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Forced vibration control of an axially moving beam with an attached nonlinear energy sink

Ye-Wei Zhang[a,*], Shuai Hou[a], Ke-Fan Xu[a], Tian-Zhi Yang[a], Li-Qun Chen[b,c]

[a] Department of Astronautics, Shenyang Aerospace University, Shenyang 110136, China
[b] Shanghai Institute of Applied Mathematics and Mechanics, Shanghai University, Shanghai 200072, China
[c] Department of Mechanics, Shanghai University, Shanghai 200444, China

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ABSTRACT

This paper investigates a highly efficient and promising control method for forced vibration control of an axially moving beam with an attached nonlinear energy sink (NES). Because of the axial velocity, external force and external excitation frequency, the beam undergoes a high-amplitude vibration. The Galerkin method is applied to discretize the dynamic equations of the beam–NES system. The steady-state responses of the beams with an attached NES and with nothing attached are acquired by numerical simulation. Furthermore, the fast Fourier transform (FFT) is applied to get the amplitude–frequency responses. From the perspective of frequency domain analysis, it is explained that the NES has little effect on the natural frequency of the beam. Results confirm that NES has a great potential to control the excessive vibration.

1. Introduction

Axial speed widely exists in vehicles, aircraft and other engineering fields, many models are simplified as the moving beam. However, owing to the external force, high amplitude of vibration often appears in the beam system. Furthermore, the structure is likely to be damaged and even collapses if the external excitation frequency approaches the first few natural frequencies.

In order to analyze the excessive vibration caused by axial speed, various researchers have analyzed the vibration characteristics. The deliberate survey on nonlinear vibration of an elastic beam subjected to tension in supercritical transport velocity ranges was studied by Wickert [1]. For a longitudinally moving plate, the Rayleigh–Ritz method was applied to analyze the vibration under the condition of being immersed in an infinite liquid by Wang and Zu [2]. The transverse vibration of various axial speeds was analyzed using the multi-scale method by Chen and Yang [3]. The nonlinear dynamic behaviors of longitudinally traveling plates and axially moving plates were studied by Wang et al. [4,5]. For the coupled longitudinal–transverse vibrations of an axially accelerating beam, the impact of mean axial speed was investigated by Ghayesh et al. [6]. A dynamic model of the translating belt spans considering transverse vibration was studied by Ding and Zu [7]. The linear and nonlinear vibration characteristics of an axially moving plate coupled with fluid were studied by Wang et al. [8]. As high amplitude of vibration will damage the structure, plenty of researchers have investigated a variety of methods to control excessive vibration of a moving beam, among which the boundary control method, feedback control method and active and passive control method have been presented to stabilize the beam system [9–11].

The nonlinear dynamic characteristics of a forced moving beam in the sub-critical axial speed regime were investigated by Ghayesh and Amabili [12]. Theoretical and experimental

* Corresponding author.
E-mail address: zhangyewei1218@126.com (Y.-W. Zhang).

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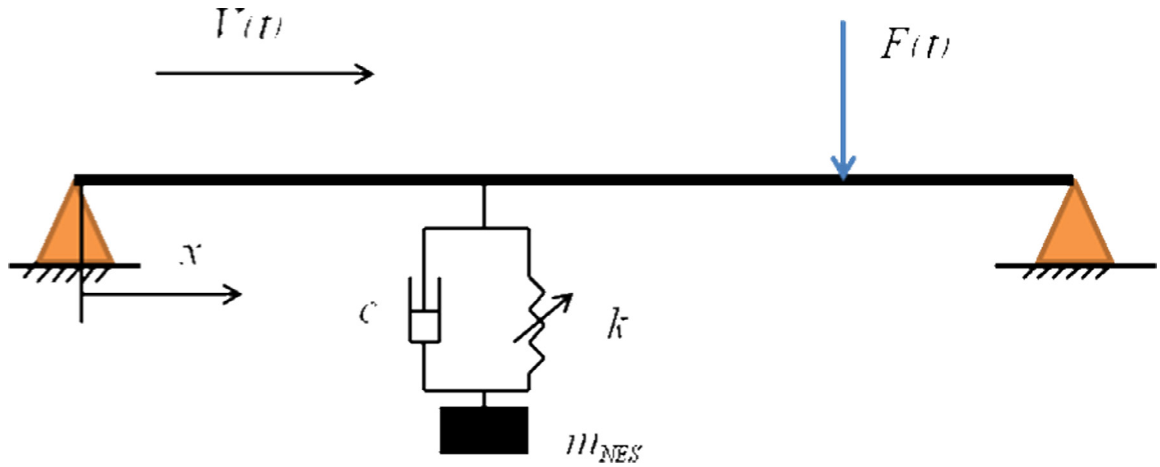

Fig. 1 – The moving beam and NES system.

methods for a forced moving beam were applied to the analysis of nonlinear vibration by Yuh and Young [13]. The axially moving viscoelastic beam model was established to analyze the nonlinear pulley–belt systems with one-way clutches by Ding and Zu [14]. The coupled longitudinal–transverse nonlinear vibration for a moving beam with a spring-support subjected to a harmonic external force was studied by Ghayesh et al. [15]. The periodic nonlinear vibration of a moving beam with periodic lateral forces was analyzed using the incremental harmonic balance theory by Huang et al. [16]. Coupled longitudinal and transverse displacements of a moving beam under a special internal resonance condition were studied by Ghayesh et al. [17].

In order to control the excessive transverse vibration caused by external force, active control methods were used to design the controller by some researchers. However, active control methods need much more equipment than passive control methods do. Fortunately, a wideband, highly efficient and well-designed nonlinear energy sink (NES) was proposed to suppress excessive vibration, consisting of a nonlinear spring with cubic stiffness, a viscous damper and a small mass [18–20]. Lots of researchers have studied how to change the NES performances to expend vibration energy [21,22]. The NES for a widely applicable scope of targeted energy transfer was investigated by Vakakis et al. [23]. The galloping amplitude was efficiently reduced by attaching a NES [24].

The nonlinear energy sink has a small additional mass and a broad frequency response. The frequency of NES depends on the amplitude and the NES has a strong damping effect on high-amplitude vibrations. The NES used as passive vibration isolation equipment to control the vibration of a nonlinear elastic string under internal resonance was extended by Luongo and Zulli [25]. The NES attached to a moving string subjected to transverse wind loadings to control the excessive vibration was studied by Zhang et al. [26]. A highly efficient vibration isolation effect was confirmed in the application of a pipe of the NES by Yang et al. [27]. A passive controller called NES was used to elastic strings excited by external harmonic forces under the condition of internal resonance by Angelo and Daniele [28]. Numerical method was applied to the beam–NES system by Georgiades and Vakakis [29], which proved that shock energy transferred apace and efficiently from the beam to the NES. Characteristics of energy transferring from nonlinear beam to NES system was investigated by Kani et al. [30]. A study on vibration control of the beam under the condition of thermal shock using a NES with proven effectiveness was completed by Zhang et al. [31]. Numerical simulations were applied to obtain the effectiveness of NES for vibration control, and good results were obtained [26,27,31].

In the previous studies, a forced axially moving beam with an attached NES has rarely been noted. Thus, in this paper, forced vibration control for a moving beam with an attached NES is investigated as a new topic. In addition, the fast Fourier transform (FFT) is applied to obtain the frequency responses. The equations for the axially moving beam with an attached NES are approximated using the Galerkin method. Appropriate NES parameters are chosen to control the vibration of initial system. Results of the steady-state responses and amplitude–frequency responses obtained by numerical algorithm with and without NES under the external force show that the NES has a great capacity to reduce the amplitude of the beam rapidly and efficiently.

2. Control equations of beam and NES

Fig. 1 shows that the system is made up of an axially moving beam which is simply-supported, and an attached NES. The vibration of the continuous system is controlled by the NES which consists of a mass, damping and a nonlinear (cubic) stiffness.

The axial speed is V, and beam length is L. Newton's second law is used to obtain the governing equation of motion of the beam–NES system.

$$\begin{aligned}
&\rho A\left(\frac{\partial^2 U(X,T)}{\partial T^2}+2V\frac{\partial^2 U(X,T)}{\partial X\partial T}+V^2\frac{\partial^2 U(X,T)}{\partial X^2}\right)\\
&-P\frac{\partial^2 U(X,T)}{\partial X^2}+EI\frac{\partial^4 U(X,T)}{\partial X^4}\\
&+\eta I\frac{\partial^5 U(X,T)}{\partial X^4\partial T}-\left(K[Y(T)-Z(T)]^3+\xi\left(\frac{\partial Y(T)}{\partial T}-\frac{\partial Z(T)}{\partial T}\right)\right)\delta(X-d)\\
&=B\cos(\Omega t) \qquad (1)
\end{aligned}$$