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Steady state dynamics and robustness of a harmonically excited essentially nonlinear oscillator coupled with a two-DOF nonlinear energy sink

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ABSTRACT

Steady state dynamical behavior of two degrees of freedom (DOF) system composed of a harmonically excited nonlinear oscillator coupled with a single DOF nonlinear energy sink (NES) is studied in comparison with the behavior of a system consisting of a nonlinear oscillator coupled with a two-DOF NES subjected to external harmonic excitation. First, an optimized set of parameters was obtained using optimization for the two-DOF system. Results show that the system with one NES has low robustness to the changes of the parameters and external force. By adding a degree of freedom to the first system, the steady state behavior of the resulting three-DOF system was investigated. Conclusions illustrated that increasing the degrees of freedom of the NES would increase the robustness of the system to the changes in system parameters and amplitude of external force.

1. Introduction

There are remarkable efforts in order to dissipate the vibration energy of mechanical systems. Due to impressive advances in techniques of nonlinear vibration analysis, these efforts have increased in recent decades. Vibration isolation and control is one of the most important fields of engineering studies, which aims to prevent transmission of undesirable vibration of host structure to adjacent systems, or to eliminate or decline the surplus vibration in the main system in order to avoid the likely damages. Elimination, decline, or isolation of oscillations is the main problem of various industrial and non-industrial practices. For instance, in mechanical systems, buildings, vibrating machinery, shipping packages, domestic applications, and in suspension systems of vehicles, vibration isolation is of particular importance.

Recent studies have shown that various oscillating systems composed of linear and/or nonlinear oscillators with linear and/or nonlinear attachments can transmit the energy in a unidirectional irreversible way [1–10]. Gendelman investigated [1] the redistribution of energy in free vibrations of a two-DOF asymmetric system consisting of coupled linear and nonlinear oscillator. Free vibrations of two and three-DOF systems of weakly coupled linear and nonlinear oscillators were studied in Ref. [2] in order to illustrate the one-way energy transfer between oscillators. Vakakis and Gendelman demonstrated that energy pumping between oscillators of systems described in Ref. [2] is due to transient resonance capture on a 1:1 resonance manifold of the system, [3]. Manevitch [4] described localized normal modes of an asymmetric system of nonlinear oscillators and a chain of nonlinear oscillators. McFarland et al. [5] performed experimental studies that

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verified the passive nonlinear energy pumping in transient dynamics of free oscillations of a two-DOF system consisting of coupled linear and essentially nonlinear oscillators. Their results confirmed the existence of the nonlinear energy transfer, which occurs at a single fast frequency. Gendelman et al. [6] studied the transition dynamics of free vibrations of a system comprising weakly coupled linear subsystem with an essentially nonlinear attachment. They concluded that energy transfer could be observed for a two-DOF system with essential mass asymmetry. Viguié et al. [7] studied the dynamic response of drill-string systems under the effect of an attached nonlinear energy sink. They showed how nonlinear passive targeted energy transfer to a lightweight attachment could be used to stabilize such systems. Viguié et al. investigated the transition dynamical behavior of a two-DOF nonlinear system consisting of a grounded Duffing oscillator coupled with an essentially nonlinear attachment [8]. Gendelman and Bar [9] examined the dynamical regimes of self-excitation in free vibration of a Van der Pol oscillator coupled with a nonlinear energy sink. Starosvetsky and Gendelman [10] developed the strategy of elimination of the undesired periodic regimes in a two-DOF system consisting of a harmonically excited linear subsystem coupled with a nonlinear energy sink (NES) with nonlinear damping. Jiang et al. [11] studied the steady state dynamical behavior of a two-DOF system of a harmonically excited linear oscillator coupled to an NES.

Energy transfer in a two-DOF system composed of a linear or nonlinear oscillator and an attachment has been widely investigated which most of them analyzed the transient response of free vibration [1–6] and some others have studied steady state response of forced vibration [10–16]. There have also been various studies about energy pumping between multi degrees of freedom (MDOF) systems coupled to a single-DOF linear or nonlinear attachment. Gendelman et al. [12] carried out a theoretical and experimental investigation of the effect of a nonlinear energy sink (NES) with relatively small mass on the dynamics of a periodically excited system. In Ref. [13], Malatkar and Nayfeh examined steady state response of a harmonically excited linear oscillator coupled with an NES, a system that previously was studied by Jiang et al. [11]. Refs. [14,15] are devoted to detailed investigation of dynamical behavior of a linear oscillator coupled with an NES under harmonic excitation. Carcaterra et al. [16] presented a novel mechanism of vibration dissipation and its application for aerospace structures. They investigated the dynamics of continuous systems coupled with nonlinear energy sink subjected to aerodynamic forces. A semi-finite symmetric linear chain of oscillators with a linear or nonlinear attachment at the end was studied in Refs. [17–20].

With analyzing a system of a harmonically excited linear oscillator coupled with a nonlinear energy sink (NES), Jiang et al. [11] found that in contrast to the classical linear vibration absorber, the NES is capable of absorbing steady state vibration energy from the linear oscillator over a relatively broad frequency range. Malatkar and Nayfeh [13] presented a theoretical study of the dynamics of the coupled system of Jiang et al. and stated some rather different points about behavior and efficiency of such a system in their paper. They demonstrated that there is a lot of noticeable dynamics over an extensive frequency range: cyclic fold, Hopf, symmetry-breaking, and period-doubling bifurcations; phase-locked motions; regions with multiple coexisting solutions; hysteresis; and chaos.

Single degree of freedom (SDOF) NES can work more efficiently as vibration isolator than linear tuned mass dampers, which are narrowband devices [21]. In addition, due to their essential stiffness nonlinearity, the NES can operate over broad frequency ranges, acting, in essence, as passive adaptive boundary controllers [22]. However, the single degree of freedom NES is efficient just in comparatively narrows ranges of external forcing amplitudes [22]. Therefore, using MDOF NESs is suggested in order to achieve relatively broadband efficiency of targeted energy transfer (TET) [23,24,25]. Tsakirtzis et al. [23] investigated the dynamics of forced vibrations of a two-DOF liner system coupled with a multi-DOF NES in their study. They found that considerable energy exchange could occur in such a system. Gourdon and Lamarque [24] also studied the transient response of a single-DOF linear oscillator attached to essentially nonlinear multi-DOF attachment. Tsakirtzis et al [25] also studied multi-frequency energy exchange from a linear oscillator to a multi-DOF NES.

Previous studies have often examined the energy transfer phenomenon from a SDOF or multi-DOF linear oscillator to a single-DOF or multi-DOF linear or nonlinear attachment. Few studies have been done on the energy transfer from nonlinear oscillator, subjected to an external force, coupled with a nonlinear attachment. Viguié [26] studied dynamical behavior of an essentially nonlinear oscillator attached to a nonlinear energy sink. He proposed a tuning methodology for obtaining an appropriate set of parameters for maximum rate of energy transfer. Habib et al. [27] studied the mitigation of a nonlinear resonance in a mechanical system. They introduced the nonlinear tuned vibration absorber, which has a broader bandwidth with respect to the classical linear absorbers. Ji [28] investigated the dynamics of a single-DOF weakly nonlinear oscillator coupled with a weakly nonlinear energy sink in order to design a nonlinear vibration absorber using three-to-one internal resonances.

Investigations conducted by Malatkar and Nayfeh [13] on the work done by Jiang et al. [11] showed that there some dynamical behaviors which have not been studied by Jiang et al. [11]. Therefore, robustness of the absorber designed for the system studied by Jiang et al. [11] is not complete. In the present study, it is illustrated that with addition of the number of NES the robustness of the steady state response of a harmonically excited nonlinear system increases.

From this review, the main purpose of this study is established as the increasing the robustness of a harmonically excited SDOF nonlinear oscillator coupled with a two-DOF NES. Change in the robustness of the system with increasing the NES's degree of freedom is examined here. This work aims to investigate the steady state response of a harmonically excited essential nonlinear oscillator coupled with a two-DOF NES. In addition, the effect of additional degrees of freedom on the robustness of the system to the changes of the system parameters and external force is examined. In the first part, steady state dynamical behavior of a two-DOF system of a nonlinear oscillator coupled with a nonlinear energy sink under external harmonic excitation is investigated in order to obtain an appropriate set of tuned parameters. For this purpose, a modified