Vibration Characteristics of Thin-walled Component and Hard Coating Vibration-damping Technique

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Abstract: Thin-walled components are widely used in advanced machines such as aircraft engines, including thin-walled discs and drums, thin-walled hollow shaft, thin blade, etc. High-order resonance are easily to appear in the case of high-speed rotation, especially due to the presence of complex boundary conditions and load conditions. A lot of high-cycle fatigue damage are appeared on the thin-walled components, due to the unavoidable the high order modal resonance risk. Resulting from the limitation of structural optimization and application of constraint layers, hard coatings with high damping properties are proposed to apply on thin-walled components to achieve vibration reduction. This paper introduces the high-order vibration characteristics of thin-walled component and the technique of hard coating vibration damping, overcomes the practical difficulties such as dynamic optimization of structure and limited application of conventional damping measures, on blade, casing and discs and drums combined structure. The research results have been applied in the engineering project.

Keywords: Thin-walled Component; High-order Vibration; Hard Coating Damping; Optimal Design

1. Introduction

A large number of thin-walled components are widely used in advanced machines such as aircraft engines including thin-walled discs and drums, thin-walled hollow shaft, thin blade, etc. It is prone to high-order resonance in the case of high-speed rotation, especially in the presence of complex boundary conditions and load conditions[1-2]. It reveals that a lot of high-cycle fatigue damages are appeared, which frequencies above 6kHz on the blade and drums and other thin-walled components, due to the energy of the disturbed airflow is still high at high frequencies and the high order modal resonance risk is unavoidable[3-4]. However, the structural optimization of the rotating thin-walled component is limited, how to make effective vibration suppression is an urgent problem in engineering[5-6]. In recent years, it has been proposed to apply hard coatings with high damping properties on thin-walled components to achieve vibration reduction[7-10]. The studies are mainly focused on the damping efficiency and microstructure characteristics of hard coatings by experimental method.

However, due to the immaturity of high-order vibration theory of the engine thin-walled component under the complex boundary and load conditions, and the damping

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mechanism of the hard coating damping is not clear, it is difficult to active design the hard damping vibration reduction for the specific structural features and vibration characteristics of the thin-walled component. Therefore, from the theory of mechanical structure dynamics and vibration reduction, based on the advanced theory of surface coating, laminates and magneto-electro-elastic multi-physics solid mechanics, study a new method of hard coating damping for aircraft engine rotating thin-walled component. It is important to study the dynamics and vibration theory of the rotating thin-walled component. On the other hand, it can provide new technology to solve the engineering urgent need of vibration reduction and anti-high cycle fatigue.

This paper introduces the high-order vibration characteristics of thin-walled component and the technique of hard coating vibration damping, overcomes the practical difficulties such as dynamic optimization of structure and limited application of conventional damping measures, on blade, casing and discs and drums combined structure. The research results have been applied in the engineering project.

2. High-order vibration characteristics, boundary conditions and vibration mechanism of rotating thin-walled component

(a) Based on the theory of thin-walled shell, the centrifugal force and Coriolis effect are introduced, and the calculation method of traveling wave frequency of thin-walled cylindrical shell with arbitrary boundary condition, local structure with mounting edge or labyrinth is given. The results show that the forward and backward traveling frequency curve of the rotating thin-walled cylindrical shell is obviously separated at the low-diameter, and the forward and backward traveling wave frequency curve is close at the high-diameter, and the trend of the front and rear traveling wave frequency are consistent. As shown in Fig.1.

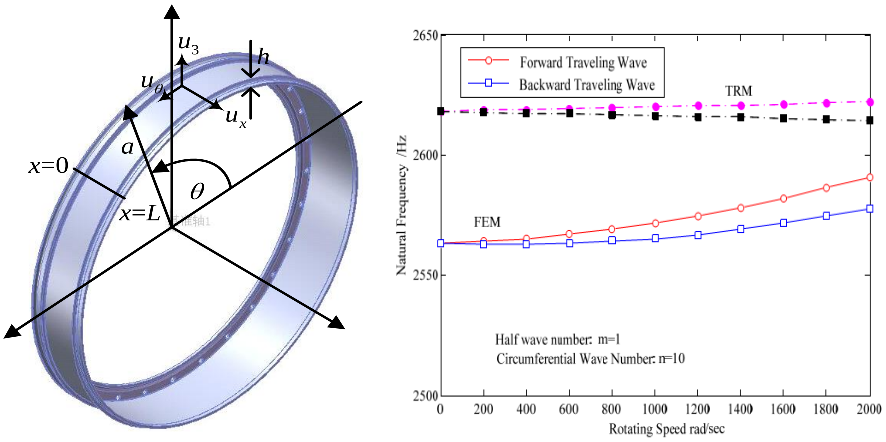


Fig. 1. Analytical solution of high-diameter traveling wave of cantilever thin - walled cylindrical shell

(b) For the case of arbitrary elastic boundary conditions, the frequency equation of the rotating thin-walled cylindrical shell is deduced by the Rayleigh-Ritz method using the adjustable orthogonal polynomial characteristic function, and the results of the high and low order natural frequencies of plate and shell combination structure obtained are consistent with the measured results.

(c) The new model of the elastic casing and the blade tip rubbing is deduced, and the resonance characteristics of respective certain order frequency and its multiplier of thin blades and thin-walled casing excited by rubbing are obtained. With the increase in speed, the more dynamic frequency resonance are excited, the vibration is more complex. Considering the multi-frequency excitation characteristics of unsteady airflow and local rub-impact, the mechanism of significantly multiplied resonance at the coupling frequency and high-order traveling wave frequency of the rotating thin-walled cylindrical shell combined structure is obtained, as shown in Fig.2.

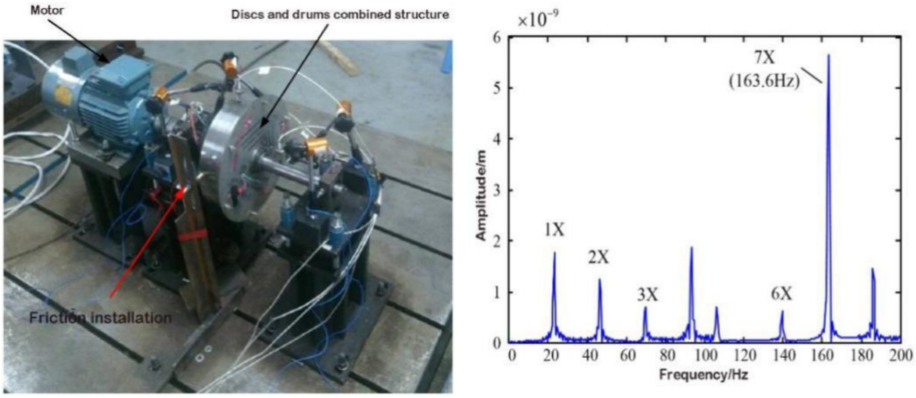
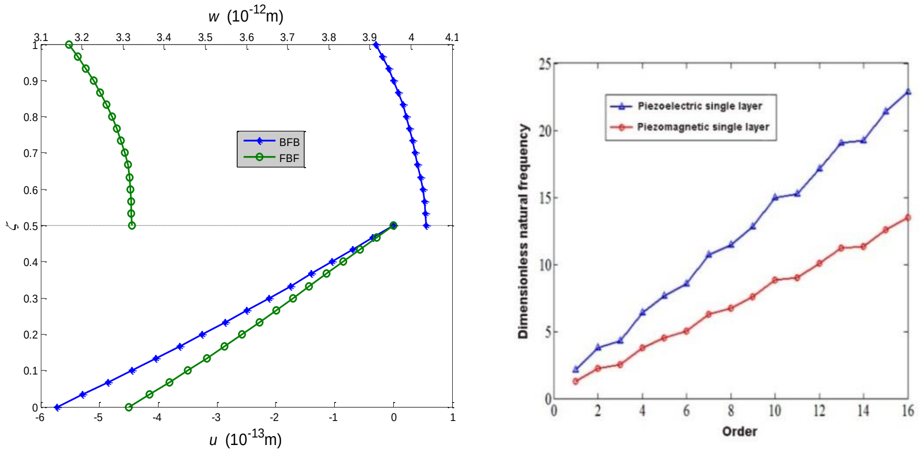


Fig. 2. High-order resonance of thin - walled shells under rub-impact excitation

3. Hard coating damping mechanism based on Laminated structure magneto-electro-elastic coupling effect

An analytic method, semi-analytical method and finite element numerical simulation method for the analysis of the vibration characteristics of the laminated structure of anisotropy and magneto-electro-elastic coupling are proposed. The effects of vibration characteristics with different materials and different loading conditions of hard coating damping whole structure are obtained. The damping mechanism and damping mechanism of hard coating are revealed.

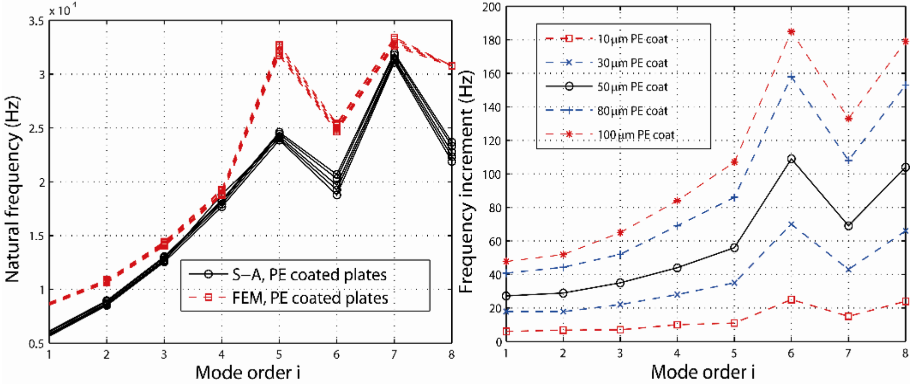
(a) The damping coating material with the ceramic base (piezoelectric effect) and the ferromagnetic base (piezomagnetic effect) is regarded as an anisotropic magneto-electro-elastic coupling material. The elastic dynamic theory of the multilayered structure with magneto-electro-elastic coupling is used to realize the accurate analysis of the vibration characteristics of the damped coating structure. The semi-analytical method based on the transfer matrix is used to realize the theoretical analysis of the multilayer circular plate structure considering the magneto-electro-elastic coupling effect. Figure3 (a) shows the displacement solution of the circular plate structure in the thickness direction of the two layers of different magneto-electro-elastic materials. Figure3 (b) is an exact solution of the 1-16 order natural frequency of a single-sided or double-sided coated circular plate structure.



(a) Displacement solution of two-layer circular plate (b) Natural frequency of the coated circular plate

Fig. 3. Semi-analytical solution of multi-layer circular plate structure considering magneto-electro-elastic effect

(b) A unified finite element scheme for multilayer anisotropic composite thin plates with piezoelectric effect is established. The natural characteristic of the damping coating plates is obtained, and compared with the semi-analytical solution using the transfer matrix method. The typical results are shown in Figure 4. Due to the application of the damping coating, the order of the 6th and 8th order modes of the thin plate are changed in comparison with the original state. The thickness of the coating has a significant effect on the natural frequency.



(a) Natural frequency and mode change (b) Coating thickness effect

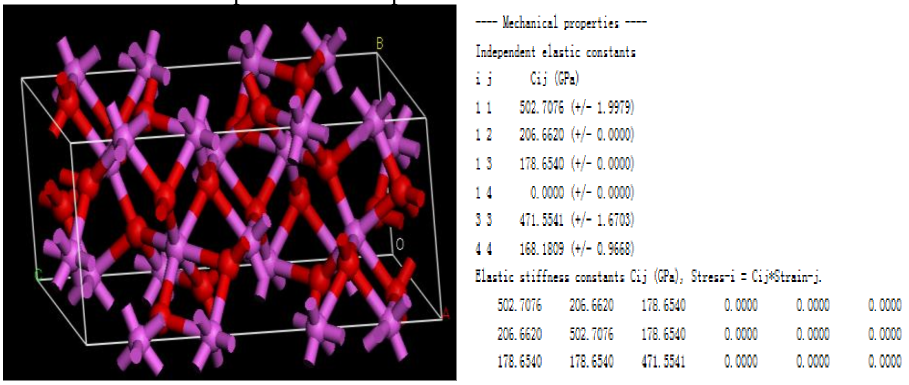
Fig. 4. Vibration characteristics of hard coated thin plates by finite element method and semi-analytical solution with transfer matrix method

4. Prediction of mechanical characteristic parameters and optimal design of vibration reduction for hard coating damping structures

A macro-meso-microscopic multiple scale mechanical analysis and numerical simulation method for the optimization design of hard coating damping structure for thin-walled component are proposed. The mechanical properties of the hard coat damping structure are predicted. The problem of theoretical calculation of mechanical properties of damping coating structure is solved. Based on the simulation of the interfacial slip and microcracks, the internal stress distribution and the interface failure critical stress of the coating structure under the action of normal and tangential combined loads are obtained; the optimization design of the hard coating of the thin-walled component is realized by the multi-objective optimization method, and is applied in the damping vibration reduction design of aero-engine thin-walled component[11-26].

(a) Application of Materials Studio molecular dynamics software to calculate the mechanical properties of damping coating and metal substrate. The mechanical properties such as Young's modulus, Poisson's ratio and elastic stiffness constant matrix of the metal oxide layer and metal layer are obtained. Fig.5 shows the ceramic-based hard coating material Al2O3 crystal model and the material properties parameter values calculated. The data obtained are the basis for the identification of damping performance parameters of hard coatings and the evaluation of their damping effectiveness.

(b) The molecular dynamics simulation of interface slip and microcracks of hard coats was carried out by LAMMPS software. The molecular dynamics model of metal with face-centered cubic structure was established, and the generation process of microcrack was simulated by applying strain rate. Figure 6 (a) shows the microstructural change between atoms, and the stress-strain relationship of the whole microcrack generation process is shown in Fig.6 (b). It can be seen that the stress peak appears when the dislocation occurs. There is another stress peak when the microcracks appear passivated, which is reasonable compared to the experimental observation.



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---- Mechanical properties ----
Independent elastic constants
i j       Cij (GPa)
1 1      502.7076 (+/- 1.9979)
1 2      206.6620 (+/- 0.0000)
1 3      178.6540 (+/- 0.0000)
1 4        0.0000 (+/- 0.0000)
3 3      471.5541 (+/- 1.6703)
4 4      168.1809 (+/- 0.9668)
Elastic stiffness constants Cij (GPa), Stress-i = Cij*Strain-j.
     502.7076    206.6620    178.6540     0.0000     0.0000     0.0000
     206.6620    502.7076    178.6540     0.0000     0.0000     0.0000
     178.6540    178.6540    471.5541     0.0000     0.0000     0.0000
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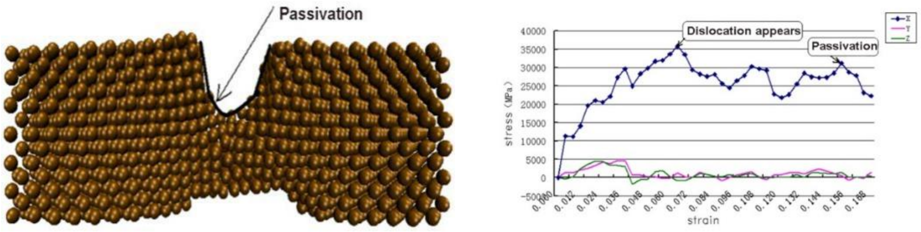
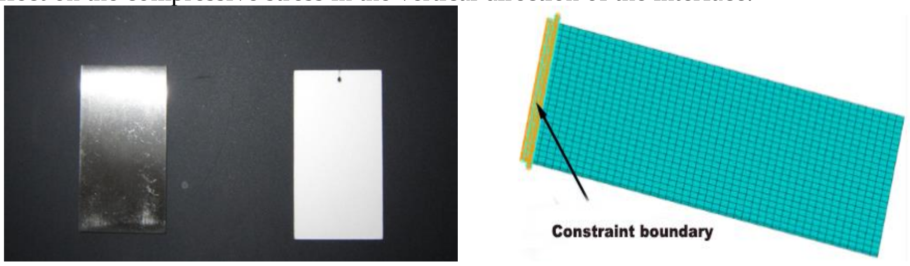
Fig. 5. Crystal model of Al_2O_3 coating and the mechanical properties parameters calculated by simulation



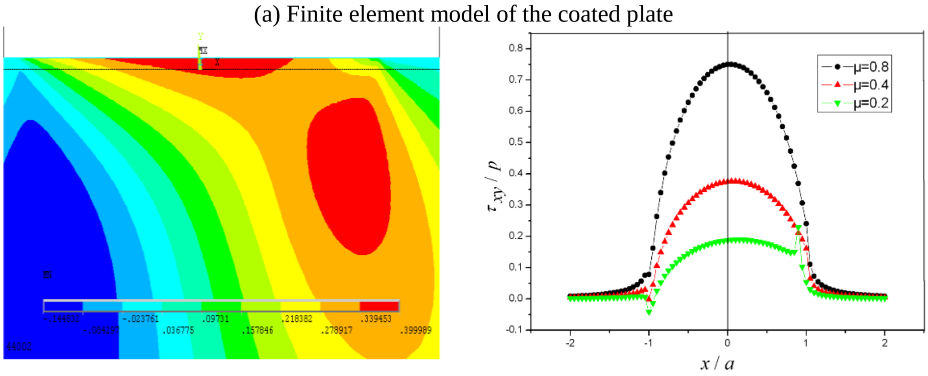
(a) Microstructural changes between metal atoms (b) stress-strain curve of structure in microcrack production

Fig. 6. Mechanism of the microcracks generation of hard coating based on molecular dynamics simulation

(c) On the macroscopic scale, the internal stress distribution rule and the interface failure critical stress of the coating structure under normal and tangential combined loads are simulated by finite element method. Fig.7 shows the shear stress cloud diagram of the hard coating structure and the trend of the shear stress of the interface under different friction coefficients. It can be seen that the increase of the friction coefficient makes the shear stress and Mises equivalent stress of the interface increase significantly, but has little effect on the compressive stress in the vertical direction of the interface.



(a) Finite element model of the coated plate



(b) Shear stress cloud diagram (c) Trend of the interface shear stress under different friction coefficient

Fig. 7. Analysis of Stress Change of Hard Coating Structure Based on Finite Element

(d) With the integrated damping capacity of the hard coating damping component, the amplitude of the resonance stress decreases and the uniformity of the high-order modal stress distribution as the target, the multi-objective optimization method is used to realize the mechanical characteristic parameters and geometric dimension optimization of the hard coat layer, and provide the basis for the active design of hard coating.

5. Conlcusions

In this paper, the high-order vibration characteristics, boundary conditions and vibration mechanism of rotating thin-walled component are descripted firstly. Then the damping mechanism of hard coating are simulated based on laminated structure considering the magneto-electro-elastic coupling effect. At last the prediction of mechanical characteristic parameters and optimal design of vibration reduction for hard coating damping structures were conducted.

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