

Suspension Model and Control of Magnetic Levitation Spherical Active Joint

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Abstract. In the work, the universal driving joint with the traditional series composite mechanical structure has the friction and wear, which make the moving parts hot, and then causes the static and dynamic performance of the joint worse. So based on the Integration of multi technology domains, such as motors, magnetic levitation and robotics, we present a new magnetic levitation spherical active joint with multi freedom degree. Then the air gap magnetic-energy principle of the electromechanical energy conversion which produces magnetic suspending force and electromagnetic torque is analyzed, and the state synchronous suspension control of rotor based on based on the principle of state reconstruction and self-detection feedback control without sensors are established. The simulation results show that the system has high precision and strong ability of anti-interference.

Introduction

The traditional robots and mechanical arms are usually composed of several single-degrees-of-freedom devices and driven by complex mechanical transmissions. Although they can move and rotate in three-dimensional space, they still have a serious of problems [1-8], such as the high complexity of structure, big volume, serious wear and friction on the surface of kinematic pairs, low efficiency, slow response and poor dynamic performance. In order to solve these problems above, a new magnetic levitation spherical motor and driving joint is introduced, for which some world and national patents has been applied [9-12]. The application of the system of magnetic levitation spherical driving joint can simplify the mechanical structure, obtain no friction and no wear between rotor and stator, realize stable levitation supporting, improve the response speed and positional accuracy of joint, and reduce the volume of mechanism.

The working mechanism of spherical surface reluctance motor[13-16] in the magnetic levitation spherical driving joint is introduced, and the magnetic suspending force and electro- magnetic torque model of joint are established based on magnetic field flux analysis[17,18], and then three-dimensional dynamics nonlinear coupling model and linearization decoupling control of spherical rotor is presented[19,20]. Finally, the suspension characters are analyzed with simulation and testing.

Maglev Spherical Joint Basic Composi-tions

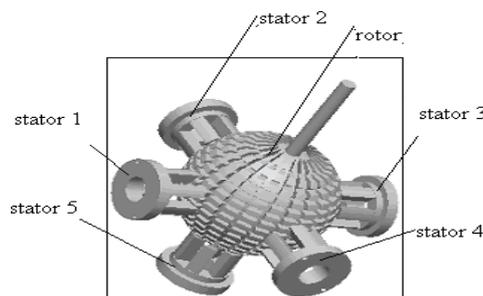


Fig. 1. Schematic Diagram of Maglev Spherical Driving Joint

The structure of stator and rotor of magnetic levitation spherical driving joint in working space is shown in Fig.1. Stator 1 and 3 are spherically symmetric around spherical rotor and should maintain coaxial along the X axis. They can drive the rotor to rotate around the X axis and generate the magnetic levitation force in the direction of X axis. Stator 2 and 4 are spherically symmetric around spherical rotor and should maintain coaxial along the Y axis. They can drive the rotor to rotate around the Y axis and generate the magnetic levitation force in the direction of Y axis. Stator 5 is arranged at the top of the spherical rotor and should maintain its axis along the X axis. It can drive the rotor to rotate around Z axis and generate the magnetic levitation force in the direction of Z axis.

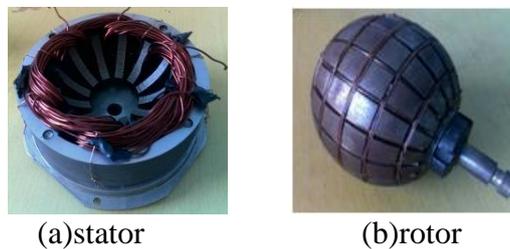


Fig.2. Stator/Rotor Structure

The structural drawing of magnetic levitation spherical driving joint's rotor and stator is shown in Fig.2. The stator is stacked with 50W470 silicon steel sheet. There are some grooves, which are used to embed with three-phase winding whose connection mode is Y shape. When current passed winding, each phase winding not only generated electromagnetic torque that can drive rotor revolve, but also provide radial magnetic levitation force to rotor. Spherical rotor is also stacked with 50W470 silicon steel sheet. On the surface of rotor, there are some orthogonal grooves. At the orthogonal point of grooves there is a hole across the center of sphere along radial direction. The Cu or Al is injected into groove and hole and then the armature structure of emanant orthogonal spherical cage shape will be formed in the core of center of sphere short sub and intersect.

Suspension Control Model of Spherical Reluctance Driving Joint with Magnetic Levitation

From foregoing, the magnetic levitation sphere driving joint is the driving joint which is supported and driven by Multi-Degree-of-Freedom spherical reluctance motor. The research for magnetic levitation sphere driving joint can start at the air-gap magnetic energy between stator and rotor of the motor following the method to study the magnetic reluctance motor. It means that establish the transform- ational relation of mechanic and electric energy according to the relevance theory of air-gap magnetic energy, and then obtain the relationship between electromagnetic torque of driving rotor and electromagnetic levitation force which can keep the rotor suspend. In order to brief the analysis, assumes that:

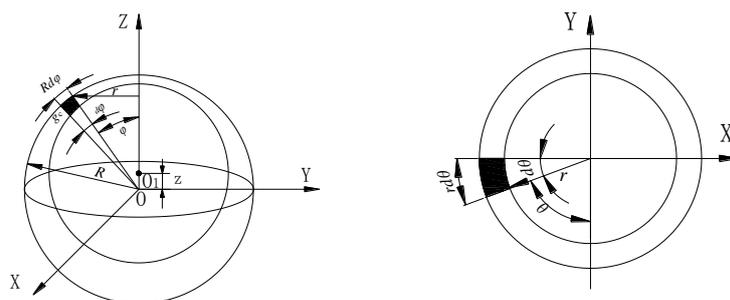


Fig.3. Schematic Diagram of the Change of Rotor Air Gap

1) three phase stator winding distribute balanced in the space, the magnetic potential generated by each phase current is sinusoidal distribution(or cosine distribution)in air-gap space, and neglect it's higher harmonic component;

- 2) neglect the effect of short range component group and distribute winding for air-gap magnetic potential, it means that the value of winding factor is 1;
- 3) neglect groove leakage inductance, end leakage inductance and magnetic saturation;
- 4) neglect the magnetic resistance of iron core and eddy current loss, only the magnetic resistance of operating air-gap is considered in the whole magnetic circuit system.

With the condition that there is no excursion for the center of sphere of rotor of the magnetic levitation sphere driving joint, the radius of spherical surface of stator salient pole is R , the radius of spherical surface of rotor salient pole is R_r , and the gap value between the inner diameter of stator salient pole and the external diameter of rotor salient pole is $g_0 = R - R_r$. Taking the symmetry axis coincides the Z-axis. Establishing the coordinate frame $f(X, Y, Z) = F(R, \varphi, \theta)$. If the center of sphere of rotor moves from point O to point O_1 under the disturbance of the driving joint, shown in Fig.3, the excursion along with Z-axis direction is z . Taking a micro-spherical-surface in the enveloping spherical surface ring on the six stators, and giving the value of the broad is $Rd\varphi$ and the length is $rd\theta$, thus its area is $\Delta A = (rd\theta) \cdot (Rd\varphi)$, ($\varphi_1 < \varphi < \varphi_2$, $0 < \theta < 2\pi$).

With the rotation of spherical rotor of the magnetic levitation sphere driving joint, the magnetic torque is created by the magnetic pulling force which is generated while one surface of salient pole of rotor overlapped with the surface of salient pole of stator partly. Moreover, this magnetic pulling force is the magnetic levitation force which keeps the rotor suspended. Therefore, the variation of air-gap length which be passed by the flux while the flux generated by magnetic field of stator flows to spherical rotor is complexity. And it is a function of φ and θ , it is obtained as $\delta_c = g_c(\varphi, \theta)$. As a result, the magnetic conductance is the function of φ and θ which can be defined as $\Lambda(\varphi, \theta)$. According to the method of dealing with the magnetic conductance of the maglev spherical reluctance motor driven by the levitation force in axial plane in document, the unit-area magnetic conductance of the maglev spherical reluctance motor driven by the levitation force in axial plane in this paper is inversely proportional to the gap e which between the stator and the rotor while their magnetic pole of salient pole aligns with each other. Furthermore, it is cosine distribution shown as

$$\frac{d\Lambda(\varphi, \theta)}{dA} = \frac{K_0 + K \cos 2(\omega t - \theta - \varphi - \psi)}{e} \quad (1)$$

Where K_0 and K are magnetic conductance constant which have the relation with the structure of stator and rotor; ω is the angular speed of the rotor relatives to the stator; ψ is the phase difference between one stator and the rotor while the stator drives the rotor rotating around the coordinate axis of the stator; e is the radial air-gap between the magnetic salient pole of stator and the rotor. Due to the width of the magnetic pole enveloping spherical surface ring on the stator is small, it means the variation range of φ ($\varphi_1 < \varphi < \varphi_2$) is small. It is considered that the surface of magnetic pole on stator is parallel with the surface of magnetic pole on the rotor which aligned with the stator, thus e could be shown as

$$e = g_0 - z \cos \varphi_0 \quad (2)$$

Where φ_0 is the angle between the normal line at the position of centroid of stator magnetic pole and Z-axis.

Thus, the magnetic conductance when flux crosses the micro-area ΔA is

$$\Delta\Lambda(\varphi, \theta) = \frac{d\Lambda(\varphi, \theta)}{dA} \cdot \Delta A = \frac{K_0 + K \cos 2(\omega t - \theta - \varphi - \psi)}{e} \cdot \Delta A \quad (3)$$

Assuming that magnetic potential (magnetic pressure) h_s of stator winding generated in air-gap distributes as sinusoidal distribution or cosine distribution [1]. It is

$$h_s = H_s \cos(\omega t - \theta) \quad (4)$$

Where H_s is magnetic potential amplitude, the product of the current I and the number of turns of stator N , that is $H_s = I \cdot N$.

The micro-magnetic-energy generated in air-gap between stator and rotor is

$$\begin{aligned} \Delta W_g &= \frac{1}{2} \Delta \Lambda(\varphi, \theta) \cdot h_s^2 \\ &= \frac{h_s^2 \cdot [K_0 + K \cos 2(\omega t - \theta - \varphi - \psi)] \cdot \Delta A}{2e} \end{aligned} \quad (5)$$

Taking the range of integration ($\varphi_1 < \varphi < \varphi_2$, $0 < \theta < 2\pi$), and getting the integral of above equation, the air-gap total magnetic energy is obtained as

$$\begin{aligned} W_g &= \int_0^{2\pi} \int_{\varphi_1}^{\varphi_2} \frac{h_s^2 \cdot [K_0 + K \cos 2(\omega t - \theta - \varphi - \psi)] \cdot R r d\theta \cdot d\varphi}{2e} \\ &= \frac{H_s^2 R^2 \pi}{2e} \int_{\varphi_1}^{\varphi_2} [K_0 + \frac{1}{2} K \cos 2(\varphi + \psi)] \sin \varphi d\varphi \end{aligned} \quad (6)$$

The equation 6 is the relation of the mechanic and electric energy transformation of magnetic levitation sphere driving joint. It is used to obtain the derivation of the difference of phase between stator and rotor and the displacement in radial direction. Thus, it can obtain the electromagnetic torque and maglev force of magnetic levitation sphere driving joint. The maglev force along Z-axial direction generated by the magnetic levitation sphere driving joint is

$$F_z = \frac{\partial W_g}{\partial z} = \frac{N^2 I^2 K(\psi) \cdot R^2 \pi \cos \varphi_0}{2(g_0 - z \cos \varphi_0)^2} \quad (7)$$

Where $K(\psi) = -\int_{\varphi_1}^{\varphi_2} [K_0 + \frac{1}{2} K \cos 2(\varphi + \psi)] \sin \varphi d\varphi$; I is the current influx in coil; N is the number of turns of stator coil.

Thus it can be seen, the levitation force of magnetic levitation sphere driving joint along Z-axial direction is inversely proportional to the square of the gap ($g_0 - z \cos \varphi_0$) which between the salient pole of stator and rotor, and proportional to the square of the magnetic potential H_s generated by coil. Consequently, changing the magnetic potential (or current in the coil) could control the displacement z at Z-axial direction of spherical rotor, and keeping the sphere driving joint rotor suspended stably. As the displacement z of rotor generated, decreasing the current i flows into coils to regulate the position of the rotor and get it returns to the equilibrium position. The current can be shown as $I = I_0 - i$. When the variation of the displacement is small ($z \ll g_0$), linearizing it as

$$F_z = K_z \cdot z - K_i \cdot i \quad (8)$$

Where K_z is displacement stiffness; K_i is current stiffness.

$$\begin{cases} K_z = \left. \frac{\partial F_z}{\partial z} \right|_{\substack{\Delta i=0 \\ z=0}} = \frac{R^2 N^2 I_0^2 K(\psi) \pi \cos^2 \varphi_0}{g_0^3} \\ K_i = \left. \frac{\partial F_z}{\partial i} \right|_{\substack{\Delta i=0 \\ z=0}} = \frac{R^2 N^2 I_0 K(\psi) \pi \cos \varphi_0}{g_0^2} \end{cases} \quad (9)$$

In terms of the Newton's Second Law, the equation of the spherical rotor's movement along Z-axial direction is

$$F_z + F_d = m \frac{d^2 z}{dt^2} \quad (10)$$

Where m is the mass of spherical rotor; F_d is disturbance except maglev levitation force.

Substituting equation 8 to 10, the equation of the spherical rotor's movement along Z-axial direction is obtained as

$$m \frac{d^2 z}{dt^2} = K_z \cdot z - K_i \cdot i + F_d \quad (11)$$

According to the law of electromagnetic induction, the relationship of current i and voltage u in winding is obtained as

$$u = Ri + \frac{d\psi}{di} = Ri + L_0 \frac{di}{dt} - K_i \frac{dz}{dt} \tag{12}$$

Where $L_0 = \frac{N^2 R^2 \pi K(\psi) \cos \varphi_0}{g_0}$ is electric induction of windings when the rotor at the equilibrium position.

The equation 8 and 12 is the open loop suspension control model of stator sub-system of the magnetic levitation sphere driving joint. The state variable is assumed without disturbance as $x_1 = z$, $x_2 = u$, $x_3 = i$. And taking the winding current i as output to get the result that the displacement of rotor is detected without sensor. Thus, according to the equation 11 and 12, the state equation and output equation of open loop is obtained as

$$\begin{cases} \dot{x} = Ax + bu \\ y = Cx \end{cases} \tag{13}$$

Where $A = \begin{bmatrix} 0 & 1 & 0 \\ \frac{K_z}{m} & 0 & -\frac{K_i}{m} \\ 0 & \frac{K_i}{L_0} & -\frac{R}{L_0} \end{bmatrix}$, $b = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{L_0} \end{bmatrix}$, $C = [0 \ 0 \ 1]$. The state structure of the system is shown as Fig.4

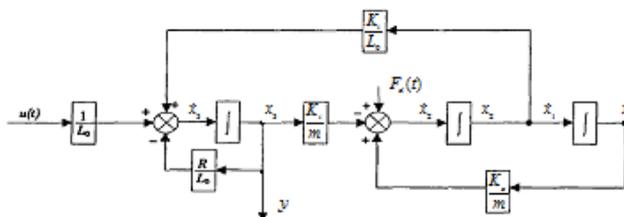


Fig.4. State Structure Drawing of the Stator Sub-System

In accordance with the state equation of sub-system (equation 13), the characteristic root of the system is positive real number or positive real part complex number. So, the system is an open loop unstable system which should be took the closed loop integrated correction to keep the suspension system of magnetic levitation sphere driving joint to content the performance requirement.

Design of Synchronous Suspension Control System Based on State Reconsti-tution

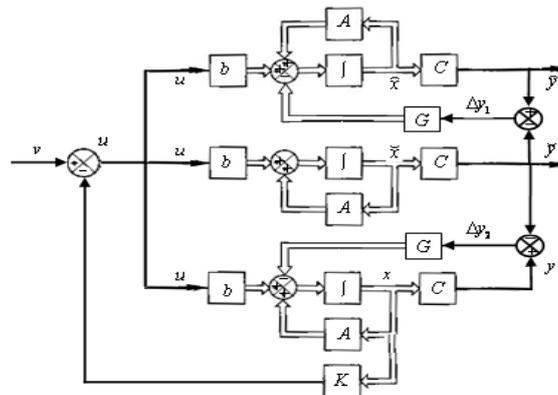


Fig.5. Structure Drawing of the Synchronous Suspension Closed Loop Control Based on State Reconstruction

The structure of synchronous suspension control system with feedback [10, 11] with observer constituted by the sub-system (Fig.4) is shown in Fig.5. In this drawing, sub-system 1 designs the

value of the feedback matrix of output error G based on the principles of state reconstruction, and makes its state \hat{x} following the state \tilde{x} of sub-system 2. Moreover, the follow error of the stable state is zero. The state observer is another sub-system which accomplished by computer or analogue circuit with the self-same structure with sub-system 1. The purpose of this design is getting the state feedback control of the spherical rotor obtains self-detected displacement at one direction without sensor, as well as realizing the position feedback, speed feedback and the integrated correction control of current feedback.

According to the equation 13, controllability matrix and observability matrix of the system is full rank. It means that the system is completely controllable and observable. Thus, it can be state reconstructed and state feedback controlled.

In order to driving the spherical rotor to move in synchronism along right about when the two systems come to steady state, and achieving self-detect state feedback control without sensor by the state observer, the output error feedback matrix can be designed according to the principle of state reconstruction to get the two stator sub-systems and the state observer with self-same state variable.

Assuming the output error feedback matrix between the sub-system and state observer is $G = [g_1 \ g_2 \ g_3]^T$, the state equation of two stator subsystem from Fig.5 is

$$\begin{cases} \dot{x}f = (A - GC)x + bu + G\dot{y} \\ \dot{x}f = Ax + bu \end{cases} \quad (14)$$

The equation of state observer is

$$x\dot{f} = (A - GC)x + bu + G\dot{y} \quad (15)$$

Their closed loop characteristic polynomial is

$$g(\lambda) = \det[\lambda I - (A - GC)] \quad (16)$$

According to the pole point assigned by the performance requirement of the system, the value of the state synchronous error feedback regulate matrix G between the two stator sub-systems and the observer can be confirmed by the above equation. Substituting the definite parameters in matrix A and C of the equation (13) to above equation, the characteristic polynomial is obtained as

$$\begin{aligned} g(\lambda) &= \det[\lambda I - (A - GC)] \\ &= \lambda^3 + \left(\frac{R}{L_0} + g_3\right)\lambda^2 + \left(\frac{K_i^2}{L_0 m} + \frac{g_2 K_i}{L_0} - \frac{K_z}{m}\right)\lambda \\ &\quad + \left(\frac{K_z K_i g_1}{m L_0} - \frac{R K_z}{m L_0} - \frac{g_3 K_z}{m}\right) \end{aligned} \quad (17)$$

In accordance with the indices of performance of the system, if the pole point assigned at $s_{1,2} = -40$ (key pole point), $s_3 = 400$, the expected closed loop characteristic polynomial of the system is

$$\begin{aligned} f(\lambda) &= (\lambda + 40)^2 (\lambda + 400) \\ &= \lambda^3 + 480\lambda^2 + 33600\lambda + 640000 \end{aligned} \quad (18)$$

Substituting the structure parameter of the system to the equation 17 and 18, and comparing them, the state reconstruction matrix can be obtained as

$$G = \begin{bmatrix} g_1 \\ g_2 \\ g_3 \end{bmatrix} = \begin{bmatrix} 0.482717334 \\ 33.6 \\ 456.4120348 \end{bmatrix}$$

Assuming the state feedback matrix is $K = [k_1 \ k_2 \ k_3]$, the system's control law is

$$v = u + Kx \quad (19)$$

After the state reconstruction is achieved, the state variable of each sub-system and observer and output variable tend to equality when the system comes to steady state. So, the closed loop state equation of the sub-system state feedback is shown as

$$x\dot{f} = (A - bK)x + by \quad (20)$$

The closed loop characteristic polynomial is

$$k(\lambda) = \det[\lambda I - (A - bK)] \quad (21)$$

Similarly, according to the pole point assigned by the performance requirement of the system, the value of the system's state feedback matrix K can be determined by above equation. Substituting the definite parameter of the matrix A and b in 13 to equation 17 and 18, characteristic polynomial is obtained as

$$\begin{aligned} k(\lambda) &= \det[\lambda I - (A - bK)] \\ &= \lambda^3 + \left(\frac{R+k_3}{L_0}\right)\lambda^2 - \left(\frac{K_z}{m} + \frac{k_2K_i - K_i^2}{L_0m}\right)\lambda - \frac{k_1K_i + RK_z + K_zk_3}{mL_0} \end{aligned} \quad (22)$$

Substituting the structure parameter of the system to equation 22 and 18, and comparing them, the state feedback matrix can be obtained as

$$K = \begin{bmatrix} k_1 \\ k_2 \\ k_3 \end{bmatrix}^T = \begin{bmatrix} -102322.801 \\ -30.24 \\ 96.7468 \end{bmatrix}^T$$

The Control System and the Simulation Analysis of the Magnetic Levitation Spherical Reluctance Driving Joint

Because of the suspension and rotation sharing the drive power source, the control system has more complex structure, and the relationship between the suspension control and the rotation control is highly coupled and nonlinear. This paper presents the control driving structure of the Y axis shown as Fig. 6. The system structure adopts two independent inverter power sources to supply power for the two joint stator windings, which are arranged symmetrically to either side of the rotor and make the rotor to suspend and rotate. And the control system of the inverter is composed of a common motor control system and a suspension control loop. The components of the system include the angular displacement control loop, the angular velocity control loop, the current control loop and the suspension control loop, etc.

The angular displacement control loop is used to ensure the steady accuracy and tracking performance of system. The current control loop is used to improve the system's rapidity, restrain the internal disturbance of current loop and limit the maximum current for ensuring the system safety. The angular velocity control loop was used to enhance the anti-load-disturbance ability of system and restrain the fluctuation of speed. Input the command signal of angular displacement θ^* and the feedback signal of the rotor's angular displacement θ_r . Compare the two signals and get the deviation signal, which will be converted to rotational velocity signal ω^* of rotor through angular displacement controller. Comparing ω^* and the feedback signal of the rotor's actual angular velocity, deviation signal of rotational velocity can be got. It will be converted to rotate speed (or torque) to control current i_q^* by angular velocity controller. At the same time, input the control current signal i_d^* of suspending force. The signal will be converted to two-phase control voltage by current controller and then be transformed to switch power (inverter) control voltage by a static/active ((d, q) / (α , β))transformation of coordinates and 2-phase/ 3-phase (2 Φ /3 Φ) transformation. The voltage will control the input-current of joint windings and adjust the radial displacement (electromagnetic levitation force) and angular displacement (electromagnetic torque) of rotor. Command signal θ^* is used to control rotating angular displacement of rotor.

According to the system requirements for each control loop, the PI controller is adopted in the control loops of the motor angular velocity and current, which can improve the fast tracking ability of system. According to the requirement of control performance, the inverse system decoupling controller based on state reconstruction is adopted in angular position control ring and a suspending position control loop. Based on the theory and system structure above, the control system simulation of the magnetic levitation spherical reluctance driving joint is carried out.

(1) the response analysis of the magnetic levitation spherical reluctance driving joint

It is the dynamic response curve with step-input signal in Fig.7. It can be seen that, the response speed of the system is rapid. And the adjustment time is less than 0.2s. The motion trial of the hot core of spherical rotor deviates from equilibrium position along X-axial direction while the input signal is sine AC signal with frequency as 50 Hz in Fig.8. With the effect of the two stator sub-system's synchronous control, it follows that the deviant of the rotor deviates from equilibrium position is stochastic and quite small which less than 4×10^{-18} m.

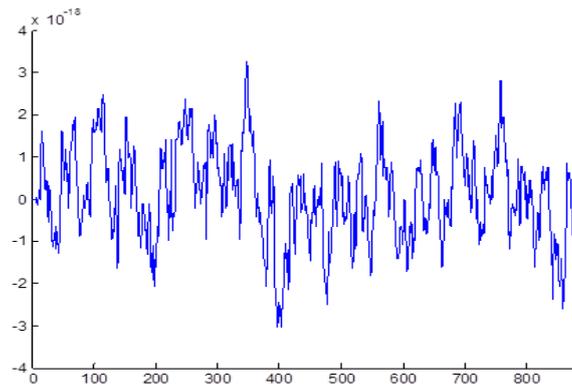


Fig. 8. Rotor Trajectory of Departure From Balance Position on Inputting 50Hz AC Signal

(2) the anti-interference analysis of the magnetic levitation spherical reluctance driving joint

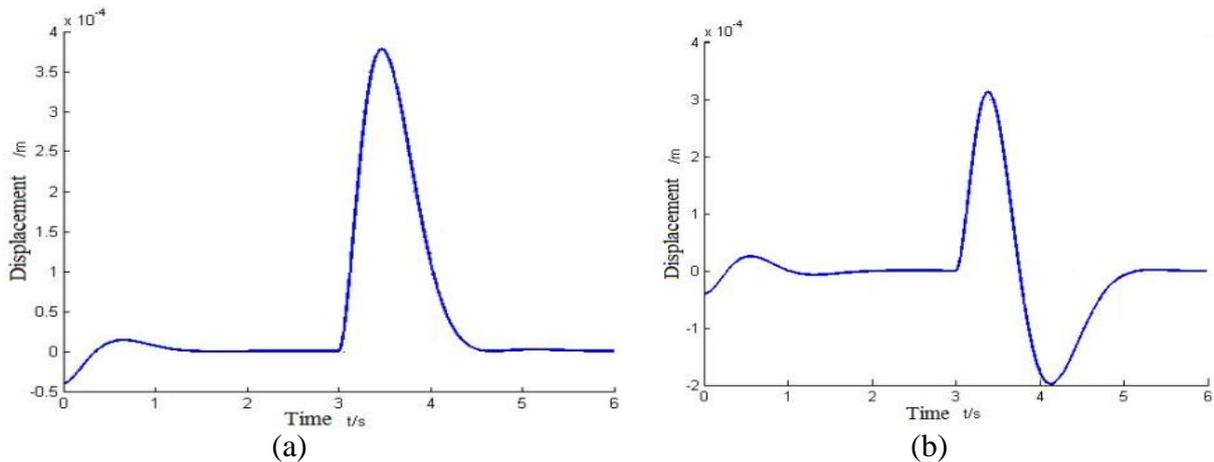


Fig.9. Interference of Step Signal in the Radial Offset

After the balance of the rotor, at the time, adding step interference signal at X direction and observe the displacement at X direction in Fig.9. It uses state observer and state feedback control in Fig.9 (a) and uses PID control in Fig.9 (b). It can be seen that the two both could get the system back to steady state soon. Using state observer and state feedback control can back to steady state pass by one oscillation. And the biggest deviant is 3.8×10^{-4} m. Using PID control can back to steady state pass by two oscillations. And its biggest deviant is 3.1×10^{-4} m. It is thus clear that basing on the use of state observer and state feedback controller; it has better capacity of resisting disturbance and robustness.

Conclusions

- (1) Based on the motor technology and magnetic levitation technology, a new type of spherical reluctance driving joint with magnetic levitation is presents, and the structure characteristics and the working principle of this joint is introduced.
- (2) With the air gap magnetic energy principle of the spherical reluctance driving joint with magnetic levitation, the electromagnetic levitation force model of the active joint system is established, and the movement and driving mechanism of suspending process is analyzed. On this foundation, together with the principle of state reconfig- uration, a non-sensor and self-sensing feedback control system for the state synchronous suspension of rotor is designed.
- (3) According to the control principle of the state reconfig- uration for the rotor suspension and system requirements, the decoupling feedback controller of spherical reluctance driving joint with magnetic levitation is built, and the simulation of controller has be carried on. The simulation results show that with the Inverse system decoupling and state feedback closed loop controlling of the spherical reluctance driving joint with magnetic levitation system based on state reconstruction, the system state synchronous suspension has high control precision and strong anti- interference.

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