



Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsv

Application of lumped-mass vibration absorber on the vibration reduction of a nonlinear beam-spring-mass system with internal resonances

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ARTICLE INFO

Article history:

Received 10 September 2014

Received in revised form

31 March 2015

Accepted 2 April 2015

Handling Editor: H. Ouyang

ABSTRACT

The objective of this study was to optimize the damping effects of a lumped-mass vibration absorber (LMVA) attached to a hinged–hinged nonlinear beam held on a nonlinear elastic foundation. The LMVA was located at various points along the beam and supported by a spring from beneath. Analysis was performed on the internal resonance conditions with the aim of eliminating internal resonance and reducing the amplitude of vibrations in the beam by altering the location and mass of the LMVA as well as the spring constant. We employed the method of multiple scales (MOMS) for the analysis of frequency response in various modes. Fixed points plots were constructed and 3D maximum amplitude contour plots (3D MACPs) were compiled to identify the LMVA combinations with the optimal damping effects. The best damping results in the 3rd mode were achieved when the LMVA was placed between $1/4l$ and $1/2l$ in combinations of $\hat{M}$ (mass of LMVA/mass of beam) and $\hat{K}$ (LMVA spring constant/elastic foundation spring constant) followed a linear relationship of $\hat{K} = 10\hat{M}$.

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1. Introduction

Vibration is a problem in nearly every device from small machine components to bridges and aircraft wings. Beams are used in a wide range of engineering problems and the internal resonance of nonlinear beam vibrations is a popular topic of research. Eftekhari et al. [1] investigated the performance of a mass-spring oscillator at the tip of a symmetrically cantilevered composite beam under chordwise base excitation. They selected oscillation parameters and the corresponding natural frequencies to produce 2:1 and 1:1 internal resonance conditions. Saturation was detected in the force modulation response at 1:1 internal resonance. Rossikhin and Shitikova [2] also examined nonlinear vibration in a suspension bridge with internal resonances of 2:1 and 1:1. They then verified the results of qualitative hydrodynamic analysis using a case study of the Golden Gate Bridge in San Francisco. Palmeri and Adhikari [3] considered a double-beam system comprising two beams connected continuously by a Winkler type inner layer. Transverse vibration in this beam system was studied using a state-space approach and the numerical results demonstrated its accuracy and versatility. van Horsen and Boertjens [4,5] investigated a suspension bridge subjected to nonlinear aerodynamics using linear springs for the simulation of suspension cables. They proposed a brilliant mathematical analysis method that has contributed substantially to subsequent research on complex fluid–structure coupled systems.

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Zhang and Li [6] investigated the bifurcations and chaotic dynamics of a 2dof nonlinear vibration absorber. Many nonlinear phenomenon of the nonlinear dynamic vibration absorber (DVA) were studied analytically and numerically. Jiang et al. [7] found that the nonlinear energy sink (NES) is capable of absorbing steady-state vibration energy from the linear oscillator over a relatively broad frequency range. The cubic nonlinear stiffness was considered in their NES system. Another approach to damping involves adjusting the location of DVAs or using tuned mass dampers (TMDs) to achieve vibration reduction, rather than changing the configuration of the damper. Wang and Chen [8] used TMDs to absorb the vibrations in rotating mechanical devices (such as CD-ROM drives). Wang and Lin [9] utilized analytical as well as numerical methods to determine the influence of dampers on the stability of systems with nonlinear fluid–solid interactions. Their approach combined internal resonance contour plots (IRCPs) and flutter speed contour plots (FSCPs), to display the integrity and accuracy of overall considerations. Wang and Hung [10] investigated the effects of a pendulum tuned mass damper (PTMD) on the vibration of a slender two-dimensional rigid body with internal resonance of 1:2. Their focus was on the damping effects of various parameters of the PTMD in the prevention of internal resonance. 3D-IRCP was first proposed to evaluate the effectiveness of various parameter combinations of PTMD prior to the design process.

Nayfeh and Mook [11] proposed a number of approaches commonly used in deriving analytical solutions to nonlinear problems, such as the Poincaré method, the Lindstedt method, the average method, and method of multiple scales (MOMS). The suitability of MOMS for damped vibrating systems has led to its adoption in numerous areas. Sedighi et al. [12] studied the nonlinear vibration of cantilever beams under preloaded nonlinear cubic spring boundary conditions. The He Parameter Expanding Method (HPEM) was used to obtain solutions specifically for that dynamic behavior. They demonstrated that series expansions with one term are sufficient to obtain an accurate solution. Wang and Chang [13] employed MOMS to determine the influence of a DVA on the free end of a linear hinged-free beam in which an elastic foundation and suspension cables were simulated using nonlinear cubic springs. They identified a combination of optimal mass and elastic modulus in the DVA capable of reducing vibrations in the beam and through a reduction in internal resonance.

Similar topics involving beams on elastic foundations have been studied in civil, mechanical, and aerospace engineering. Mundrey [14] applied this beam–foundation system to the design of railway tracks. Fu et al. [15] studied nonlinear vibrations in carbon nanotubes (CNTs), adding the stretching effect to a Bernoulli–Euler beam for the simulation of vibrating behavior in CNTs placed on an elastic matrix. Shen [16] analyzed the vibrating behavior of a postbuckling nonlinear Bernoulli–Euler beam placed on a double-layer elastic foundation. Other researchers have proven that the stiffness of the elastic foundation significantly influences the vibrating behavior of nonlinear beams. Pakdemirli and Nayfeh [17] examined a beam–spring–mass model, comprising a lumped mass on a beam supported by a nonlinear spring attached in various locations. They determined that the stretching effects of the beam had a significant effect on the frequency response of the system. Extending this concept in Ref. [17], Özkaya et al. [18] analyzed the influence of placing lumped masses on beams (without a spring support beneath the beam), preferring to focus on how the location of the lumped mass influences vibration within the beam. Özkaya [19] applied several identical lumped masses to an elastic beam and analyzed the relationships between the quantity and mass of the dampers and the frequency response of the system. The examination of nonlinear elastic beams with multiple support points by Bağdatlı et al. [20] inspired us to analyze the influence of mass–springs on internal resonance and vibration in nonlinear beams. Hereafter, we refer to this system as a beam–spring–mass system (bsms) and the spring beneath as a lumped mass vibration absorber (LMVA). In general, the idea of LMVA can be applied on the vibration reduction of any slender beam-like structures resting on elastic foundations, for example, railway tracks or pinned–pinned CNTs placed on elastic matrices [14–16]. The device of LMVA can also be installed between anchor points of the submarine cables or offshore pipelines placed on seabed to avoid internal resonance or other vibrations due to external loads.

This study used a nonlinear spring to simulate the elastic foundation under a hinged–hinged beam. A lumped mass was placed at various locations along the beam and supported by a spring from beneath. The objective of this study was to determine how the mass and location of the LMVA and the ratio between the spring constants of the spring supporting the lumped mass and the spring in the elastic foundation beneath the beam influence the propagation of vibration in the beam. We adopted the method of multiple scales (MOMS) to solve this problem and compiled fixed point plots to observe the frequency responses and determine the influence of various factors on vibrations in the main body. To deal with the complexity of the data, we used 3D maximum amplitude contour plots (3D MACPs) to identify the optimal locations for the placement of LMVA with regard to its effects on damping. Numerical simulation was used to ensure the accuracy of our results and confirm the feasibility of these methods in practical applications.

2. Development and analysis of theoretical model

2.1. Development of BSMS model

This study considered a hinged–hinged nonlinear beam–spring mass system (BSMS), the coordinate system and boundary conditions of which are presented in Fig. 1, where m denotes the mass of the elastic beam per unit length; A , E , and I_A are the cross-section area, Young's modulus, and moment of inertia of the beam, respectively; k is the liner spring constant of the elastic foundation; β signifies the nonlinear spring constant; $\bar{\mu}$ is the damping coefficient; $\hat{m}$ is the mass of the lumped mass, and $\hat{k}$ denotes the spring constant of the spring supporting the lumped mass. According to the location of the lumped mass, we denote the deformation on the left side of the beam in the transverse and longitudinal directions as

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