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Nonlinear dissipative devices in structural vibration control: A review

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A B S T R A C T

Structural vibration is a common phenomenon existing in various engineering fields such as machinery, aerospace, and civil engineering. It should be noted that the effective suppression of structural vibration is conducive to enhancing machine performance, prolonging the service life of devices, and promoting the safety and comfort of structures. Conventional linear energy dissipative devices (linear dampers) are largely restricted for wider application owing to their low performance under certain conditions, such as the detuning effect of tuned mass dampers subjected to nonstationary excitations and the excessively large forces generated in linear viscous dampers at high velocities. Recently, nonlinear energy dissipative devices (nonlinear dampers) with broadband response and high robustness are being increasingly used in practical engineering. At the present stage, nonlinear dampers can be classified into three groups, namely nonlinear stiffness dampers, nonlinear-stiffness nonlinear-damping dampers, and nonlinear damping dampers. Corresponding to each nonlinear group, three types of nonlinear dampers that are widely utilized in practical engineering are reviewed in this paper: the nonlinear energy sink (NES), particle impact damper (PID), and nonlinear viscous damper (NVD), respectively. The basic concepts, research status, engineering applications, and design approaches of these three types of nonlinear dampers are summarized. A comparison between their advantages and disadvantages in practical engineering applications is also conducted, to provide a reference source for practical applications and new research.

1. Introduction

Structural vibration issues commonly exist in fields such as machinery, aerospace, and civil engineering, which have detrimental effects on mechanical operations and structural responses. For example, chatter instability could be generated during the turning process of cutting tools, leading to inferior machining quality [1]; the engines fixed in the wings of an aircraft tend to produce unsatisfactory structure-borne noise during the running process, resulting in low comfort level during navigation [2]; under dynamic loads, such as wind and earthquake, building structures are prone to engender excessive vibration response, which threats the security of people's lives and properties [3]. To effectively suppress the structural vibrations, over one hundred years ago, the concept of vibration control was first proposed by John Milne, who

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placed a house made of timber on ball bearings to indicate that the structures can be separated from the shaking exerted by an earthquake [4]. Subsequently, Yao [5] applied the modern control theory to civil engineering, which symbolizes the beginning of the research pertaining to the vibration control of civil structures. At the present stage, the structural vibration control technology can be broadly classified into four strategies, namely passive control [6,7], active control [8,9], semi-active control [10,11], and hybrid control [12,13], all of which encompass various energy dissipation devices [14,15]. Specifically, passive energy dissipation devices have been extensively used owing to their good stability, lack external energy supply requirement, simple design, and relatively low cost.

According to the different properties of the stiffness and damping elements, energy dissipation devices can be divided into two categories: linear energy dissipative devices (linear dampers) and nonlinear energy dissipative devices (nonlinear dampers) [16]. Regarding the linear dissipative devices, the tuned mass damper (TMD) and the tuned liquid damper are the most common scenarios, both of which should tune their natural vibration frequencies to the fundamental frequency of the main structure. Based on that principle, the vibration energy can be absorbed by the tuned dampers, and then dissipated by the additional damping elements [17].

Despite the fact that linear dampers have been widely used owing to their simple concept, they are sensitive to the variation in properties of the main structure and the external excitation. Once their natural vibration frequencies shift away from the fundamental frequency of the main structure [18], or the frequency of the external excitation exceeds their effective frequency bandwidth [19], a mistuning effect may occur, leading to poor damping performance or an even worse response. It is worth mentioning that uncertainties in the properties of the main structure commonly exist in civil engineering, which may result from the following aspects: (i) the structure undergoes stiffness degeneration under severe earthquakes, and thus, nonlinear behavior appears; (ii) during design of the building structure, the estimation of structural properties was inaccurate; (iii) during the service life of the structure, structural modifications may be implemented [20]. Although some scholars have adopted the active control technology to address the adverse effect of uncertain structural properties on vibration control [21], wider application of active control devices is restricted owing to their high requirements on the control algorithm, complex configuration, and relatively high cost. Additionally, both wind and earthquake are nonstationary stochastic excitations, and it is inappropriate to conduct the optimal design of linear dampers only under stationary stochastic excitations (such as white noise [22]).

However, nonlinear dampers have been increasingly favored by various engineering fields, especially because of their wide frequency band of vibration attenuation [23,24] and high robustness [25]. According to their different nonlinear characteristics, nonlinear dampers can be classified into three groups, namely nonlinear stiffness dampers, nonlinear damping dampers, and nonlinear-stiffness nonlinear-damping dampers. The nonlinear stiffness dampers mainly include the nonlinear energy sink (NES) [26] and the nonlinear TMD [19,27–29]. The nonlinear damping dampers mainly include the nonlinear viscous damper (NVD) [30–32], the magneto-rheological damper [33,34], the friction damper [35], and the nonlinear displacement-dependent damper [36]. The nonlinear-stiffness nonlinear-damping dampers mainly include the particle impact damper (PID) [37]. By integrating the nonlinear behavior, the damping performance of energy dissipation devices can be enhanced significantly. Taking the nonlinear TMD as an example, and comparing it with the linear TMD, the former has a wider frequency band of vibration attenuation and can effectively reduce vibration with lighter auxiliary mass. Moreover, even under transient vibration with large amplitude, satisfactory damping performance can be achieved [19].

The aim of this paper is to review the state-of-the-art technologies for nonlinear dissipative devices, especially for the nonlinear energy sink, particle impact damper, and nonlinear viscous damper, which belong to the groups of nonlinear stiffness dampers, nonlinear-stiffness nonlinear-damping dampers, and nonlinear damping dampers, respectively. It should be noted that all the three types of nonlinear dampers reviewed in this paper are typically and widely used in practical engineering; among them, the NES and the PID are utilized in numerous engineering fields, whereas the applications of the NVD are mainly concentrated in civil engineering. The basic concepts, research status, engineering applications, and design approaches of the three types of nonlinear dampers are summarized, and their advantages and disadvantages in practical engineering applications are discussed. Thus, this paper may serve as a full reference source for practical applications and new research. Note that this survey paper lays emphasis on nonlinear devices for structural vibration control developed in the last few decades, especially for their design and application in civil engineering. Therefore, the contribution of control theorists from broader research fields in earlier decades is not the key content of this paper.

2. Nonlinear energy sink (NES)

2.1. Basic concept of the nonlinear energy sink

In order to effectively solve structural vibration problems, Frahm [38] first proposed the concept of dynamic vibration absorber, also known as the tuned vibration absorber, which is implemented by attaching a certain additional mass to the main structure with the appropriate spring stiffness. The tuned vibration absorber ameliorates the vibration behavior of the main structure by redistributing vibration energy, that is, the vibration energy is transferred from the main structure to the tuned vibration absorber. Subsequently, Den Hartog [39] introduced the damping elements into the tuned vibration absorber, thus forming the TMD [4,40]. It should be noted that the TMD is a kind of linear damper that has satisfactory damping performance only in a specific frequency range [41], whereas the frequency characteristics of both the external excitation and main structure tend to change with time. Under such circumstances, the TMD may lose damping effectiveness or even