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Research on vibration suppression of a mistuned blisk by a piezoelectric network

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Abstract The work aims to provide a further investigation of the dynamic characteristics of an integral bladed disk (also called 'blisk') with a Parallel Piezoelectric Network (PPN). The PPN is constructed by parallelly interconnecting the piezoelectric patches distributed in the blisk. Two kinds of PPN are considered, namely mono-periodic PPN and bi-periodic PPN. The former has a piezoelectric patch in each sector, and the later has one patch every few sectors. The vibration suppression performance of both kinds of PPN has been studied through modal analysis, forced response analysis, and statistical analysis. The research results turn out that the PPN will only affect mechanical frequencies near the electrical frequency clusters slightly, and the bi-periodic PPN will make the nodal diameter spectrum of the modes more complex, but the amplitude corresponding to the new nodal diameter component is much smaller than that of the nodal diameter component corresponding to the mono-periodic system. The mechanical coupling between the blades and the disk plays an important role in the damping effect of the PPN, and it should be paid attention to in applications. The mono-periodic PPN can effectively suppress the amplitude magnification of the forced response induced by the mistuning of the blisk; meanwhile, it can mitigate the vibration localization of the mistuned electromechanical system. If piezoelectric patches are set only in part of the sectors, the bi-periodic PPN still has a vibration suppression ability, but the effect is related to the number and spatial distribution of the piezoelectric patches.

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1. Introduction

Bladed disks in aero-engines belong to a class of structures called periodic structures. These structures consist of spatially repetitive substructures which are designed to be identical in ideal situations.[1] However, in reality, there are always small and random deviations in blade properties, and these are due

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to factors such as manufacturing tolerance, material inhomogeneity, and in-operation wear. These blade-to-blade discrepancies are called mistuning, which are typically small, but can lead to vibration concentrated in a small region of a structure. This phenomenon is known as vibration response localization. As a result, certain blades can have significantly higher forced response levels than that in an ideally tuned design. For this reason, the phenomenon is also called amplitude magnification. It is considered as one of the major factors inducing High Cycle Fatigue (HCF) of blades.[2] Therefore, it is important to reduce amplitude magnification induced by mistuning.

Dry-friction damping has been the most common approach in vibration mitigation since a long time ago, while it is not favorable due to the absence of contact interfaces in an integral bladed disk ('blisk' for short in the rest of the paper) in modern aero-engines.[3–6] These issues drive researchers to find alternative damping techniques particularly for vibration suppression of a mistuned blisk with low structural damping. In recent decades, piezoelectric materials have received considerable attention because of their properties such as light weight, high bandwidths, efficient energy conversion, and ease of integration.[7] When embedded in or bonded on fundamental structures, piezoelectric materials can transform mechanical energy to electric energy when they undergo mechanical deformations, and vice versa. Based on this energy conversion capability, various vibration reduction techniques have been developed. Passive piezoelectric damping techniques are initiated by Forward,[8] who investigated the damping effect of a piezoelectric patch shunted with an inductor. Hagood and Flotow[9] investigated the possibility of dissipating mechanical energy using piezoelectric shunt circuits containing a resistor and an inductor. They showed that a shunt circuit with a resistor and an inductor performs like a dynamic vibration absorber, especially in cases where the resistor and the inductor are optimally tuned to structural resonance in a manner analogous to a mechanical vibration absorber. The studies of Yun and Kim[10] and Moheimani[11] showed that the positions of piezoelectric patches and the reactance of a shunt circuit should be carefully selected to minimize the maximum forced response corresponding to the targeted mode. To overcome the limitation that the value of inductance is too high to be achieved in a low-frequency domain, a synthetic inductance[12] is used, and an inductance with a value of thousands of Henries has been obtained.[13] Min et al.[14] performed a numerical and experimental study for rotating piezoelectric composite subscale fan blades, and they proved that piezoelectric vibration damping could significantly reduce the vibration of composite fan blades in an aero-engine. Zhou et al.[15,16] proposed a vibration control strategy based on the passive piezoelectric shunt damping technique for a mistuned blisk. Their numerical simulation results indicated that a good performance could be achieved in terms of reducing the vibration of a slowly time-variant mistuned blisk. Then, Mokrani et al.[17,18] utilized the shape of a targeted mode to organize piezoelectric patches as a modal filter, which decreased the required inductors of a shunted circuit. Their method was firstly validated experimentally on a circular plate, and then applied to a prototype of an industrial bladed drum.

Wang et al.[19,20] attempted to bond piezoelectric patches on both blades and a disk and then connect them with a network to reduce modal localization of mistuned bladed disks. They showed that the piezoelectric network could create a new electrical energy channel, which could destroy the intrinsic mechanism for vibration localization. Focusing on the vibration suppression of a mistuned bladed disk, Yu and Wang[21,22] used a negative capacitance to improve the performance of the piezoelectric network. These research efforts offered a start on applying the piezoelectric network to suppress the multi-harmonic vibration of a mistuned bladed disk. Liu et al.[23] considered the non-engine-order excitation from a practical point of view, and the mechanisms of vibration-suppression of a piezoelectric network and a piezoelectric shunt circuit were explained by means of modal analysis and energy analysis. Li et al.[24] built piezoelectric networks among several identical structures without any mechanical coupling. It was shown through analytical derivation that the response of each component is composed of two parts: one is the response to the excitation acting on that component itself, and the other is the response to the average excitation forces over all the components. Such an additional response can perform as a "compensation" to suppress the overall response of a given component. The vibration suppression performances of both Parallel Piezoelectric Networks (PPNs) and Series Piezoelectric Networks (SPNs) have been studied by parameter studies. Results have shown that both PPNs and SPNs can effectively suppress the vibration level, though with different optimal parameters. The best performances for PPNs and SPNs are identical and better than that of passive piezoelectric shunts. The features of PPNs and SPNs were further investigated by considering a more complex yet more realistic situation where the mechanical coupling between adjacent blade sectors was taken into account.[25] It turned out that the vibration response to non-zero engine-order excitation could be reduced by a PPN, while an SPN only works for zero engine-order excitation. Their analytical and experimental results in their research work[26,27] indicated that a PPN has an advantage in vibration delocalization of a mistuned periodic structure than a traditional piezoelectric shunt circuit. Meanwhile, only resistors and capacitors have been considered in their research in order to avoid an inductance with a huge value. In these analytical models, piezoelectric patches are all assumed to be located on the surfaces of blades, which would bring an enormous influence to the flow field. Moreover, because the blade surface is usually a complex curved surface, it is difficult to bond or embed a piezoelectric patch on it. It is easier to set piezoelectric patches on the surface of the disk, which, in addition, can minimize the influence to the flow field. When piezoelectric patches are bonded on the disk surface, there will be different dynamic characteristics of the electromechanical system which should be further studied.

When piezoelectric patches are distributed in every sector of a blisk, the electrical period is the same as the mechanical period, and the electromechanical system is a mono-periodic system. Meanwhile, in a case where piezoelectric patches are distributed every few sectors, the electromechanical system becomes a bi-periodic system, which means that the electrical period is different from the mechanical period. This work is meant to contribute to a better understanding of the dynamic characteristics of a blisk with both mono-periodic and bi-periodic systems. The aim of the research in the paper is to find an effective alternative damping technique for the mistuned blisks with low structural damping. The content of the paper is organized as follows. First of all, the model of a blisk with