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Research paper

Vortex-induced vibrations mitigation through a nonlinear energy sink

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ABSTRACT

The passive suppression mechanism of the vortex-induced vibrations (VIV) of the cylinder by means of an essentially nonlinear element, the nonlinear energy sink (NES) is investigated. The flow-induced loads on the cylinder are modeled using a prevalent van der Pol oscillator which is experimentally validated, coupling to the structural vibrations in the presence of the NES structure. Based on the coupled nonlinear governing equations of motion, the performed analysis indicates that the mass and damping of NES have significant effects on the coupled frequency and damping of the aero-elastic system, leading to the shift of synchronization region and mitigation of vibration responses. It is demonstrated that the coupled system of flow-cylinder-NES behaves resonant interactions, showing periodic, aperiodic, and multiple stable responses which depend on the values of the NES parameters. In addition, it is found that the occurrence of multiple stable responses can enhance the nonlinear energy pumping effect, resulting in the increment of transferring energy from the flow via the cylinder to the NES, which is related to the essential nonlinearity of the sink stiffness. This results in a significant reduction in the VIV amplitudes of the primary circular cylinder for appropriate NES parameter values.

1. Introduction

NES, known as an end attachment that has potential ability in pumping energy from the primary system, has been widely proposed and developed in different engineering applications for suppressing vibration amplitudes of structures [1–3]. A nonlinear energy sink generally consists of three elements. The first element is an essentially nonlinear stiffness which enables the NES to resonate with the primary system. The second element is a linear damper which is used to dissipate the oscillating energy transferred through resonant interactions. The third element is the mass of the nonlinear energy sink which directly affects the coupled frequency of the primary system. The NES has significant advantages, such as absorbing vibrational energy generated by general broadband transient excitations and rapid and irreversible transferring energy, which are different from other passive controllers. These advantages make NES an attractive and prospect control approach for vibration and shock isolations [4–6].

Considerable researchers have made important contributions on the passive nonlinear energy pumping for attenuation of transient and forced vibrations [7–12]. Significant efforts have been made by Lee et al., [3] who reviewed important

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works on passively transferring unwanted energy from a primary structure to a local essentially nonlinear attachment by utilizing nonlinear energy sink. Jiang et al., [7] utilized the NES to effectively reduce the steady-state amplitude of the linear forced vibration system. Subsequently, more detailed investigations of the NES effects on vibrations of the coupled system have been done by Malatkar and Nayfeh [8]. In their work, they evaluated the dynamic responses of structures and discussed in details that the nonlinear energy pumping effect depends on the kinds of coupled system. Georgiades and Vakakis [9] evaluated the implementation of pumping energy from a linear flexible beam under shock excitation to NES, showing that the NES absorbs energy in a one-way irreversible form and dissipates the energy locally without spreading it back to the linear beam. The impacts of an attached NES on vibration suppression of a cantilever beam under shock excitation is investigated by Ahmadabadi and Khadem [10], who discussed the performance of NES by varying its parameter values. Recently, Luongo and Zulli [11] utilized the nonlinear energy sink as a passive control device for manipulating a nonlinear elastic string which is under external harmonic forces. Wang et al., [12] extended the NES to control building structures and found that the track of NES is more scalable and offers great flexibility in prescribing the associated nonlinear restoring force.

It should be noted that the above researches on employing passive nonlinear energy pumping are mostly to weakly couple an essentially nonlinear attachment to linear primary system. Flow-induced vibration phenomena commonly encountered in engineering applications, possess great potential dangers causing collapse of bridges, flutter responses of slender structures, and the fatigue failure of offshore risers [13–19]. Therefore, in the past few years, the concept of controlling flow-induced vibrations has been proposed by utilizing passive NES or other active methods [20–29]. Lee et al., [22] investigated the suppression of aero-elastic instabilities in a 2-DOF wing system by means of broadband passive targeted energy transfers. They observed that the nonlinear energy sink can significantly improve the stability of an aero-elastic system experimentally and theoretically. Afterwards, Tumkur et al., [24,25] explored the laminar vortex-induced vibrations of sprung rigid cylinders with the use of a passive nonlinear energy sink. Their computational study indicates that the induced limit cycle oscillations (LCOs) of the cylinder via laminar VIV can be significantly suppressed with proper values of the NES parameters. Mehmood et al., [30] further investigated the effects of the nonlinear energy sink on the response of vortex-induced vibrations of a circular cylinder. Significant results on the suppressing effects of NES were obtained in their study. However, the performed research works by Tumkur et al., [24,25] and Mehmood et al., [30] on VIV suppression are both limited to one determined flow speed, that is, the former only considers the Reynolds number $R_e = 100$ while the latter considers $R_e = 106$.

It should be noted that each of the two considered Reynolds numbers in Tumkur et al., [24,25] and Mehmood et al., [30] was in the synchronization regime, which is insufficient to represent the entire lock-in region when exploring the impacts of NES parameters, especially for cases of lock-in transfer patterns. Therefore, in order to comprehensively understand the energy pumping mechanism of NES during the synchronization region where VIV occurs, in the present study, we model the fluid loads by means of a modified van der Pol oscillator and perform linear and nonlinear analyzes to evaluate the NES effects on the nonlinear dynamic behaviors of circular cylinder during lock-in.

In the following parts, we first present the nonlinear governing equations of motion of the coupled aerodynamic system with consideration of the nonlinear energy sink, as presented in Section 2. Then, in Section 3, the fluctuating lift force on the cylinder is described by the developed van der Pol oscillator which was commonly utilized and discussed in academic field. In Section 4, the coupled fluid-structure model is experimentally validated and the corresponding empirical parameters are determined. Subsequently, predictions of suppressing VIV are made and the significant enhancement of the nonlinear energy pumping phenomenon is discussed in Section 5. Finally, in Section 6, some important conclusions are given out.

2. Mathematical modeling of the cylinder-NES-flow system

An elastically supported rigid circular cylinder of diameter D subjected to cross flows is considered. For certain values of flow speeds, high amplitudes of oscillations take place which is due to the matching between the flow shedding frequency and the natural frequency of the elastically-mounted circular cylinder. This phenomenon is named VIVs and the region of resonant amplitudes is called lock-in or synchronization [31–33]. While the flow speed is out of the lock-in region (pre-synchronization or post-synchronization regions), small oscillations amplitudes are observed. It should be noted that some researchers have discussed the VIV phenomenon for cylinders that there are cross-flow and in-flow vibrations, but all these studies reported that the cross-flow oscillation is one order of magnitude larger than in-line oscillation [34,35]. Therefore, in the present study, it is reasonably assumed the circular cylinder is constrained to oscillate transversely (y direction) to a uniform flow of free-stream velocity U (x direction), as shown in Fig. 1.

Based on the above assumption, in order to mitigate or suppress the vibration strength of the cylinder, we introduce the nonlinear energy sink which consists of a circular cylinder of mass m_{nes} and a nonlinear stiffness k_{nes} with a linear damper c_{nes}. It should be mentioned that the NES is placed inside the cylinder which is very beneficial to avoid the influence of the flow on the NES system and to get rid of the needed additional space by the NES structure.

Using Newton's second law, the governing equations of vortex-induced vibrations for the coupled circular cylinder and NES systems are, respectively, given by [24,30]:

$$(m - m_{nes})\ddot{y}_1 + c\dot{y}_1 + ky_1 + c_{nes}(\dot{y}_1 - \dot{y}_2) + k_{nes}(y_1 - y_2)^3 = F[\dot{y}_1, q(t)] \tag{1}$$