# Fatigue Lifespan of Engine Box Influenced by Fan Blade Out

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**Abstract.** This provides precious experience and reliable reference data for future design. This paper introduces the analysis process of Fan-blade-out, and considers the effect of windmill load on the fatigue lifespan of the case. According to Extended Operations (ETOPS) in the airworthiness regulations, the fatigue crack of it is analyzed by the unbalanced rotor load, during FBO. Compared with the lifespan in normal work of the engine, this research provides valuable design experience and reliable reference data for the case design in the near future.

## 1. Introduction

With the rapid development of modern aviation industry, the safety and reliability of aircraft in particular has caught people's attention. Many painful lessons tell people the aviation history of the world. Once it fails, generally, it influences the performance of the aircraft, but, worst, the machine crashed. As the "heart" of modern aircraft, the aero-engine is prone to all kinds of failures due to its extremely complex structure and its work in harsh environments such as high speed, high temperature and heavy loading [1-2].

In the 1940s, the advent of gas turbine engines had played an important role in the aircraft development from subsonic to supersonic, but 20 years ago, there was a tendency of the design of the engine focused on its performance, reliability and durability, not considering the structure weight, and therefore engine parts were designed to be quite heavy. Especially at the beginning of the 1960s, in order to meet the needs of aircraft speed, high thrust weight ratio, high compression ratio and high temperature requirements of turbine engines, the load of it was greatly improved, and engine vibration was more prominent, resulting in lots of strength, vibration, and fatigue incidents of engine components, such as pylon and cabin. This caused emphasis on the reliability research. Since the 1980s, the structural integrity of aero-engine had been studied in China, and the whole airplane vibration caused by aero-engine was being one of the most critical research projects [3-6]. As for early aero-engine, since the rotor speed was low, the casing stiffness relative to the rotor was relatively high. The coupling vibration of them could be ignored. If only the critical speed of rotor was calculated, this made the casing structure design conservative and heavier; significant characteristics of modern aero engine are high speed, high performance, especially for small and medium sized aircraft engine rotors, which are flexible. The rotor speed may be above the critical speed of the first order (or several orders), the casing wall is thinning, and most of the structures are revolving shells. Dynamic effects between the rotor and the case are very close, mutual coupling and interaction is increasingly strengthening, forming the structure of complex dynamic behaviours, and therefore the whole machine vibration problem is very prominent, so it is necessary to analyze the dynamic characteristics of the engine from the overall angle. In extreme cases, the unbalanced load, due to fan blade out, leads to the fatigue crack of the case. The case vibration accidents quite often occur in military and civil engines to some different degree, resulting in a large number of engines being sent back to the factory for repairs, reducing the service life, and greatly increasing the cost of maintenance. Therefore, it is vital to study the vibration of aero-engine rotor system and whole engine system for the safe and reliable operation of the aero-engine [7].

In the airworthiness, it is put forward that the British defence standard "air gas disaster engine general specification", which detailed rules for blade requirements (blade containment) in the first 12.8.7 and 19.3.5 section. The case must have sufficient strength, working at the highest speed and containing any broken or loose blade. The machine box without large rupture and serious distortion, and the size, quality, speed and trajectory of the escape debris from the engine do not harm the rest of the aircraft. The airworthiness requirements of this point can be learned that the case should be in a safe working range, without major cracks and deformation.

According to CCAR-121 R4 "public air transport carrier of large aircraft of operation qualification examination and approval rules", the definition of (ETOPS), the process is that, on the basis of single expires, the plane ferry flights can be defined as 120 minutes, that is to say, the aircraft case in this phase has no larger crack and deformation.

## 2. Introduction of engine case

With the development of high speed and high thrust ratio of aero-engine, most of the cases are designed to be thin wall cylindrical structures with weak rigidity. The function of it is to properly support the rotor system according to the designed transmission line, and form a specific airflow passage. For aircraft engines, the gearbox and the rotor system are connected by a number of main bearings, and the case of the rigid rotor will influence the characteristics of the critical speed. In the aviation engine dynamic characteristics analysis, the dynamic performance of the case structure should be considered. At the design stage of the overall engine, the rotor critical speed must be estimated and analyzed so as to analyze the rationality of the overall structure; in engine engineering design stage, the rotor, bearing, case system must also be used to analyse structural dynamic characteristics, in order to determine the accurate range of the critical speed. If Fan Blade Out (FBO) happens, it must ensure that the rotor support system runs normally.

As the composite material is widely used in aircraft, this provides a new choice for case design, from single metal material, gradually developing into a large proportion of composite engine, nowadays. According to the composition of the materials used, the case can be divided into the following types: 1) Aluminum/titanium alloy case; 2) The fiber winding intensifier case; 3) Full composite material case; 4) Ceramic matrix composite material case; 5) Other material case. Although there are various kinds of composite materials, the basic objective is to reduce the weight of the case, improve the strength and stiffness of it, increase engine weight ratio, and strengthen protection effect, etc. In this paper, the thin-walled material of the case is aluminum alloy, and the fatigue performance of the engine system is mainly considered.

## 3. Introduction of FBO process

### *3.1. Introduction analysis principle*

FBO events are a multidisciplinary and integrated analysis of implicit explicit - implicit process, using MSC. Nastran for FBO effective simulation [8]. FBO is highly nonlinear, consisting of three separate steps. The first step is implicit nonlinear analysis of FBO under the prestressed thrust load (see equation (1)), by using the fine mesh finite element model (FEM), whose result is used as the second step, explicit nonlinear, which is the initial conditions of transient dynamics (see equation (2)). The third step, implicit nonlinear analysis, is engine speed dropping process and the transient state (see equation (3)), by use of the coarse mesh analysis of rotor dynamic characteristics and unbalanced load.

$$KX = F \tag{1}$$

$$Mv = Ft \tag{2}$$

$$M\ddot{X} + C\dot{X} + KX = F(t) \tag{3}$$

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Among them, in formula one, K is the structure stiffness matrix; F is the prestressed load. In formula two, M is the structure mass; V is the impact velocity; F is the impact load; T is the impact time. In formula three, M, C and K are structural mass, damping and stiffness matrix, respectively. X is the displacement vector; F (t) is a force varying over time.

*3.2.Model of FBO*

The thickness of the case is listed in Fig. 1. The transient impact model (see Fig. 2) of FBO includes an engine pod, an engine case, a rotor, blades of the engine, and the rotor axis of the engine providing rotor rotation with three bearings. After FBO, the model (see Fig. 3) of the unbalanced analysis contains nacelle, pylon, and case.

**Figure 1.** Thickness distribution of engine case.

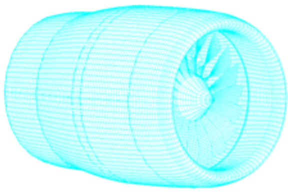

**Figure 2.** Model of FBO.

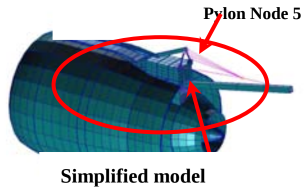


**Figure 3.** Model of engine rotor dynamics

*3.3. Results of FBO*

In this paper, two kinds of calculation analysis are carried out, and one is the normal operation of the engine (CASE 1). The second is the FBO model (CASE 2). Figures 4 and 6 show the deformation of the entire engine when the engine turns normally and abnormally, respectively. Figures 5 and 7 are varying load over time in case 1 and case 2.

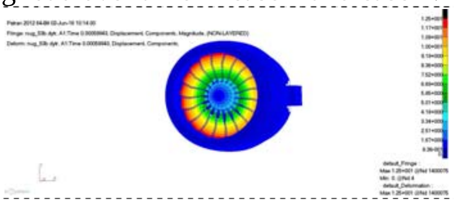

**Figure 4.** Deformation contour of working engine systems (case 1).

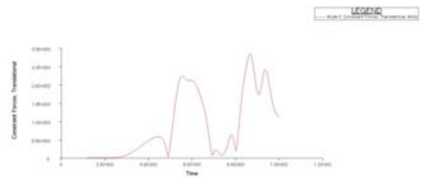

**Figure 5.** Load at hanged Point changing with time (case 1).

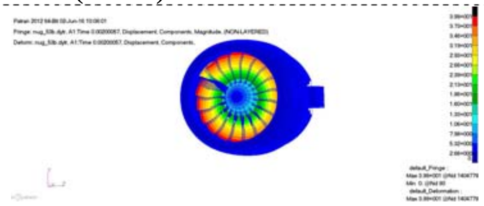

**Figure 6.** Deformation contour of working engine systems (case 2).

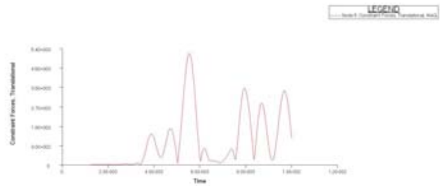

**Figure 7.** Load at hanged point changing with time (case 2).

Through the above displacement cloud graph and the load variation, the table 1 is summarized for reference.

Table 1 Comparison of CASE 1 and CASE2

| **Analysis results** | Case 1 | Case 2 |
|---|---|---|
| Load at Node 5 (Pound) | 0-3900. | 0-5400. |
| Fluctuating numbers of load | 2 | 4 |
| The combined deformation of radial and circumferential direction of engine blades (in) | 12.5 | 39.9 |

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## 4. Lifespan estimation of engine case

Although the FBO event on commercial jet engines is rare, it must be considered during the design phase of the engine. The engine structure must be able to withstand the large dynamic loads that occur during such extreme loading. As an airworthiness certification process, FAA requires engine manufacturers must successfully verify through practical tests, the engine can withstand an FBO events still located in the installation frame, and the case can continue to work safely.

The case is a typically thin-walled circular shell structure. As the main bearing component of the aero-engine, the shell has the advantages of light weight and large carrying capacity. When the case is impacted by FBO, cracks may appear, which will destroy the integrity of the case, and cause the change of dynamics characteristics. So the fatigue and crack of the case have received extensive attention by scholars.

At present, as for the fatigue life estimation method commonly used in engineering, the S-N curve is widely applied from the stress fatigue. From the strain fatigue, the Manson-Coffin formula is mainly used. After FBO, the stress of the case exceeds the yield limit of the material under the unbalanced rotor vibration, in the (ETOPS) period, and therefore, the strain fatigue life estimation method is adopted.

According to Dirlik equation of the vibration fatigue:

$$E[D]=\sum_i \frac{n_i}{N(S_i)}=\frac{S_t}{k}\int S^b p(S)dS=\frac{E[P]T}{k}\int S^b\left[\frac{S}{4m_0}e^{\frac{-S^2}{8m_0}}\right]dS \qquad (4)$$

Among them, N (Si) is the number of stress cycles at time T; ni is the actual counting cycle; Si is the total number of cycles; E [P] is the number of peaks per second;

$$N(S)=E[P]Tp(S) \qquad (5)$$

$$p(S)=\frac{\frac{D_1}{Q}e^{\frac{-Z}{Q}}+\frac{D_2 Z}{R^2}e^{\frac{-Z^2}{2R^2}}+D_3 Z e^{\frac{-Z^2}{2}}}{2\sqrt{m_0}} \qquad (6)$$

$$D_1=\frac{2(x_m-\gamma^2)}{1+\gamma^2},\quad D_2=\frac{1-\gamma-D_1+D_1^2}{1-R},\quad D_3=1-D_1-D_2,\quad \gamma=\frac{m_2}{\sqrt{m_0 m_4}}$$

$$Q=\frac{1.25(\gamma-D_3-D_2R)}{D_1},\quad R=\frac{\gamma-x_m-D_1^2}{1-\gamma-D_1+D_1^2},\quad x_m=\frac{m_1}{m_0}\sqrt{\frac{m_2}{m_4}},\quad Z=\frac{S}{2\sqrt{m_0}}$$

Vibration fatigue simulation can be completed by using the finite element analysis in time domain, and get dynamic stress or the strain results.

Through fatigue analysis, the case lifetime during normal operation is shown in the following figure 8:

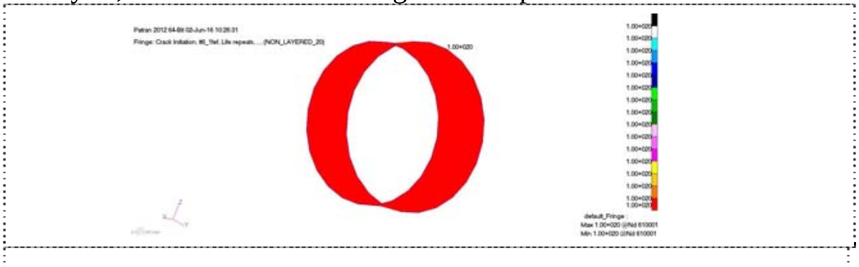

**Figure 8.** Fatigue lifespan of the case wall under normal work.

The fatigue lifespan and initial crack of the case after FBO are shown below in Figs. 9 and 10.

**Figure 9.** Crack of the case wall after damage

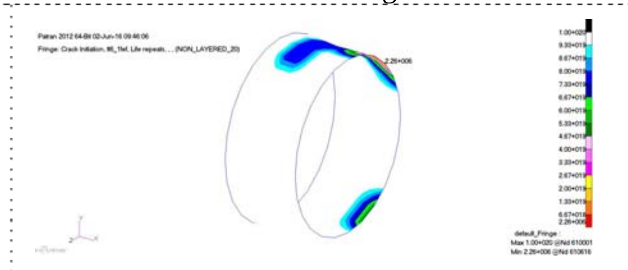

**Figure 10.** Fatigue lifespan of the case wall after damage

## 5. Discussion and conclusion

The following conclusions can be obtained from the compared simulation analysis of the CASE 1 and CASE 2.

(1) during FBO, the engine products a large amplitude of fluctuating for the nacelle, which is about 1.5 times as much as that of normal work.

(2) during FBO, the engine causes the numbers of load fluctuation, which is about twice as many as these in the normal working time.

(3) the combined deformation of the radial and circumferential direction of the blade during normal working is 12.5 inches, while that after FBO is 39.9 inches.

(4) when the engine is working normally, the case has no damage and unlimited lifespan; after FBO, the skin of the case is damaged and its life is greatly reduced, but it can still meet the airworthiness requirement.

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## References

[1] Wen Dengzhe, Several Dynamic Characteristics of Aero-engine Case Model[D]. Harbin Institute of Technology, 2015, 1-11

[2] Hong J., Chen M., Liu S.G. Application of Whole Engine Finite Element Models in Aero-engine Rotor Dynamic Simulation Analysis[R]. 2007, ASME Paper GT2007227162.

[3] Mathias L, Christophe P, Patrice C. Two-Dimensional Modeling of an Aircraft Engine Structural Bladed Disk-Case Modal Interaction [J]. Journal of Sound and Vibration, 2009, 319(1): 366-391.

[4] LIU Lu-lu , XUAN Hai-jun , ZHANG Na, Investigation on Blade Containment of Aero-engine Composite Case, ENGINEERING MECHANICS, Vol.30 Suppl, June 2013, 314-318. doi: 10.6052/j.issn.1000-4750.2012.06.S093

[5] Zhang G.F., Xu W.N., Xu B., et al. Analytical Study of Nonlinear Synchronous Full Annular Rub Motion of Flexible Rotor-Stator System and its Dynamic Stability [J]. Nonlinear Dynamics, 2009, 57(4): 579-592.

[6] Jiang J, Ulbrich H. Stability Analysis of Full Annular Rub in Rotor-to-Stator Systems [J]. Proceedings of the Applied Mathematics and Mechanics, 2003, 2(1): 88-89.

[7] Ma Shuangchao, Structure Dynamic Analysis and Model Validation of Aero-engine Casings [D], Nanjing University of Aeronautics and Astronautics, December, 2012, 1-6

[8] Mohammad Heidari and David L. Carlson, etc. An Efficient Multi-Disciplinary Simulation of Engine Fan-Blade out Event using MD Nastran, AIAA 2008-2333, 49th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 7 - 10 April 2008: 1-12