Failure Analysis on HPT Blade of CFM56-7B

Gao Yu[1, a], Chen Xin-feng[2,b] and Li Nan[3,c]

[1] M&E Division, China Academy of Civil Aviation Science and Technology, Beijing, 100028, China.

[2] M&E Division, China Academy of Civil Aviation Science and Technology, Beijing, 100028, China.

[3] R&D Division, China Academy of Civil Aviation Science and Technology, Beijing, 100028, China.

[a]gy0173@sina.com, [b]Chenxf@mail.castc.org.cn, [c]lin@mail.castc.org.cn

Keywords: Transition zone. Edge of contact. Electronic speculum. Weibull distribution. Parameter estimation. Finite element method. Johnson median rank time method. Bayes estimation.

Abstract. The high pressure turbine blade of CFM56-7B engine is risky to crack, it's failure modes include transition zone crack, shank rupture, min-neck damage, edge of contact and split-shelf clog, which could be modeled and simulated by finite element method. The root cause of crack is found by aforementioned simulation and electronic speculum to modify the blade design. And the reliability of blades could be calculated by Weibull distribution to get soft-time limitation in replace of related blades, in which the Weibull parameter would be estimated with Johnson median rank time method and Bayes estimation method for the censored data.

Introduction

Recent years, CFM56 engine has a great market share in China, it reach 56% in domestic engine market till 2011. It is necessary to study the reliability of engines. CFM56-7B is used widely among CFM56 series, statistical study on CFM56-7B operational data shows that HPT blade is damageable.

Analysis algorithm

The operational data which come from airlines would be used to calculate the reliability degree with Weibull distribution method. The estimation method such as Johnson median rank time method and Bayes estimation [1] should be applied to estimate parameters for the insufficient censored data.

In the risk assessment, severity degree and relatively failure rate would be statistical analyzed to calculate risk matrix, the result as Table 1, the most risky failure is crack of HPT blade.

Table1 Risk management of CFM56-7B

failure mode	measure	level
3# bearing failure	Improve production process	medium
Fuel filter bypass light on	Periodic clean the fuel tank	medium
HPT blade crack	Replace blades by SB 72-696	high
HMU failure	Improve design and real-time monitoring	high

Weibull distribution could be used to discribe the reliability module of parts which is conform to bath curve. For Weibull distribution function[2],

$$F(t) = 1 - \exp[-(\frac{t}{a})^{\beta}] \tag{1}$$

For the insufficient censored data, Weibull parameter such as shape parameter and scale parameter could be estimated with Johnson median rank time method and Bayes estimation method.

Johnson median rank time method. Assuming the failure time sequence changes for the dropout parts, the median sequence number could be calculated for the failure parts, the median sequence number of *No. r* is $J_r = J_{r-1} + I_r$, $I_i = (n+1-J_{r-1})/(n+2-i)$ .Assuming *J0=0*, the sample failure probability of failure parts by the median rank time method is,

$$F_n(x_r) = (J_r - 0.3)/(n+0.4) \tag{2}$$

The sample distribution function could be fitted by nonlinear least squares curve to estimate the parameter *P=[shape parameter, scale parameter]*.

Bayes estimation[3].For bi-parameter index Weibull distribution $EW(a,\theta)$, $a=a_0, x^{a_0}=t$, Weibull distribution function is,

$$\begin{cases} F(t)=(1-e^{-t})^{\theta}, t>0, \theta>0 \\ f(t)=\theta e^{-t}(1-e^{-t})^{\theta-1} \end{cases} . \quad (3)$$

Assuming there is r parts in n (1≤r≤n),the joint density function for $t(1)\le t(2)\le \cdots \le t(r)$ is,

$$p(t|\theta)=\frac{n!}{(n-r)!}\prod_{i=1}^{r}\theta e^{-t_i}(1-e^{-t_i})^{\theta-1}.[1-(1-e^{-t_r})^{\theta}]^{n-r} . \quad (4)$$

Bayes estimation for θ with scale square loss function is,

$$\frac{(a+r-k+1)\sum_{j=0}^{n-r}C^{j}{}_{n-r}(-1)^{j}(b-T-jR)^{a+r-k}}{\sum_{j=0}^{n-r}C^{j}{}_{n-r}(-1)^{j}(b-T-jR)^{a+r-k+1}} . \quad (5)$$

Then estimate the parameter *P=[shape parameter, scale parameter]*.

Failure modes of blade

The blade of CFM56-7B has been modified several times, it may failure in four modes such as transition zone crack, shank liberation, min-neck wear and edge of contact(EOC).

Analysis on transition zone crack.

Crack mostly happen in the transition zone of HPT blade under high temperature and pressure. For low ductile-brittle casting design and thick inner coating, the local stress and heat stress is high around the cooling passage of blade. The OEM such as PCC and Howmet differ much from each other on cooling passage design and positioning core ball chute of tolerance design.

Make Weibull distribution, it's found that more transition zone crack appeared on PCC blade than Howmet. So the thin coating to the inner wall would benefit. Calculating with insufficient censored data and found P=[5, 15794] by Johnson median rank time method, P=[5.44, 15033] by Bayes estimation. After getting the failure distribution function with Eq. 1, the reliability degree function could be calculated by $\exp[-(t/a)^{\beta}]$ .The results of Table 2 show that Howmet blade is reliable at 11000 cycles. In the same way, PCC blade is reliable at 14000 cycles.

Table 2 Reliability of Howmet blade

Cycle since new	10000	11000	12000	13000	14000
Johnson median rank time method	0.903	0.849	0.776	0.685	0.579
Bayes estimation method	0.897	0.833	0.746	0.635	0.507

Shank rupture

If crack of transition zone is deep enough, shank is easily to rupture ,which would lead to IFSD. It's tailored that blade between 11000 and 17800 cycle is easily to rupture due to tensile overload. It's metallographic analyzed that shank is sensitive to rupture if crack beside the cooling passage have propagated into matrix intergranularly. Surface corrosion is a key point to make crack.

In one case of electronic speculum on blade as Fig.1,2, it's found that fatigue crack appear at No.3 cooling passage which is regarded as the origin of crack. The arrow from the figure show the crystal route on crack propagation before overload[4]. Sulfide is found on the route by eddy current method which could lead to corrosion on the passage wall and make pit under concentrated stress.

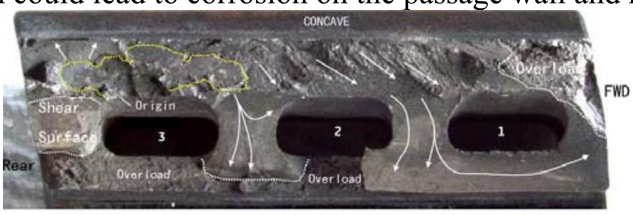

Fig.1 electronic speculum on the shank

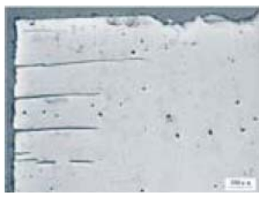

Fig.2 electronic speculum on TZ crack

Blade crack is often found in most engine OEMs, sulfide would make crack to some extent[5], transition zone and inner cooling passage is most susceptible to corrosion. It's not suggest to repair when blade corroded, refer to anti-corrosion technology from other OEM, one method is platinum plating at surface , aluminum coating into the transition zone, then platinum plating to the dovetail,. Another way is to change the casting, examine if the coating abrade the groove in assembly process.

Calculate the reliability degree by the parameter estimation method, it's found that P=[8,15830] by the Johnson method, P=[5.37,16999] by Bayes method, as Table 3 said, the blade is reliable before 13000 cycles.

Table 3 Reliability of blade

Cycle	12000	13000	14000	15000	16000
Johnson method	0.897	0.813	0.688	0.522	0.337
Bayes estimation	0.857	0.789	0.703	0.600	0.486

Contact damage

Blade is easily to crack for high contact stress such as min-neck damage and EOC, which usually lead to dovetail fracture and could not be detected by borescope. It's analyzed by finite element method that the contact stress is high at min-neck when dovetail contacting to the groove ,it usually be fatigue damaged at the influence of heat stress and centrifugal effect.

Min-neck damage. Modeling to blade and make stress analysis by finite element method, which found that stress at min-neck is high enough to crack, as Fig.3. Actually it usually take place below the min-neck of No.1 cooling passage at cycle between 11000 and 17000, that verify the method.

EOC.EOC usually caused by high shear stress of dovetail, or little gap between blade and disk . If the hours circulation ratio is low, throttle is frequently activated, EOC usually lead to low cycle fatigue.SB is issued by OEM to increase the eddy current test for blade. Modeling to blade and make contact stress analysis, as Fig.4.It found that the stress at contact area is high enough to crack[6]. Actually, EOC usually take place at upper pressure area of No.2 cooling passage at cycle between 11700 and 17300, that verify the method.

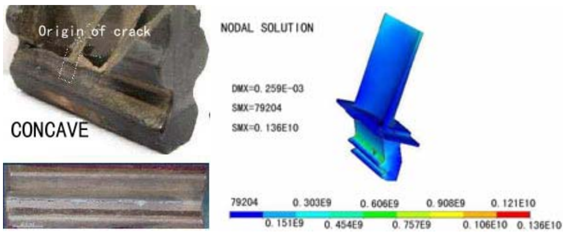

Fig.3 Modeling anaylsis on min-neck

Fig.4 Modeling analysis on EOC

For the insufficient data, Johnson method is used to make Weibull distribution, which found P=[6,15671]. So it suggest that blade should be detected by eddy current method at 12000 cycle.

Split-shelf clog

Some blades have split-shelf at cooling passage of trailing edge, it work as controlling the cooling air in the inner blade. It does works but dust is easily clogged blow the split-shelf which cause overheat locally. Finally, heat stress make crack and blade scrap. The location of crack usually take place at 25% or 50% of airfoil. Modeling to cooling passage and make heat stress analysis, as Fig.5,6. It's found that the maximum heat stress is located at 25% of trailing edge of airfoil. If no split-shelf exit, the heat stress is distributed equably in the passage. So no split-shelf is suggested.

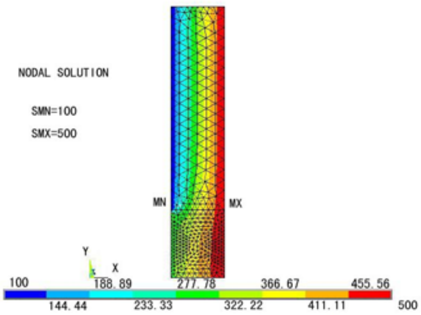

Fig.5 Pre-mod of split-shelf

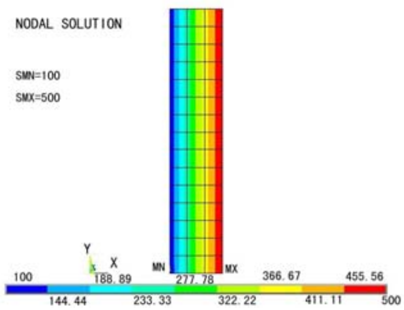

Fig.6 Post-mod of split-shelf

Research to reliability of blade

Air pollution is a key factor to the blade damage from the study above, make Weibull distribution by Johnson method based on the data from all related damage modes, as Fig.7. It found that P=[7,16346] and the blades beyond 20000 cycle should not be used anymore, so soft-time replacement is suggested to control the blade configuration.

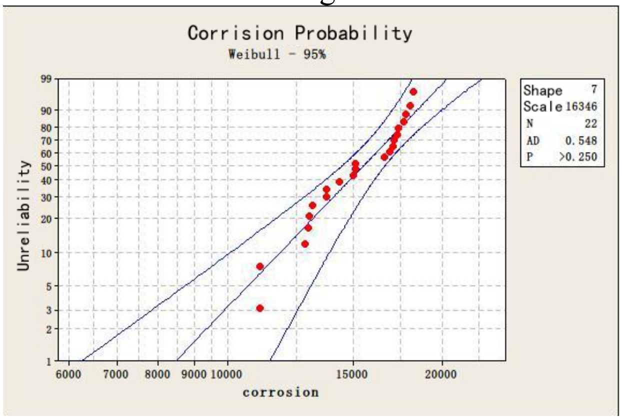

Fig.7 Weibull distribution on blade corrosion

Precaution

The HPT blade of CFM56-7B work under high pressure and temperature, it easily crack for high or low cycle fatigue. The failure mode include transition zone crack, min-neck contact, EOC and shank liberation. Although crack upon platform could be detected by borescope regularly, the crack below the platform could not be detected by NDT method, the soft-time control is the only effective way.OEM suggest the soft-time based on world fleet data, but the domestic data is more accurate for Chinese fleet. It's suggested that blade beyond 14000 cycle is not worth repairing. For blade from PCC,16000 cycle is a threshold to change the blade, but domestic status is lower than that, about 14000 cycle. For Howmet blade, 20000 cycle is a threshold to change the blade, but domestic threshold is 11000 cycle.

The design of blade is still under development, it's suggested that new thin coating should be used in transition zone to avoid oxidation corrosion. New casting should be applied to strengthen cooling effect. The design of min-neck should be improved to increase contact stress, such as film coating in dovetail. For airfoil upon platform, over-grinding is inhibit. Split-shelf should be improved to reduce the dust accumulation inner the cooling passage. It should strengthen the configuration management and performance monitoring of blades.

Reference

[1] FU Hui-min , YUE Xiao-rui: *Multiple regression analysis method for mixed data*. JOURNAL OF AEROSPACE POWER, 26 (2011).

[2] Xiong Kai-ping: *Parameter stimation of Weibull distribution for incomplete samples.* Huazhong University of Science and Technology ,(2006).

[3] Li Feng, Shi Yi-min,Jing Yuan: *Bayesian estimation for environmental factor of two parameter of Weibull distribution*. Systems Engineering and Electronics, 30(2008).

[4] Tang Hai-jun: *Investigation and Analysis on an In-Flight Shutdown of a CFM56-7B Engine*. Aviation Maintenance & Engineering, 6(2011).

[5] Yan Xiao-jun,Sun Rui-jie,Deng Ying: *Experimental study on fatigue curve law of turbine blade under combined high and low cycle loading.* Journal of Aerospace Power, 26(2011).

[6] Peng Mao-lin,Yang Zi-chun: *Analysis on the influences of the contact gap on the contact response of turbine disc-blade structures.* Journal of Aerospace Power, 26(2011).