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Research paper

Controllable parametric excitation effect on linear and nonlinear vibrational resonances in the dynamics of a buckled beam

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ABSTRACT

In this study, the effect of a controllable parametric excitation on both linear and nonlinear vibrational resonances on the dynamic of a buckled beam excited by a combination of uncontrollable low- and high-frequency periodic forces are investigated. First of all, the beam dynamic is assumed to be constrained by two periodic and independent ambient solicitations, such as wind and earthquake. An axial load of the beam represented by a periodic and parametric excitation is used to control the vibrational resonance phenomenon, induced by the presence of the two external excitations. Approximate analytical expressions for the linear response and the high-frequency force amplitude at which linear vibrational resonance occurs are obtained. An analytical expression of the amplitude of the nonlinear response at the superharmonic equal to the double of the low-frequency, is obtained. For all these expressions, we show the effect of the parametric excitation. We compare all the obtained results with the ones of the case where, the parametric force is absent. It is shown that, the presence of the parametric excitation permit the suppression of both linear and nonlinear vibrational resonances. Moreover, the vibration amplitudes of the buckled beam are significantly reduced, around certain threshold values for the amplitude and the frequency of the parametric excitation.

1. Introduction

Vibration control received considerable attentions from scientific and engineering communities [1–21]. Various methods to hold back undesirable level vibrations such as active control [1–5], passive control [6–8] and semi-active control [9–11] have been investigated. These methods have been applied in numerous fields such as economic [12–14], biology [15], communication [16] and vibration of structures in civil engineering such as beams [17–21].

Beams are nowadays very important structures at the point where several theories and applications have been developed for their study [17,19]. They are used in various architectures of civil engineering such as bridges, roads, buildings and sporting infrastructures [20,21]. During their usage, beams are generally constrained by various uncontrollable excitations which can be regular or random such as wind, impacts, variation of ambient temperature, earthquakes [11,21]. These uncontrollable excitations can induce unacceptable motions of beams. Leonard Euler, Jacques Bernoulli and Daniel Bernoulli

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developed a theoretical framework that allows the study of beam vibrations submitted to external solicitations [22–24]. Since these pioneering studies, several others have been conducted in this research field in order to analyze the influence of the ambient solicitations, on the nonlinear dynamics of beams [25–29]. To illustrate, the effect of impacts [25], electromagnetic actuation [26], on the dynamics of beams have been studied. Nonlinear resonances [27,28] and, chaotic vibration of beams subjected to external periodic excitations have been studied [29]. The analysis of the dynamics of macroscopic beam have been applied to buckled nanobeams [30]. The use of the unpleasant motions of beams for the energy harvesting concept have motivated scientists [31,32]. In the present paper, we are not only interested in the effect of various external excitations on the dynamics of beams, but also to the control of their vibrations. A buckled beam stimulated by a combination of low and high-frequency which can be practically represented by wind [11], earthquake [18] respectively; both are controlled by an axial load on the structure acting as a parametric control of the excitations.

It is noteworthy to be mentioned that an introduction of parametric excitation on the beam dynamics is very risky, because it can also contribute to produce additive bad effects, such as parametric resonances [33,34] and chaos [20,21]. Nevertheless, the use of parametric forces for the suppression of beam vibrations under the effect of external excitation have been explored [28,35–37]. The suppression of self-excited vibration have been done using a parametric excitation [35,36]. The use of the parametric anti-resonance for the suppression of beam vibration have been done [28]. Parametric excitations have been also used as a damping tool in order to suppress obnoxious vibrations [37]. According to the best of our knowledge, the use of the parametric force for the suppression of vibration of beam, in the particular case of a combination of external periodic excitations of different frequency scales is yet to be investigated. The presence of this special type of excitation under a biharmonic form, the occurrence vibrational resonance phenomenon is expected [38–41]. Moreover, in certain systems, such as beams, where a perfect stability is needed, one of the disagreeable phenomena is vibrational resonance, because of the amplification of vibration around its occurrence [38,42].

Vibrational resonance is a nonlinear phenomenon named for the first time by Landa and McClintock in the year 2000 [39], and theoretically analysed for the first time in ref. [40]. In recent years, vibrational resonance have been analysed in various systems of different fields [41–51]. To illustrate, vibrational resonance in neuronal systems [41], signal transmission [43], ecological systems [44], and signal-to-noise ratio in optical systems [45] have been studied. The enhancement/reduction of vibrational resonance amplitude in nonlinear systems with fractional-order damping [46,47] and fractional-order derivative [42] have been studied. The extension of the analysis of vibrational resonance to the nonlinear vibrational resonance [48,51], vibrational higher-order resonances [49] and both subharmonic and superharmonic vibrational resonances [50] in Duffing systems and overdamped systems have been done. Thus, in one hand, vibrational resonance is a favorable phenomenon, for systems where the augmentation of the response amplitude ameliorate their performances. In another hand, vibrational resonance is a disadvantageous phenomenon, for the systems where lower amplitude of vibrations are needed. Therefore, in this second case, it is very necessary to develop more theories for the reduction or suppression of vibrational resonance occurrence.

The study of suppression or the control of vibrational resonance with time-delayed feedback [52–57] and noise [58] have been conducted. In this investigation, a buckled beam exhibiting the vibrational resonance phenomenon that we want to suppress with a parametric excitation, of controllable amplitude and frequency is considered. According to the best of our knowledge, the suppression or the control of vibrational resonance by using a parametric force have not yet investigated in literature. The paper is organized as follows. Section 2 is devoted to the modeling of the physical system, where the apparition of the parametric excitation is shown. Section 3 presents the extension of the classical theoretical analysis for linear and nonlinear vibrational resonances, where the theoretical expressions for response amplitude and the critical values of amplitude of parametric force for which resonances occur are obtained. In Section 4, a numerical study is made in order to confirm the theoretical predictions. In this section, the effect of the parametric excitation on the suppression of linear and nonlinear vibrational resonances is shown. The fifth section is reserved to the discussions and we end with the conclusion in Section 6.

2. Analytical model

We consider a buckled beam of length L, a cross-section A, a mass per unit of length ρ, a damping coefficient δ, an inertia momentum I and Young modulus E. A scheme of this beam is given in Fig. 1. In absence of the axial force $P(T)$, by using the same approach as in [38], the equation of the motion of this beam is given by:

$$\rho A\frac{\partial^2 W}{\partial T^2}+\delta\frac{\partial W}{\partial T}+EI\frac{\partial^4 W}{\partial y^4}-\frac{EA}{2L}\frac{\partial^2 W}{\partial y^2}\times\left(\int_0^L\left(\frac{\partial W}{\partial y}\right)^2 dy\right)=S(T) \tag{1}$$

where W is the instantaneous transversal deflection of the beam. In presence of the controllable axial load $P(T)$, Eq. (1) becomes [21]:

$$\rho A\frac{\partial^2 W}{\partial T^2}+\delta\frac{\partial W}{\partial T}+EI\frac{\partial^4 W}{\partial y^4}-\frac{EA}{2L}\frac{\partial^2 W}{\partial y^2}\times\left(\int_0^L\left(\frac{\partial W}{\partial y}\right)^2 dy\right)+P(T)\frac{\partial^2 W}{\partial y^2}=S(T) \tag{2}$$