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# Assessment of semi-active friction dampers

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ABSTRACT

The use of friction dampers has been widely proposed for a variety of mechanical systems for which applying viscoelastic materials, fluid based dampers or other viscous dampers is impossible. An important example is the application of friction dampers in aircraft engines to reduce the blades' vibration amplitudes. In most cases, friction dampers have been studied in a passive manner, but significant improvements can be achieved by controlling the normal force in the contact region. The aim of this paper is to present and study five control strategies for friction dampers based on three different hysteresis cycles by using the Harmonic Balance Method (HBM), a numerical and experimental analysis. The first control strategy uses the friction force as a resistance when the system is deviating from its equilibrium position. The second control strategy maximizes the energy removal in each harmonic oscillation cycle by calculating the optimal normal force based on the last displacement peak. The third control strategy combines the first strategy with the homogenous modulation of the friction force. Finally, the last two strategies attempt to predict the system's movement based on its velocity and acceleration and our knowledge of its physical properties. Numerical and experimental studies are performed with these five strategies, which define the performance metrics. The experimental testing rig is fully identified and its parameters are used for numerical simulations. The obtained results show the satisfactory performance of the friction damper and selected strategy and the suitable agreement between the numerical and experimental results.



## 1. Introduction

Vibration attenuation in mechanical systems is a recurring issue in modern industry because the demands for lightweight and efficient machines are constant. Moreover, lightweight machines mean more flexibility, which can increase a system's vibration. In these cases, supplemental damping has been shown to be cost-effective in mitigating structural vibrations.

Among all possible devices that are applied to solve these problems, the most used has been semi-active devices. The choice of this approach is justified for its capability to adapt to changes in the system, work under a wide range of operating

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frequencies, and not demand too much energy because the actuator does not work directly against the excitation. This last point is determinant for their choice because this reason differentiates semi-active from fully active approaches.

A very simple and effective semi-active mechanism can be obtained from an association of an elastic element that is coupled to the vibratory system through a variable friction joint, such as a friction damper. Despite its conceptual simplicity, this device exhibits a displacement-dependent behaviour, which is exploited to improve its efficiency in terms of vibration suppression. Conceptually, a fast actuator applies normal loads at the coupling and changes the Coulomb static friction value $\mu N$, which changes the vibratory system's apparent physical properties, such as the stiffness, damping, and sometimes mass by adding an additional weight to the system.

Friction forces that arise from the relative motion of two contacting surfaces are a source of energy dissipation. Sometimes, this phenomenon is an unwanted effect of the design but can also be intentionally used to increase the damping of a certain system in a simple, cost-effective manner.

A friction damper was chosen instead of a viscous damper because the former can provide damping for small and large structures at low or high vibration velocities, in addition to its nonlinear behaviour. Viscous devices are not feasible for large structures because these devices require a large amount of energy to be dissipated, which can overheat the viscous fluid and degenerate the damper's performance. Some authors cite this process as a technological reason for trucks to use leaf springs, where damping is provided by friction between leaves. Viscous dampers are also not effective at low speeds and thus are occasionally impractical in civil structures that combine low speed vibrations and large masses. Additionally, some applications introduce high temperatures, which also compromise the performance of viscous dampers, such as aeronautical turbines, where friction dampers are widely used. Coulomb's model is a scientifically proven and accepted model that provides a suitable background for this topic.

Park and Kim [1] used a semi-active control approach through a dry friction damper to reduce transient vibrations in a space truss structure. These authors maximized the equivalent damping ratio of the lowest bending mode, which is considered the most dominant in these transient vibrations, and obtained an optimal settling time, during which the amplitude of the displacement signals reduced to 5% of the original peak. The settling time was approximately one third of the passive time and one half of the bang-bang control, both of which were used for comparison, indicating the power of the proposed methodology in reducing transient vibrations.

Mirtaheri et al. [2] extended the friction damper concept to a cylindrical assembly for the seismic demand of structures. This damper consisted of two main parts: an inner shaft and an outer cylinder. These two components were assembled such that one was shrink-fitted inside the other. Upon application of proper axial loading to both ends of the cylindrical friction damper (CFD), the shaft moved inside the cylinder by overcoming the friction, which led to the considerable dissipation of mechanical energy. In contrast to other friction dampers, CFDs do not use high-strength bolts to induce friction between contact surfaces, which reduces construction costs, simplifies design computations and increases the reliability compared to other types of friction dampers. These authors evaluated the energy absorption capacity by examining hysteretic loops and concluded that the CFD significantly improved the performance of structures that were subjected to earthquake loads, achieving 75% improvement compared to previous assemblies that were cited in their work.

Guglielmino and Edge [3,4] applied the controllable friction damper concept to vehicles to improve comfort and stability. These authors used this device in the vehicle's suspension to isolate the system from external excitation (road irregularities). The Rolls-Royce® Silver Ghost from the early 1900s used a passive friction disk shock absorber in its suspension.

Nitsche et al. [5] analysed how changes in the stiffness and damping modify a system's behaviour and presented an efficient control strategy to be applied to helicopter blades.

The efficiency of rotating machine applications was demonstrated by dos Santos et al. [6], who verified that one can avoid the effects from passing critical speeds with natural frequency changes from smart spring actuation, where smart spring is an association in series between a friction damper and a spring.

This short review of the literature demonstrates the wide range of applications of the friction dampers.

The aim of this work is to study the behaviour of friction dampers when applied to a vibratory system and to identify the control strategies to be used. A mathematical formulation that is based on HBM linearization is presented, which enables us to obtain some analytical equations of the dynamical behaviour of friction dampers. These results are compared to numerical and experimental results that are obtained with a one-degree-of-freedom (DOF) vibratory system. An evaluation metric is proposed to classify the performance of each strategy. Finally, the proposed device is coupled to two test rigs, one with a 2 DOF and another with a 3 DOF system, to study the performance of the proposed friction dampers on multi DOF vibratory systems.

## 2. Friction damper theoretical analysis: Harmonic balance method

The friction damper model is based on the Coulomb friction law, which states that the generic friction force is limited to

$$F_f = \mu N \tag{1}$$

The variable $\mu$ is the friction coefficient and $N$ is the normal force that acts on the contact area. Additionally, the tangential stiffness, which represents the elastic strain of the bodies in contact before the slippage, is included to obtain a more reliable model. This model is represented as shown in Fig. 1.