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Vibration Modal Analysis of Continuous Fiber Reinforced Metal Matrix Composites Low Pressure Turbine Shaft

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Abstract. In the design of advanced aircraft turbofan engine, applying the continuous fiber reinforced metal matrix composites(MMC), which have excellent properties of good mechanics, resistance to high temperatures and light mass, to manufacture some of the key components is the effective way to realize thrust increase and weight decrease. In order to realize the design and analysis to the structural integrity of this sort of composite components, with the continuous fiber reinforced metal matrix composites low pressure turbine(LPT) shaft structure as the object of study, mesoscopic mechanics method is applied to calculate mechanics properties of continuous fiber reinforced MMC; On this basis, applying composite mechanics parameters calculated by representative volume element (RVE) model as input value, meanwhile, from the point of mesoscopic mechanics method like the specific arrangement mode of fiber and matrix and the mechanics properties of MMC shaft to analyse response regularities of MMC shaft modal frequency that caused by variation of fiber volume content, layer angle, layer amount and boundary conditions of the shaft structure.

Introduction

To improve the thrust-weight ratio of engine is always the goal that is tirelessly pursued in aerodynamic. LPT shaft is an important part of engine structure and to be designed on the purpose of reducing weight will effectively improve the thrust-weight ratio of engine. However, because of the limit of material strength, fatigue endurance and critical rotate speed, it has very limited potential to reduce weight of the shaft that is designed by traditional metal or alloy. The development and application of new material and new structure will be an important approach to break through the current level to realize thrust increase and weight decrease of the engine in the future. Therefore, it is much essential to study on the solution of aircraft engine composite shaft design [1-2]. Since Fiber Reinforced MMC has higher specific strength and specific modulus, it has been widely applied to aircraft and aero-engine.

When Wojciechowski [3] proceeded to the composite material study of turbo jet engine low pressure shaft, composite layer was designed along the axial because of the high specific modulus on the direction of composite fiber. This design applied MMC materials, the titanium matrix tungsten fiber composites. Compared with the resin matrix composites, the MMC has higher shear strength and more stable physical and chemical properties [4]. Domenick [5] applied a fiber laying direction of 14° when he proceeded to the composite material design of F404 jet engine drive shaft on the purpose of simultaneously satisfying the requirements of torque and rotational speed. After applying the MMC design, the critical rotating speed increased over the operation rotating speed, but with a small margin. Critical speed was further improved by particularly dealing with the installing side that made safety rotating speed margin increase above 20%. In recent years, some domestic scholars also proceed some research for composite shaft, such as HuJing.etc [6] that study on optimal design of torque performance of carbon fiber composite drive shaft and SunQingwei. etc[7] that study on optimal design of MMC main shaft.

The study shows that the current research in composite shaft is mainly based on the numerical simulation of finite element method on the basis of macro-mechanics which have not yet been from the microstructure change of MMC that will cause meso-mechanics performance change, thereby, causing effects on vibration of engine shaft structure. This article is based on the calculation model of meso-mechanics performance parameters of composite materials to analyse MMC mechanics performance parameters and then to apply the parameters to the analysis of vibration characters of the shaft structure, studying effects on turbine shaft structure vibration characters caused by changes in fiber volume content, fiber laying angle and layer amount.

Analysis of composite mechanics and vibration theory

Continuous fiber reinforced metal matrix composites shaft applying winding technology, as shown in fig.1, can be regarded as a kind of laminated structure that consists of multiple single layer with different directions and belongs to the category of macro mechanics, meanwhile, the single layer is RVE that consists of multiple continuous fiber and matrix and belongs to the category of meso-mechanics. Therefore, it should start from meso-mechanics to study vibration character of continuous fiber reinforced metal matrix composites low pressure turbine. Firstly, the RVE is regarded as the object of study to get its meso-mechanics properties. Secondly, take the computation result of meso-mechanics as the mechanical property of single layer continuous fiber reinforced metal matrix composite material [8], furthermore, the macro mechanical properties of the laminated continuous fiber reinforced metal matrix composites is calculated. Finally, the laminated continuous fiber reinforced metal matrix composites shaft structure is taken as the object of study to proceed structural mechanics analysis.

Stresses of each single layer in the global coordinate system are σ_x σ_z τ_{xz} , 1 is the main direction of fiber, 2 is the direction perpendicular to the fiber. The angle between the fiber and the overall coordinate system is θ as shown in Fig.1. Based on the transformation relationship of stress of the single layer under arbitrary coordinate system, σ_x σ_z τ_{xz} can be transformed into σ_1 σ_2 τ_{12} that is on the direction of fiber main axis, as shown in the equation (1).

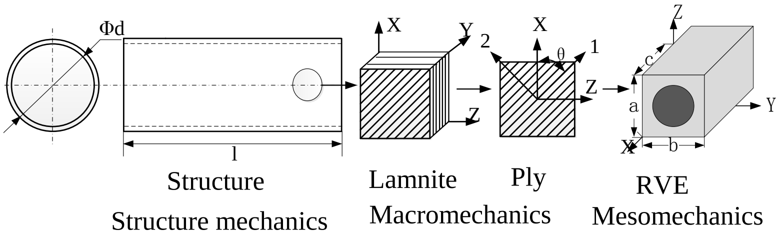

Fig.1: The relationship between fiber main axis and the structure of coordinate system

The stress transformation relations of single layer material under arbitrary coordinate system [9]

$$\begin{bmatrix} \sigma_x \\ \sigma_z \\ \tau_{xz} \end{bmatrix} = \begin{bmatrix} m^2 & n^2 & -2mn \\ n^2 & m^2 & 2mn \\ mn & -mn & m^2 - n^2 \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} \tag{1}$$

Among formula, $m = \cos\theta$, $n = \sin\theta$

By the classical laminated theory, the relationship of stress and strain of components is shown as follows:

$$\begin{Bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{21} & A_{22} & A_{26} & B_{21} & B_{22} & B_{26} \\ A_{61} & A_{62} & A_{66} & B_{61} & B_{62} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{21} & B_{22} & B_{26} & D_{21} & D_{22} & D_{26} \\ B_{61} & B_{62} & B_{66} & D_{61} & D_{62} & D_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \\ k_x \\ k_y \\ k_{xy} \end{Bmatrix} \tag{2}$$

Among formula, [A], [B], [D] are all symmetric stiffness matrix; N_x is axial tension (pressure) stress, N_{xy} is shear force, M_x、M_y are bending moments, M_{xy} is torque, $\varepsilon_x{}^0$,$\varepsilon_y{}^0$,$\gamma^0{}_{xy}$ are strain on the laminated plate, k_x、k_y are rate of curving on the laminated plate, k_{xy} is warp rate on the laminated plate.

Vibration mode analysis to the analysis of free vibration of undamped structures, the structure modal equation is,

$$[M]\{\ddot{D}\}+[K]\{D\}=\{0\} \tag{3}$$

Among formula, $\{0\}$ is zero Vector, when $\{D\}$ go through harmonic motion, it can be shown as,

$$\{D\}=\{\overline{D}\}\sin\omega t\,;\ \{\ddot{D}\}=-\omega^2\{\overline{D}\}\sin\omega t \tag{4}$$

Among formula, vector $\{\overline{D}\}$ contains amplitude of vector $\{D\}$, therefore, the eigenvalue of equation (4) can be shown as,

$$\left([K]-\omega^2[M]\right)\{\overline{D}\}=\{0\} \tag{5}$$

When laminated cylindrical shell rotate along the axial direction, centrifugal force of shell on radial direction can be seen as the Initial load caused by the initial stress. So, stiffness matrix $[K]$ in equation (5) can be resolve to,

$$[K]=[K_L]+[K_\sigma] \tag{6}$$

Among formula, $[K_L]$ is the traditional linear stiffness matrix, $[K_\sigma]$ is geometric stress stiffness matrix caused by centrifugal force, equation (5) can be shown as,

$$\left([K_L]+[K_\sigma]-\omega^2[M]\right)\{\overline{D}\}=\{0\} \tag{7}$$

The equation above is characteristic value expression. If vector $\{\overline{D}\}$ is not zero, then we must have

$$\left|[K_L]+[K_\sigma]-\omega^2[M]\right|=0 \tag{8}$$

Prediction of SiC/Ti mechanics behaviors parameters

SiC continuous fiber reinforced titanium matrix composites have high specific strength and specific stiffness, well performance in resisting high temperature ,creep and fatigue so that it is the perfect light and high temperature resistant structure material of aero-engine appropriately for 700- 900℃. SiC/Ti is typical material of low pressure turbo shaft of new generation high thrust-weight ratio aero-engine. The material parameters are shown in Table1.

Table 1: Fiber and metal of material properties

mechanical property	Young's modulus /GPa	Poisson's ratio	Fiber diameter/μm
SiC	415	0.3	140
Ti	113	0.42	-

The distribution of continuous fiber reinforced metal matrix composites reinforce composition in matrix have certain regularity and statistical equalization so that RVE can be separated and the whole composite body can be seen as being made up periodically by RVE. When composite microscopic structure constituted by the periodic extension of RVE bear symmetrical external load, because of all the RVE are similar, there are similar stress and strain field which can reflect Mesoscopic stress and strain field by using a RVE stress and strain field. Therefore, it can be applied on a RVE mesoscopic mechanics finite element method (FEM)[10-15], calculating the mesoscopic stress and strain field in order to gain the macroscopic stress-strain response of composite material body. The rule that SiC/Ti mesoscopic mechanics performance changes with the fiber volume fraction based on the RVE finite element method (FEM) is shown in Fig.2.

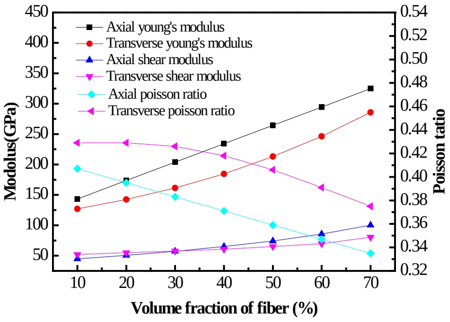

Fig.2: Effects of modulus and Poisson ratio caused by changing volume fraction of fiber

Fig.2 shows that axial young's modulus and axial shear modulus calculated by RVE finite element model increase along with the increasing of fiber volume fraction and axial Poisson's ratio decrease along with the increasing of fiber volume fraction. The radial Young modulus and the radial shear modulus also increase along with the increasing of fiber volume fraction and the radial Poisson's ratio decrease along with the increasing of fiber volume fraction.

Influence of SiC/Ti low pressure turbine shaft layer schemes on vibration mode

Any kinds of rotating machinery, especially for aero-engine, will hardly avoid appearing rotor vibration in operation, especially the vibration nearby critical rotating speed. For aircraft and engine, rotor is the vibration source. The work condition of aero-engine changes frequently include start, low rotating speed, cruise, speed-up etc. This will request the work rotation of engine main shaft changes in a large margin. Proceeding the dynamic analysis of rotor is mainly to avoid vibration, so that the vibration response of shaft is not too much intense. Subcritical design requires that top operating rotation will be under the critical rotating speed and the subcritical design should also ensure a safety rotating margin. A main aspect of composite layer design is to increase critical rotating speed of the shaft so that the safety margin will increase. With aero-engine low pressure shaft structure as an example, SiC/Ti composite low pressure shaft FEM (finite element model) is built as shown in Fig.3, and then effect regularities of the modal frequency of SiC/Ti composite low pressure shaft structure which are caused by different values of layer angle, layer amount and boundary conditions are shown in Fig.4-6.

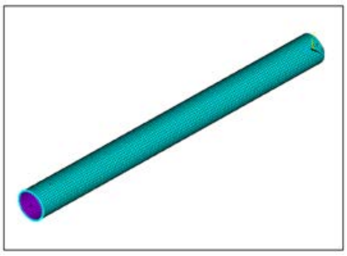

Fig.3: SiC/Ti composite shaft finite element model

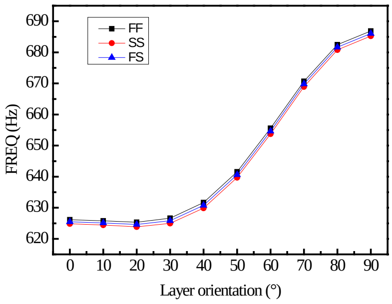

Fig.4: The effect rule caused by the changes of laying angle and margin condition

Fig.4 shows that effect caused by the change of laying angle to SiC/Ti low pressure turbo shaft mode frequency is very large. The mode frequency increase along with the increasing of laying angle and the mode frequency will meet the top value when laying angle is 90°.The change of the margin condition has very little effect to SiC/Ti low pressure turbo shaft mode frequency and it will meet the top value when it is clamped while it will meet the least value when it is simply supported.

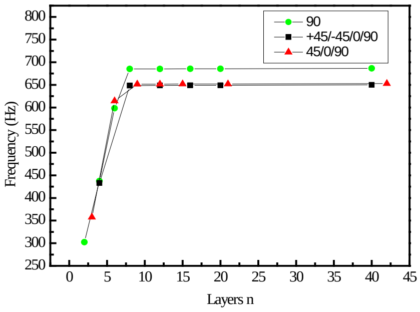

Fig.5: The effect rule caused by the changes of layer amount

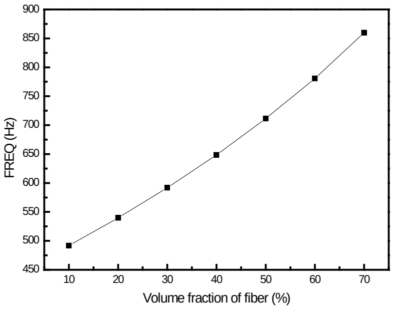

Fig.6: Effects of SiC/Ti composite low pressure shaft structure modal frequency caused by fiber volume fraction variation

Fig.5 shows that when the amount of layer is less than 10, the change of the amount of layer has very large effect to mode frequency and if the amount is more than 10, the mode frequency is substantially unchanged. Fig.6 shows that when fiber volume fraction increases just as the ply increase in every layer, with the fiber volume fraction increasing, the modal frequency of SiC/Ti composite low pressure shaft structure increases. The more the fiber volume fraction increases, the more the modal frequency of SiC/Ti composite low pressure shaft structure increases. However, as the limit of fiber arrangement geometry in matrix, fiber volume fraction can only reach as big as 70%.

Conclusions

Based on the numerical results of this investigation, the following conclusions may be drawn:

(i) With the increasing of fiber volume fraction, the modulus of continuous fiber reinforced metal matrix composites increases, on the contrary, the poisson ratio decreases. That is to say, with the increasing of fiber volume fraction, continuous fiber reinforced metal matrix composites will have a better ability to resist shape change.

(ii) The natural frequency of continuous fiber reinforced metal matrix composites low pressure turbine shaft structure changes with the laying angle and the layer amount. When laying angle is 90°, natural frequency will reach the top value. When the amount of layer is less than 10, the change of the amount of layer has very large effect to natural frequency and if the amount is more than 10, the mode frequency is substantially unchanged. The changes of boundary condition have very little effect on the natural frequency of continuous fiber reinforced metal matrix composites low pressure turbine shaft structure. Analysing the effect regularities of SiC/Ti composite low pressure shaft natural frequency caused by fiber volume content from the perspective of fiber and matrix mesoscopic arrangement, it can be concluded that the variation of fiber volume content have great effects on the natural frequency of SiC/Ti composite low pressure shaft structure.

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