Research on the Variation Mechanism of the 3-D Tip Clearance of a Cracked Blade under Multi-parameters in the Aero-engine Acceleration Process

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Abstract

The 3-D tip clearance has some advantages over the traditional radial tip clearance in the fault diagnosis of the turbine blade crack. The research on the variation mechanism of the 3-D tip clearance is of great significance, but previous researches only focused on the steady state condition of the aero-engine, lacking considerations of the aero-engine acceleration process. In this study, a numerical model of high pressure turbine blisk was established, and the centrifugal load, thermal load and aerodynamic load of the aero-engine, varying with time, were considered in this model. Besides, the cracks with different length and location were added to the trailing edge of the blade, and the 3-D tip clearance of cracked blades was calculated. The results show that there are some obvious distinctions in the 3-D tip clearance between a normal blade and cracked blades, which can reflect blade crack information accurately and effectively. The results also indicate that the 3-D tip clearance is promising in fault diagnosis of the turbine blade crack.

1 Introduction

The aero-engine is known as the heart of an airplane, providing power for the flight. The turbine is one of key components of the aero-engine, whose health status directly affects the safety and stability of the airplane. One crucial parameter to monitor the health status of the turbine is the blade tip clearance, which has a significant influence on the performance of the turbine [1]. The efficiency of the turbine can be obviously improved by decreasing the tip clearance, and the fuel consumption of the aero-engine can be reduced as well [2]. However, if the value of the tip clearance is too small, the catastrophic rubbing fault may happen to the turbine. Therefore, the tip clearance can reflect the operational status information of the turbine.

The tip clearance usually refers to the radial distance between the blade tip surface and the inner surface of the casing. Due to the blades are subjected to large centrifugal loads, thermal loads and aerodynamic loads when the turbine is running, the blades are prone to failure, and the crack is the most typical fault of the turbine blades. The crack will cause the deformation of the turbine blade, which will further lead to the changes in the tip clearance. Thus, blade crack information can be obtained by monitoring the tip clearance.

For the purpose of diagnosing the blade crack fault through the tip clearance, it’s very crucial to research the variation mechanism of the blade tip clearance. Many researches have been done by numerous scholars and experts. Lattime and Steinetz of NASA Glenn Research Center [3] have pointed out that the loads affecting the tip clearance of the high pressure turbine include engine loads and flight loads. Kypuros [4] and Harish [5] have estimated the tip clearance value of the turbine blade by establishing simplified mathematical models of the tip clearance, which take into account the radial deformation of the turbine blade, disk and casing. Chapman [6] has established a universal and realistic high pressure turbine tip clearance model, which has been integrated with a gas turbine engine simulation system to build a test platform for investigating engine performance by adjusting the tip clearance.

At the same time, many researchers have studied on the fault mechanism and diagnosis method of the crack. Poursaeidi [7] and Wassim [8] have investigated the causes of the blade crack initiation through the mechanical, metallography and chemical analysis, and the stress and strain values of a cracked blade have been obtained by performing a finite element analysis. In regard to the diagnosis method of the blade crack, the blade tip timing technique has been extensively studied [9-12]. Zhang [13] has proposed an approach for the blade crack diagnosis, combining with the blade tip time technique and the tip clearance information.

However, the previous researches on the variation mechanism of the tip clearance only concerned about the one-dimensional radial tip clearance. In fact, the deformation of a blade becomes more complicated when there is a crack on the blade, which will lead to three-dimensional spatial characteristics of the tip clearance, so the tip clearance is three-dimensional actually, such as Figure 1. Besides the radial clearance, there are two more angles which are called axial angle and circumferential angle respectively. Zhang and Tei proposed the 3-D tip clearance and researched on the effect of blade crack on the 3-D tip clearance [14]. But the variation of the 3-D tip clearance was studied only in constant turbine conditions.

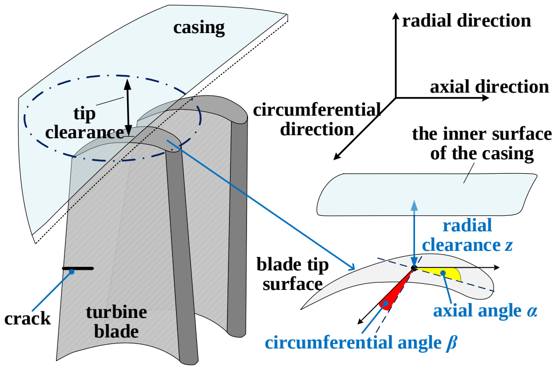


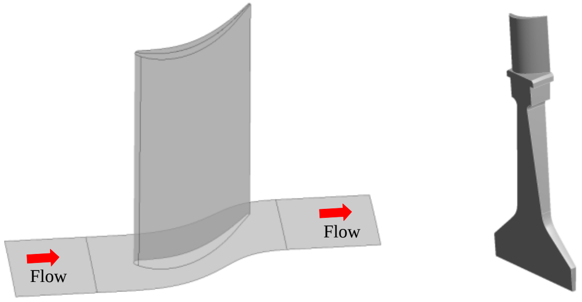
Figure 1: The 3-D tip clearance of a cracked turbine blade

Actually, in the aero-engine acceleration process, the rapidly increasing of turbine loads can easily lead to the crack propagation. Therefore, it's necessary to research the variation mechanism of a cracked blade during the acceleration process. In this study, first, numerical models of the fluid flow passage with a blade and the high pressure turbine blisk with the blade crack were established. Second, multi-loads including the time-varying centrifugal load, thermal load and aerodynamic load were applied to the model to compute the deformation of the turbine blisk, and then the 3-D tip clearance was calculate. Finally, the variation rule of the 3-D tip clearance of cracked blades in the aero-engine acceleration process was obtained, and the effect of the crack length and location on the 3-D tip clearance was analysed.

2 Numerical method

2.1 Geometrical model and grid

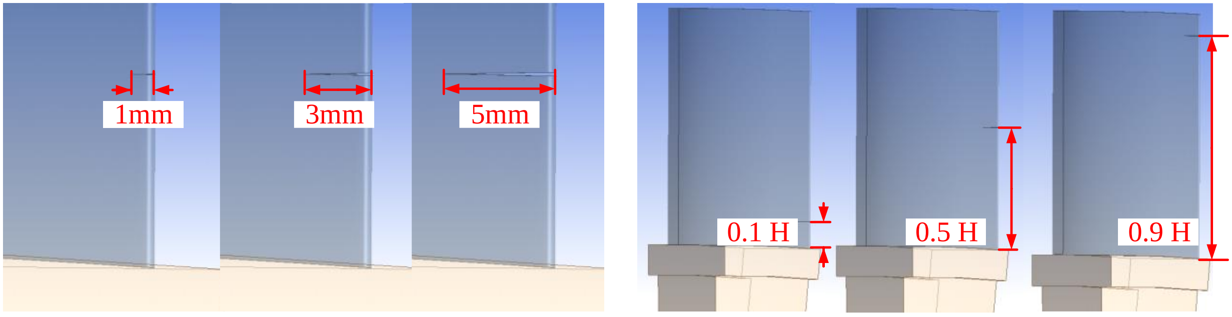
The simplified 3-D geometries of the flow passage with a blade and the blisk are shown in Figure 2. Ansys BladeGen was used to create the computational domain of the fluid flow analysis, which included only one rotor blade shown as Figure 2(a). The turbine blisk consisted of 60 blades, but the sector with only one blade was created to analyse the 3-D tip clearance in order to reduce the amount of the calculation. The geometry of the blisk was used in both the thermal analysis and the structural analysis, shown as Figure 2(b).



(a) The flow passage with one blade (b) The turbine blisk

Figure 2: The 3-D geometries of the flow passage with one blade and the turbine blisk

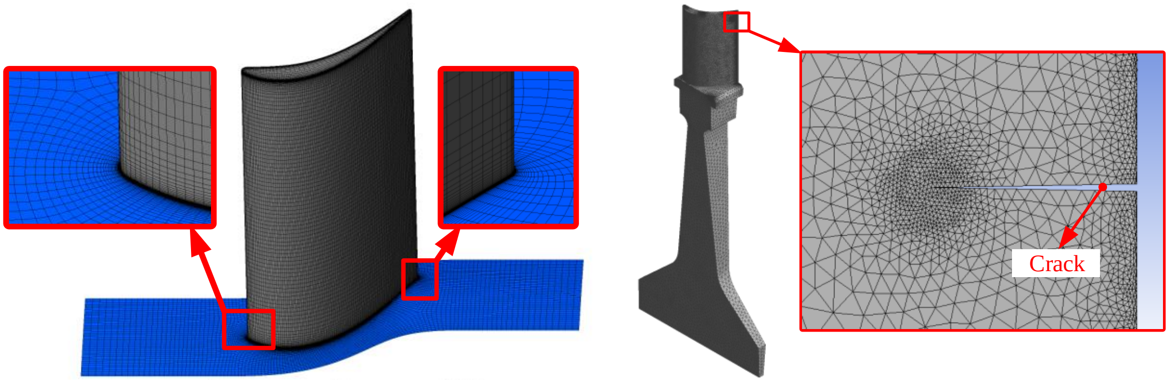
In order to investigate the variation mechanism of the 3-D tip clearance of cracked blades, several blade cracks with different length and location were added to the trailing edge of the turbine blade in this study, as shown in Figure 3. Three cracks with the length of 1mm, 3mm and 5mm were added to the turbine blade at the same location of 0.1H from the blade root, where H is the span of the turbine blade, as shown in Figure 3(a). Moreover, three cracks at different locations of 0.1H, 0.5H and 0.9H with the same length of 5mm were added at the trailing edge of the turbine blade, as shown in Figure 3(b).



(a) Cracks with different length (b) Cracks at different location

Figure 3: Different cracks at the trailing edge of the turbine blade

In this study, ANSYS TurboGrid was used to generate the structured hexahedral grid for the computational domain of the fluid flow analysis. A total of 120 layers of grids were generated along the span-wise direction and 50 layers of grids were inserted to the blade tip region, and the total number of elements was more than 2×10^6. Furthermore, in order to accurately obtain the thermal and flow characteristics of the computational domain, the grid within the boundary layers was refined to ensure y^+ was equal to 1 at the blade surface. Figure 4(a) presents the computational grids of the fluid domain with a blade.



(a) The computational grids of the fluid domain (b) The grid of the blisk and the crack front

Figure 4: The computational grids of the fluid domain and the turbine blisk

As for the thermal analysis and the structural analysis, the tetrahedral grid was generated for the geometry of the turbine blisk as shown in Figure 2(b). The grid around the crack front was refined to obtain accurate calculation results, as shown in Figure 4(b). Furthermore, the fracture mesh was inserted to generate the crack grid and pre-meshed crack was used in this study. The fracture mesh is only supported in the structural analysis, with which the mechanical properties of the cracked blades can be simulated more accurately.

2.2 Grid independence of the fluid flow analysis

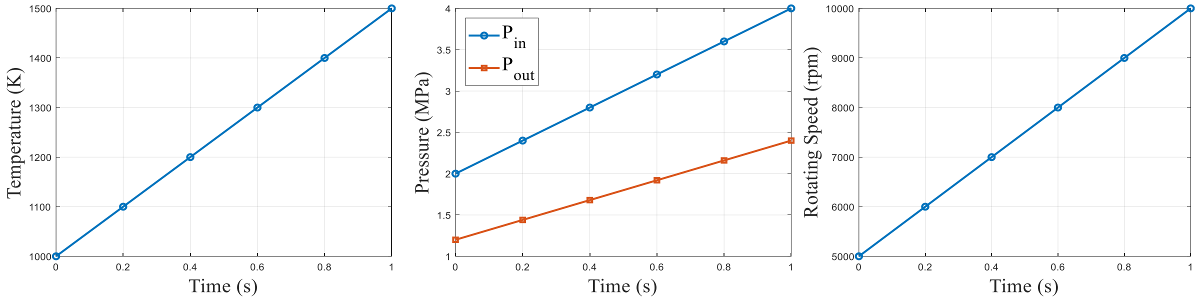
In order to ensure the reliability of the results of the fluid flow analysis and determine the appropriate number of elements to be used, a grid independence test was performed. Table 1 lists the detailed comparison of several grids with different number of nodes. The heat transfer coefficient is defined as $h=q\left(T_w-T_{aw}\right)$, where q is the heat flux of the wall surface. T_w and T_{aw} are the constant wall temperature under the isothermal boundary conditions and the adiabatic wall temperature under the adiabatic boundary conditions, respectively. The area-averaged heat transfer coefficient on the blade surface and its relative error was calculated as shown in Table 1. The relative error between the heat transfer coefficient of the No. 4 grid and that of the No. 3 grid is less than 1%, thus the No.4 grid was used for the computational domain in the fluid flow analysis.

No.	Number of nodes	Heat transfer coefficient ($W/(m^2K)$)	Relative error (%)
1	926250	5510.3362	-
2	1226890	5166.788	6.2346
3	1602110	5097.8388	1.3345
4	2096280	5112.9162	0.2958
5	2758200	5135.254	0.4369
6	3612500	5148.3241	0.2545

Table 1: Area-averaged heat transfer coefficient on the blade surface

2.3 Boundary conditions

The time-varying loads in the aero-engine acceleration process need to be determined to analyse the variation mechanism of the 3-D tip clearance of a cracked blade. As shown in Figure 5(a) and (b), the inlet total temperature, inlet total pressure and outlet average static pressure of the turbine were defined with regard to the fluid flow analysis. Figure 5(c) shows the rotating speed of the turbine rotor. To reduce the amount of calculation, the duration of the acceleration process was reduced to one second, and all of the parameters were assumed to vary with time linearly.



(a) The inlet temperature (b) The inlet and outlet pressure (c) The rotating speed

Figure 5: Time-varying loads in the aero-engine acceleration process

The surface temperature and pressure distributions of the blade obtained from the fluid flow analysis were imported into the thermal analysis and the structural analysis as boundary conditions, respectively. The body temperature distribution of the blisk, as the result of thermal analysis, was also imported into structural analysis to calculate the deformation of the blisk. Because only a sector of turbine blisk was used in the thermal and structural analysis, the cyclic symmetry boundary was defined on the sector of the turbine blisk.

2.4 Monitoring locations on the tip surface

After the structural analysis of the turbine blisk, the deformation at the blade tip surface needs to be measured to calculate the 3-D tip clearance. Four monitoring locations were chosen on the blade tip surface and each one consisted of three monitoring points, arranged in an isosceles right triangle as shown in Figure 6. Monitoring locations 1~3 locate at the leading edge, mid-chord and trailing edge of the blade tip respectively, and the distance between two monitoring points in the y axis and z axis direction is 2mm. Monitoring location 4 also locates at the trailing edge, but the distance between two measuring points is 0.8mm because of the thin thickness of the trailing edge. On each monitoring point, a vertex is created so that the deformations of the monitoring point in x, y and z directions can be measured.

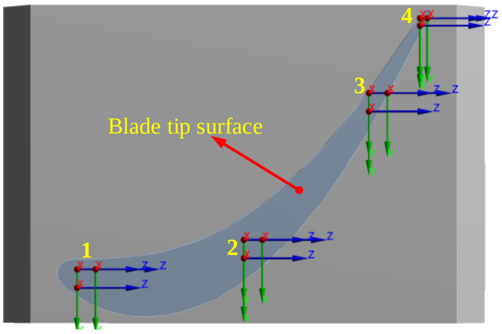
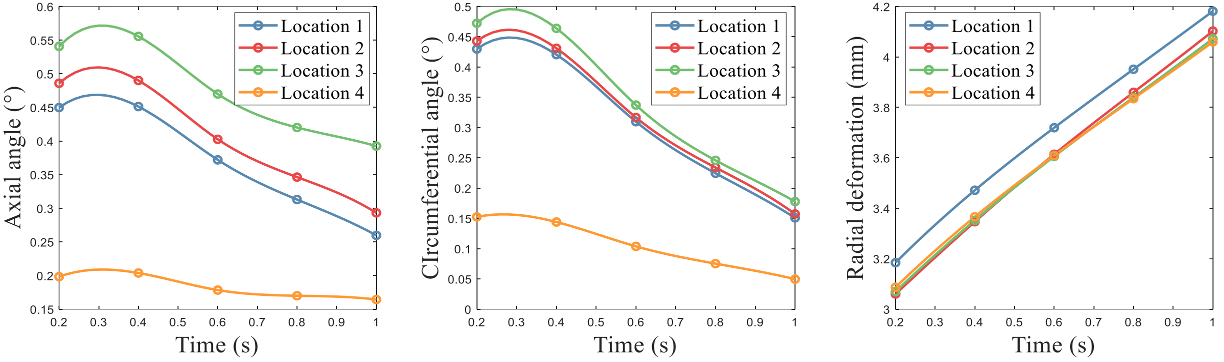


Figure 6: Monitoring points on the blade tip surface

3 Results and discussion

3.1 The 3-D tip clearance of a cracked blade in the acceleration process

A cracked blade with the length of 5mm at the location of 0.1H from the blade root was analysed. The blade tip deformations at four monitoring locations (shown in Figure 6) were measured, and the 3-D tip clearance in the aero-engine acceleration process was calculated as shown in Figure 7. It should be noted that the radial tip clearance was represented by the radial deformations of the turbine blisk because the deformation of the casing was not considered in this study.



(a) Axial angle (b) Circumferential angle (c) Radial deformation

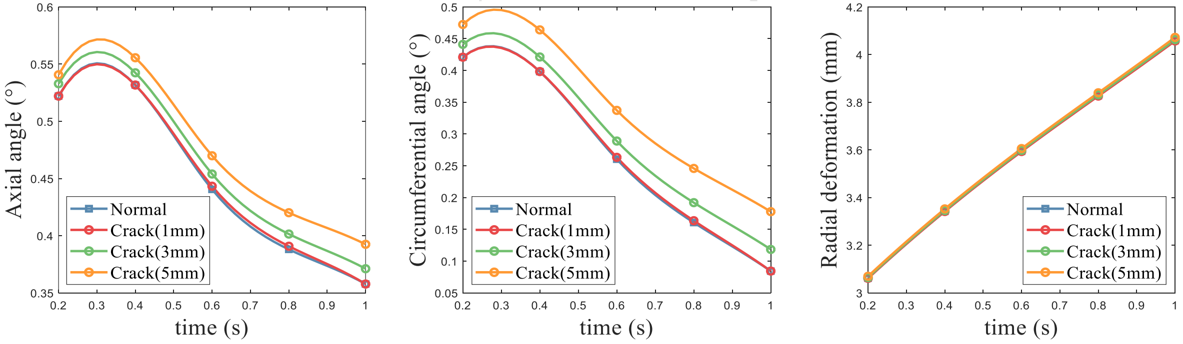
Figure 7: The 3-D tip clearance of a cracked blade in the acceleration process

In the aero-engine acceleration process, both the axial angle and circumferential angle decrease with time. Though the radial deformation of the blisk increases with time, the actual radial tip clearance still decreases because the casing is not as large in deformation as the blisk. At the same time, comparing the axial angle and circumferential angle at the monitoring locations 1, 2, and 3, the maximums of the two angles appear at the trailing edge (monitoring location 3), and the values of the two angles get smaller when the monitoring locations are away from the trailing edge of the blade. Therefore, the closer the monitoring points are to the blade crack, the more sensitive the 3-D tip clearance is to the crack failure.

However, the monitoring location 4 are much closer to the trailing edge than the monitoring location 3, but the axial angle and circumferential angle are much smaller at the monitoring location 4. So comparing with the 3-D tip clearance at the monitoring location 4, the 3-D tip clearance at the monitoring location 3 is more sensitive to the crack because the distance between the two monitoring points of the monitoring location 3 is larger. Thus, the distance between the two monitoring points have a significant effect on the sensitivity of the 3-D tip clearance to the blade crack, and the distance of 2mm is better than that of 0.8mm in this study.

3.2 The effect of the crack length on the 3-D tip clearance

Three cracks with different length at the same location (shown in Figure 3(a)) were analysed to study the effect of the crack length on the 3-D tip clearance. From the aforementioned analysis, the 3-D tip clearance of the monitoring location 3 is more sensitive to the crack fault than the 3-D tip clearance of the other monitoring locations, so the blade tip deformations at the monitoring location 3 are obtained to calculate the 3-D tip clearance, and the results are presented in Figure 8.



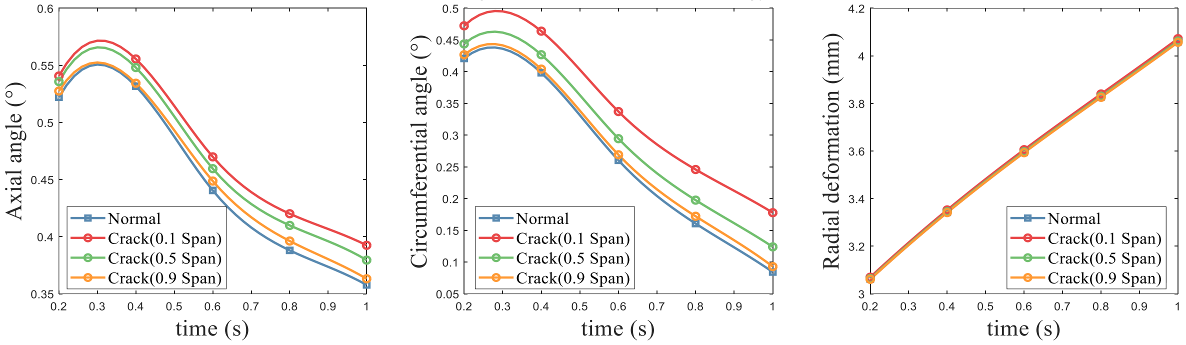
(a) Axial angle (b) Circumferential angle (c) Radial deformation

Figure 8: The 3-D tip clearance of the fault blades with different crack length at the monitoring location 3

The radial deformation of the normal blade and the cracked blades are almost the same, but there are some differences between the normal blade and the cracked blades in the axial angle and circumferential angle. Comparing the normal blade with the cracked blade with the crack length of 1mm, the axial angle and circumferential angle of the two blades are nearly the same, but with the increase of the crack length, the axial angle and circumferential angle of the cracked blades also increase obviously. The crack has a great effect on the stiffness of the blade, and the longer the crack length is, the smaller the blade stiffness becomes. Therefore, in the identical acceleration process, the blade with a longer crack has a larger deformation, and also has larger axial angle and circumferential angle.

3.3 The effect of the crack location on the 3-D tip clearance

In order to study the effect of the crack location on the 3-D tip clearance, three cracks at different location with the same length (shown in Figure 3(b)) were analysed. As mentioned above, the sensitivity of the 3-D tip clearance to the crack is the highest at the monitoring location 3, thus the 3-D tip clearance of the normal and cracked blades at the monitoring location 3 are presented in Figure 9.



(a) Axial angle (b) Circumferential angle (c) Radial deformation

Figure 9: The 3-D tip clearance of the fault blades with different crack location at the monitoring location 3

It is extremely hard to tell the differences between the normal blade and the cracked blades from the radial deformation, but the cracked blades at different location have different axial angle and circumferential angle. As shown in Figure 9, the axial angle and circumferential angle of the normal blade are the smallest compared with the axial angle and circumferential angle of the other cracked blades. Besides, the axial angel and the circumferential angle get larger when the location of the crack gets closer to the blade root.

Under the thermal load, centrifugal load and aerodynamic load, the bending and torsional deformations will happen to the turbine blade, and the most severe bending and torsional deformations occur at the location of the crack because of the low stiffness at the crack. At the same time, the deformation of the part above the crack of the blade has an effect on the axial angle and circumferential angle. Therefore, the closer the crack is to the blade root, the larger the deformation of the blade, resulting in the increase of the axial angle and circumferential angle. Thus the maximums of the axial angle and circumferential angle occur at the location of 0.1H from the blade root in this study.

Both Figure 8 and Figure 9 show the radial deformation of the normal blade and the cracked blades are almost the same, but the axial angle and circumferential angle are obviously different. So the 3-D tip clearance indeed contains more abundant fault information than traditional radial tip clearance, which can be used to fault diagnosis of the turbine blade crack in the further.

4 Conclusions

In this study, the numerical models of the flow passage with one rotor blade and the turbine blisk was established to research the variation mechanism of the 3-D tip clearance in the aero-engine acceleration process, and the thermal load, centrifugal load and aerodynamic load were added to this model. A normal blade and different cracked blades were analysed and four monitoring locations were chosen to study the effects of the crack length and location on the 3-D tip clearance. The results show the monitoring location which is closer to the trailing edge of the blade, is more sensitive to the crack fault, and the distance between two monitoring points shouldn’t be too small. Both the length and the location of the crack have an effect on the 3-D tip clearance. The longer the crack and the closer the crack is to the blade root, the larger the axial angel and the circumferential angle, however, the radial deformations of normal and cracked blades are almost the same in the identical acceleration process. The 3-D tip clearance contains abundant fault information and can be used to the fault diagnosis of the blade crack, which will be further investigated in the future.

Acknowledgments

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