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# Modeling and design of bidirectional pendulum tuned mass dampers using axial or tangential homogeneous friction damping

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ABSTRACT

As a development of the classical pendulum vibration absorber, bidirectional pendulum TMDs (BTMDs) have been recently proposed, capable to resonate with the main structure along both its horizontal directions by virtue of their optimally designed three-dimensional (3D) pendulum surface. To provide BTMDs with the required energy dissipation capability, two damping mechanisms based on respectively axial and tangential friction were invented as an alternative to ordinary viscous dashpots. The first one consists of a vertical axial-friction damper connecting the BTMD to the main structure. The second one consists of a tangential friction spatially variable along the pendulum surface in proportion to the modulus of the surface gradient vector. Both mechanisms are fundamentally characterized by a nonlinear but homogeneous first-order model which makes their effectiveness independent from the excitation level. This paper compares the two friction paradigms with the classical viscous one. To this purpose, first a unifying fully nonlinear 3D model is established through Lagrangian mechanics, then an optimal design method is proposed, based on either $H_\infty$ or $H_2$ norm minimization criteria. Extensive numerical simulations are performed to show the pros and cons of the three damping options and of the two optimization approaches. Results demonstrate that the three types exhibit a similar performance against unidirectional excitation but that the axial-friction type loses most of its effectiveness under bidirectional excitation whenever the pendulum surface is axial- or nearly axial-symmetrical, because of the insurgence of a peculiar rotational motion which virtually deactivates the friction damper. Results also show that the $H_\infty$ design criterion is more robust than the $H_2$ design criterion, and that both criteria outperform previous simplified approaches proposed in the literature. It is concluded that, once properly designed and until stroke demand does not exceed their intrinsic stroke limitations, BTMDs are an effective vibration control strategy, which can be implemented through a variety of damping options, and that the two homogeneous friction mechanisms, and particularly the tangential one, are promising paradigms to provide amplitude-independent damping to engineering pendular systems.

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## 1. Introduction

Passive tuned mass dampers (TMDs) are a mature strategy of structural vibration control, widely applied in civil and mechanical engineering [1]. The most elementary scheme of a TMD consists of a single-degree-of-freedom (SDOF) linear oscillator attached to the main structure, capable of absorbing and dissipating vibratory energy from one structural target

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mode through frequency tuning and damping optimization. According whether their restoring force is elastic or gravitational, TMDs are mainly classified in the translational and pendulum categories, and the pendulum category is further distinguished into the "supported" and the "hanging" pendulum types, depending whether the mass of the absorber is constrained to move along a physical curved recess or suspended through ropes or bars. In the last decade, supported pendulum TMDs have increasingly attracted the attention of the research community, because of their compactness, durability and versatility of shape. They include a variety of configurations, such as the ball pendulum [2,3], the rolling and sliding pendulums (with single or double concavity) [4,5] and the rocking pendulum. In [6] a novel rolling ball damper is proposed for controlling wind turbines, made of multiple steel balls rolling in a spherical concavity and dissipating through rolling friction and impact. In [7] a novel unbalanced rolling pendulum TMD is presented, where the gravitational restoring force is produced by the unbalanced distribution of mass within the rolling body. In [8] a track nonlinear energy sink (NES) is proposed, whose specially shaped, smooth and symmetric track profile provides the desired essentially nonlinear restoring force which is typical of NESs. In [9] an asymmetrical variant of the said track NES is introduced, in which the smooth track nonlinearity combines with a discontinuous impact nonlinearity. In [10] an interesting application is presented of a rolling ball pendulum embedded in hollow slabs of civil structures.

As an alternative to the pendulum schemes listed above, which are all either two-dimensional (2D) (i.e. constrained along a planar vertical profile) or three-dimensional (3D) but axial-symmetrical (i.e. constrained along a surface of revolution), bidirectional pendulum TMDs (BTMDs) have also been proposed which can be tuned to the main structure along both horizontal directions even when the corresponding structural target frequencies are different, by virtue of an optimally designed (generally non-axial-symmetrical) 3D pendulum surface. This concept has been implemented in two main variants, respectively belonging to the supported and to the hanging pendulum types. The first variant is the rolling-pendulum BTMD introduced in [11]. In this case, the 3D pendulum surface is realized by a special 3D rolling-pendulum bearing, made of two identical concavities symmetrically facing each other and sandwiching a rolling ball. By varying the shape of the two concavities and the radius of the rolling ball, any 3D surface can be obtained. The second variant is the hanging-pendulum BTMD proposed in [12]. In this case, the 3D pendulum surface is realized by a special Y-shaped arrangement of the suspending cables. By varying the length of the vertical cable and/or of the inclined cables, any toroidal surface can be obtained.

In these two variants of BTMDs, energy dissipation is produced either by classical horizontal viscous dampers [11] or by an original arrangement of a vertical axial-friction damper [12]. A third damping option has been very recently proposed for supported BTMDs by the same author, consisting of a tangential rolling- or sliding-friction spatially variable along the pendulum surface in proportion to the modulus of the surface gradient vector [13]. Both the axial-friction and the tangential-friction mechanisms mentioned above are fundamentally characterized by a nonlinear but homogeneous first-order model. Therefore, in the small-displacement domain both friction types ensure the BTMD an equivalent damping ratio and an effectiveness which are independent from the amplitude of motion [14], contrary to what happens when a constant friction acts in the direction of motion of the absorber, in which case the equivalent damping ratio becomes inversely proportional to the amplitude and the effectiveness becomes amplitude-dependent [15,10].

Focusing on bidirectional pendulum TMDs of the supported type, this paper compares the two friction paradigms, respectively called the homogeneous-axial BTMD (HA-BTMD) and the homogeneous-tangential BTMD (HT-BTMD) and jointly denoted as the homogeneous BTMD (H-BTMD), with the classical viscous paradigm, here named the viscous BTMD (V-BTMD). To this purpose, first a unifying fully nonlinear 3D BTMD model is derived through Lagrangian mechanics, then an optimal design methodology is proposed. Extensive numerical simulations of the optimally designed devices mounted on SDOF and multi-degree-of-freedom (MDOF) structures are finally performed under stationary force input, revealing the respective pros and cons of the three damping options. Main contributions of this paper are as follows: (i) establishing a common modelling framework, representative of all three existing BTMD types, by combining contributions from previous studies; (ii) presenting a common BTMD design procedure, rigorously valid for SDOF linear structures under low-amplitude harmonic or white-noise force excitations but extendable to more general cases, whose main novelty resides in the solution, never attempted before for H-BTMDs, of an $H_\infty$ or $H_2$ norm minimization, here numerically performed for various design scenarios; (iii) showing the superior robustness of the $H_\infty$ optimal solution over the $H_2$ optimal solution, and the greater effectiveness of both solutions over existing simplified optimization criteria; (iv) evaluating the optimal BTMDs in a variety of cases, for different structural features and excitation levels; (v) proving, both analytically and numerically, the superior 3D performance of the HT-BTMD over the HA-BTMD, this latter exhibiting, in axial- or nearly axial-symmetrical cases, a peculiar (so far undocumented), insufficiently-damped rotational mode which drastically reduces its mitigation capabilities; (vi) showing, on the other hand, the substantial equivalence of the V-BTMD and of the HT-BTMD in a variety of design situations.

The remaining of this paper is organized as follows: in Section 2 the fully nonlinear 3D model of a BTMD of either viscous, axial-friction or tangential-friction damping types is derived; in Section 3 an optimal design method is presented for the three types; in Section 4 the three alternatives are compared in the small-displacement domain; in Section 5 the three alternatives are compared in the large-displacement domain; in Section 6 a case study is illustrated; in Section 7 conclusions are drawn.

## 2. The BTMD unifying analytical model

This section establishes the fully nonlinear 3D model of a BTMD accounting for: (i) one or more viscous dampers connecting it to the supporting structure; (ii) an axial-friction damper connecting it to the supporting structure; (iii) a variable tan-

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