Influence on the Flutter Characteristics of Hollow Fan Blade with Different Rib Number

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Abstract. The wide-chord hollow fan blade was one of the new technology which had been applied on the aeroengine. It could effectively improve the performance of aeroengine. The energy method had been used to analysis the influence of the different rib number on the flutter characteristic of the hollow fan blade. The results show that the hollow structure does not change the distribution location of the unsteady aeronautical power. The rib can improve the anti-vibration characteristics of hollow blade. When the rib number is four, the aerodynamic damping ratio is higher than the basic solid blade under the same phase angle which can extend the adaptive capacity for the poor working contexts.

Keyword: Wide chord · Hollow-blade · Energy method · Flutter · Rib number

The fan blade is one of the key components of large bypass ratio turbofan engine. Compared with the original blade, the wide-chord blade can effectively increase the compressor surge margin, increase the redundancy degree of external damage, and improve the engine thrust. The use of wide-chord blade can also reduce the number of compressor blades. However, the height and the centrifugal load of fan/compressor blade is continuous increasing with the development of large bypass ratio turbofan engine towards high power, high load and high performance. In order to meet its reliability, it is necessary to further increase its disk mass. The wide-chord hollow fan blades were investigated to solve this problem. The weight loss of hollow blade leads to the reduction of blade rigidity which makes the possibility of blade flutter increasing [1, 2]. Therefore, the research on the blade flutter prediction occupies an important position in the design of hollow fan.

The flutter of the hollow fan blade is a new problem in turbomachinery flutter. Scholars at home and abroad have carried out relevant research on this problem. Vahdati M. and other researchers have [3] studied the flutter characteristics of wide-chord fan blades by means of fluid-solid coupling method. They think that the flow separation is the key factor affecting the stall flutter of blades, and the acoustic flutter is mainly related to the reflection of acoustic wave. The research results has a certain promotion effect on understanding the flutter mechanism of wide-chord blades. However the blade model is solid

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blade which cannot truly reflect the flutter characteristics of wide-chord hollow blades of turbofan engines. Chew J.W. and others have [4] studied the flutter characteristics of two different kind of the transonic fan blades at different speed conditions. The two kind of fan blades represent respectively typical fan blades used in military turbofan engines with small bypass ratio and civil turbofan engines with large bypass ratio. The advanced linear method and unsteady nonlinear method were used to calculate the unsteady flow field. The research direction of domestic scholars on wide-chord hollow fan blade mainly focuses on the structure of wide-chord hollow fan blade. Ma lei [5] discussed the influence of the number and thickness of rib on the structural strength, maximum deformation and vibration of hollow blades. Ji Fusen and others [6] explored the structural design and rapid strength analysis method of coreless hollow fan blade aiming at the application research of wide-chord hollow fan blade technology in the design of large bypass ratio aeroengine. The geometric characteristic parameters of the coreless hollow blade were defined. Also the influence of the number and width of ribs on the strength and stiffness of hollow blade were analyzed emphatically in the research. Wu Xinchen [7] carried out the research on the key manufacturing technology of two-layer TC4 titanium alloy hollow fan blades based on SPF /DB which captured some key manufacturing technologies. Yu Yang and others [8] analyzed the design parameters of hollow blade model cavity and stiffener in the structural design parameters of wide-chord hollow fan. The research results show that the increase of the number of ribs or the increase of the thickness ratio of ribs to skin has little influence on the maximum stress value of skin, but has a great influence on the maximum stress value of rib. Wang Ying and others [9] studied the transient response of wide-chord hollow fan blade under aerodynamic effect by using numerical simulation method. The deformation response under the unsteady boundary also was obtained. Yang Wen and others [10] used numerical simulation method to study the modal characteristics and response characteristics of wide-chord hollow fan blades under impulse excitation. The results show that the deformation of fan blades used in the study is mainly bending deformation during vibration.

To sum up, there is little research on the flutter characteristics of wide-chord hollow blades. Based on a solid blade, a set of wide-chord hollow fan blades with different numbers of ribs are designed. The flutter characteristics of wide-chord hollow blades with different numbers of ribs are calculated by using the energy method. The influence of the number of ribs on the flutter characteristics of hollow blades under the same compressor condition is emphatically studied, which provides some technical support for the flutter prediction of hollow blades in the design stage.

1 Numerical Simulation Method

1.1 Energy Method

The structural dynamics method was used to get the vibration mode, vibration frequency and amplitude distribution of the blade. These rules are incorporated into the numerical simulation of the three-dimensional unsteady viscous flow field. The moving rules of the grid near the blade wall are obtained by assuming the blade simple harmonic vibration. The harmonic balance method is used to calculate the three-dimensional unsteady flow field. It is a frequency domain method for unsteady flow field calculation in compressor internal flow channel. The method not only has good nonlinear simulation ability, but also has some advantages in computational efficiency.

The energy method is a commonly used flutter boundary prediction method. The energy method adopts the viewpoint of energy to establish the criterion of aerodynamic stability. In the case of neglecting mechanical damping, whether the blade flutter occurs or not is judged by the positive or negative energy exchange between the blade and the surrounding gas in a vibration period. The unsteady average accumulate power in a vibration period is used as the judgment quantity in the analysis. The unsteady mean accumulated power is defined as follows [11–13]:

$$P(\vec{\boldsymbol{x}}) = \frac{1}{T}\int_{t0}^{t_0+T} p(\vec{\boldsymbol{x}}, t)\vec{\boldsymbol{V}}(\vec{x}, t)\cdot\vec{\boldsymbol{n}}(\vec{x}, t)\mathrm{dt}\ \forall\vec{\mathrm{x}}\in\partial\mathrm{B} \tag{1}$$

In formula (1): T is the vibration period of the blade. t_0 refers to any time after the unsteady flow field is completely established. $p(\vec{\mathbf{x}}, t)$ refers to the static pressure. $\vec{\boldsymbol{V}}(\vec{x}, t)$ refers to the velocity vector. $\partial\mathrm{B}$ refers to the surface of the blade. $\vec{\boldsymbol{n}}(\vec{x}, t)$ refers to the unit vector in the direction of the inner normal of the blade surface. The total power of the unsteady force of the fluid on the blade L can be obtained by integrating the unsteady accumulated power along the surface of the blade:

$$L = \iint_{\partial B} P(\vec{\mathbf{x}})dS \tag{2}$$

When the unsteady total power is greater than 0, it is considered that flutter will occur according to the criterion of energy method., the unsteady time-average accumulated power per unit blade surface area $L\mathrm{s}$ is used in order to analyze the blade flutter more conveniently. $L\mathrm{s}$ is defined as below:

$$L\mathrm{s} = L/s \tag{3}$$

The aerodynamic damping coefficient Ξ is used to judge the aeroelastic stability of blades to compare the possibility of flutter of different blades under different conditions. The aerodynamic damping coefficient is defined as follows:

$$\Xi = \frac{-W}{\pi X_0 c(\overline{P_t} - \overline{P})} \tag{4}$$

In formula (4): W refers to the work done by the aerodynamic force in one period. X_0 refers to the amplitude of the blade. c is the chord length of the blade. $\overline{P_t}$ refers to the total pressure of the incoming flow. $\overline{P}$ refers to the static pressure of the incoming flow. If the mechanical damping and other factors can be neglected,, the blade is aeroelastic stable when the aerodynamic damping coefficient is greater than 0.

2 Calculation Model

According to different design requirements, the cavity inside the blade can be designed into different structural forms. With the development of wide chord hollow blades, the first generation of honeycomb hollow blades have been replaced by hollow blades with truss core and centerless structure. Figure 1 shows the hollow blades with different structures. Therefore, it is carried out that the research on aeroelastic stability of wide-chord hollow blade with coreless structure in this paper [14].

The design parameters of wide-chord hollow [15] blades with coreless structure mainly includes: the rib number N, the rib width W, the vane basin thickness of the cavity H1 the blade back thickness H2. A set of wide-chord hollow blade with different rib number are designed accord to the design parameters of wide-chord hollow blades with coreless structure based on that first stage blade of a fan (Fig. 2).

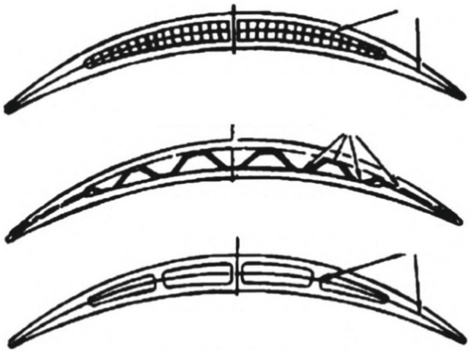


Fig. 1. Schematics diagram of hollow blade with different internal structure

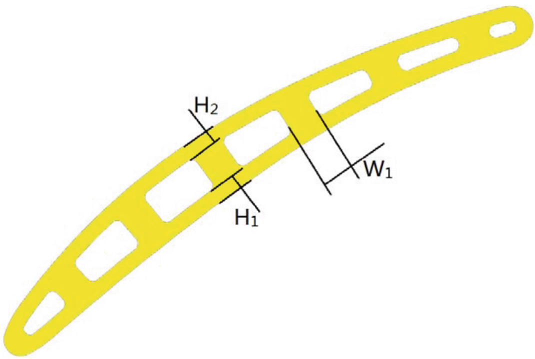


Fig. 2 The parameters of hollow blade with ribs

3 Calculation Results and Discussion

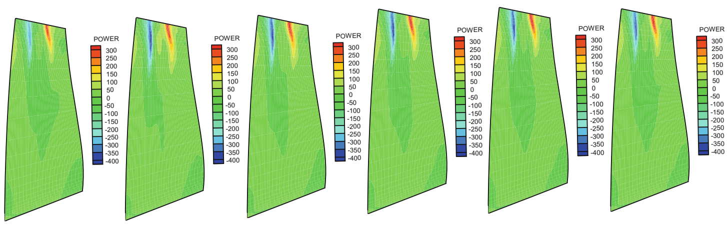
The main conditions of the design point are shown as below. The rotor design speed is 1122.596 rad/s. The inlet total pressure of the rotor is 101325 Pa. The total temperature is 288 K, and the outlet back pressure is 94700 Pa. The blade material is titanium alloy TC4 whose density 4440 kg/m^3, elastic modulus 109 GPA and Poisson's ratio 0.2386.

The first-order natural frequencies of different blades are obtained by structural dynamics calculation. Table 1 shows the first-order vibration frequency of different blades. As can be seen from Table 1, the first-order vibration frequency of hollow blades will increase with the increasing rib number which is mainly because the ribs effectively improve the rigidity of the blades themselves. When the rib number is greater than 2, the first-order vibration frequency of hollow blades is greater than that of solid blades.

Table 1. First frequency of solid blade and wide-chord hollow blade with different number of rib

Blade type	First-order vibration frequency/(Hz)
Solid blade	205.77
N = 0	183.14
N = 1	195.48
N = 2	201.65
N = 3	205.98
N = 4	207.83

Figure 3 shows the distribution of unsteady aerodynamic work on the blade surface of hollow blade and solid blade with different ribs. From Fig. 3, the change of the internal structure of the hollow blade does not change the main distribution area of the unsteady aerodynamic force on the blade surface. Blade, the area of the unsteady dynamic negative power region of the hollow blade surface decreases with the increasing rib number inside the cavity. It is mainly due to the increasing rib number which increases the displacement restriction on the vibration of the hollow blade surface skin, and then reduces the deformation of the hollow blade surface skin.



(A) solid blades (b)N=0 (c) N=1 (D) n=2 (e) n=3 (F) n=4

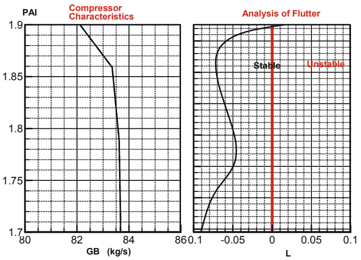
Fig. 3. Unsafe flow power distribution of the different blade

Table 2 shows the unsteady time-averaged accumulated power of per unit blade surface area for different blades at the design point. As can be seen from the table, the work exchange between the air flow and the blade is negative at the design point which means the blade does work on the air flow. All blades will not flutter at this time from the perspective of energy method. When the rib number is more than 1, the amplitude of the work done by the hollow blade to the air flow is larger than that of the solid blade to the air flow. Also the velocity of vibration amplitude attenuation of the hollow blade is faster than that of the solid blade.

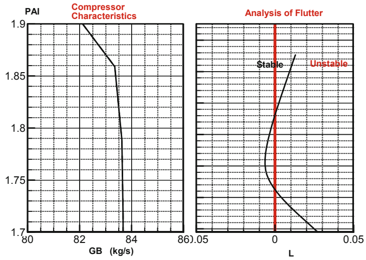
Table 2. LS of different kinds of blades at design Point

Blade type	Unsteady time-averaged cumulative power per blade surface area LS (w/m^2)
Solid blade	−0.046341
N = 0	−0.004639
N = 1	−0.040398
N = 2	−0.056988
N = 3	−0.06737
N = 4	−0.068607

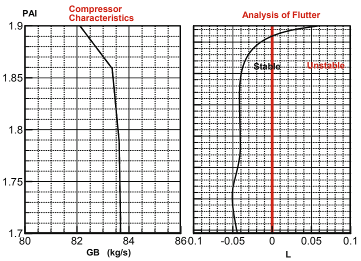
Figure 4 shows the characteristic line and Ls variation curve of different kind of blades at design rotation speed. The x-axis is the unsteady average accumulated power, and the y-axis is the compressor pressure ratio in the Ls figure. As can be seen from Fig. 4, when the pressure ratio reaches the maximum, the unsteady average accumulated power on all blade surfaces is greater than 0 which means the air flow does work on the blade. The vibration of the blade will not gradually weaken with the accumulation of time. Also the possibility of flutter occurring is the greatest. With the decrease of compressor pressure ratio, the unsteady average accumulated power Ls on the blade surface changes from positive to negative. The blade begins to do work on the flow during these pressure ratios. According to the criterion of energy method, it is considered that the blade is at the critical point of flutter and non-flutter when the unsteady average accumulated power equals to 0. It can be seen from Fig. 4a–f that the compressor pressure ratio corresponding to the flutter critical point of different blade is different. The air flow does positive work on the blade in a large range of compressor ratio in the Ls diagram when then rib number is zero as shown from Fig. 4b. The blade is in flutter state, which is mainly due to the lack of supporting effect of ribs on the blade skin, and the overall rigidity of the blade is greatly reduced. It can be seen from Fig. 4c–f that when the ribs in the cavity are supporting the hollow blade, the compressor pressure ratio corresponding to the flutter critical point of the hollow blade is effectively improved. The hollow blade can ensure the compressor in normal operation under most working state. The compressor pressure ratio corresponding to the flutter critical point of the hollow blade becomes larger with the increasing rib number of the hollow blade which means that the compressor can stably work under a wider working condition range. It can be seen that when the rib number is 1 and 2, the compressor pressure ratio corresponding to the flutter critical point of the hollow blades is smaller than that of the solid blades which does not show the corresponding advantages of hollow blades compared with solid blades. When the rib number is larger than 2, the pressure ratio corresponding to the flutter critical point of the hollow blades is close to or greater than that of the solid blade. The hollow blades have stronger adaptability to severe working conditions than solid blades.



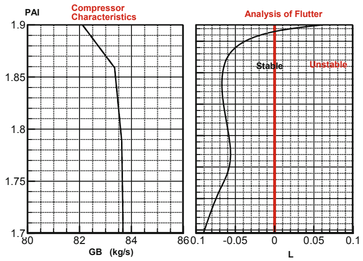
(a) solid blades



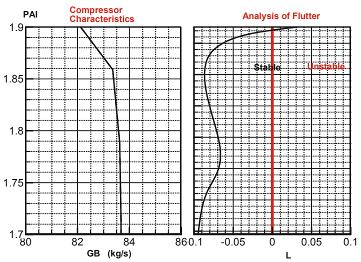
(b)N=0



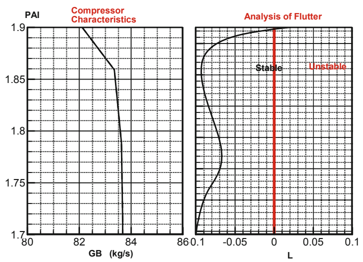
(c)N=1



(d)N=2



(e)N=3



(f)N=4

Fig. 4. The Ls Curve And Characteristic Curve of Different Blade at 100% rev

Figure 5 shows the aerodynamic damping coefficient curve of different blades at different phase angles. It has not been considered that the effect of the interblade phase angle when analyzing the influence of rib number on the aeroelastic stability. The interblade phase angle reflects the interaction between oscillating blades which has a significant effect on the aeroelastic stability of turbomachinery. As can be seen from Fig. 5, the aerodynamic damping coefficients of different blades vary in a simple and harmonic manner with the change of phase angle. The aerodynamic damping coefficients reach a minimum value when the phase angle is 90°. The solid blades and hollow blades without ribs are in aeroelastic instability stage in a large angular phase angle range. The aerodynamic damping coefficient of the hollow blade with N = 4 is larger than that of the solid blade and the hollow blade with N = 0 at all phase angles which is mainly due to the fact that the rib effectively improves the aerodynamic stability of the hollow blade and reduces the phase angle range of the blade in the aeroelastic instability state. The aerodynamic stability of hollow blades with N = 4 is better than that of solid blades.

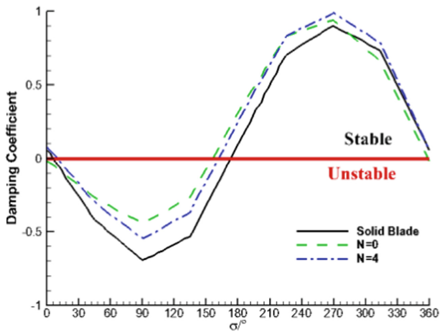


Fig. 5. The aerodynamic damping coefficient curve of different blade

4 Conclusion

In this paper, the number of stiffeners in the structural parameters of hollow wide chord blades is taken as the starting point, the unsteady flow field of hollow blades with different numbers of stiffeners is simulated numerically, and the flutter is predicted.

1. Although the weight of the blade is effectively reduced for the hollow blade without rib, the pressure ratio corresponding to the flutter critical point is far less than that corresponding to the solid blade. The hollow blade has no practicality.
2. The hollow blade with ribs improves the compressor pressure ratio corresponding to the flutter critical point, and effectively expands the normal working range of the blade compared with the hollow blade without ribs. Also the compressor pressure ratio corresponding to the flutter critical point of hollow blade increases with the increasing rib number.
3. The compressor pressure ratio corresponding to the flutter critical point of the hollow blade is greater than that corresponding to the solid blade at the design point when rib number is 4. The hollow blade has better anti-flutter performance than the solid blade.
4. The hollow blade with N = 4 is in the aerodynamic stability range in a larger phase angle range than the solid blade and the hollow blade without ribs at the design point.

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