Improving fatigue life of gas turbine fan blade using advanced composite materials

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Abstract: The application of fiber reinforced composites in gas turbine engines for aircraft helps to increase fatigue life, and also provides the high stiffness, low weight and high strength. In the emerging technology, gas turbine engine performance has been keeps on improving day by day to achieve better in the market between the competitors. Based on all the needs aviation engine plans to reduce the weight of the components wherever it is possible by changing the material selection and design process. Composite material is one of the key materials using in most of aircraft structural components and parts now a days. Here we considered the fan blade of turbofan engine and replaced existing materials with composite material. The objective is to find and improve the fatigue life of gas turbine engine mechanical system components by using advanced composite materials in place of existing materials. Fatigue analysis will be done in commercial finite element packages, based on the results margin and life of the fan blade is calculated.

Key words: Fan blade, Composite material, Fatigue, CFRP.

1. Introduction
The gas turbine engine is the most predominant part in aviation industry. Mainly in aircraft applications gas turbine engine helps to produce power as in the form of thrust to accelerate the aircraft forward. It is a type of internal combustion air breathing engine. It has a rotating compressor part coupled to a turbine, and combustor will be there between compressor and turbine, where combustion process will occur once fuel injection done. The basic operation of the gas turbine is parallel to the steam power plant, but here the working fluid is air whereas in steam turbine is water. Gas turbine engine consist of various stages to achieve the required thrust. In general, it has some stages like diffuser, compressor, combustion chamber, turbine and nozzle exhaust with rotating and non-rotating components like fan, rotor & stator.

1.1 Operations
Initially the air enters into the diffuser with help of fan; it sucks the atmospheric air into engine. It flows through a compressor where the entire air is being compressed in to higher pressure with maintaining some pressure ratio. Later the highly compressed air arrives into combustion chamber where the fuel injector will be placed; it will spray the fuel into the compressed air at two areas, once it is done combustion will take place with high amount of ignition. After that process the high
temperature gas passes through the turbine, due to the high energy formation, it produces some work as input for shaft by driving the turbine with more rotational speed. Once the turbine starts rotating, mechanically compressor also starts rotate because both are coupled with the shaft. Based on the engine capacity and requirements, shaft will be designed. Mostly and widely used shafts are two i.e. two spool engine, each shaft was separated by compressor and turbine like LPC- LPT-fan and HPC-HPT. High energy in the form of thrust will generate once it enter into nozzle area, where exhaust velocity will be high, because of expansion gas waves.

1.2 Working principle
Gas turbine mainly works on the principle of Brayton cycle. In Brayton cycle, gases will undergo four stages of thermodynamic processes: (i) isentropic compression, (ii) isobaric (constant pressure) combustion, (iii) isentropic expansion, (iv) reversible constant pressure heat rejection.

1.3 Gas turbine engine types
In general, gas turbine has several types of engines in different classification each will vary from the design, configuration and engine performance based on the requirements. (i) Turbo jet engine, (ii) Turbo fan engine, (iii) Turbo prop engine. Mostly all conventional aircraft (commercial) will use turbofan engine only. Turbo fan engines equipped with fan in front that sucks all air and pushes inside bypass for additional thrust. Almost all the turbofan engines are categorized through fan blade and bypass ratio. Mass flow rate of air passing through the engine to the mass flow rate of air by passing over the engine are termed as bypass ratio. Engine thrust efficiency is based on bypass ratio only. Based on current applications there are only two classifications of turbofan engines are existing one is conventional
turbofan i.e. fan are directly coupled with low speed shaft or spool and another is geared turbofan i.e. fan are connected with gear & gearing systems are coupled with low speed shaft. Fan is another critical component among the other parts in engine in weight and cost wise (design and material selection).

2. Scope and Objective
Fan blade is one of the major parts used in aircraft engine and its failure is mainly caused by fatigue due to repetitive cyclic loads during flight operations from take-off to landing and also engine servicing. At present, already all aviation parts and engine components are changing to composite from metallic and non-metallic alloys, in order to achieve high stiffness and strength in less weight. Composite material is one of the key materials using in most of aircraft structural components nowadays. The usage of composites in aircraft helps to increase fatigue life, and also provides the high stiffness, low weight and high strength. With all above statement and future requirements, aviation engine plans to reduce the weight of the components wherever it is possible by changing the material selection and design process. In this paper we considering the fan blade of turbofan engine, the existing material of turbofan blade was replaced by composite materials. The main objective is to find fatigue life of fan blade by using composite materials and it helps to improve the efficiency by material optimization.

3. Materials used
The selected materials are fibre reinforced polymer, which is a most widely used advanced composite material in present era. The materials are carbon/epoxy fibre reinforced polymer, S-Glass/Epoxy fibre reinforced polymer, E-Glass/epoxy fibre reinforced polymer, Kevlar/epoxy fibre reinforced polymer, Carbon phenolic FRP. To find the stress range, life and damage and to compare with existing fan blade materials titanium alloy.

4. Design and analysis

4.1 Fan Blade Modelling
In this project, we considered CFM 56 engine design geometry of the turbofan blade and hub portion for this analysis. The aerofoil shape of fan blade remains same as original. Based on the loading coordinate system model has been rotated. Diameter of the fan blade was 1.56 metre.

![Figure 4. Geometry of Fan Blade with Hub portion.](image-url)
The entire analysis was carried out in ANSYS Workbench Module, include design, FE modelling (pre-processor), analysis (solver) and fatigue tool results (postprocessor).

4.2 Finite element analysis
The entire model was meshed with refined second order tetra elements. Mesh quality like aspect ratio, warping factor, jacobian ratio, and skew angle has been maintained as per structural analysis. Totally 305,650 nodes were present in the model. In this analysis, totally 30 fan blades are considered with each having a sector with 12deg.

Figure 5. Mesh patterns of fan blade with hub portion

4.3 Boundary conditions and loads
Hub portion has been constrained in all directions as remote displacements connected with RBE3 connections. Based on the literature and early records, the fan rotating speed was taken from CFM56 existing speed data. Normally fan blade and hub was connected with low speed shaft in case of two spool engine. i.e. low pressure compressor, low pressure turbine and fan disk race portion are connected in single shaft. Here, the speed N1 shaft (1000rpm to 3800rpm) will be much lower than N2 shaft (high pressure compressor and high pressure turbine). Air intake pressure load is very less compared to rotational speed of the fan blade. Since there is no much thermal load will act on the fan blade. So, we are neglecting the thermal effect and pressure load in the analysis.
In figure 6 shows the structural force applications and constraints. Here we applied rotational speed as angular velocity which is converted into rad/sec from rpm. This angular velocity will produce centrifugal forces, which will make fan blade to undergo more deformation radially at tip; same time will create more stress at blade root. Constraint equations are defined at hub inner race shaft portion in all six degrees of freedom.

4.4 Material properties
In this analysis, we are keeping the hub portion with titanium alloy itself. But, we are changing the material of fan blade with fibre reinforced polymer material. Carbon fibre reinforced polymer: It is strong and light fibre. CFRP is high cost but it gives high strength-to-weight ratio. Carbon fibres are anisotropic in nature. Polymer used in CFRP is epoxy resin. Glass fibre reinforced polymer: It is exceptional in its strength and it is lightweight too. Glass fibres are isotropic in nature. E-Glass was widely used reinforcement whereas S-Glass is the second mostly popular glass fibre; it was stronger than most advanced fibres due to its low stiffness limits to aerospace applications mostly. Kevlar fibre reinforced polymer: Kevlar is another name for aramid fibre. It is made from aromatic polyamide – family of nylons. It is having high tensile strength, intermediate modulus and poor compressive strength. Fibres do not bond well leading to a weak fibre/matrix interface.
Fatigue analysis was carried out by using stress based theory in Ansys. In this analysis we consider loading cycle as constant amplitude function.

5. Results

von mises stress was calculated to use the stress range as input for fatigue calculation to find life and damage of the component. The blades of the rotor are fixed to the outer area of the disc at their roots. The blade is subjected to a flow of pressurized gases which force the rotor to rotate at its required speed. Consequently, the fan blade experiences centrifugal force which produces a tensile stress, and also bending stress.

The figure represents the von mises stress plots for composite materials used in this analysis and compared with titanium alloy and structural steel.
With these stress contour, life cycle and damage contour also to be plotted following. The life cycle and damage plot provided a clear idea about the use of composite materials in engine fan blade.
Table 1. Results comparison with materials

| Materials                | von mises stress (MPa or N/mm²) | Min. Life Cycle* | Damage** |
|--------------------------|---------------------------------|------------------|----------|
| Carbon/Epoxy FRP         | 159                             | 2E+08            | 0.005    |
| S-Glass/Epoxy FRP        | 180                             | 2E+08            | 0.005    |
| E-Glass/Epoxy FRP        | 175                             | 1.4E+07          | 0.07     |
### Table 1: Properties of Materials

| Material          | Density | Young's Modulus | Yield Limit |
|-------------------|---------|-----------------|-------------|
| Kevlar/Epoxy FRP  | 170     | 1.4E+08         | 0.007       |
| Titanium alloy    | 321     | 2E+11           | 0.000005    |
| Structural Steel  | 630     | 1576            | 634.5       |
| Carbon Phenolic   | 107     | No data         | No data     |

* 1 Life cycles = 2 hour, ** Damage factor should be less than 1. Damage factor is equal to actual life cycle to design life cycle.

6. Conclusion

From the above results and plots, von mises stresses are calculated and compared with the yield limit of the materials. The fatigue life calculation has been done by the S-N Curve to find the life and damage of the component. This has been clearly shows that usage of composite life will improve the fatigue life of the actual design cycles required. At any cost all the fan blades should be replaced with maximum 50000 cycles. So there is no need of high life cycle greater than 100 Million cycles. Instead of using titanium alloys for more cycles, we can optimize the material with composite like carbon fiber either with UD or woven fabric, Kevlar/Epoxy and S-Glass/Epoxy fibres. It will reduce the weight of the engine; if the weight reduces aircraft performance will be more efficient than present. So it will increase the business cost program efficiency and also marketing strategy for engine manufacturers like Rolls Royce, GE and Pratt & Whitney etc; in order to compete with airline customers like Airbus, Boeing, MRJ, Embraer and Bombardier.

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