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High capacity variable friction damper based on band brake technology

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ABSTRACT

Implementation of high performance controllable damping devices can ameliorate cost-effectiveness of structural systems for mitigation of natural hazards. However, the applications of these damping systems are limited due to a lack of (1) mechanical robustness; (2) electrical reliability; and (3) large resisting force capability. To broaden the implementation of modern damping systems, a novel semi-active damping device is proposed. The device, termed Banded Rotary Friction Device (BRFD), has enhanced applicability compared to other proposed damping systems due to its cost-effectiveness, high damping performance, mechanical robustness, and technological simplicity. Its mechanical principle is based on a band brake, which results in a high amplification of the applied force while enabling a variable control force. The theoretical model of the BRFD is presented and experimentally verified by subjecting a prototype to various harmonic loads. Results show that the prototype BRFD is capable of a maximum force of 45 kN (10 kips) using only a 267 N (60 lb) actuation force, therefore providing a mechanical advantage of 169. A 3-stage dynamic model previously developed by the authors can successfully be used to model the dynamic behavior of the BRFD.

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1. Introduction

Passive supplemental damping devices have become widely accepted in structural engineering for natural hazard mitigation [1,2]. However, they are typically only applicable to a limited bandwidth of excitations because their damping forces cannot be varied post manufacturing. Active dampers are possible alternatives to provide higher mitigation performance. Nevertheless, they require large external power sources that may not be available during or after a natural hazard, have the potential to destabilize a system, and can be expensive to operate during sustained wind events [3].

Semi-active damping strategies combine some of the benefits of passive and active strategies [4]. They are purely reactive systems, in the sense that they cannot add energy to the controlled system, and can alter their mechanical properties to provide additional controllability using a fraction of the power required by active strategies. Semi-active devices are divided into four classes: variable stiffness [5,6], variable orifices [7], variable fluid [8] and variable friction [9] devices.

In particular, variable friction devices are capable of high energy dissipation, independent of velocity by dissipating mechanical energy into heat via a friction force that is controlled by an actuator with a varying normal force. Examples of actuators used in variable friction devices include: pneumatic [10,11], hydraulic [12], electromagnetic [13,14], electro-mechanical [15,16] and piezoelectric [17–20]. This controllability of the normal force minimizes obstacles found in passive friction devices, namely, the response produced by the strong nonlinear behavior, degradation of sliding interface, and cold weld [21,2].

Literature cites several examples of working variable friction prototypes for structural control applications. A semi-active independently variable friction device possessing a 25 kN (5.5 kips) maximum damping force provided by an electromechanical actuator has been experimentally verified [15]. Others [18,22] have investigated piezoelectric friction devices (PFD) of 0.5 kN (2.2 kips) and 25 kN (5.5 kips) damping force capacity, respectively. An electromagnetic friction damper device (EFD) having a 2.84 kN (0.64 kips) damping force capacity has also been developed [23].

Despite these efforts to produce semi-active friction devices suited for structural control applications, combined with studies demonstrating their economic advantages over passive systems, (see [24–26]), their implementation has remained limited. This could be due to low damping capability and the unavailability of mechanically reliable technologies [27].

In an effort to provide both high damping capacity and high mechanical reliability, the authors have recently proposed a variable friction device based on automotive dual servo drum brake

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technology. The technology, termed the Modified Friction Device (MFD), was theoretically presented [28] and a prototype fabricated and demonstrated [27]. While the prototype was a small scale version constructed from a 200 mm (8 in) automotive duo-servo drum brake, a key feature found in the experimental verification was a discontinuity of the friction dynamics when the rotation reversed due to the internal layout of the braking shoes and bracing pins. This discontinuity led to a sharp reduction in the damping force provided during a substantial portion of a damping cycle. Under specific conditions of limited displacement, the damper was found to provide very limited damping force, irrespective of the applied force. The maximum damping force obtained from the prototype was 3.1 kN (0.7 kip).

The objective of this paper is to introduce a second generation of rotary variable friction devices with substantially enhanced applicability to mitigation of structural vibrations. This second generation device is designed to be capable of producing a damping force of one order of magnitude higher while overcoming the limitations found in the dynamics of the MFD and preserving a simple and mechanically robust design. This novel device, presented for the first time, is based on band brake technology, and is termed Banded Rotary Friction Device (BRFD). Band brakes have been used in mining and marine mooring applications for decades [29,30] and have proven to be a mechanically robust technology [31]. Their maintenance costs are known to be limited due to their simple mechanics, no internal parts or hydraulic fluid, and the easy replacement/availability of friction material [32]. In this paper, the BRFD is introduced, and a working prototype is experimentally verified. The 3-stage dynamic model developed by the authors [27] is used to characterize its behavior.

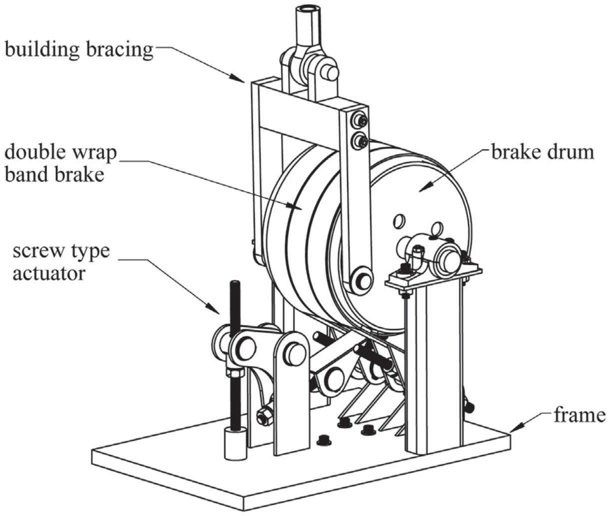
The paper is organized as follows. The next section introduces the BRFD and provides its theoretical background. This is followed by a presentation of a 3-stage dynamic model used in the characterization of the device's dynamic behavior. The subsequent section discusses the experimental methodology and the prototyping of the BRFD, along with a presentation and discussion of the experimental results. The last section concludes the paper by providing a summary of the findings.

2. Banded Rotary Friction Device

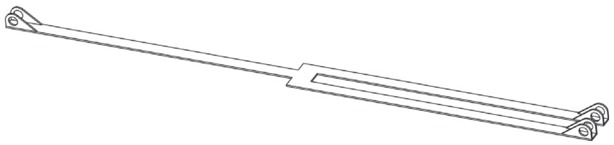
The BRFD utilizes existing band brake technology. A band brake is a robust and reliable friction brake consisting of a flexible band lined with friction material that tightens concentrically around a cylindrical drum to slow or stop its rotation. The BRFD is a double band brake system, consisting of a band lined with a friction material [32], doubled wrapped around a drum, as shown in Fig. 1a. It is capable of providing variable braking torques as a linear function of an applied force, which is significantly amplified by the brake's positive servo effect.

A 45 kN (10 kips) capacity prototype was fabricated based on the schematic shown in Fig. 1a. The flat double wrap band is illustrated in Fig. 1b. The band is lined with friction material and wrapped 670° around the circumference of the steel drum and anchored at both ends. The single end of the band is attached to an actuation mechanism consisting of a threaded rod for the purpose of varying the force applied to the band brake, and the double end of the band is anchored to the rigid frame. The prototype has been designed to be installed within a structural bracing scheme. Such an implementation scheme is discussed below.

2.1. Implementation within a structural system



(a) double wrap band brake system



(b) double wrap band brake

Fig. 1. Banded rotary friction device.

The BRFD is designed to transform displacement into rotation, θ. The device can therefore be integrated within a multiplicity of structural control schemes, including hybrid base-isolation systems, semi-active tuned mass dampers, and bracing elements. Fig. 2 shows the BRFD installed in two possible configurations associated with a building lateral load resisting system. Fig. 2(a) is a chevron system that transduces interstory drift δ into rotation θ of the BRFD via the addition of a connecting link. Fig. 2(b) is a toggle bracing configuration. The toggle bracing is used in structural motion engineering to amplify the interstory drift [33]. While more expensive than a typical chevron system, a toggle bracing system allows the BRFD to reach a maximum frictional force faster, thus increasing the mitigation performance of the device. In both configurations the inter story drift $\delta = x/H$, where x and H are the lateral displacement of the floor and the story height, respectively. An expression for the linear displacement y can be written as

$$y = \theta \cdot r_b \tag{1}$$

where r_b is the distance from the center of the drum to the brace connection. For the chevron configuration where $y = x$ the rotation can be derived as

$$\theta = \frac{\delta \cdot H}{r_b} \tag{2}$$

For the toggle configuration, assuming small displacements, it can be shown that [34]

$$y = \frac{\sin(\alpha)}{\cos(\alpha + \beta)} \cdot x \tag{3}$$

and

$$\theta = \frac{\sin(\alpha)}{\cos(\alpha + \beta)} \frac{\delta \cdot H}{r_b} \tag{4}$$

Eqs. (2) and (4) can be used in a performance-based design procedure [3]. The following section derives the equations governing the BRFD friction mechanism.

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