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Activation characteristic of a vibro-impact energy sink and its application to chatter control in turning

T. Li *, D. Qiu, S. Seguy, A. Berlioz

Institut Clément Ader (ICA), CNRS-INSA-ISAE-Mines Albi-UPS, Université de Toulouse, 3 rue Caroline Aigle, 31400 Toulouse, France

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ABSTRACT

The ultimate goal of this paper is to propose a procedure for the optimal design of a Vibro-Impact (VI) Nonlinear Energy Sink (NES) to control the vibration of any possible linear or nonlinear main systems. To this end, the activation characteristic of VI NES at a range of displacement amplitude of a main system is generalized from linear systems to nonlinear systems. It is theoretically proved and experimentally observed that this activation characteristic is almost independent of frequency, which provides direct proof for the effectiveness of VI NES in a broad frequency bandwidth. In terms of vibration control, this feature is very attractive and builds a bridge between linear and nonlinear systems. Then it is applied for the design of VI NES attached to nonlinear systems. In this way, the design of VI NES for a nonlinear system is simplified to the optimal design for a linear system, which is designed to be similar to this target nonlinear system. Because the latter can be analytically calculated, the proposed method is feasible from a quantitative perspective. Finally, this activation characteristic and a proposed design method are applied to control chatter in a turning process, and results prove its feasibility.

1. Introduction

In engineering, clearance is common for structures such as linkage, gear train and joint. Impacts come into being when two objects contact, and can result in energy transfer and dissipation. This phenomenon is applied to vibration control since seventy years ago [1] and an auxiliary device is termed as impact damper. Later, there are extensive studies around impact damper and its dynamics as a typical vibro-impact system [2,3]. The focus here is put on some recent studies since they are tightly related to the work of this paper.

Recently, impact damper is re-examined under the context of Targeted Energy Transfer (TET) [4,5] and called Vibro-Impact (VI) Nonlinear Energy Sink (NES) [6–8]. The main advance comes from the analytical study of underlying Hamiltonian system [9] and the application of multiple scales method [10]. Consequently, special orbits that lead to TET are found from the former, and a Slow Invariant Manifold (SIM) that controls the variation of resonance captures are obtained from the latter. Some following analytical and numerical studies reveal further information about the complicated dynamics of this VI system, especially Strongly Modulated Response (SMR) [11,12] and bifurcation analysis from the perspective of impact time difference [13].

* Corresponding author.
E-mail addresses: tli@insa-toulouse.fr (T. Li), qiu@insa-toulouse.fr (D. Qiu), sebastien.seguy@insa-toulouse.fr (S. Seguy), alain.berlioz@univ-tlse3.fr (A. Berlioz).

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In addition to the explanation of its dynamics, there are also many researches about its characteristic as a damper. In general, two aspects of study results are obtained [8,9], namely activation characteristic and parameter optimization. In terms of activation, VI NES is observed to respond fast at an initial stage when a main system is perturbed, and it is effective in a broad frequency range from the results of frequency spectrum analysis. With respect to parameter design, many suggestions are proposed, for example a medium clearance is better. Around these two aspects, it is found that the impact number per cycle of a main system matters for energy transfer and dissipation [14]. Then, the efficiency of different response regimes with different impact number per cycle is compared in [15], and it is found that the limit between response with permanent two impacts per cycle and that with intermittent two impacts per cycle (SMR) is optimal. Its essence behind is transient resonance captures with two impacts per cycle. This conclusion also holds for a linear system coupled with two VI NES in parallel [16]. In [15], there is another interesting phenomenon, just a range of clearance will be effective for a fixed outside excitation. Equivalently, a fixed clearance will only be effective in a displacement amplitude range of a main system [16].

This feature is very interesting in terms of vibration control and is very special as a NES. In [17], this kind of characteristic is also tried to be designed for a nonlinear vibration absorber but in a general way. Its basic philosophy of design can be reflected by the response regime with two impacts per cycle of systems coupled with VI NES.

Whether this effective activation of VI NES only depends on the displacement amplitude and has nothing to do with frequency? If the answer is positive, it could be applied as a design criterion for VI NES to control the vibration of nonlinear systems at some displacement levels. Its benefit is evident since it maybe impossible to get reliable results from analytical studies of nonlinear systems coupled with VI NES, and the above-mentioned idea may provide a feasible solution.

The difficulty of the application of NES to control vibration is already observed. For example, VI NES is attached to a cutting tool to quench its chatter in [18]. Experimental results demonstrate that an appropriately designed VI NES can effectively reduce the vibration of a cutting tool. However, its analytical development is based on a simplified equation and still has a distance to predict real responses, which is the same case for a turning system coupled with a cubic NES [19]. The problem is the same for a helicopter [20,21]. Considering the difficulty of analytical study for any nonlinear systems coupled with VI NES, the possibility to apply its activation characteristic and to simplify its design for nonlinear systems will be explored.

The paper is organized as follows. In Section 2, a theoretical analysis for the activation characteristic of VI NES is presented. In Section 3 and Section 4, this activation characteristic is validated by numerical and experimental results from different linear and nonlinear main systems, respectively. In Section 5, a design procedure of VI NES is proposed and applied to control chatter in turning. Finally, conclusion is addressed.

2. Analytical treatment

In essence, the analytical development here is similar to that of former studies [10,11,14], but some important information of SIM is neglected and will be further analyzed.

2.1. Analytical formulation

A LO under periodic excitation and coupled with a VI NES is showed in Fig. 1. Its motion between impacts is described by the following equation:

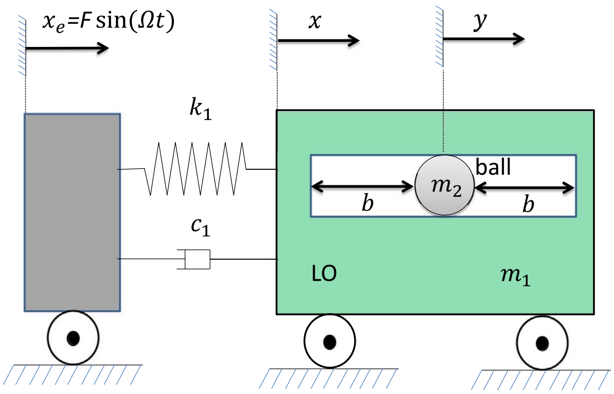

Fig. 1. Schema of a LO coupled with a VI NES under periodic excitation.