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The effect and design of time delay in feedback control for a nonlinear isolation system

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ABSTRACT

The optimum value of time delay of active control used in a nonlinear isolation system for different types of external excitation is studied in this paper. Based on the mathematical model of the nonlinear isolator with time-delayed active control, the stability, response and displacement transmissibility of the system are analyzed to obtain the standards for appropriate values of time delay and control strengths. The effects of nonlinearity and time delay on the stability and vibration response are discussed in details. For impact excitation and random excitation, the optimal value of time delay is obtained based on the vibration dissipation time via eigenvalues analysis, while for harmonic excitation, the optimal values are determined based on multiple vibration properties including natural frequency, amplitude death region and effective isolation region by the Averaging Method. This paper establishes the relationship between the parameters and vibration properties of a nonlinear isolation system which provides the guidance for optimizing time-delayed active control for different types of excitation in engineering practices.

1. Introduction

Nonlinear isolation systems are widely applied in various practices such as high-precision machinery [1] and vehicle suspension systems [2,3] for protecting instruments and providing comfortable work environments for people especially drivers. To achieve the High-Static-Low-Dynamic (HSLD) property in application, an isolator so-called Quasi-Zero-Stiffness vibration isolator (QZS-VI) is proposed and studied [4–8]. The QZS-VI could realize high static stiffness and ultra-low resonance frequency characteristics by appropriate geometrical design of nonlinearity. Although the multi-steady states and bifurcation phenomenon are induced by nonlinearity, it is found that nonlinearity could bring advantages in vibration suppression in some previous researches. For the strong nonlinearity in isolation system for multi-module floating airport, the multi-steady states band is defined as amplitude death region because the state with lower amplitude in the multi-steady states band is close to zero [9,10]. There are also some studies on designing truss structures to obtain better vibration isolation via damping nonlinearity induced by geometrical nonlinear relationship [11,12].

Although the QZS-VIs can achieve vibration suppression over a broad frequency band based on its HSLD property, strong nonlinear behaviors including multi-steady states and bifurcation phenomenon would induce by strong nonlinearity. Therefore, different control devices and methods are introduced to enhance the stability and improve vibration isolation effectiveness. The effective isolation frequency band could be increased for appropriate design of the QZS structures [13–16]. The control mechanism is that reducing the resonance frequency to leave larger frequency band for isolation. It should be noted that, complex active control

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methods for vibration isolation or suppression are usually not preferable in practice because of its high energy cost and construction/ installation expense. Because the effect of time-delayed control could be adjusted by changing the value of time delay without adding control gain, the time-delayed active feedback control attracts lots of attention for the benefit for vibration control performance. From the analysis of vibration suppression in literature about delayed feedback control, it is found that time delay could improve the vibration absorption. The concept of delayed-resonator vibration absorber is first proposed by Olgac et al. [17,18], and the servo motor could be used to introduce the delayed control signal for driving the vibration suppression performance of a vibration absorber [19–21]. Based on Incremental Harmonic Balance (IHB) method and parametrical identification, the time delay in control loop cannot be ignored since the time delay affects the responses of a vibration absorber [22]. Xu et. al. [23–25] investigated a delayed-resonator vibration absorber with nonlinear master and slave structures and the relative experiment verified that the vibration could be absorbed by time-delayed feedback control. Cai et. al. [26,27] applied multi-time-delay active control for vibration suppression of continuous structure. The experimental results also verify the effect and advantage of time-delay control method. The time-delayed active control is taken into consideration for a QZS-VI in [28], and the main results demonstrate that the equilibrium stability region on parameter plane is increased and the resonant peak is reduced with delayed control.

Although the lower amplitude in the steady state band could be defined as quasi-amplitude death region [9,10], the jumping phenomenon for the multi-steady states is not sufficiently safe for isolation system under a large perturbation or impact excitation in applications. In addition, the analysis about time-delayed active control in vibration suppression shows the effect of time delay on isolation effectiveness of resonant peak and natural frequency, but the effective isolation frequency band of a nonlinear system is different from that of a linear system. Therefore, in order to provide guidance of parameter design of nonlinear isolator with time-delayed control, the optimal value of time delay is explored for the nonlinear isolation system theoretically in this study. Since the Averaging Method could theoretically solve the approximate solution for vibration system with segmented property, parametrical excitation system and high dimensional system [29–32], in this study, it choses AM as the perturbation solving method for the vibration system with base excitation. Based on the eigenvalues analysis and Averaging Method, considering multiple nonlinear vibration properties containing dissipation time of vibration, resonant peak, multi-steady states band, effective isolation frequency band and displacement transmissibility etc. as the improvement standards, the optimal values of time delay for impact excitation and periodic excitation could be obtained. The main results in this paper demonstrate the optimization method for a time-delayed control nonlinear isolation system without changing the High-Static-Low-Frequency (HSLD) advantage brought by the nonlinear structure.

2. Nonlinear isolation system with time-delayed control

For a nonlinear vibration system with an external displacement excitation $z(t)$, time-delayed feedback control is introduced into the system as shown in Fig. 1.

As the model shown in Fig. 1, the mass of the vibration system is M which is connected with base via nonlinear spring and linear damper. The stiffness of the nonlinear isolation structure is supposed to satisfy a nonlinear function as $f{=}k_l(\cdot){+}k_n(\cdot)^3$, which could be realized by the Quasi-Zero-Stiffness (QZS) structure [4–8]. The damping effect is also considered with a property $f{=}c{\cdot}d(\cdot)/dt$. The absolute motion of the mass M is denoted by $x(t)$, the base excitation is $z(t)$, the relative motion between base and mass is $x(t){-}z(t)$. The control signal $u(x,\ \dot{x},\ x_\tau,\ \dot{x}_\tau)$ is linear function of the absolute motion and velocity of the mass, thus the dynamic equation of the platform can be obtained as

$$M\ddot{x} + k_l(x - z) + k_n(x - z)^3 + c(\dot{x} - \dot{z}) = u(x, \dot{x}, x_\tau, \dot{x}_\tau). \tag{1}$$

In order to highlight the effect of time delay in active control, the control signal $u(x,\ \dot{x},\ x_\tau,\ \dot{x}_\tau)$ is set as $u(x,\ \dot{x},\ x_\tau,\ \dot{x}_\tau){=}p_1(x_\tau{-}x) + p_2(\dot{x}_\tau - \dot{x})$ where p_1 and p_2 are control strength, and the system is without control when time delay equals to zero. The definition and symbol of structural parameters are shown in Table A1 in Appendix A. Introducing dimensionless transfer as

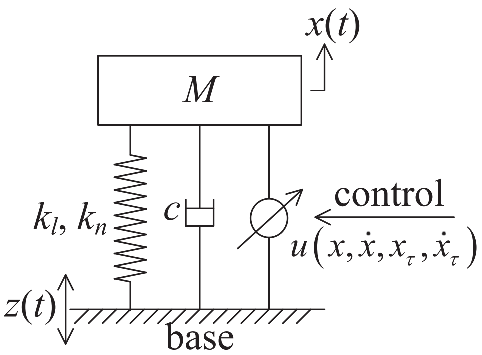

Fig. 1. Model of a nonlinear isolation system with time-delayed feedback control.