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Essentially nonlinear piezoelectric shunt circuits applied to mistuned bladed disks

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ABSTRACT

An essentially nonlinear piezoelectric shunt circuit is proposed for the practical realization of nonlinear energy sink, and then applied to a mistuned bladed disk for blade vibration reduction. First, the global dynamics of a single degree-of-freedom linear mechanical oscillator, coupled to an essentially nonlinear shunted piezoelectric attachment, is studied. Under certain conditions, the nonlinear targeted energy transfer, i.e. a fast, passive energy transfer from the mechanical oscillator to the nonlinear attachment is observed. A numerical method, referred to as the variable-coefficient harmonic balance method, is developed to calculate quasi-periodic responses arising in the electromechanical system under harmonic forcing. Characterized by the nonexistence of a resonance frequency, the essentially nonlinear shunt circuit is able to work robustly over a broad frequency band with a smaller inductance requirement compared with the linear resonant shunt circuit.

The application of piezoelectric shunt damping to simplified blade–disk structures is then taken into consideration. Shunted piezoelectrics are attached onto the disk surface in our damping strategy in order to reduce blade vibrations. Essential nonlinearity is also introduced into the piezoelectric shunted bladed disk system. Since the piezoelectric-based nonlinear energy sink is not a priori tuned to any specific frequency, a sound damping performance is achieved when blades become inevitably mistuned.

1. Introduction

Nonlinear targeted energy transfers and nonlinear mode localization phenomena have been widely investigated in recent decades [1]. Nonlinear targeted energy transfer (or nonlinear energy pumping) was first observed by Gendelman [2]. Since then, numerous research efforts have been devoted to the dynamics of a linear oscillator (designed as a “primary system”) weakly coupled to a local nonlinear attachment of small mass, possessing essential (strong) stiffness nonlinearity [3]. It is shown that under certain conditions this type of essentially nonlinear attachment can passively absorb energy from the linear nonconservative structure, in essence acting as nonlinear energy sink (NES). The need for essential nonlinearity has been emphasized, since the transition of mode localization in nonlinear systems raises the possibility of energy transfer from one mode to another. Moreover, such essentially nonlinear oscillators do not have preferential resonant frequencies of oscillation, which enables them to resonantly interact with modes of the primary system at arbitrary frequency ranges.

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Experimental evidences of nonlinear energy sinks have been reported in a number of studies [4,5]. In these experimental works, special care has been paid towards the design and practical implementation of essentially nonlinear stiffness elements and the accurate measurement of their stiffness characteristics. Essential nonlinearity is realized by using very sophisticated mechanical elements (e.g. wires [6,7] and membranes [8]). As pointed out by Viguié [9], such geometrically nonlinear stiffness designs also introduce a weight penalty to the host structure and need significant installation space for efficient vibration mitigation. These inherent limitations stimulate us to seek new intermedia for the practical realization of nonlinear energy sinks.

In addition, nonlinear mode localization in periodically coupled oscillators due to nonlinear effects has also drawn increased attention [10,11]. Mode localization may also occur in linear systems composed of a multiple of coupled subsystems, such as bladed disks. As is known universally, localization of vibration energy in rotating bladed disks can be catastrophic since it may lead to failure of high-speed rotating blades [12]. Hence the study of the motion confinement phenomenon due to nonlinear effects can prove to be beneficial in such applications where localization phenomena are unwanted.

Piezoelectric materials have been extensively used as sensors and actuators for vibration controls in recent decades owing to their ideal properties: light weight, high bandwidths, efficient energy conversion and easy integration [13]. Embedded or bonded to the vibrating structures, piezoelectric materials can convert mechanical energy into electric energy and vice versa. By exploiting this energy conversion capability, various schemes and vibration control techniques have been developed. The application of passive piezoelectric shunt damping for turbomachine blades was first investigated through experiments performed by Cross and Fleeter [14]. Schwarwendahl et al. [15] have proposed the integration of the resonant shunted piezoelectric stack into the blade in order to protect the material from centrifugal loading and environmental degradation. In particular, Yu and Wang [16,17] have recently explored the feasibility of utilizing piezoelectric absorbers attached onto both the blade and disk to reduce the vibration of periodic structures. A passive piezoelectric network is derived to achieve multiple spatial harmonic vibration suppression. This research effort offers a very good start in the application of piezoelectric shunt damping to simplified bladed disk structures.

In addition to passive piezoelectric shunting, a number of active piezoelectric control approaches applied to blades have been also devised to improve structure damping. Watanabe et al. [18] have attached piezoelectric actuators on airfoil trailing edges to actively control flutter on airfoils in a linear transonic cascade. Considering the practical implementation of piezoelectric elements within rotor blades, Duffy et al. [19,20] have demonstrated the effectiveness of a piezoelectric-damped plate under centrifugal loading.

Another piezoelectric application is given in our previous research concerning the friction ring damper [21]. Piezoelectric transducers are circumferentially attached onto the disk to provide excitation for experimental validation of friction damping (see Fig. 1). In this case, blade vibration is successfully excited only by shaking the disk through piezoelectric actuators. Therefore, an inverse energy transfer from the blades to the disk is naturally desired.

The location of piezoelectric elements in bladed disks is an issue of major concern. In most of the current applications, piezoelectric patches are mounted onto blade surfaces [14,16,18,19]. In general however, it is not thought to be practical since objects attached onto blades will disturb the flow field in the cascade. A trend is toward a compact integration of piezoelectric materials into the blade [15]. For instance, it is stated that the full-size fan blade does have adequate thickness to incorporate embedded piezoelectric elements [19]. While for small-sized blades in higher stage, it seems that there is not enough space inside. In addition, such incorporation itself may also bring about new problems, like manufacturing difficulties and blade strength degradation.

Based on the above arguments, an essentially nonlinear piezoelectric shunt circuit is first proposed in this research as a practical realization of nonlinear energy sink. This piezoelectric-based NES possesses attractive features. The most significant advantage is that various forms of nonlinearity can be readily achieved through proper circuit design. For instance, on the basis of traditional resonant shunt circuits, cubic nonlinearity can be introduced by an additional ferroelectric capacitance. The small size of the piezoelectric absorber and easy integration also make the nonlinear piezoelectric shunting appealing for practical use.

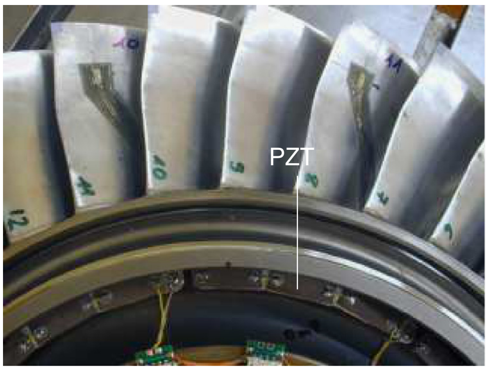

Fig. 1. Position of piezoelectric transducers in the bladed disk.