



# Dynamic effects of delayed feedback control on nonlinear vibration isolation floating raft systems



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## ABSTRACT

Vibration suppression and chaotification are the key issues in the study of the concealment capability of underwater vehicles. Time delay control is superior in chaotification, but the involved dynamics are sensitive and complex. This paper presents an analysis to obtain an analytical solution of the nonlinear delay differential equations and determine the effect of delay control on the vibration amplitude. Besides, by checking the stability of the analytical solution, dependence of chaotification upon the time delay control parameters is examined. Based on the theoretical derivation, the effects of different configurations of system parameters and delay control parameters on vibration amplitude are demonstrated in numerical simulation. What's more, the outcome of our results shows the significant role the time delay control plays in vibration suppression and chaotification. According to the analytical solution and stability analysis, not only can the appropriate delay be found to reduce the vibration amplitude, but also the suitable delay control setting can be selected for chaotification.

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## 1. Introduction

Line spectra of noise radiated from machinery vibration of underwater vehicles signify dynamical characteristics of operating systems, which are usually employed as a means for the identification of vehicles. In order to enhance the concealment capability of underwater vehicles, much effort has been dedicated to methodologies of line spectra reduction [1,2]. In recent years, an innovative idea of using chaotification to alter the features and suppress the intensity of line spectra has attracted great attention. Line spectra reduction based on chaotification is a practical implementation of anti-chaos control. In this niche area, research is still at the preliminary stage.

In line spectrum reduction, one of the major tasks is to provoke chaotic behavior to reduce and mask up line spectra. In general, chaotic behavior of mechanical systems usually occurs in specific conditions confined within narrow ranges of parameters [1,2]. The incidence of chaos tends to be sensitive to the variation of system parameters. To induce chaotic behaviors across a large parametric domain and retain chaotification persistent to a varying circumstance (i.e., varying external excitation), anti-control of chaos is accordingly required in order to achieve desirable outcomes.

Among various control methods, time delay control is particularly considered because a time delayed feedback may infinitely increase the number of dimensions of a system. It is known that complex behaviors of a dynamical system are

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closely associated with its dimensions, so that time delay control becomes a cost-effective way for chaotification [3,4]. Studies of time delay control have been developed in various research fields [5–13]. Delayed feedback control has been frequently applied in controlling chaos, improving the stability of periodic solutions and stabilizing unstable equilibrium since the pioneering work given by Pyragas [14]. Xu et al. [15,16] also showed that the delay may be used as a simple but efficient ‘switch’ to control motions of a system, namely, either from an order to chaos or from a chaotic motion to an order for different applications. The delay feedback control method was proposed by Wang et al. [17] typically for chaotification of a continuous-time minimum phase system. They noted that if the original system has an exponentially stable equilibrium point, then a simple time delay output–feedback controller with arbitrarily small amplitude can drive the system chaotic. Recently, an optimal time delay control method [3] was introduced to chaotify a Duffing-type isolation system. The intensity of line spectra is maximally suppressed by applying optimal time delay. Moreover, Li et al. have conducted a stability analysis of a vibration isolation floating raft system under time-delayed feedback control and provided a theoretical guidance that chaotification likely occurs in regions defined by a set of critical conditions of control gain and time delay [4]. A further development has been accomplished to extend the research to nonlinear time delay control [18], which makes chaotification available by only using tiny control. As time delay feedback is introduced, the system dynamics exhibit sensitive and complex features which however become troublesome and tough factors in the design of control laws [4]. In this paper, to obtain a better understanding of the complicated behaviors induced by time delayed control, analytical solutions are sought to examine the effects of time delay and control gain on the dynamic performance of the vibration isolation floating raft system.

It is noticed from numerical experiments that the effect of line spectra reduction and chaotification by time delay feedback control is closely associated with the ratio of excitation frequency and natural frequency of the system. It initiates our motivation to study the dynamic characteristic features of the system with different excitation frequencies, control parameters and system parameters, to obtain general guidance for line spectra reduction design of vibration isolation systems. However, it is impossible to obtain the analytical condition for a nonlinear dynamic system, especially for the time delay nonlinear system. In this paper, it is the objective to obtain the approximate analytical solutions by means of the method of multiple scales [19–21], which is capable of treating nonlinear dynamic system with time delay.

In this paper, the analytical solutions of nonlinear vibration isolation floating raft system with time delay control are obtained by the multi-scale method and the stability of the solution is studied. The effects of delay feedback control parameters and system parameters on dynamic behaviors of the system are investigated, which provide us useful clues for the improvement of vibration suppression and chaotification design.

## 2. Formulation of the problem

The nonlinear vibration isolation floating raft system can be considered as a 2-DOF mass–spring system, as shown in Fig. 1.  $M_1$  and  $M_2$  denote the isolated equipment and the floating raft, respectively.  $M_1$  is supported by a linear damper and a nonlinear spring which possesses quadratic and cubic nonlinearity. The floating raft  $M_2$  is connected with a fixed plane using a linear damper and a linear spring. In addition, there is an actuator between  $M_1$  and  $M_2$ , which is utilized to implement time-delayed feedback control for chaotification. When the origins of coordinates are set at the position where the springs are not compressed, the equation of the two-DOF nonlinear spring–mass system can be given by

$$\begin{aligned} M_1 \ddot{X}_1 + C_1(\dot{X}_1 - \dot{X}_2) + K_1(X_1 - X_2) - U_1(X_1 - X_2)^2 + U_2(X_1 - X_2)^3 &= F_0 \cos \Omega T + M_1 g \\ M_2 \ddot{X}_2 + C_2 \dot{X}_2 + K_2 X_2 &= C_1(\dot{X}_1 - \dot{X}_2) + K_1(X_1 - X_2) - U_1(X_1 - X_2)^2 + U_2(X_1 - X_2)^3 + M_2 g \end{aligned} \quad (1)$$

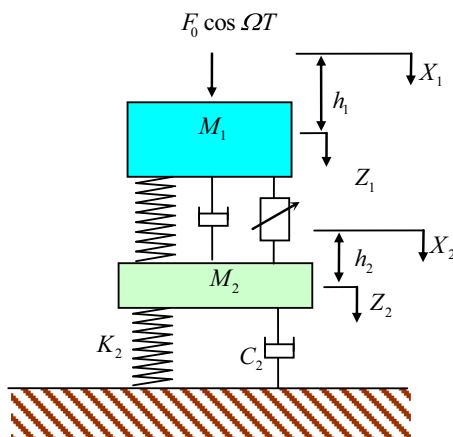


Fig. 1. A schematic diagram of the vibration isolation floating raft system.

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