(k)$ and $x_2(k)$ in Fig.2 are sine and cosine signals with angular frequencies equal to $d_0(k)$, respectively. In operation, the filter adjusts the weight coefficients $w_1$ and $w_2$ by LMS adaptive algorithm, so that the amplitude and phase of the synthetic signal $y(k)$ are consistent with $d_0(k)$ when reaching the steady state. $y(k)$ is the extracted rotor unbalanced vibration displacement signal.

3.2 LMS algorithm analysis

Step factor $\mu$ is one of the core problems of LMS algorithm. Step factor directly determines the convergence speed and steady-state error of the system. When the step factor becomes larger, the convergence of the system will become faster, but the steady-state error will be larger. If the step factor becomes smaller, the convergence of the system will be slower and the steady-state error will smaller.

In order to solve the above contradiction, variable step is used to instead of fixed step to update the weight coefficient, and the functional relationship between step factor and error signal is constructed first, so that the step factor changes with the error signal. The step can be adjusted according to the size of the error signal. Therefore, the convergence speed can be accelerated in case of large error and the steady-state error can be reduced in case of small error. Step factor adjustment function is as follow[4]:

$$\mu(k) = b[1 - \exp(-a|e(k)|^2)]$$

(1)

Where, $a$ and $b$ are parameters of the adjustment function, $\mu$ is step factor. $|e(k)|$ is the error.

According to Formula (1), step factor $\mu$ is related to $|e(k)|$. That is, the larger $|e(k)|$ is, the larger step factor is, the smaller $|e(k)|$ is, the smaller step factor is. It shows that Formula (1) can be used to achieve the step factor varies with the absolute value of the error.

4. Unbalanced vibration control based on adaptive feedback compensation controller

In this section, the feedback compensation controller based on LMS adaptive algorithm is adopted. The LMS algorithm is used to adjust the compensation signal output by the compensation controller to offset the influence of unbalanced excitation force on the radial displacement of the rotor, so as to reduce the
radial displacement of the rotor and rotate around its geometric center.

4.1 Design of adaptive feedback control compensation controller
The closed-loop control is used to realize the suspension operation of the rotor. The adaptive feedback compensator can generate compensation signal and input it to the bearingless motorized spindle controller. The controller can generate compensation force to offset the influence of unbalanced excitation force on the rotor, thus eliminating the unbalanced vibration of the rotor[5].

![Fig.3 Diagram of Suspension system based on adaptive feedback compensation control](image)

In Fig.3, \( r, c, \omega_r, d \) and \( s \) are reference displacement signals, vibration compensation signals, rotor angular velocity, unbalance excited centrifugal force and actual displacement signals, respectively.

The compensation signal \( c \) has the same characteristics as the sines and cosines of unbalanced displacement, and the compensation signal can be written as:

\[
c(k) = A_c \sin(\omega_c k + \varphi)
\]

Where, \( \omega_r \) is rotor angular velocity, \( A_c \) is constant coefficient. \( \varphi \) is rotor mechanical angle.

Expand Formula (2) and get:

\[
c(k) = A_c \sin(\omega_r k) \cos \varphi + A_c \cos(\omega_r k) \sin \varphi
\]

Set \( A_c \cos \varphi = w_1(k) \), \( A_c \sin \varphi = w_2(k) \). Formula (3) can be written as:

\[
c(k) = w_1(k) \sin(\omega_r k) + w_2(k) \cos(\omega_r k)
\]

In Formula (4), \( w_1(k) \) and \( w_2(k) \) are both adaptive adjustment parameters, denoted as \( W = [w_1(k) \ w_2(k)]^T \). By adjusting the parameters, the influence of the unbalanced excitation force on the rotor can be offset by the compensation force when reaching the steady state. Fig.4 is the block diagram of an adaptive feedback compensation controller.

![Fig.4 Diagram of adaptive feedback compensation controller](image)

4.2 Adaptive compensation algorithm
The LMS adaptive algorithm uses the gradient descent method to adjust the value of the weight coefficient in real time to minimize the objective function in steady state. Therefore, the objective function needs to be determined first. The objective function in this section is[6]:

\[
\xi = E[s^2(k)]
\]

Fig.5 is the equivalent transfer function model of Fig.4. \( G_{CL}(q^{-1}) \) is the closed-loop transfer function of the system, \( G_P(q^{-1}) \) is the transfer function from unbalanced excitation force to system displacement output, and the reference displacement signal is set to 0.
Fig. 5 Equivalent transfer function model of the suspension system

At this point, the displacement signal output by the suspension system can be expressed as:

\[ s(k) = d(k)G_D(q^{-1}) - c(k)G_{CL}(q^{-1}) \]  

(6)

The updating rules of adaptive parameters are as follows:

\[ W(k + 1) = W(k) + \mu s(k) \begin{bmatrix} \sin(\omega k) \\ \cos(\omega k) \end{bmatrix} \]  

(7)

In Formula (7), \( \mu = \lambda \gamma \), \( \mu \) is a parameter that needs to be adjusted according to actual use. Based on the above section, the adaptive rules of \( w_1(k) \) and \( w_2(k) \) can be written as follows:

\[ \begin{bmatrix} w_1(k + 1) \\ w_2(k + 1) \end{bmatrix} = \begin{bmatrix} w_1(k) \\ w_2(k) \end{bmatrix} + \mu s(k) \begin{bmatrix} \sin(\omega k) \\ \cos(\omega k) \end{bmatrix} \]  

(8)

Using the adaptive algorithm shown in Formula (8) to adjust the compensation signal, the influence of unbalanced excitation force on the rotor can be eliminated.

4.3 Simulation analysis

Fig. 6 shows the structure of unbalance vibration compensation control system of bearingless motorized spindle based on adaptive feedback compensation controller.

Fig. 7 shows the radial displacement curve of the rotor in \( \alpha\beta \) static coordinate system without vibration control compensation. It can be seen from the Figure that the radial displacement of the rotor fluctuates periodically due to the unbalanced excitation force, and the suspension accuracy of the rotor is greatly affected.
Simulation results after vibration control compensation are shown in Figure 8.

![Displacement waveform images](image1.png)  ![Displacement waveform images](image2.png)

(a) $\alpha$-direction displacement waveform  (b) $\beta$-direction displacement waveform

**Fig.7 Displacement waveform of $\alpha\beta$ without vibration control compensation**

It can be seen from Fig.8 that in the starting stage, the rotor has a small unbalanced vibration with an amplitude of about $8 \mu m$ because the control force of unbalanced vibration is not completely established. After stable operation at a given speed, under the action of the unbalance displacement control compensator, the radial displacement of the rotor along axis $\alpha$ and $\beta$ gradually approaches $0 \mu m$, the center points of the rotor and stator basically coincides, the unbalance vibration of the rotor is effectively controlled, and the suspension accuracy is improved.

Comparing Fig.7 and Fig.8, It can be seen that using the proposed adaptive feedback vibration compensation control strategy, the unbalance vibration displacement signal of the rotor is greatly weakened in the dynamic process, the unbalanced vibration displacement in the steady state is close to $0 \mu m$, and the influence of unbalanced excitation centrifugal force on the rotor is weakened. It shows that the effect of unbalanced vibration control is obvious, and the proposed compensation control algorithm is effective and feasible.

5. Conclusion

This paper introduced the principle of unbalance vibration compensation principle of bearingless motorized spindle, recommend the algorithm of unbalance vibration displacement extraction based on LMS, and designed a controller based on the minimum principle of rotor vibration displacement. The simulation analysis of bearingless motorized spindle control system based on adaptive feedback compensation controller was established by using MATLAB-Simulink. The simulation results showed that the compensation control strategy can effectively suppress the rotor unbalanced vibration and improve the suspension control accuracy.

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