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Research on high acceleration high precision air suspension control system performance evaluation algorithm

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Abstract. The motion performance of the high acceleration high precision air suspension platform is affected by the electromechanical characteristics of the drive system, the fluid characteristics of the air suspension guide rail and the load disturbance. The mathematical model of the system is established, and the controller performance is designed based on the optimal objective function value. The ideal controller performance is proposed as the evaluation benchmark. The performance of the system is evaluated by the ratio of the optimal objective value and the evaluation benchmark. Based on the established evaluation index, the influence of noise disturbance and estimation vector on the stability and robustness of the system is evaluated, and the system performance is further optimized.

1. Introduction

The precision air suspension platform is a complex kinematic system with high acceleration, high precision, high speed, no friction and fast stability. The comprehensive performance of the system is affected by the hardware structure, control system and driving mode. The motion performance of the high-acceleration and high-precision air suspension platform is affected by the electromechanical characteristics of the drive system, the fluid characteristics of the air suspension guide rail and the load disturbance, so it is necessary to analyze the factors that affect the running performance of the system.

There are many criteria for judging the operating performance of the air suspension system, in which the system stability and track accuracy are the most important. Stability is the basic requirement of the control system. Load disturbance is also a factor that can't be neglected in the control system. Erkorkmaz et al.[1] use the input shaping and state feedback controller to suppress the residual vibration of the air suspension platform and realize the precision control of the air suspension platform. Ham[2] and Viktorov[3] respectively in the application of fuzzy algorithm and neural network algorithm to suppress the residual vibration and vibration control system by input shaping technique. Although these control algorithms have certain compensation to the system, but the system performance also affected.

Dai Yi et al.[4] analyzed the influence of controller parameters on system performance by IP plus predictive feed-forward control method, and proposed the selection principle of controller. The dynamic performance of linear motor servo system with different load characteristics is compared and analyzed by Nanjing University of Aeronautics and Astronautics He Jiayuan[5] from the dynamic performance indicators and following error. Zhu Xiaogang[6] established a servo control system model with speed feed-forward and acceleration feed-forward, and analyzed the influence of different load on the control performance of air suspension platform. The above research on the precision air suspension platform focuses on the design of the control method and the influence of different load on the system, and does not propose a criterion which can be used as the evaluation standard to judge the performance of the control system. Therefore, a performance evaluation method of high acceleration high precision air suspension control system based on optimal objective function is proposed in this paper. The controller performance is designed based on the optimal objective function value according to the mathematical model of the system. The performance of the ideal controller is taken as the evaluation criterion, and the ratio of the optimal target value and the evaluation criterion of the precision air suspension system is taken as the performance evaluation index of the system, which is used to quantify the influence of noise disturbance and estimation vector on system stability and robustness.

2. System modeling

Due to external disturbances (such as the ripple of the linear motor, the electrical noise in the drive and the measurement noise, the cable power generated by the cable, etc.), changes in the environment and changes in system parameters will directly affect movement accuracy and fast stability of high acceleration high precision air suspension platform. Therefore, the control of the precision air suspension platform is simply in the expected minimum time through the rapid and optimal control strategy to make accurate movement to reach the ideal location.

For the high acceleration high precision air suspension platform shown in Fig. 1, both the X and Y movement directions are in the form of parallel-mounted two-motor drive, the thrust direction of the two motors is the same, and the push rod is pushed to move.

The mathematical model of the high acceleration high precision air suspension platform is described by a linear system with multiple inputs and outputs, namely,

$$\begin{cases} x(k+1)=A_c x(k)+B_c u_c(k)+B_{c,w} w(k) \\ y_c(k)=C_c x(k)+v(k) \end{cases} \tag{1}$$

The system is affected by the internal and external environment of the system. Form in, $k \in Z^+$ is the number of time steps, $x=[x_1,\cdots,x_n]^T \in R^n$, $u_c=[u_{c1},\cdots,u_{c\mathrm{m}}]^T \in R^m$, $y_c=[y_{c1},\cdots,y_{c\mathrm{p}}]^T \in R^p$, $w=[w_1,\cdots,w_n]^T \in R^n$, $v=[v_1,\cdots,v_p]^T \in R^p$ are the system state vector, control vector, output vector, system disturbance and random measurement noise vector.

The system state vector is set to the displacement and velocity of the center of the fader, $x(k+1)=[x_1,x_2,v_1,v_2]^T$. Form in, x_1 and x_2 are the center of the displacement data items, which can be measured directly through the precision grating; Speed items v_1 and v_2 cannot be directly measured, the need to estimate the value of the algorithm; $A_c \in R^{n*n}$, $B_c \in R^{n*m}$, $C_c \in R^{\mathrm{q}*n}$, $B_{c,w} \in R^{\mathrm{n}*1}$ are the constant matrices with appropriate dimensions, which are subject to external disturbances.

$$A_c=\begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ A_{31} & A_{32} & 0 & A_{34} \\ 0 & A_{42} & A_{43} & A_{44} \end{bmatrix}, B_c=\begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 1 \\ B_{41} & B_{42} \end{bmatrix}, C_c=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}, B_{c,w}=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

According to the speed synchronization deviation, the control strategy is divided into two parts: the optimal estimate of the state vector and the optimal gain of the system. Based on the established system dynamics model, the optimal control rate $u_c(k)$ is designed,

$$u_c(k)=-L(k)\cdot\left[x_1(k),x_2(k),\hat{v}_1(k),\hat{v}_2(k)\right]^T \tag{2}$$

Form in, $\hat{v}_1(k)$, $\hat{v}_2(k)$ respectively represent the estimated values of the velocity terms v_1 , v_2 . According to the optimal control rate to be further designed as the control system performance index analysis of the optimal objective function value to minimize its value:

$$J_{Aoofv}=E\left[x^T(N)Q_1x(N)+\sum_{k=0}^{N-1}\left(x^T(k)Q_2x(k)+u_c^{\ T}(k)Ru_c(k)\right)\right] \tag{3}$$

Form in, Q_1, Q_2 are the state vector weighting matrix, which are the symmetric nonnegative matrix. R is the input vector weighting matrix， which are the symmetric positive definite matrix.

3. Control performance evaluation

In order to evaluate the current high acceleration high precision air suspension motion platform controller performance deviates from the optimal performance of the controller, the random performance indicator is adopt to evaluate the performance of the control system. According to the control loop and input and output data to get the performance measurement of the control system, which is used to quantify the degree of performance of the evaluation control system under this control.

3.1. Control performance evaluation benchmark

Since the velocity term of the system state vector is estimated from the initial value, the actual calculated velocity theoretical value should be the ideal value. Set the instantaneous velocity v of time t: $v=\lim_{\Delta t\to 0}\frac{\Delta x}{\Delta t}$.

When Δt is smaller, the average speed $\bar{v}$ is closer to the instantaneous velocity. Therefore, the optimal objective function of the ideal controller is:

$$J_{Ioofv}=E\left[x^T(N)Q_1x(N)+\sum_{k=0}^{N-1}\left(x^T(k)Q_2x(k)+u_c^{\ T}(k)Ru_c(k)\right)\right] \tag{4}$$

Form in, $x(k+1)=[x_1,x_2,\bar{v}_1,\bar{v}_2]^T$.

3.2. Control system evaluation index

The optimal target value of the high acceleration high precision air suspension system is compared with the evaluation standard. The ratio is taken as the scale and criterion for evaluating the performance of the system:

$$\eta=\frac{J_{Aoofv}}{J_{Ioofv}} \tag{5}$$

The effect of noise perturbation and estimation vectors on the stability and robustness of the system are evaluated by this performance index. J_{Aoofv} represent the optimal objective function value of the system; J_{Ioofv} represent the system theory optimal objective function value.

The significance of the evaluation index η is: the closer the value to the value 1 indicates that the control performance of the control system is less affected by the noise disturbance and the estimated vector, and the performance is better than the control performance without ideal. Specifically, the value of the evaluation index is expressed as a value between 0 and 1. When it is greater than or equal to 0.9, it indicates that the performance of the controller is excellent and when the evaluation value is between 0.6 and 0.9, the performance of the controller is good and when the evaluation value is less than 0.6, it means that the performance of the controller is low and needs improvement.

4. Simulation analysis

Based on the above mentioned above, a model of the air suspension system is established, considering a double input and double output discrete time system with a shape like (1), the initial state of each parameter and system is as follows:

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$$A_c = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0.1 & -0.2 & 0 & -0.15 \\ 0 & -0.56 & 0.1 & -0.23 \end{bmatrix}, B_c = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 1 \\ 321 & 348 \end{bmatrix}, C_c = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}, B_{c,w} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

System disturbance: $w(k) \sim N(0, I_{4*4})$; Random measurement noise: $v(k) \sim N(0, I_{2*2})$; Initial state vector: $x(0) = [100,100,0,0]^T$;State estimate initial value: $\hat{x}(0) = [97.12 \quad 49.3 \quad 0.05 \quad 0.05]^T$; Filtering estimation error variance initial value: $p(0) = 4I_{4*4}$; State vector weighted matrix: $Q_1 = Q_2 = 25I_{4*4}$; Input vector weighted matrix: $R = I_{2*2}$.

According to the system parameters and initial conditions given above, the kalman filter gain matrix *K(k)* is calculated: $K = \begin{bmatrix} 0.7525 & -0.2238 \\ -0.2475 & 0.7762 \\ 0.0198 & -0.0587 \\ 0.0715 & -0.0970 \end{bmatrix}$. At the optimal gain for linear quadratic regulator is calculated: $L = \begin{bmatrix} 1.2885 & -2.5370 & -0.0071 & -1.9164 \\ -1.1905 & 2.3410 & 0.0071 & 1.7693 \end{bmatrix}$.

Based on the filter gain and optimal gain of linear quadratic regulator, the optimal state estimation can be further calculated, which is shown in Figure 2,and the output of the system corresponding is shown in Figure 3. Based on the proposed control performance evaluation index calculation method, the value is calculated, which is shown as Figure 4.

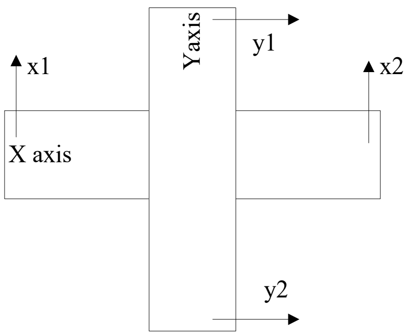


Figure 1. Structure schematic of high acceleration high precision air suspension platform.

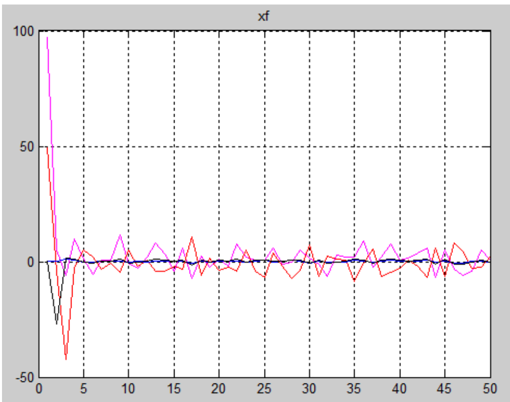
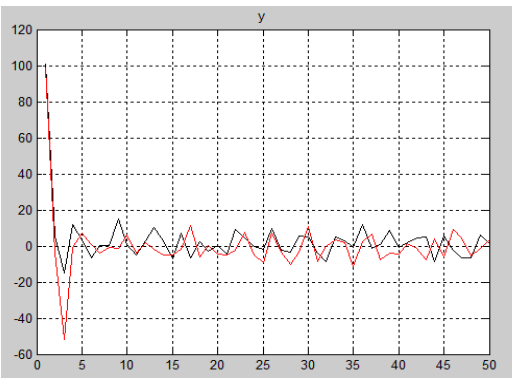


Figure 2. Optimal state vector estimation.



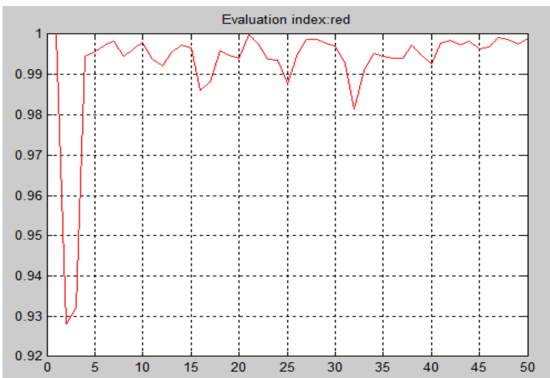


Figure 3. System output response.

Figure 4. High acceleration high precision air suspension system control performance index value.

It can be seen from the figure 4, high acceleration high precision air suspension system control performance index value eventually tends to 1, which means good control performance. This means that although the noise and disturbance have some influence on the system control performance, the system can maintain the stable output and have high control performance through the compensation effect of the designed control algorithm.

5. Conclusion

In this paper, the mathematical model of the system is established based on the characteristics of the high acceleration high precision air suspension system, and the current controller performance is calculated based on the optimal objective function value. The performance of the ideal controller is taken as the evaluation criterion, and the ratio of the optimal target value and the evaluation criterion of the precision air suspension system is taken as the performance evaluation index of the system. The performance index is used to quantify the influence of the performance of the air suspension system under this control strategy and the control performance of the system, and to evaluate the influence of the noise disturbance and the estimation vector on the stability and robustness of the system. Then the system performance is optimal.

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