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# Investigation on a mechanical vibration absorber with tunable piecewise-linear stiffness

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The design and characterization of a mechanical vibration absorber are addressed. A distinctive feature of the absorber is its tunable piecewise-linear stiffness, which is realized by means of a slider with two stop-blocks installed constraining the bilateral deflections of the elastic support. A new analytical approach named as the equivalent stiffness technique (EST) is introduced and then employed to obtain the analytical relations of the frequency, amplitude and phase with a view to exhibit a more comprehensive characterization of the absorber. Experiments are conducted to demonstrate the feasibility of the design. The experimental data show good agreement with the analytical results. The final results indicate that the tunable stiffness absorber (TSA) possesses a typical nonlinear characteristic at each given position of the slider, and its stiffness can be tuned in real time over a wide range by adjusting the slider position. Hence the TSA has a large optimum vibration-absorption range together with a wide suppression band around each optimal position, which contributes to its excellent capacity of vibration absorption.



## 1. Introduction

In order to reduce the vibration of the primary structure (PS), the devices for damping vibrations of bodies are invented [1]. So far, various forms of vibration absorbers and dampers have been proposed. In contrast to the vibration damper, where the energy is dissipated by the damper, the exciting force is opposed by the absorber [2,3]. As for linear and nonlinear absorbers, the former has a good effect just in a narrow frequency band, and the latter extends the frequency bandwidth but loses its effectiveness to some extent. Giving consideration to the bandwidth and effectiveness, tunable parameters nonlinear absorber is a preferable choice.

Before a new design is proposed, investigations on the previous researches are provided. It is found that the concept of the absorber and the damper is somewhat confusing in practical use. In fact, most of the so-called dampers are belong to the category of absorber. Typical vibration absorbers can be classified as follows:

### *1.1. Tunable mass absorber (TMA)*

One kind of the TMA tunes the natural frequency by tuning its equivalent mass, such as the design of rotational-pendulum vibration absorber realized frequency tuning by adjusting the rotational speed [4]. Another kind often referred

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to as tuned mass damper (TMD), which is designed for tuning the phase relationship between the main mass and the absorber mass through damping control. One of the relevant work is the semi-active tuned mass dampers with phase control by a variable friction force [5]. Some other studies, such as vibration absorber based on controlled semi-active damper [6] and the absorber with real-time controlled magnetorheological damper [7], are also very typical. The drawbacks of the TMA and TMD are related to the narrow bandwidth of optimal control, so an accurate tuning which must continue over times is required [8]. There is also a type of passive multiple TMD that is often used to suppress random vibrations [9,10]. It consisting of many TMDs with distributed natural frequencies. This form of structure can indeed broaden the damping range, but its robustness and effectiveness are contradictory [11].

### 1.2. Impact damper

The impact damper undergoes momentum transfer between the main mass and impact mass [12]. Gharib and Ghani introduced a new passive vibration device called the linear particle chain impact damper [13], therein they summed up the most common types of the impact damper such as single unit impact damper [14], multiunit impact damper [15], bean bag impact damper [16], particle/granular impact damper [17,18], resilient impact damper [19] and buffered impact damper [20]. All these works were aimed at producing more effective collisions in order to induce continuous momentum transfer from the main mass to absorber mass.

### 1.3. Nonlinear stiffness absorber (NSA)

The NSA is designed with a focus on various forms of nonlinear stiffness. Typical studies in recent years are nonlinear energy sink (NES) and quasi-zero stiffness (QZS) absorber. The concept of NES means an essentially nonlinear restoring force vanishing linear stiffness. Benefiting from nonlinearity, the NES has no natural frequency and can thus adapt itself to the frequency of the PS [21–23]. The concept of QZS absorber is proposed basing on the idea of selecting the eigenfrequency of the vibration isolator as small as possible, because the frequency range over which a linear passive vibration isolator is effective is often limited by the mount stiffness required to support a static load. Theoretical and experimental studies on the QZS have been done by a number of investigators [24–27].

### 1.4. Tunable stiffness absorber (TSA)

The TSA extend its working frequency band through stiffness tuning. As early as 1969, Lohr had proposed a design for variable stiffness polymer dampers that changed stiffness through temperature control [28]. In 1992, Walsh et al. proposed a vibration absorber using a pair of leaf spring as the variable stiffness element and adjusting the stiffness by changing the gap between the two beams [29]. In 1993, an active variable stiffness system is proposed as a seismic response control system [30]. Some other related works were introduced by Patten et al. [31] and Yang et al. [32]. The main limitation of these devices is that the stiffness is provided only in on-off mode. To overcome this limitation, semi-active continuously and independently variable stiffness devices were developed by Nagarajaiah et al. [33–35]. In the recent studies, there is a development of a mechanical semi-active vibration absorber whose natural frequency can be adjusted in real time by adjusting its geometry parameters [36]. This design broadens the vibration-absorbing band, but for each tuned frequency, the system exhibits a linear characteristic. Similarly, Yang et al. investigated a two-DOF absorber with tunable stiffness and damping. The mass blocks are suspended by the sheet metals which act as spring elements, and the two parts are connected by the slider and bolts. By adjusting the distance between two bolts, the stiffness tuning is realized [37]. Liu et al. presented a beam-like semi-active electromagnetic vibration absorber, which consists of a flexible ferromagnetic cantilever beam, a ferromagnetic mass attached to the free end of the beam, and an E-shaped electromagnet. By changing the current of the electromagnet, the stiffness of this absorber is online tunable [38]. Different from the above studies, Benacchio et al. proposed design of a magnetic vibration absorber with tunable stiffness, which is able to tune the linear stiffness together with the nonlinear cubic and quintic stiffnesses by means of repulsive magnets located in the axis of the main vibrating magnetic mass and a set of corrective magnets located off the main axis. Through changing the system's geometry, the absorber can be tunes as three forms: nonlinear tuned vibration absorber, NES, and bi-stable absorber [8].

In summary, to obtain better vibration suppression effect, the structural design of the vibration absorber shows an increasingly complex trend. In all types of absorbers, TSA is a relatively better choice. However, due to the difficulties of structural design and implementation, research on the nonlinear TSA is rare in previous studies, and real-time stiffness tuning during vibration is still not easy to achieve. In this paper, a nonlinear mechanical TSA with simple and practical structure is proposed to realize the real-time tuning of stiffness. The implementation of the design is by means of two stop-blocks mounted on a slider constraining the bilateral deflections of its elastic support, consequently, the absorber presents piecewise linear characteristic and its stiffness can be easily tuned by adjusting the position of the slider.

In order to deal with nonlinear problems more intuitively and conveniently, we use a new proposed analytical approach named as equivalent stiffness technique (EST) in this study. The EST is relatively simple in calculation and can be used to analyze various nonlinear restoring force problems, such as fractional exponent, piecewise, and even sinusoidal restoring force [39,40]. Moreover, the EST can be employed to analyze the two-degree-of-freedom nonlinear systems. Therefore, Section 2 presents and models the experimental setup whilst introducing the EST to convert the equation of motion. Experimen-