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A Preliminary Evaluation Method For Fan Blade Rubbing Stability Based On Finite Element Analysis

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ABSTRACT

A tighter fan blade-casing clearance is desired to obtain better aerodynamic efficiency and stability in the aero engine. But the risk of blade-casing rubbing will increase and lead to unexpected blade vibrations or damage. Unstable rubbing will damage the engine structure and should be avoided. Fan blade rubbing stability must be evaluated during the initial design phase. At present, many scholars use numerical analysis research methods, this method involves many parameters, and the analysis process is complex. This paper adopts a simple and relative method to evaluate the fan blade rubbing stability. The rubbing loads are applied on the tip of the fan blade and the deformation of the tip nodes are obtained. By comparing the rubbing force and the amplitude of the tip deformation, a relative rubbing stability of different design of fan blade could be achieved. The results of this method are compared with that calculated by delayed differential equation. The agreement of these results shows the validity of this method.

INTRODUCTION

With the development of technology and the needs of practical applications, high thrust, high aerodynamic efficiency and high stability have become the primary indicators of aero-engine design, In order to achieve this purpose, the engine designer usually reduce the fan blade-casing clearance as much as possible, which will make the blade and the casing to occur with the chances of rubbing, because the blade tip part of the rotation line speed is larger, so rubbing caused by the blade impact is also larger. According to the U.S. Department of Transportation, in the 14 years since 1962, approximately 10% of the more than 40 million flight hours recorded have been caused by rubbing between rotors and stators(Ikeda et al., 1988). Therefore, before the engine is put into operation, we should fully consider rubbing phenomenon between the balde and the casing, assess the fan blade rubbing stability. At present the domestic and foreign research blade-casing rubbing problem mainly focus on numerical analysis and experimental two methods.

In terms of numerical analysis: Liu Shuguo et al, based on the LS-DYNA program platform, numerically simulated the transient blade-casing rubbing process from contact mechanics and collision dynamics, and thus analyzed the dynamic response of the blade caused by the rubbing(Liu et al., 2011). Legrand et al, applied the theory related to contact mechanics to establish a numerical model of full three-dimensional blade rubbing, and applied the results to the testing of blade rubbing vibration(Legrand et al.,2012). Ma et al, considered the deformation of the blade and the casing and proposed a model of the normal friction during the rubbing process, which better reflects the dynamics of the blade during the rubbing process(Ma et al., 2015). Turner et al studied the kinetic characteristics of the blade and the casing when the rubbing occurs continuously by replacing the rubbing force with an impulse force as a way to simplify the rubbing process(Turner et al., 2012a, Turner et al., 2008b). Chen Dawei et al constructed a parametric model of the fan blade structure to determine the rubbing characteristics of different shaped blades based on the wear degree of the wear-resistant coating(Chen et al., 2021).

In terms of experiments: Padova et al, used equipment in the gas turbine laboratory at Ohio State University to investigate the problem of rubbing of titanium fan blades at high speed rotation(Padova et al., 2012). Wei et al. conducted experiments on large bypass ratio fans, the phenomenon of turbine blades rubbing against the casing occurred accidentally, and then a fault tree analysis was used to elaborate the causes, and finally the problem was improved by improving the tip clearance, reducing the starting speed, and increasing the axial length of the wear-resistant coating(Feifei et al., 2015). Chen Guo et al. proposed a new rubbing model based on the traditional elastic rubbing model, taking into account the variation of the number of blades and the tip clearance of the blades, and subsequently carried out a full circumferential rubbing experiment using the engine experimental equipment with the attached casing(Chen et al., 2015).

Combined with the above survey, although both numerical analysis and experimental methods can better analyze the blade-casing rubbing process, but the numerical analysis method needs to establish a complex dynamic model according to the structural characteristics of the blade, while the results of finite element analysis usually only play a verification effect. Although the experimental method is relatively straightforward, it costs a lot of effort to build the test platform, and the economic cost is extremely high.

Based on the above investigation, this paper directly adopts the method of finite element analysis and establishes three-dimensional fan blade finite element models through ANSYS. Since the rubbing process mainly occurs at the position of the leading edge of the blade tip originally, the rubbing process is simplified to a quasi-static processes fristly, a gradually increasing rubbing force applied to the chord length of the specified portion of nodes, while a displacement constraint is applied to the bottom of the airfoil. The radial displacement of the nodes at the trailing edge of the blade tip is observed through ANSYS processor Post26, and then evaluate the rubbing stability of different blade designs according to the relative characteristics of the force-displacement curve.

METHODOLOGY

Basic Assumption

In this paper, to simplify the finite element model, the vibration of the blade is not considered during the rubbing, and according to the actual operation of the engine, the rubbing force suffered by the fan blade during the rubbing can be decomposed into three components: Axial force F_t, circumferential force F_a, radial force F_r, as shown in Figure 1. In general, the axial component of the rubbing force is smaller than the circumferential and radial components(Salvat et al., 2013, Olgac et al., 2014), so the rubbing force is simplified to two portion: a radial rubbing force along the radial direction(F_r) and a tangential rubbing force perpendicular to the blade pressure face(F_{at}).

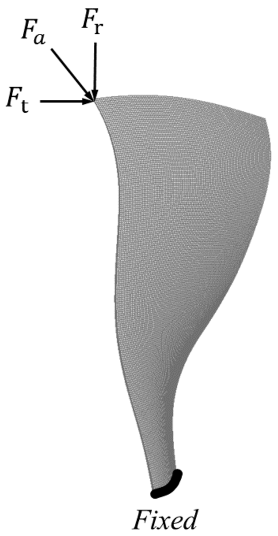

Figure 1 Illustration of Blade Tip Rubbing Force

Assuming that the rubbing process conforms to Cullen's law of friction, the radial force F_r and tangential rubbing force F_{at} received by the leading edge of the blade tip satisfy the following relationship:

$$F_{at} = \mu F_r$$

Among them, μ is the friction factor of the blade-casing rubbing, which is influenced by several actual operating parameters of the fan blade and the structure of the blade and casing.

Nextly, only the airfoil part is selected to build the finite element model in this paper, and displacement constraints are applied on the flow path line. The rubbing stability assessment of the selected displacement point for the node on the trailing edge of the blade tip, because of the special torsional structure of the blade, the trailing edge of the blade tip may buckle when rubbing occurs at the leading edge, it is because of this phenomenon, so that the rubbing process will produce instability factors.

Based on the above assumptions and conditions, to carry out finite element analysis of blade rubbing, the logic flow chart is shown in Figure 2.

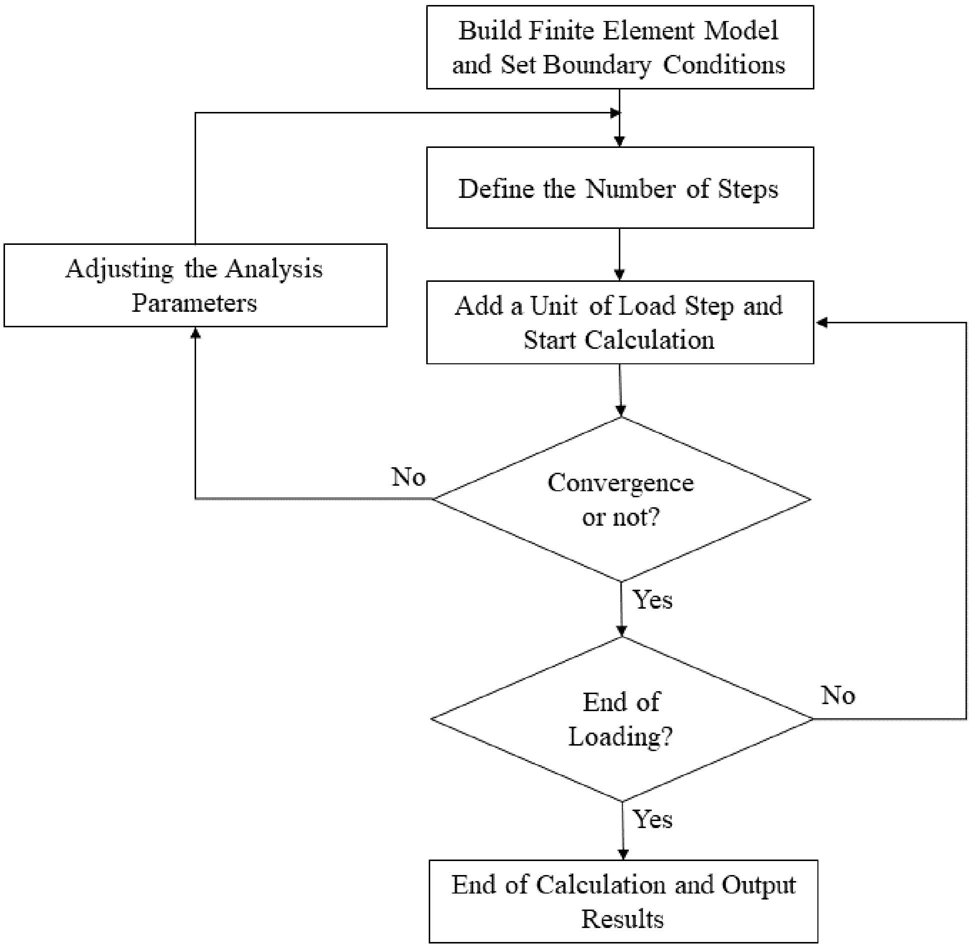

Figure 2 Flow Chart of Finite Element Analysis Logic

Simplified Finite Element Model Of Blade Rubbing

To show the feasibility of the method, the finite element analysis was carried out using composite fan blade and titanium alloy fan blade respectively, in which the composite fan blade model was finite element modeled using SOLID185 element type, and the finite element model was divided into 101505 nodes, the airfoil is divided into 4 elements in the thickness direction, 100 elements in the width direction and 200 elements in the height direction. The titanium alloy fan blade model also adopts SOLID185 element type for finite element modeling, and the finite element model is divided into 112211 nodes, the airfoil is divided into 10 elements in the thickness direction, 100 elements in the width direction and 100 elements in the height direction. The titanium alloy fan blade used in this article is the TC4 titanium alloy wide chord fan blade of a certain type of large-containment-ratio turbofan engine, the details of the parameters are shown in Table 1. The parameters of carbon fiber material and resin material used for layup of composite fan blade are shown in Table 2 and Table 3. The airfoil finite element models are shown in Figure 3 and Figure 4.

Parameters	Value
Material	TC4
Densities Kg/m^3	4453
Elastic modulus GPa	112
Poisson's ratio	0.32

Table 1 Titanium Fan Blade Parameters

Para meters	Value
Densities Kg/m^3	1490
X Tensile strength MPa	2231
Y,Z Tensile strength MPa	29
X Compression strength MPa	-1082
Y,Z Compression strength MPa	-100
XY, XZ Shear strength MPa	60
YZ Shear strength MPa	32

Table 2 Carbon Fiber Parameters

Parameters	Value
Densities Kg/m^3	1160
Elastic modulus MPa	3780
Shear modulus of elasticity MPa	1400
Poisson's ratio	0.35

Table 3 Resin Parameters

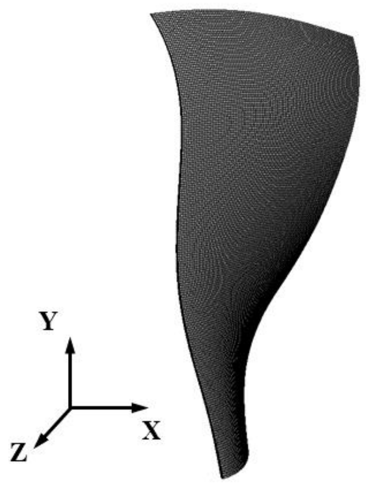

Figure 3 Finite Element Model of Composite Fan Blade

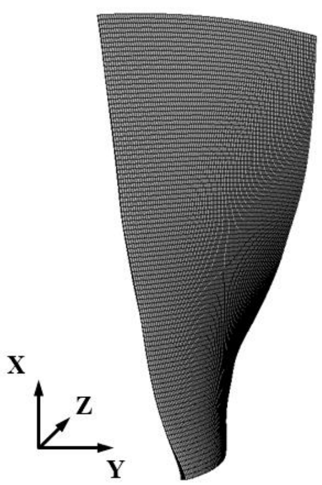

Figure 4 Finite Element Model of Titanium Alloy Fan Blade

The blade-casing rubbing is a complex process, including single point, multi-point, local and full circumferential rubbing. In this paper, 2.5%, 3% and 3.5% of the maximum chord length of the blade tip will be taken as the rubbing area, and the rubbing force will be applied on this area, combined with the literatur(Wang, 2018; Chen et al., 2015), the friction factors of 0.1, 0.2, 0.3 and 0.4 will be taken to determine the direction of the combined rubbing force. The all-directions displacement constraints imposed on the finite element model of the fan blade are shown schematically in Fig 5, and the load application is shown in Fig. 6

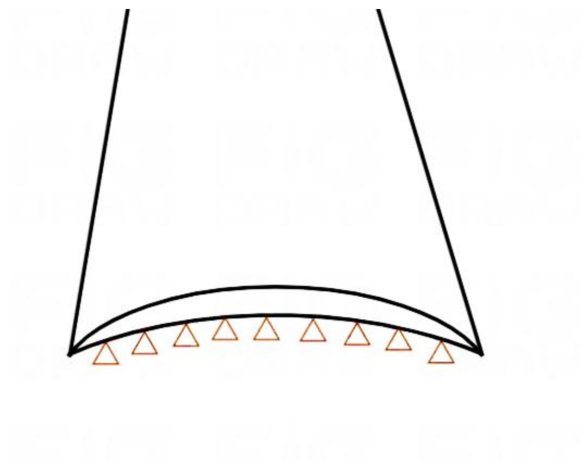

Figure 5 Blade Airfoil Bottom Displacement Constraint

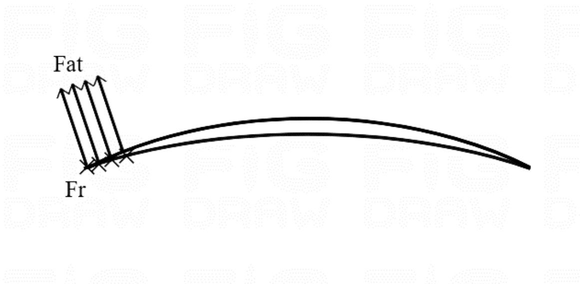

Figure 6 Diagram of Radial and Circumferential Forces

RESULTS AND DISCUSSION

Most of the flow path of current engine casing design for convergence flow path. When the rubbing process occurs, blade trailing edge do not directly towards the direction of the center of rotation deformation, it first briefly buckled insteadly, with the increase of the rubbing force, it will produce a displacement toward the center of rotation, as the trend shown in the curve. When the radial displacement of the trailing edge back to 0, the lower the radial rubbing force, it means that the blade in the rubbing process and the casing of the touching force is smaller, the higher the structure stability during rubbing. The lower the peak value of the curve, the lower the probability that the trailing edge will continue to rub after the leading edge has touched, and the higher the stability of the rubbing.

The force-displacement results obtained from the finite element analysis of the composite fan blade are shown in Fig 7 (2.5% portion of nodes, it means 2.5% of the maximum chord length of the blade tip), Fig 8 (3% portion of nodes) and Fig 9 (3.5% portion of nodes). While the analytical data results of the titanium fan blade are shown in Fig 10 (2.5% portion of nodes), Fig 11 (2.5% portion of nodes) and Fig 12 (3% portion of nodes), where the horizontal coordinates $f_r(\%)$ are the single node normalized radial rubbing force and the vertical coordinates $U_r(\%)$ are the normalized radial displacement of the blade tip trailing edge.

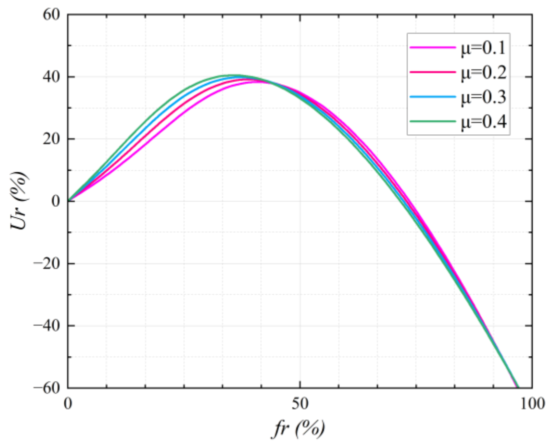

Fig 7 Force-Displacement Curve of the Composite Fan Blade When 2.5% Rubbing Force is Applied

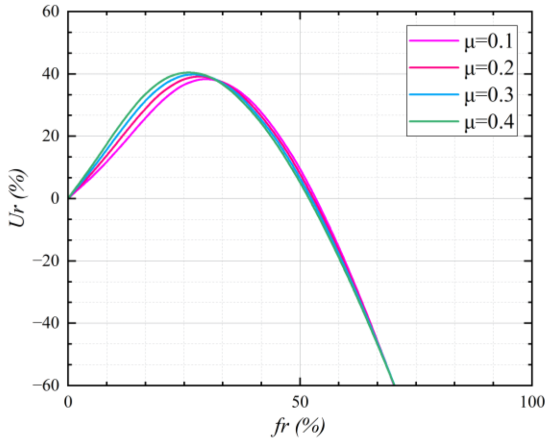

Fig 8 Force-Displacement Curve of the Composite Fan Blade When 3% Rubbing Force is Applied

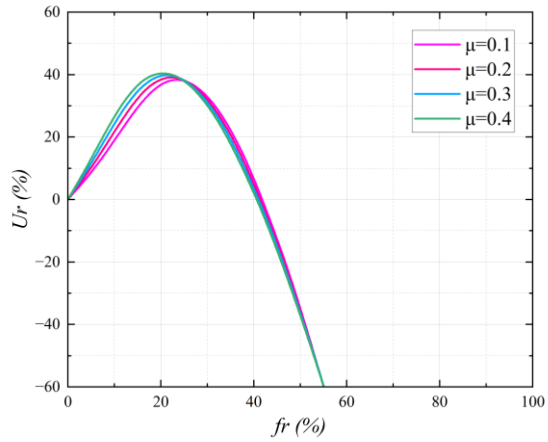

Fig 9 Force-Displacement Curve of the Composite Fan Blade When 3.5% Rubbing Force is Applied

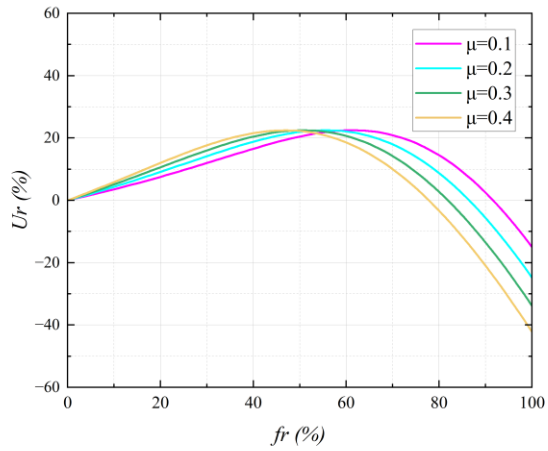

Fig 10 Force-Displacement Curve of the Titanium Fan Blade When 2.5% Rubbing Force is Applied

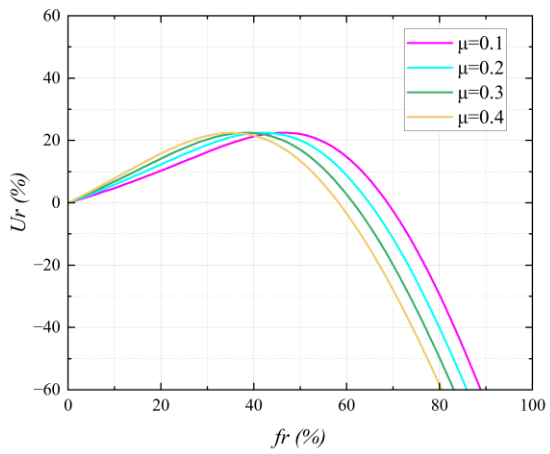

Fig 11 Force-Displacement Curve of the Titanium Fan Blade When 3% Rubbing Force is Applied

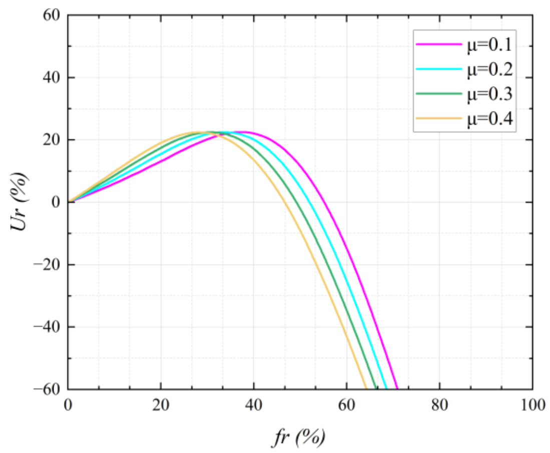

Fig 12 Force-Displacement Curve of the Titanium Fan Blade When 3.5% Rubbing Force is Applied

By analyzing the above curve, we can get, when the composite fan blade rubbing occurs at 2.5% of the blade tip, the force-displacement curve and x-axis intersection is concentrated in 72%, when the rubbing occurs at 3% of the blade tip, the force-displacement curve and x-axis intersection is concentrated in 52%, when the rubbing occurs at 3.5% of the blade tip, the force-displacement curve and x-axis intersection is concentrated in 41%, considering that the number of nodes applied by the rubbing force is different, in the simulation, considering the different number of nodes, the number of nodes applied in the simulation of 2.5%, 3% and 3.5% of the composite fan blade are 120, 165 and 210 respectively, combined with the influence of the number of nodes, we can finally judge that the influence of the rubbing stability with the rubbing area is very small, at the same time, for the composite fan blade, we can also see from the graph that the influence of the friction factor on the friction stability is also very small.

The same can be analyzed for the titanium fan blade, take the friction factor as 0.1, when the touching range is 2.5%, the intersection point is 91%, when the touching range is 3%, the intersection point is 69%, when the touching range is 3.5%, the intersection point is 55%, analyze the titanium alloy fan blade 2.5%, 3%, 3.5% touching when the number of nodes exerted by the touching force is 33, 44, 55, respectively, so that It can be concluded that, similar to the composite fan blade, the influence of the rubbing area on the rubbing stability is relatively small, but the difference is that the friction factor has a greater influence on the rubbing stability of the titanium fan blade.

In order to compare the rubbing stability of compound fan blade and titanium fan blade, now the rubbing force in the finite element analysis to do the normalization process, because in a very small parameter change range, the blade displacement change is not large, so take 3% rubbing region, 0.2 friction factor to analysis, as shown in Figure 13, and the zero point is marked with triangle symbol, the peak value is marked with circle symbol. The blade peak at the radial displacement contour as shown in Figure 14.

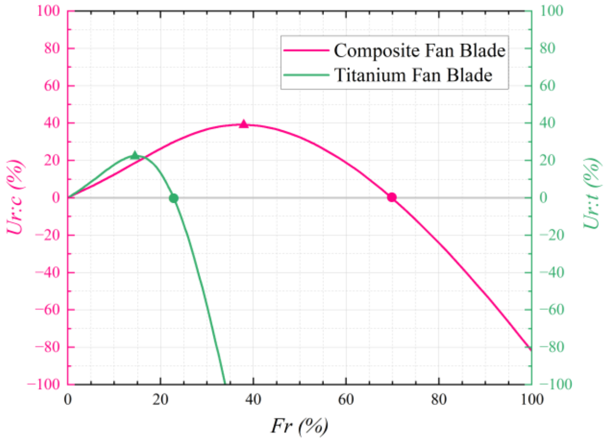

Figure 13 Comparison of the Rubbing of Titanium and Composite Fan Blades

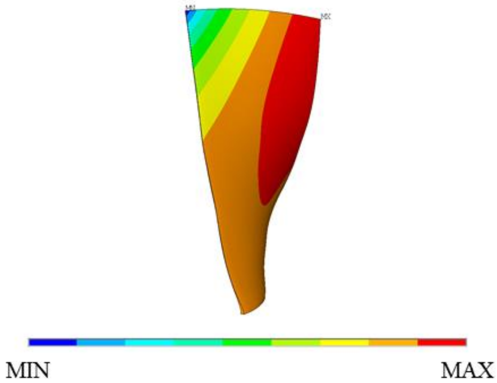

Figure 14 Radial Displacement Contour at the Peak of the Titanium Fan Blade

It can be concluded from the figure 13 that the rubbing force between the blade and the casing is less than 25% when the titanium fan blade occur rubbing phenonmenon, while the rubbing force between the blade and the casing is less than 70% when the composite fan blade occur rubbing phenonmenon, in addition, the peak of the radial displacement of the titanium fan blade is only half of that of the composite fan blade, so the rubbing stability of the titanium fan blade is higher than that of the composite fan blade.

With regard to the structural stability of the blade during rubbing, Xiao Jia analyzed the structural failure risk of titanium and composite fan blades during the rubbing, and the results showed that although the rubbing vibration response of the titanium fan blade is larger, the maximum Mises stress level of its blade is slightly smaller than that of the composite fan blade, it mean that there is no significant structural failure risk(Xiao Jiaoguangyi, 2021). And this conclusion is consistent with the conclusions obtained from the method described in this paper.

CONCLUSIONS

①In this paper, a finite element analysis-based rubbing stability assessment method was established by establishing a finite element model and some basic assumption. It show a simple practicability and clear physical significance by appling on the comparision between composite and titanium alloy fan blades.

②The force-displacement curves of titanium alloy and composite fan blades in the rubbing process are obtained by finite element analysis method, and it can be found that under the same rubbing conditions, the force of titanium alloy fan blades in rubbing with the casing is smaller, which means that the probability of structural failure of the blades is lower than that of composite fan blades. And the maximum displacement of the trailing edge of the titanium alloy fan blade is smaller than composite fan blade, so it have a higher rubbing stability.

At the same time this paper in the establishment of this analysis method, did not consider the blade vibration and the role of the casing, in future research will do further improvement and development of the model.

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