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Research on Time Delay of Control in Hybrid Vibration Isolation System

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Abstract

The asymptomatic stability problem of robust with time lag is widely existed in active vibration isolation system. The influence of time lag on the optimal control algorithm is studied in this paper. And by utilizing LMI tools in MATLAB, variable step method is introduced to get the maximum allowable upper bound of the robust time lag in the optimal control system. Numerical simulation results verified the theory and contributed to the conclusion that with time lag increasing, the effect of controlling will become worse ,once the time lag exceed the maximum allowable delay boundary, the system will diverge.At the same time ,the upper bound can be improved by increasing feedback control and decreasing the corresponding weight of the control goals weighting matrix. The work of this paper is beneficial for the relevant experimental design.

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Keywords: Active vibration isolation system; time delay; optimal control; LMI

1. Introduction

In field of active vibration isolation in machinery and equipment,the phenomenon of time delay is inevitably existed. The whole process including the sensor signal acquisition and transmission, the control algorithm computing and the actuators actuation process, may lead to a delay for control force acted on the structure. Active vibration isolation system requires a fast dynamic response, so a small time delay will lead to control efficiency decreasing, and even instability.

Over the last decade years, there has been much work concerned with time delay problems. For time delay in structure control, transposition technique, Taylor series expansion, state estimation and other

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methods have been already proposed. Considering time delay, YuAo He used genetic algorithms and proposed an active control algorithm for structure control, and then used seismic wave as an excitation signal to do the simulation[1-4].

Currently, methods involving predictive control and time delay compensation is much more used to reduce bad influence of time delay on active vibration isolation system, but a better result is still to achieve. The main reason is such an attempt increases the complexity of the algorithm inevitably, and the computational and control system delay is increasing at the same time. So for a small-scale system ,engineering application face much difficulty. In fact, by utilizing experiment, inherent time delay of the controller can be achieved. then design hardware circuit and control algorithm would be of more engineering significance. By utilizing LMI tools, the maximum allowable delay upper bound for LGQ isolation system was calculated and an experiment was designed accordingly in the paper. The designing mode provides engineers a new way of thinking.

2. Stability research of delay independent system

2.1. stability requirements of delay independent system

Delay system can be shown as

$$\dot{x}(t) = Ax(t) + A_d x(k-d) \tag{1}$$

Where $x(t) \in R^{n\times n}$ is a system state variable, A 、 $A_d \in R^{n\times n}$ are constant matrix, $d > 0$ is control delay time. From [5] we can get the following theorem

THEOREM: if there is a scalar $\overline{d} > 0$， symmetric positive definite matrix $P > 0$， $G > 0$， $Z > 0$ ，makes

$$\begin{bmatrix} P(A+A_d)+(A+A_d)^T P & PA_d - G & \overline{d}(A+A_d)Z \\ * & -G-Z & \overline{d}A_d^T Z \\ * & * & -Z \end{bmatrix} < 0 \tag{2}$$

To all the delay time $d \in \left[0, \overline{d}\right]$, system (1) is asymptotically stable.

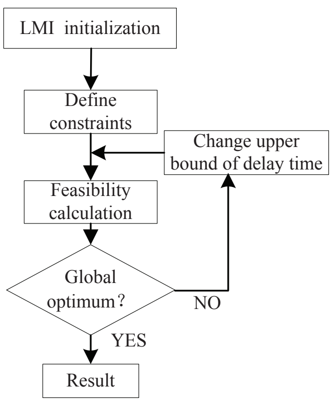

Fig 1 the solving flow chart of time delay upper bound

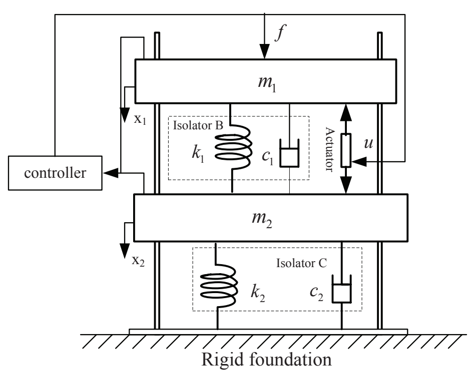

Fig 2 Schematic diagram of active vibration isolation system

2.2. LMI calculation of delay upper bound

Linear matrix inequality (LMI) toolbox is high-performance software package for solving general inequality problems. For feasibility problem, linear objective function minimization problem with linear matrix inequality constraints and the generalized eigenvalue minimization problem, the toolkit provides a solver respectively [10].

GEVP solver can be used to solve the delay stability upper bound problem as type (1), but this method increase the complexity of the programming at the same time, because matrix transformation must be done to the factors related to delay in inequality (3) before GEVP solver can be used. In fact, with the use of FEASP solver and applying delay factor variable step trial and error method, the delay upper bound can be got wonderfully,. Solving process is shown in Figure 1.

3. Active vibration isolation modeling and delay analysis

Single-layer active vibration isolation platform based on flexible foundation can be simplified to the double-layer active vibration isolation system, the actuator which is applied as the active control element used for force output is placed between the isolated equipment and the Middle mass. The state signals of isolated equipment and Middle mass is then collected by the Controller.

Active vibration isolation system is shown as figure 2， where m_1 、 m_2 denotes respectively the mass of isolated equipment and the Middle mass block, k_1 、 k_2 、 c_1 and c_2 denotes respectively the stiffness and damping of the upper and lower isolator. u and f denotes respectively the output force of the actuator and external exciting force.

Active vibration system mathematical model shown as Figure (2) can be denote as the following differential equations:

$$\begin{cases} m_1\ddot{x}_1 + c_1(\dot{x}_1 - \dot{x}_2) + k_1(x_1 - x_2) = f - u \\ m_2\ddot{x}_2 + c_1(\dot{x}_2 - \dot{x}_1) + k_1(x_2 - x_1) + c_2\dot{x}_2 + k_2x_2 = u \end{cases} \tag{3}$$

Combined with modern control theory, the state space expression of the above equations can be got

$$\dot{x}(t) = Ax(t) + Bu(t) + Ef(t) \tag{4}$$

Assuming the control delay time as d, equation (4) can be transferred to

$$\dot{x}(t) = Ax(t) + Bu(t-d) + Ef(t) \tag{5}$$

Then optimal force is

$$u(t-d) = -Kx(t-d) \tag{6}$$

Where K is the gain matrix of force feedback, assuming $A_d = -BK$, equation (5) can be written as

$$\dot{x}(t) = Ax(t) + A_d x(t-d) + Ef(t) \tag{7}$$

In order to analysis the system stability, we can consider increment equation of the equation (7)

$$\Delta\dot{x}(t) = A\Delta x(t) + A_d\Delta x(t-d) \tag{8}$$

Then the method mentioned in Section 1 can be used to solve the above equation.

4. System delay test experiment

Basic composition of pulse excitation system for testing delay time is shown in Figure 3. For the system, how to ensure the accuracy of the inherent delay tested must be considered firstly.

Figure 4 shows the lag time test graph of the active vibration isolation system, the curves of different color represents respectively the acceleration signal collected from the vibration isolation system and directly from the signal generate module. From the graph we can acknowledge that the inherent time lag d = 5.6ms, time involving signal acquisition, conversion and output is denoted as T1 = 4.2ms, and the response time denoted as T2-T1 involving actuator, power amplifier and the sensor is in 1.4ms or less. The result shows that the major delay in system is produced by the controller, optimizing the control algorithm and improving hardware circuit are two main points for reducing inherent time lag in isolation system.

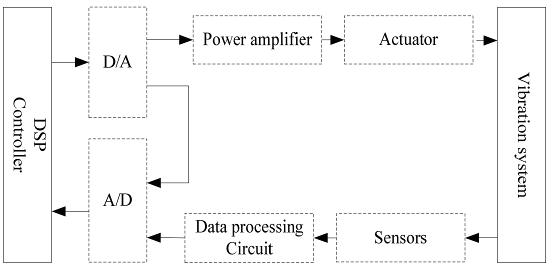

Fig.3 Time delay testing system of active vibration isolation system

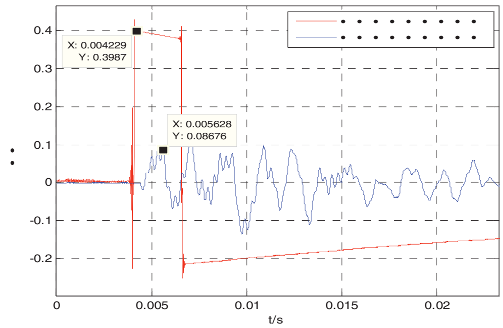

Fig.4 Time history graph of delay testing signals in the delayed vibration system

5. Optimal control experiment

In order to verify the effectiveness of optimal control method proposed above, optimal control experiment based on DSP is designed. The only difference between optimal control experiment and delay testing experiment is that only the displacement sensor is used in the former. Velocity signals are obtained through differential operation, then for feedback controlling. The inherent control delay for time delay test experiment d=5.6ms, and the result requires that the upper delay bound of the system d⩾5.6ms. We can get the feedback control force and discrete it.The objective for two-layer isolation system is to minimize the force $F = k_2 x_2 + c_2 \dot{x}_2$ transmitted to the base.

The experiment is designed to illustrate the relationship between isolation performance and exciting frequency. Keep control parameters and the amplitude of the exciting force constant, then change exciting frequency to 16Hz、18Hz、25Hz、32Hzand 70Hz, at the same time, DSP is used to control the vibration and NI data acquisition device is used to record the output force of the exciter and actuator, so the displacement of the upper and lower mass block. Due to space limitations, only comparison results for isolation effects under 16HZ is presented below as figure 5, comparing to passive vibration isolation, the power of characteristic line spectrum decrease respectively by 8.4dB、5.8dB、3.7dB、2.9dB. Once exciting frequency exceed 70HZ, the power of characteristic line spectrum cannot be decreased. But we found that a longtime stability of the controller couldn't be easily achieved especially external excitation were at a high frequency. After analytic, the main reasons are as following:

(1) The inherent delay of the controller is still too large. A worse impact on the system would be got if the external excitation were at a high frequency

(2) Power amplifier couldn't be maintained at a good linearity and stability, especially the power amplification factor varies with the excitation frequency changes. So it is difficult to select a proper amplifier gain.

(3) There is still gaps existed at the position actuator connected to the upper mass block which has negative effect on actuator output.

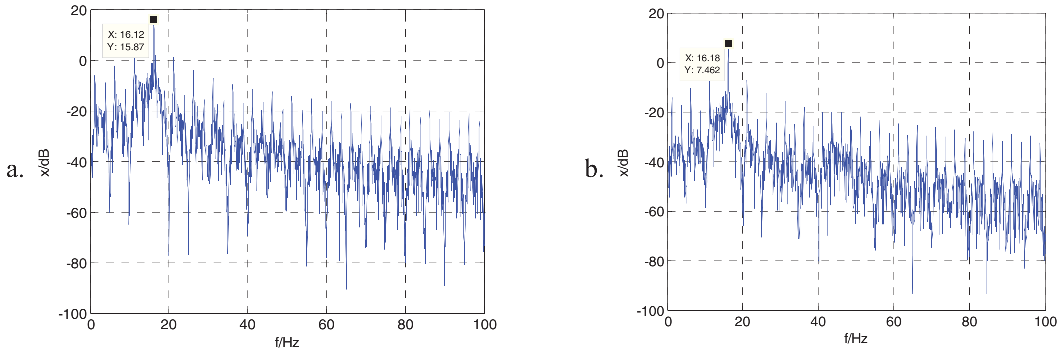

Fig.5 The power spectra of the displacements of m2（f=16Hz）; a. Passive vibration isolation; b. Active control of vibration

6. Conclusion

The active control of vibration experimental system which includes delay testing and optimal control experiment is designed to verified the control effects of the optimal algorithm described in the paper. Delay testing is a prerequisite for optimal control experiments, the pulse excitation testing program designed in the paper can test the inherent delay of the system accurately and provide foundation for optimal control algorithm. The results of the optimal control experiment shows that a good isolation performance for low-frequency can be achieved which verify the effectiveness of the control algorithm.

To sum up, before the designing of LGQ controller for active vibration isolation system, the range of the delay can be tested which make it possible to choose the controlling hardware properly , thus reduce the inherent delay and decrease the complexity of isolation system designing in the end.

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