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Influence analysis of time delay to active mass damper control system using pole assignment method

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ABSTRACT

To reduce the influence of time delay on the Active Mass Damper (AMD) control systems, influence analysis of time delay on system poles and stability is applied in the paper. A formula of the maximum time delay for ensuring system stability is established, by which the influence analysis of control gains on system stability is further arisen. In addition, the compensation controller is designed based on the given analysis results and pole assignment. A numerical example and an experiment are illustrated to verify that the performance of time-delay system. The result is consistent to that of the long-time delay control system, as well as to proof the better effectiveness of the new method proposed in this article.

1. Introduction

In recent years, considerable effort has been devoted to the development and application of the AMD control systems to reduce dynamic responses and increase serviceability of civil engineering structures under environmental loadings such as wind and earthquake [1–5]. The studies of both influence analysis and compensation of unavoidable time delay have attribute to the improvement of the quality and effectiveness in using the AMD control systems. These studies include works in system performance, system stability, compensation algorithm and so on [6–9]. Generally, the first two cases attract more attention. For example, Soong investigated the influence of time delay on the stability of a SDOF system with an optimal direct output feedback controlled mass damper, and gave explicit formulas and numerical solutions to determine the maximum delay time which causes onset of system instability [10].

For a neutral system, Kwon and Park established a delay-dependent criterion for asymptotic stability in terms of LMI based on the Lyapunov method [11]. In Mohamed et al.'s article [12], the effect of the time delay on system stability was investigated and time delay compensation was treated by two methods. De La Sen, on the other hand, dealt with the synthesis problem of pole-placement-based controllers for systems with point delays, and special emphasis has been devoted to obtain the set of proper controllers and to the achievement of prescribed (finite or infinite) closed-loop spectrum of the designer's choice [13]. Pavel et al. proposed a novel method of control system design which applies meromorphic transfer functions as models for retarded linear time delay systems.

After introducing an auxiliary state model, a finite-spectrum observer is designed to close a stabilizing state feedback. The observer finite spectrum is the key to implement a state feedback stabilization scheme and to apply the affine

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parametrization in controller design [14]. To reduce the influence of the time delay, positive feedback or velocity-feedback control for time-delayed control system was confirmed to be superior to the developed methodology of using time delayed, negative feedback or velocity-feedback control [15,16]. In addition, five methods for the compensation of fixed time-delay were presented and investigated for active control of civil engineering structures in the literature [17]. In addition to those, an optimal control method based on zero-order holder for seismic-excited linear structures with time delay in control has been investigated and had positive performance [18,19]. Moreover, an H_∞ controller design approach for vibration attenuation of seismic-excited building structures with time delay in control input has been presented by CHENG-WU CHEN [20]. Similarly, a fuzzy robust controller which combines H_∞ control performance with Tagagi–Sugeno (T–S) fuzzy control for the control of delayed nonlinear structural systems under external excitations has been presented [21]. For linear neutral systems, asymptotic stability with multiple delays has been addressed in literature [22]. By using the characteristic equation approach, new delay-independent stability criteria have been derived in terms of the spectral radius of modulus matrices. Michiels et al. proposed a novel method for determining (controller) parameters in retarded time-delay systems, which combines direct pole placement and the minimization of the spectral abscissa, reaping the benefits of the advantages of both approaches [23]. Ram et al. *however,* solved the partial pole placement problem by applying a hybrid combination of this result and the method of receptances. This examination allows for the partial assignment of desired poles with no spillover when there is time delay between the measured or estimated state and actuation of the control [24]. Lastly, Li et al. considered the pole assignment problems for time-invariant linear and quadratic control system, with time-delay in the control, and derived the invariant subspaces from which the closed-loop eigenvectors were chosen [25].

Based on above review, this paper aims to reduce the influence of time delay on the AMD control systems, which is arranged as follows. Section 2 will give formulas and numerical solutions to determine the maximum delay time that causes onset of system instability based on the influence of time delay on system poles. Based on numerical model, an influence analysis of control gains and structural parameters on system stability will be carried out in Section 3. In Section 4, compensation controller will be designed for time delay based on the numerical results and pole assignment algorithm. In the last section, a numerical example and an experiment will be illustrated to verify the efficiency of the proposed method.

2. Single-degree-of-freedom system

Consider a class of a SDOF system with a time delay described by

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = f(t) - g_x x(t-\tau) - g_{\dot{x}}\dot{x}(t-\tau) \tag{1}$$

where m, c and k stand for the mass, damping and stiffness of the SDOF system, respectively. g_x and $g_{\dot{x}}$ stand for control gain according to displacement and velocity (called displacement gain and velocity gain for the sake of simplicity). $f(t)$ is external excitation, and τ is the time delay.

The characteristic equation of the system, obtained by taking Laplace transforms of the Eq. (1), is given by

$$ms^2 + cs + k + e^{-s\tau}(g_x + g_{\dot{x}}s) = 0 \tag{2}$$

Denoting system poles as

$$s = a + bi \tag{3}$$

where, i stands for an imaginary unit and $i = \sqrt{-1}$. a, b are real constants.

By substituting the above equation into Eq. (2) one can get

$$\left[m\left(a^2 - b^2\right) + ca + k\right] + (2abm + cb)i + e^{-a\tau}e^{-b\tau i}\left[(g_x + ag_{\dot{x}}) + \left(bg_{\dot{x}}\right)i\right] = 0 \tag{4}$$

Since $e^{-b\tau i} = \cos(-b\tau) + i\cdot\sin(-b\tau)$, hence

$$\begin{aligned}&\left[m\left(a^2 - b^2\right) + ca + k\right] + \left[(g_x + ag_{\dot{x}})\cos(b\tau) + \left(bg_{\dot{x}}\right)\sin(b\tau)\right]e^{-a\tau}\\&+\left\{(2abm + cb) + \left[\left(bg_{\dot{x}}\right)\cos(b\tau) - (g_x + ag_{\dot{x}})\sin(b\tau)\right]e^{-a\tau}\right\}i = 0\end{aligned} \tag{5}$$

Namely

$$\begin{cases}\left[m\left(a^2 - b^2\right) + ca + k\right] + \left[(g_x + ag_{\dot{x}})\cos(b\tau) + \left(bg_{\dot{x}}\right)\sin(b\tau)\right]e^{-a\tau} = 0\\(2abm + cb) + \left[\left(bg_{\dot{x}}\right)\cos(b\tau) - (g_x + ag_{\dot{x}})\sin(b\tau)\right]e^{-a\tau} = 0\end{cases} \tag{6}$$

From Eq. (6), it can be seen that a and b are dependent on control gains and time delays when m, c, k are real constants. That is to say, system poles (or system performance) are (or is) determined by control gains and time delays. Hence system performance can be adjusted by adjusting control gains or time delays.

When the time delay is equal to the maximum value ensuring control system stable, then $a = 0$ and it then follows from