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Modeling, design, and testing of a proof-of-concept prototype damper with friction and eddy current damping effects

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ABSTRACT

Friction is considered as one of the most reliable mechanisms of energy dissipation that has been utilized extensively in passive damping devices to mitigate vibration of civil engineering structures subjected to extreme natural hazards such as earthquakes and windstorms. However, passive friction dampers are well-known for having a highly nonlinear hysteretic behavior caused by stick-slip motion at low velocities, a phenomenon that is inherent in friction and increases the acceleration response of the structure under control unfavorably. The authors have recently proposed the theoretical concept of a new type of damping device termed as “Passive Electromagnetic Eddy Current Friction Damper” (PEMECFD) in which an eddy current damping mechanism was utilized not only to decrease the undesirable effects of stick-slip motion, but also to increase the energy dissipation capacity of the damping device as a whole. That study was focused on demonstration of the theoretical performance of the proposed damping device through numerical simulations. This paper further investigates the influence of eddy current damping on energy dissipation due to friction through modeling, design, and testing of a proof-of-concept prototype damper. The design of this damper has been improved over the design in the previous study. The normal force in this damper is produced by the repulsive magnetic force between two cuboidal permanent magnets (PMs) magnetized in the direction normal to the direction of the motion. The eddy current damping force is generated because of the motion of the two PMs and two additional PMs relative to a copper plate in their vicinity. The dynamic models for the force-displacement relationship of the prototype damper are based on LuGre friction model, electromagnetic theory, and inertial effects of the prototype damper. The parameters of the dynamic models have been identified through a series of characterization tests on the prototype damper under harmonic excitations of different frequencies in the laboratory. Finally, the identified dynamic models have been validated by subjecting the prototype damper to two different random excitations. The results indicate that the proposed dynamic models are capable of representing force-displacement behavior of the new type of passive damping device for a wide range of operating conditions.

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1. Introduction

Energy dissipation is critical to limiting damage to civil engineering structures subjected to extreme natural hazards such as earthquakes and windstorms [1–3]. Therefore a wide variety of mechanisms has been proposed and developed for the purpose of enhancing the energy dissipation capability of buildings and bridges [4–7]. Friction is one of the most effective mechanisms for dissipating kinetic energy that can be developed by relative motion between two rough surfaces in contact [8]. It has been widely utilized to dissipate the input seismic energy in civil engineering structures through passive friction devices because of their solid-based configurations that require significantly lesser maintenance than other passive damping devices, and also because of their simplicity, reliability, and significantly lower cost of installation and operation [9–17]. These passive friction dampers are capable of dissipating significantly larger amount of the kinetic energy of civil engineering structures during strong earthquakes and windstorms compared to other types of passive dampers such as viscous fluid dampers, viscoelastic dampers, and metallic yielding dampers [5,18,19]. The solid-based configuration of a passive friction damper has also significant advantages over other types of passive dampers, in particular, over fluid-based dampers that may suffer from fluid degradation and leakage during their lifespan [5,19,20]. Furthermore, in contrast to fluid-based passive dampers [21], the force produced by a passive friction damper is not so much affected by the frequency content of the input excitation since its dynamic behavior is independent of velocity across the damper [5,19,22].

A friction force between two sliding surfaces depends directly on the normal force between these two surfaces. The two most common types of systems used for producing normal force in these passive friction dampers are clamping and pre-compressing systems [19,23]. Passive friction dampers with clamping systems are often designed in a flat configuration in which bolt connections are used to clamp the moving parts to each other in the direction normal to the friction surface [9–12]. However, passive friction dampers with pre-compressing systems are often tubular-shaped and consist of pre-compressed springs to press friction pads to the inner surface of the wall of the damper housing in the direction normal to the motion of the piston [13,16,17]. In recent years, a particular attention has been devoted to a new class of friction dampers making use of variable [24–26] or permanent [14] magnetic actuation systems for producing normal force. These new types of friction dampers have been proved to be promising in vibration control of civil engineering structures during extreme natural hazards because of their high energy dissipation capability and cost-effectiveness, since they consist of low cost components, such as electromagnets, permanent magnets, and steel plates [14]. However, in spite of all advantages that passive friction dampers offer, they still suffer from major issues related to their highly nonlinear hysteretic behavior because of stick-slip motion at low velocities in which the dynamic state of the damper makes abrupt transitions from the sliding phase to the sticking phase, and vice versa. This jerky motion contaminates the acceleration response of the structure with high-frequency pulses during the action of the damper. These pulses may induce damages to non-structural elements and reduce the comfort of occupants, particularly in high-rise buildings subjected to long duration external excitations [19,27,28].

Eddy current damping is another effective solid-based mechanism for dissipating kinetic energy. Eddy currents are induced in a good conductor, such as copper, because of a moving permanent magnetic source in the vicinity of the conductor [29]. The interaction of the induced magnetic field because of eddy currents and the external magnetic field causes a braking force, called as eddy current damping force, against the motion of the permanent magnetic source [19,23,30]. This force is proportional to the velocity of the permeant magnetic source for the velocities in the range of engineering applications and behaves like a viscous force [31]. Therefore, eddy current damping is capable of dissipating the kinetic energy of civil engineering structures smoothly during strong earthquakes and windstorms similar to viscous damping.

In a recent study, the authors have presented the theoretical concept of a new type of passive damping device termed as passive electromagnetic eddy current friction damper (PEMECFD) that combines the advantages of both friction and eddy current damping to dissipate kinetic energy [19,23]. The theoretical performance of this damping device was demonstrated through numerical simulations. This paper is focused on the investigation of the influence of eddy current damping on increasing the efficiency of friction mechanism in dissipating kinetic energy, since eddy current damping has two beneficial effects on the dynamic behavior of the proposed damper: (1) smoothing the nonlinear hysteretic behavior of the friction part by lessening the undesirable effects of stick-slip motion, and (2) increasing the energy dissipation capacity of the proposed damper as a whole. This has been demonstrated through modeling, design, and testing of a proof-of-concept prototype damper. Two dynamic models have been developed to demonstrate the force-displacement relationship of the prototype damper. A series of characterization tests have been conducted on the prototype damper under harmonic excitations of different frequencies in the laboratory to identify parameters of these dynamic models. Identified dynamic models have been validated by subjecting the prototype damper to two different random excitations.

2. Dynamic model

Fig. 1(a) shows the longitudinal cross-section of the dynamic model developed to characterize the force-displacement relationship of the proof-of-concept prototype damper. The characterization process is carried out in two coordinate systems S:XYZ and S′:X′Y′Z′ linked to the laboratory and moving reference frames, respectively, as shown in Fig. 1(a). All physical quantities involved in this process are measured and calculated in the laboratory reference frame (LRF) except for calculation of the eddy current damping force which, for the sake of simplicity, is made in the moving reference frame (MRF). The dynamic model exclusively includes the key components of the damper responsible for the generation of the friction and eddy