Failure Assessment of Aero-engine Support Structure due to Blade-off

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Abstract: Aero-engine blade-off event could cause serious malfunction and endanger flight safety, which is an important issue widely concerned for a long period. This paper presents a comprehensive review on the regulation requirements, the major research methods and status at home and abroad. Firstly, the relevant certification regulations and standards about aero-engine structure safety due to blade-off event were overviewed and the research gaps between the abroad and the domestic were compared. Then, the simulation and experimental methodologies on aero-engine supporting structures undertake abnormal load due to blade-off event were discussed as major issue. Finally, the safety certification verification technology system for aero-engine support structures during blade-off event was proposed.

Key words: aero-engine; blade-off; airworthiness; certification standard; support structure; failure analysis; safety assessment

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0 Introduction

The constructions and working conditions of aviation gas turbine engines are complicated, especially those of the engine rotors which endure long-term operation under severe conditions of high load, high temperature and high speed. The rotor parts (including discs, blades, wheels and drums, etc.) are inevitably subjected to fatigue fracture due to various complex causes, thus being hard to predict. Once the fatigue fracture occurs in certain rotor parts, the broken part would be thrown out by tremendous centrifugal force.

In more than one decade from 1988, numbers of serious accidents happened to domestic military airplanes caused by compressor or turbine rotor blade fractures, and resulted in huge economic losses and casualties[1-8]. Accidents due to rotor failures and serious accidents caused by blade-off happened more than once nearly every year since 1994 in China military aviation. From 1994 to 2004, at least 18 blade-off accidents occurred on military aircrafts, and caused in-flight shutdown, aircraft fire or crash, also resulted in huge economic losses and casualties[9-24]. On 17 November, 2007, the right engine of a Boeing 737-300 airplane of U. S. Southwest Airlines ingested an unknown object during its flight. This led to the falling of the intake cone which then hit a fan blade and caused a blade fracture, and resulted in severe damages to the engine and its mount, the fuselage and the aircraft wings subsequently[25]. As shown from the above cases, the engine blade fractures may cause serious engine troubles such as structural damages, in-flight shutdown or fire, and threatening the safety of aircrafts.

The dynamic loads generated on the engine after fan blade off (FBO) could be divided into two types: one is the large-magnitude collision

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(impact) load within the engine caused by the broken blade tip impacting the containment part and the blade root touching other blades; the other is rotational load vector applied on the fan rotor due to the unbalanced mass resulted from the loss of the broken blade. The impact load and the unbalancing load due to the blade-off would further result in rotor failure and support part failure, especially for turbofan engine with large bypass ratio, since the centrifugal force caused by first-stage fan blade broken at root would reach 50—60 t[26], which are severe challenges to aircraft security. Since extensive researches have been carried out on the structural containment of aero-engine casing after fan blade-off, this paper mainly discusses the secondary containment issues.

The airworthiness regulations and standards home and abroad on the structural safety of aero-engine after blade out event are reviewed and compared. The airworthiness verification methods are listed, and the critical numerical simulation technology and testing validation method are summarized and compared. In the end, the technology roadmap on the blade out issue is given and the construction method of the airworthiness compliance verification system is proposed for the safety of aero-engine load carrying structures during blade our event.

1 Airworthiness Regulations and Standards

To improve aero-engine safety, organizations around the world proposed clear provisions and requirements on engine structural safety in airworthiness regulations and military standards, including the Federal Aviation Airworthiness Standards Part 33 (FAR33)[27] of the United States, the European standards (CS-E)[28], and the China Civil Aviation Regulations Part 33 (CCAR33)[29], etc.

1.1 Airworthiness requirements

For flight safety, the engine structure must be able to withstand the huge ultimate dynamic load generated by fan blade-off. In a large-sized commercial engine, such transient dynamic event may last from 20 to 600 ms. As an indispensable aero-engine certification process, the containment of blade-off must be considered in engine design. Regarding this, the US Federal Aviation Regulations FAR33.94 explicitly specified that, at the highest operation speed, after the blade is broken from the root (or from at least 80% point of the blade on blisk), the engine must be able to contain the broken piece and continue to work for 15 s without engine fire or mount falling off, unless an automatic shutdown is induced by the engine damage. FAA requires engine manufacturers to successfully verify via real test whether their engines are capable to withstand fan blade-off and remain on engine mounts, and continue to work for at least 15 s with no broken pieces flowing away and no engine fire simultaneously[30].

In the Item 810 of CS-E, aero-engine should keep operating for at least 15 s without engine fire or mount failure after a (compressor or turbine) blade breaks from root or damages more than 80% at maximum engine power.

China Civil Aviation Regulations Part 33 (CCAR33) is developed with reference to the 11th Amendment of the US Federal Aviation Regulations FAR-33. The first revision of it (CCAR-33-R1) come into force on 19 April 2002, with reference to the 20th Amendment of FAR-33. In January 2011, the Civil Aviation Administration of China revised the Airworthiness Regulations on Aero-engine to CCAR33-R2. Item 33.23 of CCAR33-R2 (Components and structures of engine mount), Item 33.75 (Safety Analysis) and Item 33.94 (Blade Containment and Rotor Unbalance Test) also explicitly state that, while running at maximum permissible speed, the engine should contain broken pieces and keep operating for at least 15 s without engine fire or mount failure after a most dangerous (compressor or fan) blade-off occurs at the outermost disk mortise or a blisk damage more than 80%.

1.2 Military standards

The U.S. standards MIL-STD-1783 (hereinafter referred to as 1783) was initiated in 1969, and officially released on 30 November 1984. It could be considered as the latest American military standard for structural strength and service life of aero-engine. It has also been fully adopted by the U. S. Air Force standard MIL-E-87231 which issued on 30 September 1985. On 15 October 1973, a new military specification MIL-E-5007D (hereinafter referred to as 5007D) was issued.

The British specification DEF STAN 00-971 (hereinafter referred to as 00-971) issued on 5 May 1987 is the latest general specification for military engine in U. K., and it replaces the military standards D. ENG2100 and 2300 which were issued 20 years before. Referred to the American standards 5007D and 1783, 00-971 has many requirements same to them. However, there are more specifications on and more methods for structural strength and service life in 00-971 in numbers and details than those in 1783. The characteristic of 00-971 is its strong operability, containing lots of strict definitions and explanations inherited and developed from British experiences, so that its implementation would not incur too much controversy[31-33].

The military standard of the People's Republic of China GJB241-87 (hereinafter referred to as GJB241-87) was issued on February 17th, 1987 with the U. S. 5007D as its blueprint[34]. It is the first general specification for military aero-engines in China. Based on GJB241-87, a revised version GJB241A replaced the GJB241-87 in 2006 with reference to relevant contents written in U. S. military standards MIL-E-5007E, MIL-E-5007F, and JSGS-87231A.

1.3 Comparative analysis

It is clearly written in both FAR33 and CCAR-33 that the engine should be able to operate continuously for 15 s and maintain its shutdown capability during the period from blade-off to engine shutdown (Fig. 1).

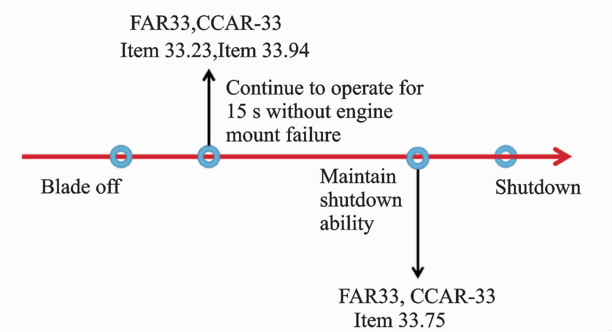


Fig. 1 Comparison of airworthiness standards

It is also required in both military standards 1783 and 00-971 that the rotors, bearing seats, support cases and engine mounts should not be damaged to fail under the unbalanced centrifugal forces generated by a rotor blade-off.

Table 1 lists the comparison of military standards in different countries. Generally, the unbalanced centrifugal force generated by blade-off (on fan, low pressure compressor, or turbine) may be more than 15 times maneuver load, which means it is an abnormal load applied on structural parts such as rotor, bearing seat, support case and engine mount. Once a fan blade-off occurred on an aero-engine developed in China by the end of 1970s, and resulted in extremely severe secondary damages since such abnormal load had not been considered in the ultimate strength of both disc-shaft connections and bearing seats. That is a lesson worth remembering. The static tests of engine bearing seats carried out by other countries also showed that the requirement on consideration of abnormal blade-off load is reasonable[35].

Although in Chinese standards GJB241A and 5007D there are no concepts as limit load and abnormal load, they are useful. Actually all engine parts which have strength and stiffness requirements must withstand these two loads. The limit (yielding) load is the maximum load engine parts endure within working envelope, which may bring elastic deformation to related parts but such deformation is neither destructive nor permanent, giving no significant influence on engine operation or performance. Engine parts could maintain their normal working under limit load. Abnormal load does not appear in normal engine operation.

Table 1 Comparison of military standards

Source	Specification	Term	Content
U. S.	MIL-STD-1783	4. 8. 6 5. 8	The rotors, bearings, support system and engine mount should satisfy the limit load requirements when a (fan, compressor or turbine) blade breaks from root at engine maximum permissible static speed.
U. K.	DEF STAN 00-971	19. 3. 6	The engine should keep operating for 15 s without damages, which may endanger aircraft safety after a (compressor or turbine) blade breaks from root at maximum engine speed.
China	GJB241A	3. 3. 2. 3 3. 8. 6. 2 4. 4. 2. 4. 6	The engine should have sufficient strength to withstand single or composite limit loads without catastrophic damages.

It is a strength margin reserved to ensure no integral structural destruction occurs in abnormal conditions such as misuse. Usually it is required that engine parts should not be destroyed under abnormal load, but permanent deformation is permitted and the parts are not required to keep working. It is suggested to add some appropriate requirements on abnormal load concerning blade-off in GJB241A based on Chinese engine developing experiences and by referring to 1783 and 00-971.

2 Verification Methods

2. 1 Analysis on blade-off mechanism

Blade off refers to part or entire rotor blade breaks and impacts the casing during engine operation[36]. The fan blade-off process could be attributed to nonlinear impact dynamics and rotor dynamics. The first phase after fan blade-off is the unbalanced rotor rotation and a new axis comes into appearance due to unbalanced load. The second phase begins when the broken blade hits engine casing and splinters into pieces. These pieces fly along radial direction, curls and breaks into fragments when they impact the engine casing. The third phase is characterized by casing failure in the form of plastic deformation and damages due to huge impact load on tiny area in a very short time. In the fourth phase, the root of the broken blade impacts adjacent blades as rotor continues its rotation. At this moment, the dynamic behaviors of the remaining blades appear to be frictions between blades and casing or between blades and stators due to unbalanced rotor rotation and casing deformation. These would cause the rupture of rotor blades. The fifth phase is the last phase that the unbalanced dynamic load transfers to the overall structure. The energy which rotor transmits to support parts through impacts and bearings would generate huge load and then transfer to other engine parts, leading to failures of flanges connected by bolts, or resulting in failures of relevant protection systems.

It is required in engine structural integrity, reliability and airworthiness that engine structure should be able to withstand blade-off load and continue to run for at least 15 s without non-containment or engine fire[37]. There are strict regulations and requirements on casing containment in aero-engine specifications[38-39]. Early studies on engine and rotor response to blade-off mainly focus on the worst condition, estimating the maximum response amplitude of rotor system under sudden unbalanced load[40-41]. The purpose is to ensure that the rotor system could withstand the critical load. However, more theoretical and experimental researches need to be carried out on the influences of abnormal blade-off load on structural safety of engine support parts such as rotor-bearing system and engine-mount-pylon. The technology roadmap of the research on the dynamic response of the aero-engine during blade out event is proposed in Fig. 2.

2. 2 Numerical analysis methods

The numerical analysis generally used in aviation combines an explicit analysis for impacting

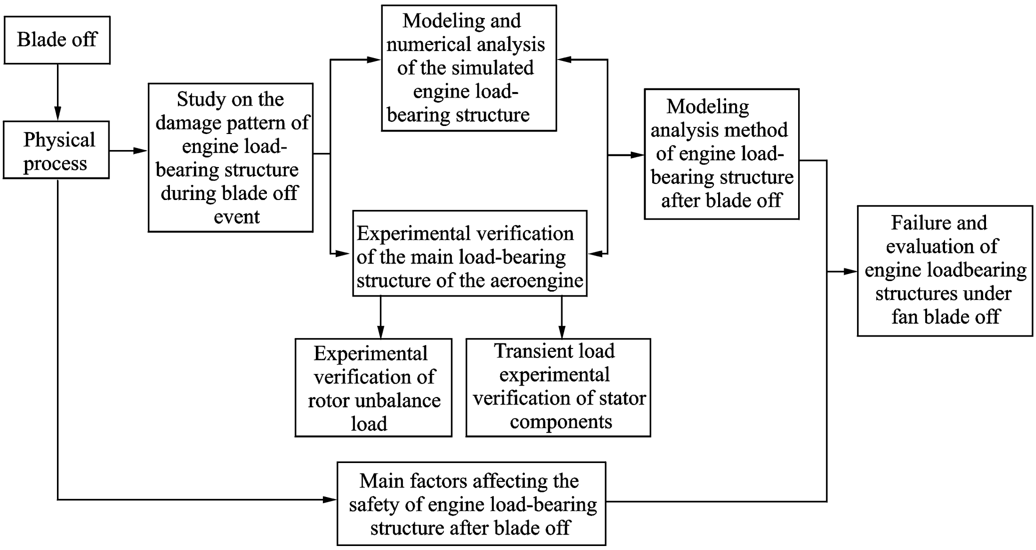


Fig. 2 Technological roadmap of research on dynamic response of the aero-engine during blade out event

phase by a fine finite element model of a fan and casing sector, and an implicit analysis for post-impact phase (which involving rotor dynamic response) by a rough grid model of engine including cradle and part of wings.

For the typical impact phase in the containment, there has been a great number of research, which have mature numerical methods. At abroad, Kraus et al. [42] involved an energy balance method based on the comparison of the kinetic energy of the released blade and the strain energy of the containment zone to the containment design procedure and introduced LS DYNA simulations for the analysis of the safety of blade containment in turbine casings, which allow for the consideration of several crucial effects that cannot be assessed with the conventional methods. Armendáriz et al. [43] focused on the response of the structure after the break of a propeller blade until the end of the phenomenon and analyzed the effects of stiffness and strength changes on the engine mounting system in a non-linear explicit finite element solver. Leont'ev[44] presented the results of simulating the dynamic characteristics of turbofan engines (TFE) during and after fan blade-out using a nonlinear unsteady engine model.

At home, Xuan et al. [45] presented the results of a series of blade containment tests where a double edge notched blade was released at certain rotating speed which subsequently impacted the inner wall of the containment ring. He et al. [46-48] carried out experiments on high-speed spin tester and numerical simulations employing a sufficiently fine mesh and suitable material relations to study the mechanism of the aero-engine fan blade/casing impact process. The effect of the mesh sizes, contact penalty factor and the friction coefficient in the simulation were investigated. In addition, the effects of multi-blade interaction on the blade containment capability of the aero-engine casing were studied and found that multi-blade effects enhance the penetration ability of the released blade. Wang[49] investigated the dynamic influence of a safety design named “fusing” by mechanism analysis and established an explicit FBO model to evaluate the effectiveness and potential dynamic influence of fusing design. Yang[50] explained the key points of aero engine containment requirements in FAR Part 33, and introduces the implementation of MS analysis and fan blade-off test in the engine airworthiness certification.

Shmotin and his collaborators[51] used the above method to research the structural containment behavior after FBO (Fan Blade Off), including prestress calculation, impact and unbalance simulation, etc., taking LS-DYNA as the solver.

As early as in 1983, Stallone and his colleagues[36] were the first to try to analyze in time domain the rotor dynamic effects generated by unbalanced FBO load. Lawrence et al.[52] researched the influences of asymmetric rotors (caused by blade-off) on fan blade-off response. Cosme et al.[53] analyzed the effects of rotor imbalance after blade-off with a solver called Plexus, compared the simulation with the test results of a hollow blade FBO. The comparison showed the simulation correlates well with test results on the impacting position, the interval between first impact and root impacting trailing blade, the main occurrences, and the time it took to reach the maximum value. Sinha et al.[54-55] used an engine LS-DYNA model to simulate the whole process of blade-off. They simulated the FBO during 80—100 ms at engine level, and analyzed the blade trajectory, the energy dissipation, the rotor orbit, the impacting and rubbings between rotor and stator as well as between two rotors. Husband[56] established an engine model including nacelle, air intake and exhaust cone, aluminum honeycomb and Kevlar, filling in the gaps in FBO transient and long-time simulation. Jain[57] established an accurate three-dimensional model for a third stage fan rotor, casing and low-pressure shaft; studied the mesh refinement, the contact modeling, the high-strain-rate effect, and the rotor centroid changes; and compared them with test results.

Either explicit or implicit method has shortcomings and limitations, so it is difficult to use only one of them to analyze the entire process. In 2009, the Boeing Commercial Airplanes and the MSC Software worked with world-wide jet engine manufacturers and NASA to develop a unified process simulation software for engine fan blade-off. Sadeghi et al. of MSC Software used MD Nastran to conduct efficient multi-disciplinary simulation for aero-engine blade-off, proposed a hybrid approach which combined explicit and implicit methods during integration process. Taking advantages of the two methods, this approach is called an integration way for analysis on fan blade-off and rotor dynamics (i. e., the SOL 700 and SOL 400 in MD NASTRAN)[38].

2.3 Test verification

In the 1970s, the U. S. Lewis Research Center cooperated with Pratt & Whitney to conduct a test on the dynamic response of flexible rotor system under blade-off load. Unbalanced load was applied suddenly to rotor running above critical bending speed to simulate blade-off on engine rotor. As shown in the schematic diagram of test rig (as shown in Fig. 3), five discs were symmetrically placed on the axis, the four at both ends were used to generate gyroscopic moment and the middle one had holes in it. Balancing masses were installed in holes during normal operation, and the unbalanced load generated suddenly when one mass flew out. The test results showed that a sudden unbalanced load applied to the rotor would trigger a transient response first, appeared as significant beat vibration if the temporal speed near a certain first-order critical speed. The vibration amplitude reached steady-state imbalance response amplitude within the first vibration cycle after sudden unbalanced load generated. Then the amplitude reached to the maximum after another 2 to 3 vibration cycles, and the maximum value would be 2 to 4 times larger than the steady-state imbalance amplitude (according to the proximity of temporal speed to critical speed). After the beat vibration stopped, the occurance of a steady-state large imbalance vibration to the rotor would depend on the structure of the missing rotational part. Steady-state imbalance vibration may occur after the transient response and beat vibration disappear, or the rotor vibration may be unstable and even lead to shaft broken if plastic bending deformation occur to the shaft under the unbal-

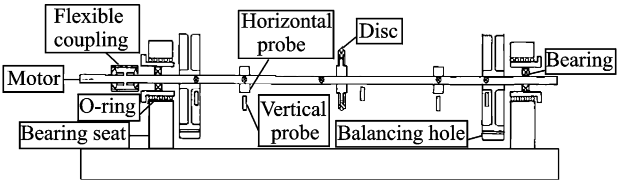


Fig. 3 Test rig of flexible rotor subjected to sudden unbalanced load[63]

anced load[58].

Kalinowsk et al.[59] established a rotor simulation test rig for blade-off to study the dynamic characteristics of rotor system under sudden unbalanced load, as shown in Fig. 4. They researched rigid rotor system at subcritical state, verified impact effect of sudden unbalanced load response, and obtained test data for their mechanical model and simulation analysis[60].

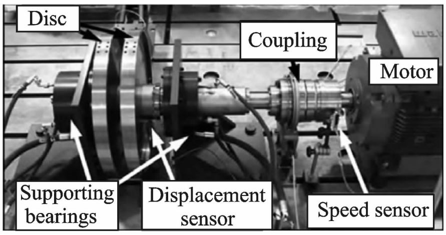
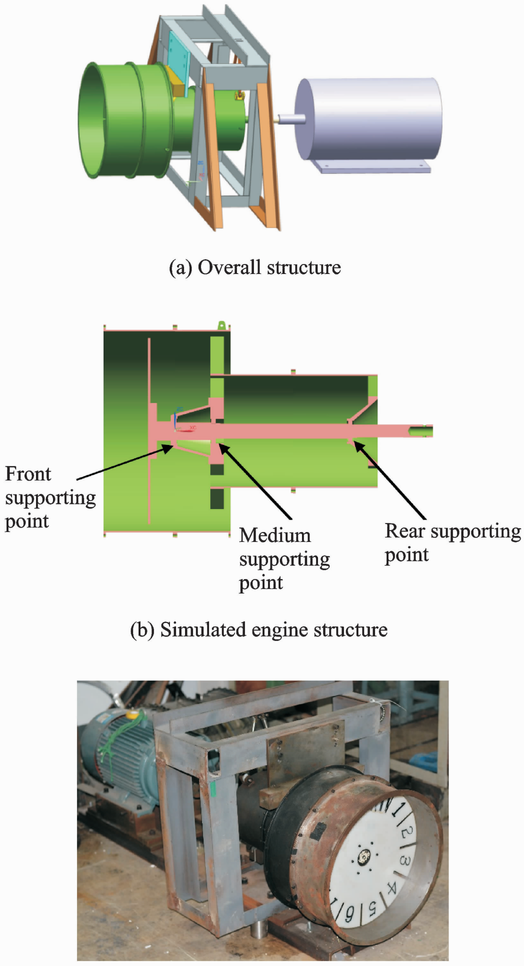


Fig. 4 Rotor simulation test rig for blade-off

Li et al. of Beijing University of Aeronautics and Astronautics presented systematic experimental research results for transient response of rotor system with elastic damping support after blade-off[61]. They conducted tests at different rotor speed, with different film clearances of squeeze film damper (SFD), and by applying different sudden imbalance. Hong et al. conducted respective research on rotor system dynamics under large imbalance load[62]. Aimed at the aero-engine dynamic response to blade-off load, they analyzed the physical process and mechanical behavior of engine structures including casing, rotor-bearing system and engine mount. The experimental analysis model for rotor system dynamics was established based on the structural and mechanical characteristics of turbofan engine with large bypass ratio, and numerical simulation was carried out. Yet experimental simulation research on engine FBO has not been published. Wu[63] from Nanjing University of Aeronautics and Astronautics established a scaled engine rotation simulation test rig for blade-off, as shown in Fig. 5. During blade-off tests, they set sensors or transducers at key positions to pick up displacement, force and acceleration so as to measure the axis orbit, load of main bearing structures, vibration of and force on bearing seat, as well as engine vibration.


(a) Overall structure

(b) Simulated engine structure

(c) Photos of subscale blade-off testing rig

Fig. 5 Scaled engine rotation simulation test rig for blade-off

In summary, numerous studies have been conducted overseas on damage mechanism and computer simulation of blade-off in recent years. A series of theoretical methods valuable both in scientific and engineering have been found for engine dynamic response to blade-off. All these efficiently guide the structural dynamics design for engine safety and greatly reduce the time and cost expended in traditional test verification. While in the independent development of high bypass ratio turbofan engine in China, the structural integrity and safety design under severe load conditions still lack experiences.

3 Developing Trend

Summarizing the airworthiness verification systems in developed countries, it can be concluded that, the airworthiness verification system is a closed loop in principle. All airworthiness compliance verification systems contain basically the numerical simulations and verification testing estimations in different level, including coupon tests, component tests, rig tests, engine tests and so on. A wide variety of design criteria have been proposed in western developed countries after years of investigation, which could be used in the design and manufacture process and build up strict technical barriers from the developing country.

Furthermore, the airworthiness compliance verification of engine structural safety after fan blade-off in China is still in its infancy. The simulation and experimental investigation on abnormal load caused by fan blade-off are neither systematic nor in-depth. Recently, the composite fan blade, swept blade, arch blade, first- and second-generation titanium alloy hollow blade have already been used on aero-engine, and three-dimensional braided composite blade, metal-based composite blade and new generation metal hollow blade will play an important role in the foreseeable future. Therefore, it is necessary to investigate the failure mode and mechanism of engine structures after blade-off through systematic study on the physical process of blade-off. Besides, the development and application of new materials should be paid active attentions. Effective airworthiness compliance verification systems should be established in steps of material constitutive modeling and acquisition, digital simulation and verification, single static part test, single rotating part test, engine test, as shown in Fig. 6.

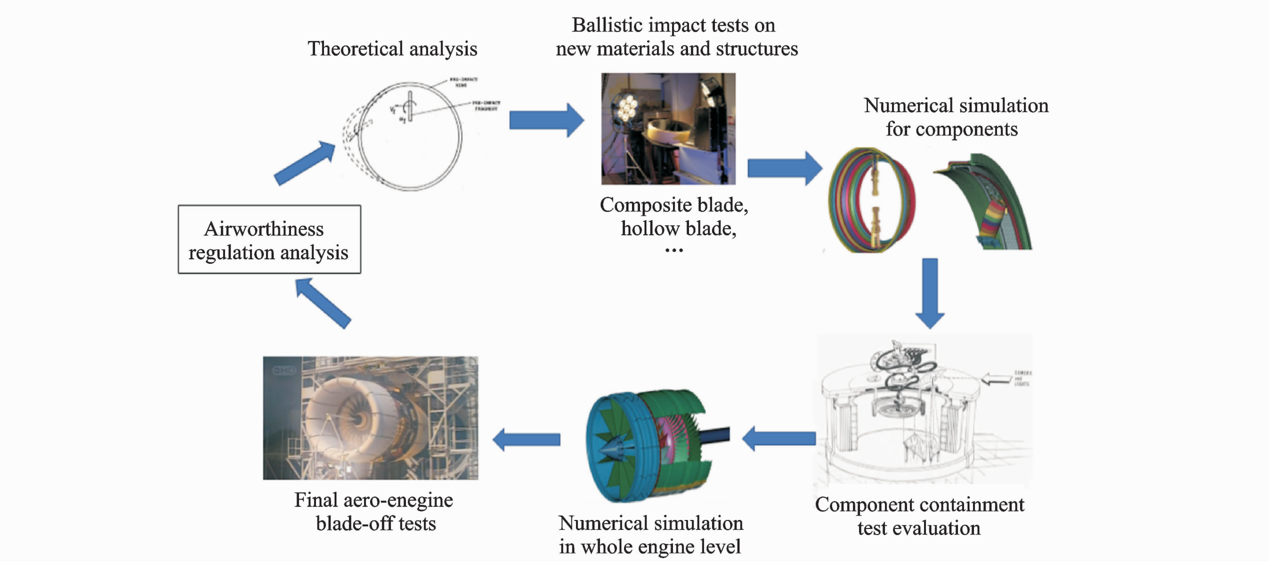


Fig. 6 Technological roadmap for safety analysis during blade off event

4 Conclusions

The relevant issues on the investigation about the failure analysis and assessment of aero-engine support structure due to blade-off event were reviewed. The main conclusions are drawn that:

(1) Comparing the relevant certification regulations and standards about aero-engine structure safety due to blade-off event between the abroad and the domestic ones, we suggest to add some appropriate requirements on abnormal load concerning blade-off in GJB241A based on Chinese engine developing experiences and by referring to 1783 and 00-971.

(2) The simulation and experimental methodologies on aero-engine supporting structures undertake abnormal load due to blade-off event were discussed. Results imply that the criteria of airworthiness compliance verification for design

and manufacture processes, employed by the developed countries, has become strict technical barriers to the developing countries.

(3) The safety certification verification technology system for aero-engine supporting structures during blade-off event was proposed. To establish the airworthiness compliance verification system for engine structural safety after fan blade-off in China, the in-depth investigation of the failure mode and mechanism of engine structures after blade-off are urgently needed.

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