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Frequency intermittency and energy pumping by linear attachments

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ABSTRACT

The present paper considers the problem of realizing an effective targeted energy pumping from a linear oscillator to a set of ungrounded linear resonators attached to it. Theoretical as well as numerical results demonstrate the efficacy of using a complex attachment as a passive absorber of broadband energy injected into the primary structure. The paper unveils also the existence of an instantaneous frequency associated with the master response characterized by intermittency: a rather surprising result for a linear autonomous system. Comparison with nonlinear energy sinks demonstrates that the two systems have some analogies in this respect and that the linear complex attachment is a very efficient energy trap.

1. Introduction

In the past three decades new methods have been invented and employed for vibrations absorption of stationary and transient responses of many types of engineering structures. Conventional vibration absorbers designed for civil structures are generally linear and require the addition of large masses added to the primary structure, which makes these systems of limited interest. Moreover, they are effective over a narrow frequency range, showing poor performance in case of broadband inputs. To mitigate some of these problems, nonlinear techniques have been extensively studied [1–16].

One such method involves the use of a weakly nonlinear vibration absorber, added to the principal structure, which can operate under various types of external excitation [1–6]. Damping in the absorber plays a fundamental role and governs the effective bandwidth of absorption, introducing a tradeoff between attenuation efficiency and bandwidth.

Strongly nonlinear passive absorbers [2–5] have shown to provide better performance than the corresponding linear and weakly nonlinear devices. These include targeted energy pumping into the nonlinear absorber. Energy pumping describes controlled and irreversible transfer of vibrational energy, from a vibrating main structure to a passive, essentially nonlinear, attachment, where it remains trapped and dissipated. The attachment essentially acts as a nonlinear energy sink (NES); a number of papers have shown that a proper design of the absorbing structure permits a nonlinear mode of vibration, which leads to energy pumping [8–10]. Several studies employ NES with cubic stiffness nonlinearity [6,7,11,15] and in some, the mass of the NES is comparable to that of the primary structure [11,15]. Strong nonlinear attachments are effective over a wider range of frequencies than common linear and weakly nonlinear devices [12–14].

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Despite the important advantages of using NES, they are accompanied by certain drawbacks. One relates to systems containing nonlinearities, namely the existence of additional branches of undesired periodic responses, giving rise to high-amplitude excitations of the entire system [51]. There exist certain conditions, i.e. cubic nonlinearity with light quadratic damping, where the vibration induced by the NES may be very high. Another drawback is that energy pumping is activated only above a specific energy value: when the vibratory energy is below a threshold level, NES is not effective [15]. Finally, a small mass for the NES is required for an efficient application to real structures [11,15], while in many examples the mass of the NES is of the same order than the one of the primary.

Research on nonlinear attachments has been focused on finding methods for efficient energy pumping. It is well known that irreversibility, in physical systems with a finite number of degrees of freedom, develops as a consequence of nonlinearities [16,17]. Nonlinearity destroys the periodic motion in linear systems [46], thus the energy remains widely spread among the degrees of freedom and never reorganizes itself to return to its source, giving rise to irreversibility. However, weak nonlinearities are not as effective in producing irreversibility: this result has been empirically confirmed [1–6], and holds in general for Hamiltonian isochronous or non-isochronous systems, as stated by Nekhoroshev's theorem [18,19], or by the complementary and more celebrated Kolmogorov–Arnold–Moser theorem [18,20], respectively. In a nutshell, the theorems show that the motion of a weakly nonlinear system remains very close to that of the corresponding linearized system, without developing irreversibility.

These arguments suggest that irreversibility (i) is a result of particular strong nonlinearities and (ii) does not normally take place in linear systems, because their modal energies are constants of motion. However, the latter notion requires deeper investigations in light of results from a special class of linear systems [21–36,45], which exhibit irreversible energy transfer. A prototypical example of these systems consists of a principal structure, called master, which is a one dimensional resonator, coupled to a large number of parallel resonators, constituting the attachment. The whole system is linear but its special architecture allows a very effective energy pumping, from the principal to the attachment, which acts as a linear energy sink (LES). We refer to the whole system simply as master–attachment, while complex attachment (CoAt) is adopted for the satellite structure.

The energy sharing process in master–attachment systems has been investigated in some detail [21–36], which was, in part, inspired by the fuzzy damping concept introduced by Soize et al. [21]. The prototypical system addressed here relates to many engineering applications with fundamental physical questions. In fact, the schematization of many engineering architectures frequently uses the paradigm of an attachment of a population of resonators to a master system, like in any vehicle analysis where a principal structure, like the car body, the airplane fuselage, or the hull of a ship, are coupled to a very large number of resonating components. The high level of damping experienced in these structures cannot simply be explained by the concept of nonlinear connections. Moreover, many interesting applications of the concept of CoAt can be used for designing novel vibration absorbers [40].

Using a deterministic approach, it has been shown [22–25] that satellite oscillators act as a viscous damper on the master structure, increasing considerably its effective damping. Moreover, the damping induced on the master is independent on the energy dissipation within the attachment. Further, if the number of resonators is high, approaching infinity, even for vanishing values of loss factor in each oscillator the satellite structure acts as a viscous damper on the master. Weaver, in a series of investigations [26,27], generally corroborates these results, providing alternative approaches. In the case of a finite number of resonators, the damping behavior of the attachment holds true only for early times. There exists a return time t^*, after which the energy is returned to the master and the satellite structure stops acting as a viscous damper. On this basis the term apparent damping has been used to describe the complete energy transfer from the master to the attachment which takes place up to the time t^*. Thus, the time behavior of a finite structure is qualitatively different of the one of an infinite structure after t^*. This is consistent with the notion that in linear undamped systems energy transfer from the master to the satellite oscillators is reversible.

A related issue concerns the definition of apparent damping compared to true dissipation. The problem was tackled by several authors: Langley [29], Celik and Akay [30], Strasberg [24] and Maidanik [28]. Particularly, Maidanik showed linear systems require a physical loss mechanism for the energy to be actually dissipated. If the resonators of the attachment have zero loss, as long as their number is finite, no matter how large, the resulting damping is only apparent and no energy is dissipated.

A generalization of the estimate of the return time t^* has been provided by Carcaterra and Akay [31]. They showed that t^* can be modified with the frequency distribution within the set of oscillators, i.e. t^* depends on the number of degrees of freedom N: the higher the N the longer the t^* [31–37,45]. A family of special frequency distributions was shown to be able to trap the energy within a linear attachment very effectively [35,36].

In spite of the rich literature on the subject, there still exist a number of issues related to the use of a CoAt for targeted energy transfer that deserve to be further investigated. The attention, in the early studies, has been mainly focused on the early stage of the energy sharing process. However, in later stages, the motion of the master undergoes a transition, from an almost-periodic to a random-like motion, a process that has not been completely understood. Other important issues that arise from these arguments include whether apparent damping is actually an irreversible phenomenon.

The purpose of this paper is to provide insight into these open questions. In this work we present theoretical and numerical evidences of energy pumping employing LES. The basic phenomenology of a CoAt is introduced in Section 2, where a comparative study with an essentially nonlinear attachment is also provided, in Section 2.1. In Section 3, a theoretical model describing the mechanism behind apparent damping is proposed, which predicts the existence of an