Adaptive Control of Additive Manufacturing Equipment Based on Air Bearing Positioning

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Abstract—The air bearing guide rail is used as the three-dimensional positioning mechanism of additive manufacturing. However, in the high acceleration and high speed high dynamic motion, it is easy to cause the residual vibration of the system, damage the positioning accuracy of the system and increase the stability time of the system. Therefore, under the condition that the expected dynamic and static performance of additive manufacturing equipment is controllable, the robust adaptive control is used to compensate manufacturing error and environmental disturbance. According to Lyapunov stability theory, the established controller is adjusted to ensure the global asymptotic stability of the whole control system, so as to improve the system reliability and robustness to parameter changes.

1. Introduction
Additive manufacturing is an important development direction of intelligent manufacturing. Based on the principle of discrete accumulation, various types of bindable materials, such as metal powder, fluid material, plastic and ceramics, are stacked layer by layer to construct the three-dimensional forming of objects, which is suitable for the rapid manufacturing industry of complex structure, personalized and diversified products. At present, China's additive manufacturing industry is in the stage of rapid development, and the industrial scale is gradually increasing. A full chain additive manufacturing technology innovation system covering metal materials, technology, equipment technology and application of major engineering models has been initially established [1-2]. However, compared with developed countries such as Europe, America and Japan, China's additive manufacturing technology and equipment still lags behind the international leading level. Therefore, it is of great significance to combine artificial intelligence technology to promote high reliability, high performance, high precision additive manufacturing technology and equipment and its supporting technologies.

At present, the main three-axis motion mechanism of the additive manufacturing equipment is the ball screw and lead screw combined with linear guide. This kind of reducer has a certain return distance difference, which leads to the low positioning accuracy of three axis, especially the Z axis of vertical motion, and the effective travel range is small and limited by the structure. As a high precision motion system composed of high thrust weight ratio direct drive, high performance servo control and gas lubrication support, air bearing system uses linear motor direct drive to eliminate nonlinear interference such as friction and dead zone in the system. Therefore, this paper considers the air bearing guide rail as the three-dimensional positioning mechanism of additive manufacturing, to effectively solve the problem of low positioning accuracy and achieve rapid and accurate positioning.
Due to the high acceleration and high speed high dynamic motion, it is easy to cause the residual vibration of the system, damage the positioning accuracy of the system and increase the stability time of the system. In order to improve the performance and accuracy of the structure, real-time vibration control must be carried out. In order to solve the problem of long positioning time of air bearing system, a fast vibration suppression and accurate positioning method based on two degree of freedom controller is proposed [3]. In [4], the input shaping and state feedback controller are used to suppress the residual vibration of the air bearing platform to realize the precise control of the air bearing platform. In [5], approximate time optimal control and delay control are combined to suppress the residual vibration of the platform and reduce the stability time. In [6-7], the fuzzy algorithm and neural network algorithm are applied to realize vibration control, and input shaping technology is used to suppress the residual vibration of the system.

In the past research, our team used synchronous optimal control algorithm to suppress external interference and reduce synchronization error, and proposed control performance evaluation criteria [8-9]. On this basis, under the condition that the expected dynamic and static performance of the additive manufacturing equipment is controllable, based on robust adaptive control, the manufacturing error and environmental disturbance are compensated to ensure the global asymptotic stability of the whole control system, so as to improve the reliability of the system and the robustness to parameter changes.

The design idea of the whole system is as follows:

2. Controller design

The additive manufacturing equipment based on air bearing is to drive the 3D printing nozzle to move in three-dimensional direction with the air floating guide rail unit, so as to realize the smooth movement without friction and vibration. Because x-axis, y-axis and z-axis have corresponding axial control units, and the principle is the same, this paper takes single axis as the research object.

The mathematical model is established as follows:

$$\ddot{q} + C \dot{q} + K_d q = u + d$$

Where $q$ is the vibration trajectory parameter of the system, $C$ is the system damping, $K_d$ is the system frequency, $d$ is the environmental disturbance, and $u$ is the input.

According to the mathematical model, an adaptive controller is designed, and the control output of which is taken as the control input of the air bearing system.

Define the system tracking error $e_1$:

$$e_1 = q - q_d$$

Where $q_d$ is the reference trajectory of the precision air suspension system.

Let $e = [e_1 \ \dot{e}_1]$ obtain the dynamic equation of the system tracking error as:
Where \( A_0 = \begin{bmatrix} 0 & 1 \\ 0 & \alpha \end{bmatrix} \) and \( B = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \).

Select a matrix \( K = [k_1 \ k_2] \), \( k_1 \) and \( k_2 \) is the vector of the matrix respectively, so that the matrix \( A \) is the Herwitz matrix,

\[
A = A_0 - BK = \begin{bmatrix} 0 & 1 \\ -k_1 & -k_2 \end{bmatrix}
\]

Then the dynamic equation of tracking error can be rewritten as follows:

\[
\dot{e} = Ae + B[K e + F(x) + u + d - \dot{q}_d]
\]  \hfill (3)

The adaptive method is used to approximate and parameter estimate \( F(x) \) to minimize the system tracking error.

The adaptive control law is designed as follows:

\[
\dot{\theta} = \alpha Y^T B^T P e
\]

Where \( \dot{\theta} \) is used to achieve the tracking performance index, \( u_h \) is used to reduce the impact of external interference and \( \dot{\theta} \) is the estimated value of the adaptive parameter. Among them, the control gain \( \gamma > 0 \), \( \alpha \) is a normal number adaptive gain, \( P \) is a symmetric matrix, \( Y \) is a positive definite matrix, the robust compensation coefficient \( \eta > |\Delta F| \Delta F \) represents the uncertainty of the system.

Among them, \( P = P^T > 0 \) satisfies the following Riccati-like equation:

\[
PA + A^T P + Q + PB \left( \frac{1}{\rho^2} I - \frac{1}{\gamma^2} \right) B^T P = 0
\]  \hfill (5)

Among them, the attenuation factor \( \rho > 0 \), the weight matrix \( Q = Q^T > 0 \). So the following conclusions can be drawn:

If \( d \in L_2[0, \infty) \), where \( L_2[0, \infty) \) represents the square integrable function space, the air bearing system can achieve the following tracking performance indicators:

\[
\frac{1}{2} \int_0^T e^T Q e dt \leq
\]

\[
e^T(0)P e(0) + \frac{1}{2\alpha} \dot{\theta}^T(0) \dot{\theta}(0) + \frac{1}{2} \alpha^2 \int_0^T \|d\|^2 dt
\]  \hfill (6)
By substituting (4) into (3), the following results can be obtained:

\[ \dot{e} = A\dot{e} + B[-Y(\dot{\theta} - \theta^*) + \Delta P + u_h + u_e + d] \]

The estimation error \( \dot{\theta} \) of the adaptive parameter \( \theta^* \) is defined as follows:

\[ \dot{\theta} = \dot{\theta} - \theta^* \]

Then

\[ \dot{e} = A\dot{e} + B[-Y\dot{\theta} + \Delta P + u_h + u_e + d] \]  
\( \text{(7)} \)

3. Proof of stability

Based on Lyapunov stability theory, the adaptive control law of the adaptive controller is adjusted to ensure the stability of the system. The Lyapunov equation is established as follows:

\[ V = \frac{1}{2} e^T Pe + \frac{1}{2\alpha} \dot{\theta}^T \dot{\theta} \]  
\( \text{(8)} \)

The derivation of Lyapunov equation to time is rewritten as follows: the derivative of \( V \) to time \( t \) is obtained,

\[ \dot{V} = \frac{1}{2} e^T Pe + \frac{1}{2} e^T \dot{P} e + \frac{1}{\alpha} \dot{\theta}^T \dot{\theta} \]

\[ = \frac{1}{2} e^T (A^T P + PA)e - \dot{\theta}^T Y B^T Pe + u_h^T B^T Pe \]

\[ + u_e^T B^T Pe + \Delta \dot{\theta}^T B^T Pe + d^T B^T Pe + \frac{1}{\alpha} \dot{\theta}^T \dot{\theta} \]

\[ = -\frac{1}{2} e^T Q e + \frac{1}{2} \rho^2 \dot{d}^T d - \frac{1}{2} \frac{(1 - \rho \Delta P \rho - \rho d)}{\rho} \left( \frac{1}{\rho} B^T P \rho - \rho d \right) \]

\[ = -\dot{\theta}^T Y B^T Pe + u_e^T B^T Pe + \Delta \dot{\theta}^T B^T Pe + d^T B^T Pe + \frac{1}{\alpha} \dot{\theta}^T \dot{\theta} \]

Since

\[ u_e^T B^T Pe + \Delta \dot{\theta}^T B^T Pe \leq -\eta |B^T Pe| + |\Delta \theta||B^T Pe| = -(n - |\Delta \theta|)|B^T Pe| \leq 0 \]

Then

\[ \dot{V} \leq -\frac{1}{2} e^T Q e + \frac{1}{2} \rho^2 \dot{d}^T d \]

By integrating the rewritten equation, the adaptive control law of the adaptive controller is adjusted. For \( \dot{V} \) integral from 0 to \( T \), the formula is as follows:

\[ V(T) - V(0) \leq -\frac{1}{2} \int_0^T e^T Q e dt + \frac{1}{2} \rho^2 \int_0^T \dot{d}^T d dt \]

Since \( V(T) \geq 0 \), then:

\[ \frac{1}{2} \int_0^T e^T Q e dt \leq V(0) + \frac{1}{2} \rho^2 \int_0^T \dot{d}^T d dt = \]

\[ e^T(0) Pe(0) + \frac{1}{2\alpha} \dot{\theta}^T(0) \dot{\theta}(0) + \frac{1}{2} \rho^2 \int_0^T \dot{d}^T d dt \]

Therefore, the performance index of the adaptive control is realized.

4. Conclusion

In the additive manufacturing equipment described in this paper, the 3D printing nozzle is driven to move in the three-dimensional direction based on the air floating guide rail unit, so as to realize the smooth movement without friction and vibration, so as to eliminate the error caused by low structural
accuracy in the existing technology. And through the real-time feedback adjustment of the designed control unit, the precise positioning of 3D printing is realized. In this paper, a robust adaptive control is proposed to compensate manufacturing errors and environmental disturbances when the expected dynamic and static performance of additive manufacturing equipment is controllable. Then the controller is adjusted according to Lyapunov stability theory to ensure the global asymptotic stability of the whole control system, so as to improve the reliability of the system and the robustness to parameter changes.

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