Aerospace Science and Technology 49 (2016) 101–111

Contents lists available at ScienceDirect

Aerospace Science and Technology

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Multi-blade effects on aero-engine blade containment ☆

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ARTICLE INFO

Article history:
Received 28 May 2015
Received in revised form 25 October 2015
Accepted 10 November 2015
Available online 4 December 2015

Keywords:
Aero-engine
Blade containment
Multi-blade effects
Containment capability

ABSTRACT

To study the effects of multi-blade interaction on the blade containment capability of the aero-engine casing, series of blade containment tests and the corresponding numerical analysis for the fan and the turbine components are carried out. Numerical models are validated through the correlation of the numerical results with the experimental data. Combined with the experiments and the FEM analysis, it is found that multi-blade effects enhance the penetration ability of the released blade for both the fan and the turbine components. Consequently, the containment capability of the casing is weakened for the fan stage. But for the turbine stage, the containment capability of the turbine casing varies significantly with deviation of the impact site, which is caused by the multi-blade effects. If the impact site moves to the circular groove on the inner wall of the turbine casing, the casing's containment capability is significantly enhanced; otherwise, the containment capability of the turbine casing remains weakened.

1. Introduction

Due to high cycle fatigue, bird strikes, overheating, material defects, etc., a major hazard in modern jet-powered commercial and military aviation is the failure of a blade of an aero-engine fan, compressor or turbine at very high rotating speeds. Failed rotating components can be released as high-energy fragments which could perforate the engine cowling and damage fuel tanks, hydraulic lines, auxiliary power units and other accessories, affecting flight safety and even leading to serious plane crash with hundreds of passenger fatalities. In accordance with international aviation regulatory organizations, such as the Federal Aviation Administration in the United States [1], Ministry of Defense in the United Kingdom [2] and Civil Aviation Administration of China [3], every modern commercial turbofan engine must successfully demonstrate its ability to contain a liberated blade inside the casing structure and the casing can maintain sufficient structural integrity to survive the large dynamic loads imparted by the unbalanced rotor during spool down.

The containment process of failed rotating blades is very complex, which involves high-energy, high-speed interactions of numerous locally and remotely located engine components. It belongs to the nonlinear structural dynamics issues, including large deformation, material plastic behaviors, damage mechanics and contact interaction between multiple structural components. With the aid of advanced explicit finite element codes, the blade-out event has been investigated by many researchers [4–14]. It is extensively approved that the effects of multiple blade interaction during a blade-out event cannot be neglected. However, investigations on how multi-blade interaction affects the containment process are very limited and the conclusions obtained are quite different from each other. Sarkar and Atluri [4] performed experiments using a T58 rotor and found that thicker rings are required to contain the blade fragments when the remaining blades are introduced. However, opposite conclusions were drawn by Kraus and Frischbier [6] based on a low pressure turbine.

The contradictions about the influence of multi-blade interactions on blade containment existed in literatures indicate that more efforts are needed. Furthermore, it is also necessary to figure out the factors that lead to the contradictions. Researchers know that there are large geometrical and material differences between the fan and the turbine components in an aero-engine. Therefore, in the current study, series of aero-engine fan and turbine blade containment tests are conducted on high-speed spin tester. FEM method is introduced and validated by the experimental data to assist the analysis. Based on the experiments and the numerical simulations, multi-blade effects on the blade containment capabil-

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☆ Supported by State Key Laboratory of Synthetical Automation for Process Industries (2013ZCX06), the Fundamental Research Funds for the Central Universities (N140404022) and Natural Science Foundation of Liaoning Province (2015020085).

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http://dx.doi.org/10.1016/j.ast.2015.11.037
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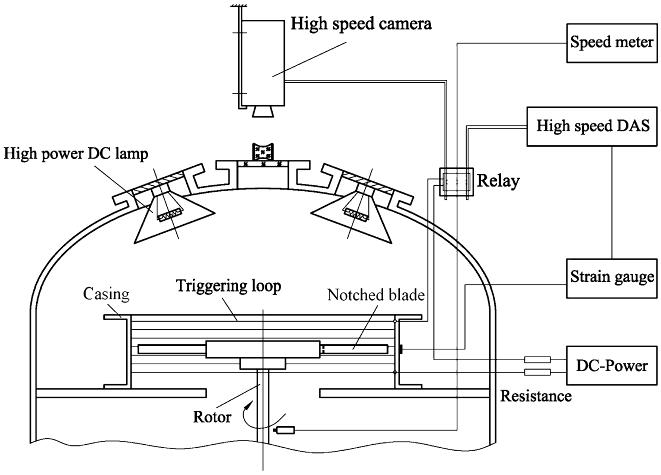

Fig. 1. Schematic of the test facility.

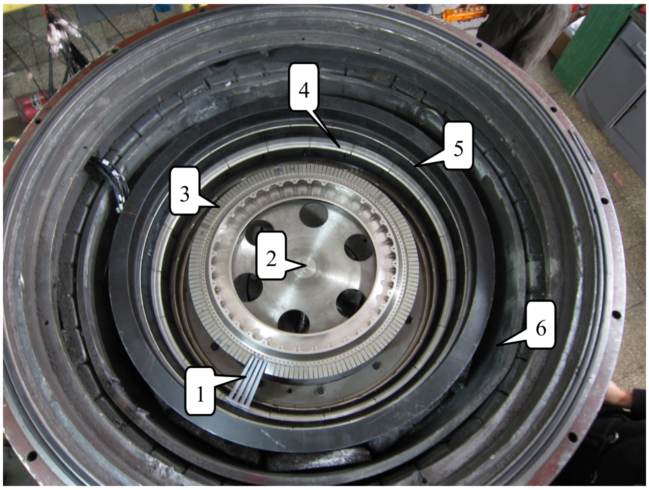

Fig. 2. Assembly of the test components for the low-pressure turbine stage. 1–4—bladed sector, 2—mounting disk, 3—balance mass, 4—liner, 5—casing, and 6—testing chamber.

ity of the aero-engine casing during a blade-out event are carried out.

2. Experimental setup

Series of aero-engine first-stage fan and low-pressure turbine blade containment tests were carried out on ZUST1 high-speed rotor spin tester at the High-speed Rotating Machinery Laboratory in Zhejiang University. A schematic of the test frame is shown in Fig. 1. To study the multi-blade effects, containment tests with more or less adjacent blades were conducted. The details for the first-stage fan blade containment test, such as the geometrical properties and the material of the blade and the casing, the testing method and data, can be found in our previous work [13]. For the low-pressure turbine component, the assembly of a test with three adjacent blades is shown in Fig. 2. In this test, the rotor consisted of four real blades and the other blades were substituted with balance mass. The second blade was released to impact against the casing with one blade ahead and two tracing blades behind along the direction of rotation. The assigned released blade was notched at two side edges on root to force it to crack within predicted speed range. The geometrical properties for the low-pressure turbine components are given in Table 1. The materials of the turbine blade, casing and liner are Chinese standard DZ417G, GH4169 and GH536 respectively. In testing, the rotor was driven through the electromotor and accelerated to the desired speed range. Upon the designated blade was successfully released, dynamic strain gauge and high-speed camera were triggered and transient strain data and photography of the containment process were recorded.

Table 1
Geometrical property for the low-pressure turbine components.

Blade mass	76 g
Maximum thickness of the blade	3.1 mm
Average width of the blade	24.3 mm
Average length of the blade	152 mm
Centroid radius of the blade	394 mm
Number of blades on the rotor	157
Thickness of the casing	1.35 mm
Inner radius of the casing	494 mm
Thickness of the liner	1.0 mm
Inner radius of the liner	483 mm

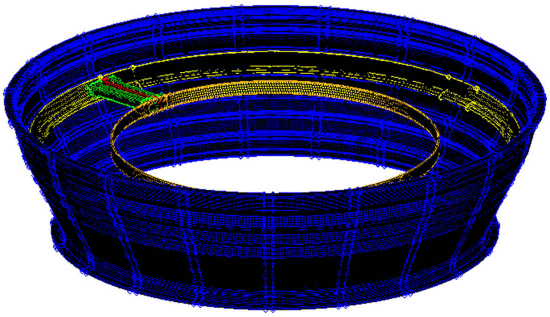

Fig. 3. Finite element model for the low-pressure turbine components.

3. Numerical modeling and validations

Full engine blade-out testing and various complex component level rig testing carried out on the special testing equipment are extremely expensive, and only very limited test data is available to help us study the mechanism of the containment process. The common practice for studying the blade containment is the combination of experimental tests and numerical analysis. Firstly, numerical method is validated through the comparisons with test data. Then, the numerical method is used to assist the study of the blade-out event.

According to the investigation on modeling method and key parameter selections of aeroengine blade containment analysis using ANSYS/LS-DYNA software in reference [15], reliable numerical models were established for each blade containment test. The FEM models have a very fine mesh, and the mesh is more refined where large deformations and strain gradients may appear or the material is likely to fail. Mesh details of the first-stage fan components are presented in [13]. For the low-pressure turbine components, the element sizes of the released blade, the casing and the liner are 0.6 mm, 0.45 mm and 0.8 mm respectively, and the mesh details are shown in Figs. 3–4.

The Johnson–Cook (J–C) constitutive relation and fracture criterion are selected as the material model. The Johnson–Cook (J–C) constitutive relation [16] can be expressed as

$$\sigma_e = \left[A + B\left(\varepsilon_e^p\right)^n\right]\left[1 + C\ln\dot{\varepsilon}^*\right]\left[1 - T^{*m}\right], \tag{1}$$

where A, B, C, n and m are material constants; σ_e is the equivalent von Mises stress; ε_e^p is the equivalent plastic strain; $\dot{\varepsilon}^* = \dot{\varepsilon}_e^p/\dot{\varepsilon}_0$ is a dimensionless strain rate, and $\dot{\varepsilon}_0$ is a user-defined reference strain rate; $T^* = (T - T_r)/(T_m - T_r)$ is the homologous temperature, where T is the absolute temperature, T_r is the room temperature and T_m is the melting temperature of the material, respectively.