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Modelling and tuning for a time-delayed vibration absorber with friction

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ABSTRACT

This paper presents an integrated analytical and experimental study to the modelling and tuning of a time-delayed vibration absorber (TDVA) with friction. In system modelling, this paper firstly applies the method of averaging to obtain the frequency response function (FRF), and then uses the derived FRF to evaluate the fitness of different friction models. After the determination of the system model, this paper employs the obtained FRF to evaluate the vibration absorption performance with respect to tunable parameters. A significant feature of the TDVA with friction is that its stability is dependent on the excitation parameters. To ensure the stability of the time-delayed control, this paper defines a sufficient condition for stability estimation. Experimental measurements show that the dynamic response of the TDVA with friction can be accurately predicted and the time-delayed control can be precisely achieved by using the modelling and tuning technique provided in this paper.

1. Introduction

To improve the accuracy and smoothness of a dynamic system such as 3D printing process, robotic manipulation, workpiece machining, and vehicle suspension system, vibration absorption techniques are often applied to these systems. Among the vibration control strategies, an active approach called the TDVA has attracted extensive interest over the past two decades.

The TDVA was first proposed by Olgac and Holm-Hansen [1]. Different from other techniques, the TDVA uses time delay and feedback gain to tune the absorber's resonant frequency, and thus provides good performances in real time tunability and applicability in wide frequency band. In experimental applications of the TDVA, Olgac et al. [2–4] first applied it to vibration suppression of flexible beams, where the piezoelectric actuator was adopted and the time delay was chosen at the magnitude of 1 ms to tune resonant frequency over 700 Hz. Then, Olgac et al. [5], Liu et al. [6], and Xu et al. [7–9] studied vibration absorption of mass-spring systems, where the electromagnetic actuator was adopted and the time delay was chosen at the magnitude of 10 ms to tune resonant frequency under 40 Hz. A common feature of these applications is that the actuators were considered as linear. However, the assumption of linearity is appropriate only when the motion of the actuator is small. Long-stroke electromagnetic actuators have been widely used in low (or ultra-low) frequency vibration absorption. Usually,

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Nomenclature

m_1	Total mass of the primary system
k_1	Total stiffness of the primary sheet springs
c_1	Equivalent viscous damping of the primary sheet springs
f_c	Control force acted on the secondary system
g	Feedback gain of the control
F_c	Coulomb force of the Stribeck friction
V_s	Stribeck velocity
x_1	Displacement of the primary system
x	Displacement of base excitation
z	Relative displacement between the secondary system and the shaker
ω	Excitation frequency
ϑ	Phase lag of y
θ	Phase lag of z
A	Complex representation of Y and ϑ
m_2	Total mass of the secondary system
k_2	Total stiffness of the secondary sheet springs
c_2	Equivalent viscous damping of the secondary sheet springs
f_r	Stribeck friction force between the mover and the stator of the actuator
τ	Time delay of the control
σ_s	Stribeck ratio of static friction to Coulomb friction
c_3	Viscous damping of the Stribeck friction
x_2	Displacement of the secondary system
y	Displacement of the primary system
X	Amplitude of base excitation
Y	Amplitude of y
Z	Amplitude of z
c_z	Equivalent viscous damping of the Stribeck friction in harmonic response
B	Complex representation of Z and θ

the long-stroke actuator uses motion guide to restrict the motion of its mover. When the guide is in small scale, the friction will be dominant even if ball or needle bearings are used. This friction, consequently, brings some challenging problems in the application of the TDVA.

Firstly, the friction presents a challenge to the modelling of the TDVA. Extensive studies on friction identification [10–14] indicated that the static model is precise enough to describe the effect of friction in systems with long-stroke motion. However, the static model has multiple representations and currently no agreement has been made in the research community on which representation is appropriate. For example, in the study of vibration absorbers, Ricciardelli et al. [15], Vidmar et al. [16], and Fang et al. [17] employed the Coulomb friction representation, whereas Chatterjee et al. [18,19] adopted the Stribeck friction representation. Although theoretical and numerical analysis were conducted in Refs. [15–19], the direct evidence, i.e. the experimental validation, has not yet been provided. Therefore, in order to develop an accurate model for the TDVA with friction, the experimental technique, including model evaluation and parameter calibration, should be proposed.

Secondly, the friction presents a challenge to the parameter tuning of the TDVA. When the system is treated as linear, see Refs. [1–9], the parameter tuning can be simply studied by frequency response (FR) analysis using Fourier transform. However, when the system has friction of a strongly nonlinear feature, Fourier transform can no longer be used due to the nonlinearity. Therefore, other approaches are required to achieve parameter tuning.

Aiming at solving these two challenging problems, we propose an integrated solution via FR analysis. Once the function of FR is obtained, we cannot only use it to identify the model of TDVA with friction, but also use it to analyze the vibration absorption performance with respect to tunable parameters. To this end, we adopt the method of averaging which is suitable for non-smooth nonlinearity and has been extensively studied in Refs. [20–22]. The method of averaging assumes that the response of the nonlinear system is nearly sinusoidal with slowly time-varying amplitude and phase-lag. It transforms the equation of motion into a set of ordinary differential equations with the slowly time-varying variables whose equilibrium solution is the FRF. Correspondingly, we apply the sinusoidal excitation in the experiment and then extract the response's amplitude and phase-lag, which are then treated as the samples of the FRF. By substituting the extracted samples into the FRF, we can identify the model of the TDVA with friction via parameter estimation. Then we use the determined FRF to analyze the vibration absorption performance with respect to tunable parameters. To ensure the stability of the time-delayed control, we