Research Status of Aero-Engine Blade Fly-off

Longfei Zhang¹,², Jing Li¹, * and Ying Kou³
¹School of Mechanical and Electrical Engineering, Changchun University of Science and Technology, Changchun, China
²School of Mechanical and Vehicle Engineering, Changchun University, Changchun, China
³School of Mechanical and Aerospace Engineering, Jilin University, Changchun, China

*Corresponding author e-mail: 2000800030@cust.edu.cn

Abstract. The research of aero engine blade out (Fan Blade Out, FBO) is an important problem that must be solved in the design stage of the reliability and safety of the whole structure. The turbofan blades are broken due to fatigue fracture or foreign object impact, and the rotor system produces large vortex under the action of huge unbalanced force, which causes the tip of the blade to collide with the casing and friction in turn. This paper analyzes the aero-engine FBO, and provides a systematic basic theory for the design, innovation and development, which has certain reference value.

Keywords: Blade Out, Fatigue Fracture, Foreign Object Impact

1. Research Background
The aero-engine is a complex thermodynamic machine that rotates at high speed. The comprehensive requirements of aerodynamic performance and structural efficiency make it appear "lightweight" and "heavy load". In addition, the engine's working conditions and loads during the entire life cycle are very complicated. The structure faces challenges of high temperature, high strength and complex vibration. The failures caused by structural strength problems account for 60% to 70% of the failures of the whole machine, and vibration characteristics have become an important indicator of structural safety strength [1]. Therefore, the safety and reliability of the engine should be significantly improved compared with ordinary machinery. Therefore, the aero engine is known as the "jewel in the crown of industry." As shown in Figure 1.
Due to the long-term complex environment of alternating stress, the blades of aero-engines are broken due to fatigue fracture or impact by foreign objects. The rotor system produces large vortex under the action of huge unbalanced force, which makes the tip of the blade and aero-engine casing collided and rubbed [2].

FBO (Blade Flying Off) is a typical failure that may occur. It refers to a serious air disaster where the blades are partially broken or even the entire blades fly out when the engine is working, causing engine accidents and causing deaths.

The main reasons for this failure due to the long-term high-temperature, high-pressure, high-strength and complex vibration environment of the aero engine, the blade is subjected to alternating loads to produce stress concentration and plastic deformation, which will eventually lead to partial fracture of the blade; the flying blade will also impact can also cause serious consequences; the rotor system produces a large vortex due to the unbalanced force (it is very easy to cause secondary), causing the blade tip to collide and rub against the casing [3]. The dynamic response of the whole machine caused by the blade flying off is shown in Figure 2.

2. Main Research Status

2.1 Spring-Concentrated Mass Model
After the turbofan blades fall off, the blades will collide with and rub against the casing under the action of the sudden imbalance force, which involves highly nonlinear dynamics and so on [4]. Limited by the complexity of nonlinear dynamics, many scholars simplified the continuum rotor to a spring-concentrated mass model in the early stages of studying FBO problems, and then used the model of sudden imbalance force to calculate the transient response and the reaction at the support Force [5] [6], as well as the influence of key parameters such as structural damping, gyro torque and support stiffness on the law of vibration response [7] [8].

RenXingmin [9] used the transfer matrix method to calculate the transient response of the sudden unbalanced force, and the aero-engine dual rotor was equivalent to the mass disk model without mass shaft. Although this equivalent model can greatly simplify the calculation, it does not reflect the real
physical model. At the same time, a lot of research work has been carried out on the dynamic stability of the rotor system.

2.2 Beam Theory
In the research on the rotation axis of the continuum, a large number of previous studies were based on the Euler-Bernoulli beam theory. Timoshenko [10] emphasized the influence of shear force and moment of inertia on the vibration of the beam structure. Later, many scholars conducted a lot of engineering practice research, such as gas turbine blades, helicopter propellers, airplane wings and satellite solar panels. In order to improve the high efficiency of the rotating blades, the slenderness rate of the corresponding parts must be increased. Therefore, the influence of shear force should be considered in the analysis of the dynamic characteristics of the beam structure. Due to the huge amount of calculation and calculation difficulty involved in the calculation of transient response, a lot of research has focused on the analysis of the natural frequency and mode shape of the free vibration of the Timoshenko beam, and the analysis of stability.

Ozdemir [11] equated the turbofan blades to a rotating wedge-shaped beam, and used the differential transformation method to solve the natural frequency of the model.

Lee [12] did not consider the Coriolis force term, and derived the dynamic equation of the bending vibration of a rotating variable cross-section beam under the condition of elastic root restraint, and analyzed the influence of parameters such as speed, moment of inertia and taper ratio on stability.

Sinha [13] calculated the effect of centrifugal load on the natural frequency of turbofan blades.

2.3 Receiver Bump
FBO makes the rotor of the aero engine under the action of unbalanced force, the blade and the casing have full-circle friction, especially in the dry friction reverse vortex, extensive and in-depth research has been carried out.

Sinha [14] considered that the impact load was not on the axis of the blade, so the impact will cause the blade torsional vibration, consider the bending-torsion-longitudinal coupled vibration when the tip of the blade is subjected to the impact load, and establish the corresponding nonlinear dynamic equation group.

Ma Hui et al. [15][16] further considered the deformation of the casing, proposed a stiffness equivalent method to simulate the impact load of the blade and casing, and verified their theoretical model with experiments.

Ma [17] considered the impact of the casing stiffness on the friction between the blades and the casing, and analyzed the numerical simulation signal using the time-frequency analysis method.

Turner [18] studied the stiffness change characteristics of the blade during rubbing according to the periodic impact model.

Liu Yang [19] et al. took the safety and reliability of the aero-engine structure as the starting point for their research, and studied that after the blades fall off, the rotor whirls under a huge unbalanced force, and then the blades and casing rub against each other to calculate the transient state of the entire system response.

This research decomposes the FBO problem into three steps to solve the problem. The first step is the transient dynamic analysis of the variable cross-section shaft, the second step is the transient dynamic analysis of the blade tip impacted, and the third step is the analysis of the shaft and the blade.

The derivation of all nonlinear dynamic equations is based on the continuum Timoshenko beam theory. Whether it is a variable cross-section shaft or a pre-twisted blade, the transient response is solved using the same set of theoretical foundations. First, the kinetic energy T, potential energy U, external force energy W and dissipation function R of the system are calculated according to the idea of Lagrange equation, and then according to Lagrange The equation derives the nonlinear dynamic equation of the system. Next, the Galerkin method is used to convert the dynamic equation of the continuum into a matrix form. Finally, the Runge-Kutta method is used to calculate the transient response of the system; secondly, the Galerkin method is used to solve the multi-support, The
expression of the mode shape function of the variable cross-section shaft. The idea here is to use multi-segment constant cross-section rotating shafts to simulate variable cross-section rotating shafts. Finally, the transient response of the impact of the blade tip is analyzed. In the process of deriving linear dynamics equations, considering the influence of the centrifugal load generated by the rotation of the turbofan blades around the shaft, as well as the influence of the Coriolis force term, based on the idea of Lagrange equations, we get the information about the section rotation angle, bending deformation and longitudinal direction. Deform the nonlinear dynamic equations of three variables. Next, the transient response of the blade tip subjected to impact under two working conditions of constant speed and variable speed is solved and compared. The non-linear dynamic equation derived above can effectively simulate the collision and friction process of the blade and the casing.

3. Conclusion
The aero-engine blades are exposed to complex environments such as alternating stress for a long time, and the turbofan blades are broken due to fatigue fracture, impact by foreign objects, etc., and the rotor system produces large turbulence under the action of huge unbalanced force, which makes the blades collide and rub against the receiver. According to the status quo of aero-engine blade fly-off and the existing technology, a systematic basic theory is provided for design, innovation and development. But from the perspective of close to the real physical model, improvements can be made from the following aspects:
(1) Consider the rigidity of the dovetail joint between the blade root and the hub, that is, the blade is no longer an absolute cantilever structure.
(2) The blade is no longer a complete elastic body, and plastic deformation will occur after the blade collides;
(3) Further analyze the principle of the contact stiffness between the blade tip and the casing, and improve the impact load model;
(4) In order to verify the validity of the above theoretical mathematical model, real experiments are needed to verify and optimize the model.

References
[1] Ma Yanhong, Liang Zhichao, Wang Guihua. Review of research on the loss of aero-engine blades [J]. Journal of Aerospace Power, 2016 (3): 513-526.
[2] Liu Yang, LI Cheng, LI Fucai, LI Hongguang. Non-linear Transient Rotor-dynamics Analysis of Fan Blade Out. State Key Lab of Mechanical System and Vibration, Shanghai Jiao Tong University. 2019, 55(13): 23-37.
[3] Guo Mingming. Research on the blasting fly-off method of aero-engine fan casing containment test blades [D]. Hangzhou: Zhejiang University, 2016.
[4] Ye Dong. Research on the Unbalance Response of High-speed Flexible Rotor Sudden Increase [D]. Zhejiang University, 2014.
[5] Li Tao, Ren Xingmin, Yue Cong, et al. Study on the transient response characteristics of a single-disk rotor with sudden imbalance [J]. Mechanical Science and Technology for Aerospace Engineering, 2012, 31(6): 924-927.
[6] Ye Dong. Research on the Unbalance Response of High-speed Flexible Rotor Sudden Increase [D]. Zhejiang University, 2014.
[7] Chen Guo. Coupling dynamic model and vibration analysis of aero-engine [J]. Chinese Journal of Theoretical and Applied Mechanics, 2010 (3): 548-559.
[8] Zhou Hailun, Luo Guihuo, Ai Yanting, et al. Analysis of sudden imbalance response of rotor system with floating ring squeeze film damper [J]. Journal of Aerospace Power, 2014, 29(3): 578-584.
[9] Ren Xingmin, Gu Jialiu. Sudden unbalance response of aero-engine rotor-support system [J]. Journal of Vibration Engineering, 1991, 4(3): 75-82.
[10] Weaver Jr W, Timoshenko S P, Young D H. Vibration problems in engineering [M]. John
Wiley & Sons, 1990.

[11] OzdemirOzgumus O, Kaya M O. Vibration analysis of a rotating tapered Timoshenko beam using DTM [J]. Meccanica, 2010, 45(1): 33-42.

[12] Lee S Y, Lin S M. Bending vibrations of rotating nonuniform Timoshenko beam with an elastically restrained root [J]. TRANSACTIONS-AMERICAN SOCIETY OF MECHANICAL ENGINEERS JOURNAL OF APPLIED MECHANICS, 1994, 61: 949-949.

[13] Sinha S K, Turner K E. Natural frequencies of a pre-twisted blade in a centrifugal force field [J]. Journal of Sound and Vibration, 2011, 330(11): 2655-2681.

[14] Sinha S K. Combined torsional-bending-axial dynamics of a twisted rotating cantilever Timoshenko beam with contact-impact loads at the free end [J]. Journal of applied mechanics, 2007, 74(3): 505-522.

[15] Tai Xingyu, Ma Hui, Tan Zhen. Dynamic characteristics analysis of rubbing fault based on continuum rotating beam model [J]. Journal of VibrationandShock.

[16] Ma H, Tai X, Han Q. A revised model for rubbing between rotating blade and elastic casing [J]. Journal of Sound and Vibration, 2015, 337: 301-320.

[17] Ma H, Yin F, Tai X. Vibration response analysis caused by rubbing between rotating blade and casing [J]. Journal of Mechanical Science and Technology, 2016, 30(5): 1983-1995.

[18] Turner K E. Stiffness characteristics of airfoils under pulse loading [D]. TheOhioStateUniversity, 2009.

[19] Liu Yang. Non-linear Transient Rotor-dynamics Analysis of Fan Blade Out [D].Shanghai Jiao Tong University, 2017.