



# Theoretical and experimental investigation of position-controlled semi-active friction damper for seismic structures

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## ARTICLE INFO

### Article history:

Received 8 April 2017

Received in revised form 14 September 2017

Accepted 24 September 2017

### Keywords:

Semi-active control

Friction damper

Position control

Variable damper

Leverage mechanism

Energy dissipation device

Adaptive system

## ABSTRACT

A semi-active friction damper (SAFD) can be employed for the seismic protection of structural systems. The effectiveness of an SAFD in absorbing seismic energy is usually superior to that of its passive counterpart, since its slip force can be altered in real time according to structural response and excitation. Most existing SAFDs are controlled by adjusting the clamping force applied on the friction interface. Thus, the implementation of SAFDs in practice requires precision control of the clamping force, which is usually substantially larger than the slip force. This may increase the implementation complexity and cost of SAFDs. To avoid this problem, this study proposes a novel position-controlled SAFD, named the leverage-type controllable friction damper (LCFD). The LCFD system combines a traditional passive friction damper and a leverage mechanism with a movable central pivot. By simply controlling the pivot position, the damping force generated by the LCFD system can be adjusted in real time. In order to verify the feasibility of the proposed SAFD, a prototype LCFD was tested by using a shaking table. The test results demonstrate that the equivalent friction force and hysteresis loop of the LCFD can be regulated by controlling the pivot position. By considering 16 ground motions with two different intensities, the adaptive feature of the LCFD for seismic structural control is further demonstrated numerically.

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## 1. Introduction

Numerous studies have demonstrated that incorporating energy dissipation devices into a seismic structure can effectively enhance the seismic resistance capacity of a structure [1–4]. Friction dampers, a kind of energy dissipation device, have been successfully applied in numerous civil engineering structures for seismic protection [5–7]. Design methods and guidelines for structures with friction dampers have been developed and incorporated in some seismic provisions [8–12]. A typical friction damper generally consists of one or multiple friction interfaces and a constant normal force (clamping force) is applied at these interfaces. The frictional interfaces slip when the applied seismic load exceeds the maximum static friction force (slip force) of the damper, and thus provide the structure to be protected an additional energy dissipation source through friction behavior [1,2]. This type of passive friction damper (PFD) does not require additional control energy to

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operate and is thus more reliable and also easier to implement and maintain compared with active control devices. Nevertheless, the slip force of a PFD is usually a fixed value, which is predetermined according to a given seismic load specified by design codes in practice, and once the device is designed and manufactured, the slip force may no longer be altered. PFDs may thus not be able to meet the seismic demand of a structure subjected to an earthquake with an intensity or characteristics different from those specified in the design code. For instance, a PFD may not be activated in a moderate earthquake whose intensity is lower than that of the design earthquake, or a PFD may not provide sufficient energy dissipation capacity under a severe earthquake whose intensity is higher than that of the design one.

To improve the seismic control performance of friction-type dampers, semi-active friction dampers (SAFDs) have been proposed [13–16]. Also called a variable or controllable friction damper, an SAFD is able to generate a slip force that adapts to external excitations. A typical SAFD usually consists of one or more friction interfaces and a controllable clamping mechanism that produces an adjustable normal contact force between these interfaces. By controlling the normal force, the slip force of the damper can be regulated in real time. An SAFD is usually able to produce more favorable damping effects than those produced by a PFD, since its slip force can be adjusted instantaneously according to the dynamic characteristics of seismic loads and structural responses, while consuming substantially less control energy than that consumed by an active device, since the control action of SAFDs is applied internally rather than directly on the controlled structural system, which usually has large mass. The application of SAFDs generally requires the installation of a sensing system to monitor the system response and excitation, and also a suitable control law to determine the most appropriate slip force in real time, such that the seismic response of the controlled structure can be more effectively suppressed [17–19].

In order to make the slip force of SAFDs variable, many damper mechanisms and configurations have been proposed in the literature. Kannan et al. [20] and Samani et al. [21] adopted a hydraulic power source, which is able to produce large actuation forces, to regulate the clamping force of an SAFD, with a large variable slip force achieved. Laflamme et al. [22] and Cao et al. [23] proposed and tested a reliable SAFD, termed the modified friction device (MFD), for large-scale structures. They have demonstrated that the MFD, which consists of a variable friction mechanism based on a vehicle duo-servo drum brake, a mechanically robust and matured technology, and is capable of producing a large damping forces, while operating on a battery power. Later on, Downey et al. [24] incorporated a toggle brace with a variable friction device similar to the MFD, named banded rotary friction device (BRFD) that is capable of providing variable braking torques as a linear function of an applied force significantly amplified by the brake's positive servo effect. The toggle brace, which is commonly used in damper systems for amplifying the motion of inter-story drift, allows the BRFD to reach a maximum frictional force faster and thus enhances the control performance. Yang and Agrawal [25] adopted an electromagnetic device to control the clamping force of an SAFD installed in a base isolation system to enhance the seismic safety of a building structure. Nishitani et al. [26] utilized an oil damper with an electromagnetic relief valve to mimic a friction damper with a variable slip force level. Narasimhan and Nagarajaiah [27] developed a variable friction device that is composed of four pairs of friction and stiffness elements arranged in a rhombus configuration, with each arm consisting of friction and stiffness elements placed in parallel. The level of friction force is adjusted smoothly by changing the angle of the rhombus arms via a linear electromechanical actuator.

More recently, numerous researchers have proposed various SAFD configurations with piezoelectric actuators that provide variable clamping forces [28–34]. As an actuation source for structural vibration control, piezo-ceramic materials have many advantages, including light weight, swift response, easy implementation, and low control power [35]. Nevertheless, the major drawback of using piezoelectric actuators is that the actuation force generated by a piezo-ceramic material is usually limited and very sensitive to the stiffness of the boundary or support conditions due to its stroke limitation, which is tens of micrometers. To increase the level of the controllable slip force for a piezoelectric SAFD, Pardo-Varela and Llera [36] proposed a configuration that consists of multiple friction interfaces and piezoelectric actuators placed in a very stiff clamping system.

As mentioned above, for most existing SAFD systems, the level of the slip force is regulated by controlling the clamping force applied at the friction interfaces. In other words, the variation of the slip force is realized by using a force-controlled mechanism that controls the clamping force. At any time instant, the variable slip force of these SAFDs is the product of the clamping force and the friction coefficient between the contact interfaces. Therefore, for a given slip force, the required clamping force is reversely proportional to the friction coefficient. Moreover, because of practical concerns, such as compression capacity, wear resistance, friction stability, and durability, the selection of suitable friction materials for SAFDs is usually very limited. The most commonly used friction materials are metals or composite materials that usually have a frictional coefficient of 0.1–0.4 [30,35,37]. The magnitude of the controllable clamping force must be much larger than the desired slip force, which can have an order of around one hundred metric tons for controlling a real seismic structure. Consequently, in practice, producing and precisely controlling this huge clamping force in real time may be difficult and costly. To avoid this problem, the present study proposes a novel SAFD called the leverage-type controllable friction damper (LCFD). The proposed system consists of a traditional PFD with a constant slip force and a controllable leverage mechanism that has a movable central pivot. By instantaneously adjusting the pivot position on the lever arm, the LCFD is able to convert the passive friction force into an equivalent controllable force. Therefore, different from most existing SAFDs, which are usually force-controlled, the proposed LCFD is essentially a position-controlled system with a cost-effective traditional PFD.

The objective of the present study is to develop an analytical method and a numerical tool for the proposed semi-active system, and to demonstrate the system's feasibility and adaptive nature via experimental and numerical approaches. The development of control laws is not the focus of this study. The rest of this paper is organized as follows. Using Lagrange's equation, Section 2 derives the governing equation of motion for a structure with the LCFD in a comprehensive way, since the concept of LCFDs is proposed for the first time. A numerical simulation method based on the derived analytical model is

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