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Nonlinear analysis for dual-frequency concurrent energy harvesting

Zhimiao Yan [a,*], Hong Lei [a], Ting Tan [a], Weipeng Sun [b], Wenhu Huang [a]

[a] *School of Astronautics, Harbin Institute of Technology, Harbin 150001, China*
[b] *Institute of Water Resources and Hydro-electric Engineering, Xi'an University of Technology, Xi'an 710048, China*

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ABSTRACT

The dual-frequency responses of the hybrid energy harvester undergoing the base excitation and galloping were analyzed numerically. In this work, an approximate dual-frequency analytical method is proposed for the nonlinear analysis of such a system. To obtain the approximate analytical solutions of the full coupled distributed-parameter model, the forcing interactions is first neglected. Then, the electromechanical decoupled governing equation is developed using the equivalent structure method. The hybrid mechanical response is finally separated to be the self-excited and forced responses for deriving the analytical solutions, which are confirmed by the numerical simulations of the full coupled model. The forced response has great impacts on the self-excited response. The boundary of Hopf bifurcation is analytically determined by the onset wind speed to galloping, which is linearly increased by the electrical damping. Quenching phenomenon appears when the increasing base excitation suppresses the galloping. The theoretical quenching boundary depends on the forced mode velocity. The quenching region increases with the base acceleration and electrical damping, but decreases with the wind speed. Superior to the base-excitation-alone case, the existence of the aerodynamic force protects the hybrid energy harvester at resonance from damages caused by the excessive large displacement. From the view of the harvested power, the hybrid system surpasses the base-excitation-alone system or the galloping-alone system. This study advances our knowledge on intrinsic nonlinear dynamics of the dual-frequency energy harvesting system by taking advantage of the analytical solutions.

1. Introduction

Low-level power harvesting from ambient vibrations is developed in the last two decades for micro-electro-mechanical systems [1], wireless sensor networks [2,3], civil embedded monitors [4], wearable [5] and implanted devices [6]. As an alternative of conventional small batteries, energy harvesting technology avoids periodic disposal of the power supplier, reduces the maintaining cost and benefits the miniaturization of such devices [7–9]. The direct piezoelectric effect is one of the mechanisms to transform the unused vibrational energy into the electrical energy. The primary merit of the piezoelectric energy harvesting is that it has large electromechanical coupling factor and outputs high voltages [7].

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[*] Corresponding author.
E-mail address: zhimiaoy@hit.edu.cn (Z. Yan).

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A variety of vibration types, including forced and self-excited oscillations, were investigated for piezoelectric energy harvesting [10–16]. Galloping is one self-excited aeroelastic instability phenomenon, which results in relatively large vibrational amplitude with low oscillatory frequency at low wind speed. As such, it has become a research focus for low-frequency piezoelectric energy harvesting from the environmental wind energy in recent years. Barrero-Gil et al. [16] theoretically investigated the potential of harvesting energy from transverse galloping using a single degree of freedom model with quasi-steady hypothesis. Sirohi and Mahadik [17] designed a galloping-based energy harvester with triangular cross section for wireless sensor nodes. The proposed numerical model showed good correlation with their experimental measurements. Using Euler–Bernoulli beam theory, an electromechanical coupled distributed parameter model was developed by Abdelkefi et al. [18] for galloping energy harvesters and confirmed by wind tunnel experimental data [17]. In practical applications, galloping piezoelectric energy harvesters are often installed on the structures where the base excitations may present. The concept of harvesting energy from ambient and galloping vibrations was proposed by Yan et al. [19]. An electromechanical coupled nonlinear distributed-parameter model was derived. The direct numerical results indicated that the response of the hybrid harvester contained two harmonic frequencies when the base-excitation frequency was away from the global natural frequency of the harvester. As the external frequency comes close to the global frequency, quenching phenomenon appears. Nonlinear properties of the system were later characterized numerically by phase portraits, power spectra, and Poincaré sections [20]. Due to the limitation of the numerical approach, it is very difficult to find out the physical causes behind the noticed nonlinear phenomena.

For near resonance responses of the hybrid energy harvester, Bibo and Daqaq [21] proposed analytical solutions using a nondimensional lumped-parameter model with the method of multiple scales. The wind speed, base excitation amplitude and excitation frequency were found to have great impacts on the total harvested power near resonance. Still, no analytical solutions for the non-resonance region with the dual-frequency responses reported by Yan et al. [19] have been proposed. The boundaries of Hopf bifurcation and quenching are not clear. Different from using the method of multiple scales, an equivalent structure method was proposed by Tan et al. [22] in order to facilitate the derivation of the analytical solutions for the vibration-based energy harvesters. This method was demonstrated in different types of oscillations and interface circuits [23]. Analytical solutions for mono-frequency (modified frequency based on excitation frequency or natural frequency) responses were derived but not for multi-frequency responses.

In this study, approximate theoretical expressions for the dual-frequency responses will be proposed for the hybrid energy harvester via the modified electromechanical decoupled method. First, the full electromechanical coupled nonlinear distributed-parameter model will be briefly retrospected. The complex force expressions in this full model will be simplified via neglecting the forcing interaction terms. The equivalent structure method will be employed to derive the decoupled mechanical governing equation for the forced and self-excited responses. Such governing equation will be separated into two equations to determine the analytical solutions for these two types of responses. The boundaries of Hopf bifurcation and quenching will be analytically presented. The proposed approximate analytical solutions will be assessed by the full electromechanical coupled governing equations. The effects of the load resistance, wind speed, excitation acceleration and frequency on the quenching, galloping and harvested power will be investigated. The physical causes of the nonlinear phenomena will be explored. The performances of the hybrid, galloping-alone, base-excitation-alone energy harvesters will be compared and discussed.

2. Mathematical modeling

2.1. Electromechanical coupled model

The piezoelectric energy harvester considered in this study is composed of a cantilever beam and a bluff body attached to the beam, as shown in Fig. 1. The cantilever beam consists of one aluminum and two piezoelectric layers. The two piezoelectric sheets are bonded on both sides of the aluminum layer and connected in parallel with opposite polarity to a load resistance. The system undergoes the harmonic base excitation at the fixed end of the beam and wind force on the tip bluff body. The tip bluff body is assumed to undergo the uniform incoming wind speed. The effects of non-uniform wind and turbulence are neglected and the quasi-steady hypothesis is employed to establish the aerodynamic model. This quasi-steady aerodynamic model was validated by the experimental data of the galloping energy harvester [18]. There may exist interactions between vortex-induced vibration and galloping under the uniform incoming wind force [24]. For the case considering the energy harvesting mainly from galloping, the Strouhal number of the onset galloping wind speed is very small [16]. As a result, the interaction between the vortex-induced vibration and galloping will not occur. Following Barrero-Gil et al. [16], only the galloping effect is considered to establish the wind force. The geometric and material parameters of the system are presented in Table 1. Following Yan et al. [19], the electromechanical coupled governing equations are expressed as follows

$$
\begin{aligned}
&EI\frac{\partial^4 v_{rel}(x,t)}{\partial x^4}+c_sI\frac{\partial^5 v_{rel}(x,t)}{\partial x^4\partial t}+c_a\frac{\partial v_{rel}(x,t)}{\partial t}+m\frac{\partial^2 v_{rel}(x,t)}{\partial t^2}+\left(\frac{\mathrm{d}\delta(x)}{\mathrm{d}x}-\frac{\mathrm{d}\delta(x-L)}{\mathrm{d}x}\right)\vartheta_pV(t)\\
&\quad=F_{tip}\delta(x-L)-M_{tip}\frac{\mathrm{d}\delta(x-L)}{\mathrm{d}x}-[m+M_t\delta(x-L)]\frac{\partial^2 v_b(t)}{\partial t^2}+M_tL_c\frac{\partial^2 v_b(t)}{\partial t^2}\frac{\mathrm{d}\delta(x-L)}{\mathrm{d}x} \qquad (1)
\end{aligned}
$$