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Forced vibration analysis of the hard-coating blisk considering the strain-dependent manner of the hard-coating damper

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ABSTRACT

This paper focuses on the passive vibration reduction of the blisk by the hard-coating damper, and investigates the nonlinear dynamics of the hard-coating blisk. Based on the discrete values obtained by the testing, the high-order polynomials are used to characterize the mechanical parameters of the hard-coating damper considering its strain-dependent manner. The boundary conditions and continuity conditions of the disk and the hard-coating blades are satisfied by introducing the artificial springs at their interface. The dynamic model of the hard-coating blisk is constructed by an analytical energy-based approach. An iterative solution procedure based on the Newton–Raphson method is developed to obtain dynamic characteristics of the hard-coating blisk. An academic blisk deposited NiCoCrAlY + YSZ hard coating is selected as the benchmark case to conduct the nonlinear numerical calculation, and the obtained results are compared with those obtained by the experimental test. In particular, the specific influence of the hard-coating damper and the unique strain-dependent manner on the vibration characteristics of the blisk are investigated respectively in terms of the resonant frequencies and corresponding responses.

1. Introduction

The integrally bladed disk (also known as blisk) that works in high rotational speed, high temperature and high pressure is a core mechanical structure and the main function conversion component of power plants (such as gas turbines and compressors), and it obtains widespread use in the design of modern aero-engines increasingly. Generally, it is manufactured as the single structure either by welding blades on rotors or by machining entire bladed disks from single pieces of metal, instead of an assembly of a disk and some removable blades and joint dovetail attachments. As a result, the number of parts, the weight of mechanical structures and the aerodynamic losses are reduced obviously, and the negative problem of the crack initiation with its subsequent propagation at joints can also be eliminated effectively [1]. However, the blisk does not benefit from the vibration damping provided by the dovetail attachments correspondingly, which is different from and inferior to the traditional bladed disk assemblies. Therefore, the blisk is always vulnerable to the high-level vibration and/or the severe resonance during working, which can lead to the high-cycle fatigue failures and shorten the working lifespan in the harsh environments. Therefore, introducing the external/additional damping resources is very significant and necessary to reduce the excessive dynamic response or vibratory stress.

Traditionally, the shroud friction dampers [2,3], the under-platform dampers [4,5] and the friction ring dampers [6–8] have been usually adopted to the traditional bladed disk assemblies for passive vibration reduction, but these dampers cannot use in the blisk due to its special one-piece structure. In recent years, some improved dampers have been adopted for damping treatment, such as the viscoelastic dampers [9,10], constrained dampers [11,12] and adaptive/active piezoelectric dampers [13–15], however, the aforementioned dampers are incompetent for the blisk under working conditions of the high temperature, high pressure and strong corrosion. Generally, hard coating is a kind of coating material prepared by the metals, the ceramics and their mixtures, and it has been usually employed as the surface treatment, such as the thermal barrier coatings, anti-friction/wear coatings and anti-corrosion coatings [16–19]. And then, recent researches reveal that the hard coating does have the significant damping capacities which are generated by the internal particles friction of the hard-coating materials [20–22]. Now, because of the nicer stability of mechanical performances under severe environments and the better flexibility (or simplicity) in the engineering implementations

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[23], a new research field about passive vibration reduction by using the hard-coating damper has received a reasonable amount of attentions [24–28].

In order to implement the hard-coating damping vibration technology of the blisk effectively, the theoretical and experimental investigation of dynamic behaviors of the hard-coating blisk is very necessary. In the Ref. [29], the semi-analytical modeling and vibration characteristics analysis of an academic blisk deposited NiCrAlY coating are conducted respectively, then the influence of the hard-coating damper and coating thickness on the given blisk are studied. Subsequently, by the non-dominated sorting genetic algorithm (NSGA-II) coupled with the Kriging surrogate model, the damping capacities of the NiCrAlY hard coating on the beam-plate blisk are optimized by Chen et al. [30], which gives the designers a useful guidance to achieve the more superior performance of the hard-coating damper in engineering applications. Similarly, the mixed hard coating of NiCoCrAlY + yttria-stabilized zirconia is deposited on blades by the APS (atmospheric plasma spraying) technology, and the frequency-response functions of the hard-coating blisk are obtained by the Rayleigh damping model and Ritz method [31]. Moreover, the reduced-order modeling and vibration analysis of a high-fidelity blisk deposited NiCoCrAlY + YSZ hard coating are carried out by Gao and Sun [32] with the higher computational efficiency, and the specific influence of coating area are further studied for the damping optimization. However, these researches do not consider the strain-dependent manner of the hard-coating damper that the storage modulus and loss factor vary nonlinearly with the strain amplitudes of the hard-coating structures [33,34]. And, the dynamics investigation of the hard-coating blisk considering strain-dependent manner becomes a very challenging task undoubtedly.

To create the dynamic model of the hard-coating composite structures accurately, the strain-dependent mechanical parameters of the hard-coating damper should be achieved in advance [35,36]. Fortunately, this identified research has made good progress recently. The response decays of a Nimonic beam-deposited the hard-coating damper under different excitations has been obtained by Patsias et al. [37] to investigate the damping properties and the elastic modulus of the hard-coating damper corresponding to different strains levels. Then, a mixed procedure comprising experimental test and numerical calculation has been proposed by Tassini et al. [33] to identify the strain-dependent mechanical parameters of the hard-coating damper, and then, the specific differences of the mechanical parameters of the hard-coating damper prepared by the air plasma spraying (APS) technology and the electron beam-physical vapor deposition (EB-PVD) technology were investigated particularly. In addition, Sun et al. [38] analyzed the vibration characteristics of a titanium plate deposited NiCoCrAlY + YSZ hard coating, and the storage modulus and the loss factor of the hard-coating damper were identified by the FRFs. Next, based on a novel experiment system, the test methods were developed by Reed et al. [39] to study the strain-dependent stiffness and damping characteristics of the hard-coating dampers at high strain levels. The above-mentioned investigations provided an important and useful support for the dynamic modeling of the blisk deposited the nonlinear the hard-coating damper.

The purpose of this paper is on the development of analytical modeling considering the strain-dependent manner of the hard-coating damper and the dynamic investigation of the hard-coating blisk. The main research context is organized as follows: In Sec. 2, the strain-dependent mechanical parameters of the hard-coating materials are introduced and characterized by the high-order polynomials. In Sec. 3, the analytical model of a the hard-coating blisk is established by the analytical energy-based approach combining the complex modulus theory with the Ritz method. In addition, a unified iterative solution procedure based on the Newton–Raphson method is developed to solve resonant frequencies and responses of the hard-coating blisk. In Sec. 4, an academic blisk with depositing NiCoCrAlY + YSZ hard coating on both sides of all the blades is chosen as a benchmark case to conduct the nonlinear number calculation, and the numerical results are compared with those obtained by the experimental test to validate the proposed nonlinear analytical model. In addition, the specific influences of the hard-coating damper and the unique strain-dependent manner on the resonant frequencies and responses of the blisk are investigated respectively. Finally, some important conclusions about this study are listed in Sec. 5.

2. Strain-dependent manner of the hard-coating damper

The mechanical properties of the hard-coating damper are very unique, which can be summarized as follows. Firstly, the damping capacities of the hard-coating damper are superior to substrate metal remarkably, but inferior to the viscoelastic materials, thus the damping capacities of both the hard-coating damper and substrate should be considered together during the dynamic investigation of composite structures. Secondly, compared to the viscoelastic materials, the damping capacities of the hard-coating damper are effective over a wide temperature range and the damping failure does not occur at high temperature. Thirdly, the elastic modulus of the hard-coating damper always changes with the strain amplitudes which is called the strain-dependent manner.

The concept of a complex modulus (or stiffness) in vibration problems with viscous or structural (hysteretic) damping is something that has been known for decades. Most often the complex modulus can be defined as the sum of the storage modulus (real part) and the loss modulus (imaginary part) [40]. In this paper, the complex modulus of the hard-coating damper considering the strain-dependent manner $\tilde{E}_c(\varepsilon_e)$ can be expressed as

$$\tilde{E}_c(\varepsilon_e) = E_c(\varepsilon_e) + \mathrm{i}E'_c(\varepsilon_e) = E_c(\varepsilon_e)\left[1 + \mathrm{i}\eta_c(\varepsilon_e)\right] \tag{1}$$

where, $E_c(\varepsilon_e)$, $E'_c(\varepsilon_e)$ and $\eta_c(\varepsilon_e)$ represent the nonlinear storage modulus, the nonlinear loss modulus and the nonlinear loss factor, respectively; ε_e denotes the equivalent strain.

In the research of [36] and [41], the nonlinear storage modulus and the nonlinear loss modulus of the hard-coating damper can be expressed respectively as

$$E_c(\varepsilon_e) = \sum_{Np=0}^{NP} \varepsilon_e^n E_{c,Np} = E_{c,0} + \varepsilon_e E_{c,1} + \cdots + \varepsilon_e^N E_{c,NP} \tag{2}$$

$$E'_c(\varepsilon_e) = \sum_{Np=0}^{NP} \varepsilon_e^n E'_{c,Np} = E'_{c,0} + \varepsilon_e E'_{c,1} + \cdots + \varepsilon_e^N E'_{c,NP} \tag{3}$$

By substituting Eq. (2) and Eq. (3) into Eq. (1), the nonlinear complex modulus and loss factor of the hard-coating damper can be obtained respectively as

$$\tilde{E}_c(\varepsilon_e) = \left(E_{c,0} + E'_{c,0}\right) + \varepsilon_e\left(E_{c,1} + E'_{c,1}\right) + \cdots + \varepsilon_e^N\left(E_{c,N} + E'_{c,NP}\right) \tag{4}$$

$$\eta_c(\varepsilon_e) = \frac{E'_c(\varepsilon_e)}{E_c(\varepsilon_e)} = \frac{E'_{c,0} + \varepsilon_e E'_{c,1} + \cdots + \varepsilon_e^N E'_{c,NP}}{E_{c,0} + \varepsilon_e E_{c,1} + \cdots + \varepsilon_e^N E_{c,NP}} \tag{5}$$

The data of the hard-coating damper obtained by the test are usually the discrete point values, which can be fitted by the high-order polynomials to characterize the strain-dependent manner of the hard-coating damper. In this paper, the fitting curves of the storage modulus and the loss factors of the NiCoCrAlY + YSZ hard