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Research paper

Vibration mitigation of a nonlinear rotor system with linear and nonlinear vibration absorbers

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ABSTRACT

Steady state dynamics of a horizontally supported Jeffcott rotor system under nonlinear restoring forces has been studied in this work. Vibration reduction of the rotor system using linear tuned mass dampers (TMD), nonlinear energy sinks (NES), and combined energy sinks (TMD-NES) was studied. In addition, the analysis on the effects of different parameters on the dynamics of the rotor system has been conducted. In this study, semi-analytical modified complex averaging technique (MCXA), numerical arc-length continuation method, and ODE integration method have been used to solve the governing equations. The obtained results showed, all three types of absorbers including TMD, NES, and combined TMD-NES sufficiently good performance in vibration reduction of primary rotor system. In a closer view, it shows that TMD-NES, TMD, and NES have respectively better performance in vibration reduction. On the other hand, combined TMD-NES, NES, and TMD give respectively broader frequency range of stability. Finally, it's concluded that in spite of good efficiency in vibration reduction for the design condition, all types of absorbers should be modified to be more robust against changes in parameters of primary system.

1. Introduction

Rotor systems such as various types of turbines, bladed discs, fans, helicopters, and rotating shafts, are of the most applicable systems in the modern world. Undesired vibrations and chaotic dynamics of such systems may cause fatigue, instability, damages and lots of destructions. Therefore, vibration analysis and control in such systems are of high importance.

Numerous studies have been conducted to analyze different types of rotor systems [1–7]. Shahgholi et al. [1] studied the free vibration of a nonlinear slender rotating shaft with simply support conditions. Considering the rotary inertia and gyroscopic effect, they concluded that for natural vibrations of a slender rotating shaft, backward and forward modes are involved. In 2015, Shahgholi et al. [2] studied the stability of a rotor system close to the major critical speeds, in which several discs were mounted on a simply supported nonlinear spinning shaft. They showed that for the higher and lower rotational speeds there are direct and inverse relationships between the backward frequency and the number of discs, respectively. They also revealed that with respect to shaft with small number of discs, by increasing the number of discs bifurcations occur in the lower speeds. In 2001, Lin and Hsiao [3] studied the linear vibration of rotating Timoshenko beam. For this purpose, they considered all inertia effect and coupling between extensional and flexural deformations. The effect of Coriolis force was also considered in their study. They proposed a method based on the power series solution to solve the natural

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frequency of the rotating Timoshenko beam. Saeed and El-Gohary [4] studied the nonlinear vibration of a horizontally supported Jeffcot rotor system. For this purpose, they considered nonlinear restoring force due to the bearing clearance and also the rotor weight. Using multiple scales perturbation technique they conducted bifurcation analysis of the aforementioned system. According to their analysis, since there are three different solutions in an interval of rotational speed, the system would be very sensitive to the initial conditions. They also demonstrated that for soft spring, localized and non-localized oscillation in both the horizontal and vertical modes are occurred. In [5] the nonlinear normal modes of a horizontally supported Jeffcott rotor are investigated. Their study showed that in the case where the eccentricity is small, the whirling motion is localized in the horizontal or vertical direction in the resonance. On the other hand, when the eccentricity is large, two kinds of whirling motion, which are localized in the vertical direction and nonlocalized in any direction, coexist simultaneously in a region of rotational speed. In [6] a reduced order modeling based on complex nonlinear modal analysis is presented and applied to bladed disks with shroud contact. The methodology is applied to both a simplified and a large-scale model of a bladed disk with shroud contact interfaces. Forced response functions, backbone curves for varying normal preload, and excitation level as well as flutter-induced limit cycle oscillations are analyzed. In [7], an extended analysis of the eddy current based damping device for a last stage steam turbine blading presented in GT2009-59,593 is conducted. A transient electromagnetic finite element analysis of the eddy current damper is performed, and for the validation of the finite element model, a test rig was built that allows for the direct measurement of damping forces when forcing a sinusoidal relative motion.

One of the most important issues in modern structures design is an enhancement of their static and dynamic characteristics. The objective might be efficient noise reduction, suppressing undesired structural vibrations, etc. These aims can be achieved by a concept of structural control. There are a large variety of structural control strategies. Based on their inherent characteristics, these can be classified into four main groups: passive, semi-active, active, and hybrid methods. In passive systems the control is activated by the structural motion and the input energy is dissipated by damping devices or attaching a linear or nonlinear absorber. No external force or energy is applied. Semi-active control devices are a natural extension of passive ones. The embedded active elements control the properties of passive devices and adapt their behavior based on the collected information on excitation and structural response. In active control strategies system control is achieved by the externally activated actuators applying control load directly to the structure. The controller signal is determined via a control law, on the basis of the measurements of external disturbance and structural response. A state of the art review of different control methods in structural and mechanical engineering was presented by Saaed et al. [8], in which a comprehensive discussion on structural control strategies was supplemented by an overview of passive and active devices used in control engineering. In [9–16] passive and active method for vibration control for rotor systems are presented. In a nutshell in contrast to active control devices, passive absorbers are not dependent to external force and feedback to control the system. Besides, passive devices don't require much maintenance as the active ones do. On the other hand, active devices are capable of covering multiple modes of vibration using active feedback control; while it would be a challenge to design a single passive absorber so that it can affect all the modes of a vibrating system.

Considering the benefits and limitations of active and passive vibration control, it's been a challenging effort to design a broadband passive control, particularly for nonlinear systems. Saeed and Kamel [9] investigated the vibration control of the horizontally suspended Jeffcott rotor system. They used Proportional-Derivative (PD)-controller via two pairs of electromagnetic poles. The nonlinearity due to the electromagnetic coupling was also considered in their model. Their results showed high efficiency of the controller to mitigate the nonlinear vibration of the considered system. In 2017, Heindel et al. [10] investigated the resonance elimination of a Jeffcott rotor with active bearings. They theoretically and practically proved the efficiency of active bearings in elimination of both bearing forces and the resonance of a Jeffcott rotor system.

Roy and Chandraker [17] studied the modal analysis of higher order finite element model for a generally viscoelastic rotor supported by the journal bearing. They considered the gyroscopic couple, internal damping and fluid film forces of journal bearings. A complex modal coordinate is used to indicate the directivity of modes and information about the direction of the whirl. Ebrahimi et al. [18] theoretically and experimentally studied the nonlinear dynamics of a flexible rotor supported on the active magnetic bearings (AMB). The effects of auxiliary bearings stiffness and rotational speed on the dynamic behavior of the system are investigated by the bifurcation diagrams, dynamic trajectories, Poincareḿaps and maximum Lyapunov exponent.

Because of the difficulties in installation and also the expenses and the needed energy for active vibration control, passive control methods has taken considerable attention of scientists in recent decades. Targeted Energy Transfer (TET) via nonlinear energy sinks (NESs) has been recently one of the most common approaches in both linear and nonlinear vibration control due to the broader frequency range of efficiency compared to tuned mass dampers (TMDs) [19–24].

In Ref. [19], a review of the concept of non-linear energy sink, its fundamental theoretical aspects of targeted energy transfer (TET) is discussed. Then, the results of experimental studies that validate the TET phenomenon, and some engineering applications of TET are discussed. In [20], robustness of a harmonically excited essentially nonlinear oscillator coupled with a two-DOF nonlinear energy sink in translation vibration is studied. In [20], it is shown that with increasing the degrees of freedom of the nonlinear absorber, the robustness of the system with variation in amplitude and frequency of exciting force, and etc. are increased. In [21] theoretically and experimentally the effect of a nonlinear energy sink (NES) on the steady state dynamics of a weakly coupled system in translational vibration is studied. In [22] the studied model of [21] is re-examined. They found that with using NES, system represent different nonlinear phenomenon such as cyclic-fold, Hopf, symmetry-breaking, and period-doubling bifurcations; phase-locked motions; regions with multiple coexisting