

Structural Design and Verification of HF120 Turbofan Engine

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ABSTRACT

The HF120 turbofan engine had achieved top-class low fuel consumption and high thrust-weight ratio in the class of engine with comparable thrust, and at the same time, shown compliance with Federal Aviation Regulations. In order to accomplish these goals, characteristic structural design requirements as typified by life-limited parts design concept have been established. HF120 parts were confirmed to meet these design requirements in compliance with Federal Aviation Regulations by applying methods including CAE optimization and enhanced structural configuration. This paper uses the fan rotor as an example of how the rotating parts in the HF120 was verified to meet design requirements and Federal Aviation Regulations through computational fluid dynamics, numerical impact analysis, frequency analysis and substantiation test. The low-pressure turbine stage1 nozzle is used here as an example of how structural parts achieved lightweight, compact and low fuel consumption.

1. Introduction

The HF120 turbofan engine (HF120), developed by a joint venture of General Electric Company (GE) and Honda, not only achieved the target of competitive fuel consumption and thrust-weight ratio, but also acquired Type Certificate from the Federal Aviation Administration (FAA) by demonstrating compliance with Federal Aviation Regulations (FAR). Design requirements for the HF120 were defined to comply with the FAR while ensuring competitive engine performance. This paper describes structural design and verification methods applied to the HF120.

The HF120 engine comprises two shafts of low and high pressure, a cold section that includes the fan, the two-stage low-pressure compressor and a single-stage high-pressure compressor, and a hot section that includes a combustor, single-stage high-pressure turbine and the two-stage low-pressure turbine (LPT) as shown in Fig. 1. The fan, located at the inlet of the engine, sends inlet air into a bypass duct and a core passage. The compressor further raises the pressure of the passage air. Next, fuel is sprayed over the compressed air for combustion in the combustor. The turbine, located downstream, takes energy from the high-temperature gas that is used to rotate the compressor and fan via a rotating shaft.

This paper uses the fan rotor and the low-pressure turbine stage 1 nozzle (LPT1 nozzle) as examples of the structural design and verification. Specifically, the fan rotor highlights the adopted analysis method on computational fluid dynamics (CFD), numerical impact analyses and modal analysis, as well as the verification method combined with testing. The LPT1 nozzle highlights the structural characteristics. The latter part of this paper explains the life-limited parts design concept applied to the HF120 design.

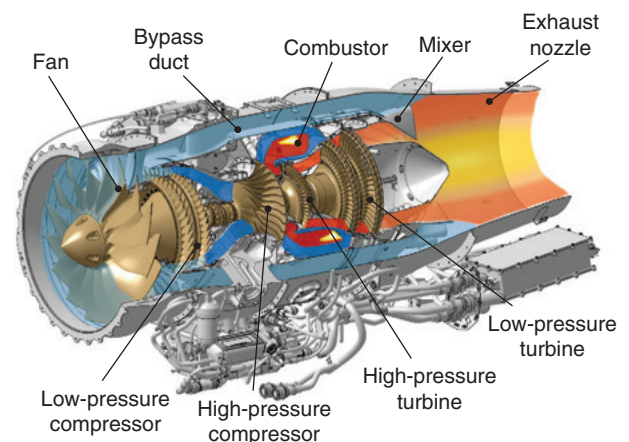


Fig. 1 Cutaway model of HF120 turbofan engine

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2. Fan Rotor Verification

2.1. Characteristics of Fan Rotor

Fan rotor design must take into account, among other things, damage that could be caused by foreign object ingestion as well as distortion of inlet air flow. The HF120 engine fan rotor is a light weight bladed disk configuration composed of 16 blades and a disk. Balancing of aerodynamics and structural strength, the design achieved both high efficiency and light weight. This chapter explains the verification methods used to assess Fan Blade Out (FBO), Foreign Object Damage (FOD), and High Cycle Fatigue (HCF), which are unique requirements of a fan rotor.

2.2. FBO Verification

FBO refers to separation of a fan rotor blade. The FAR⁽¹⁾ includes the following regulations for a FBO event. A failed blade must not cause damage to the aircraft, and under no-thrust-lever operation for at least 15 seconds after the blade is released, the engine must contain any damage without catching fire or failure of engine mounting attachments. To avoid damage by a failed blade, an HF120 design requirement was that the fan case must contain the failed blade. This section explains the containment verification method.

A detailed simulation using impact analysis software was performed. Figure 2 shows one of the analysis models. In this model, one blade of the rotating fan rotor is released around its root. This model is used to study the fan case configurations capable of containing the released blade (Fig. 3). GE and Honda had studied various configurations of the fan case and selected an appropriate one. An engine testing was then conducted to substantiate the configuration. The test result demonstrated that the fan case meets the containment requirement. The test also demonstrated compliance with FAR.

2.3. FOD Verification

A fan rotor is also required to conform to airworthiness when an engine has FOD, hail, slab of ice, or bird ingestion. This paper highlights medium-size bird ingestion

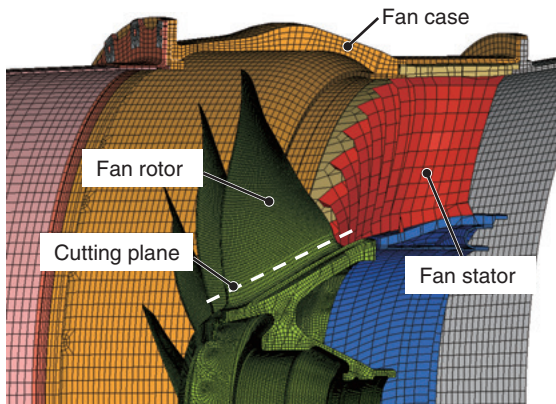


Fig. 2 Cutaway view of FBO analysis model

verification. The design must ensure that sufficient engine thrust remains after the bird ingestion, even under conditions such as in take-off when the engine thrust reaches its maximum. The FAR⁽²⁾ defines the size and quantity of the medium-size bird to be verified, as well as requiring engine thrust loss to be 25% or less. Thus, the design requirement also restricts thrust loss to 25% or less for a bird ingestion event in accordance with the FAR.

To verify whether the fan rotor meets this requirement, a detailed simulation was performed to predict damage to the fan rotor. The modeling method known as “Smoothed Particle Hydrodynamics (SPH)” was applied to bird modeling. An analysis model is shown in Fig. 4. The SPH analysis method is superior in predicting large distortions to a Lagrangian analysis and is thus appropriate for simulating bird impact on fan blades. Further work shortened the analysis run-time. To support this effort, studies were performed in advance to balance model size and analysis run-time. It was demonstrated that deformations of blades hit by the bird’s trunk have a dominant influence on thrust loss. Based on this finding, specific blades are hit by bird

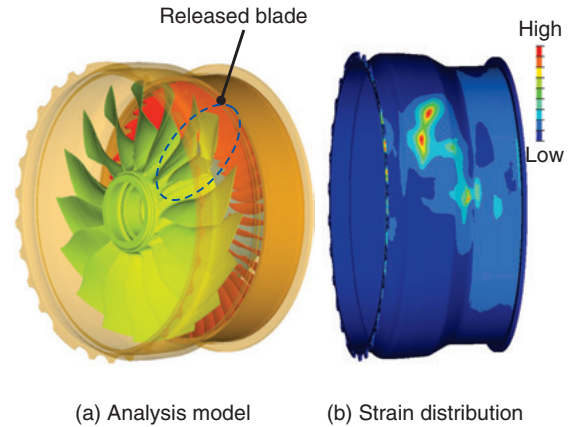


Fig. 3 Equivalent plastic strain of FBO damaged fan case

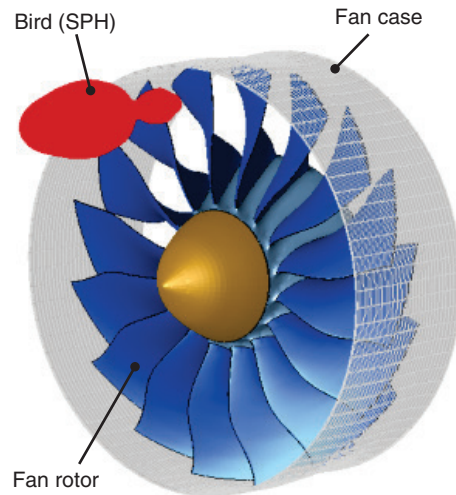


Fig. 4 Bird ingestion analysis model

trunk are constructed of elastic-plastic elements, and the other blades are constructed of rigid elements in the model. Validation of this modeling method was performed using the existing engine, and the test result showed good correlation between analysis and testing (Fig. 5).

Using this analysis method, HF120 fan rotor configuration that satisfies the design requirement was identified. Then, a substantiation testing was conducted to demonstrate design compliance with FAR requirements. Figure 6 shows the rig test configuration of medium-size bird ingestion for the fan rotor. The damaged fan rotor blade was installed into an engine for thrust measurement. The result demonstrated less than 25% thrust loss, which meets both the design requirement and the FAR. Note that the test was conducted with the Honda Bioethics Committee's approval.

2.4. HCF Verification

Fan rotor blades can be excited by airflow distortion at engine inlet in integral multiples of engine speed. Another

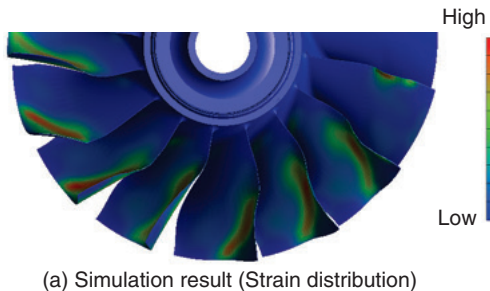


Fig. 5 Comparison between simulation and test

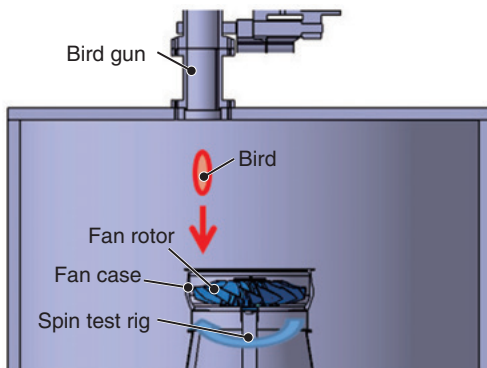


Fig. 6 Bird ingestion test layout

excitation source is non-uniform pressure distribution caused by the fan stator vanes located downstream (Fig. 7). FAR⁽³⁾ limits stress induced from HCF that can be caused by these vibrations. Generally, stiffer blades lead to an increase in weight of the fan rotor and also other structural parts. Thus, in order to design a fan rotor with adequate blade strength, verification of HCF should be performed with appropriate accuracy.

The first step was to predict mode shapes and natural frequencies by simulation. Figure 8 shows a typical mode analysis result. The second step was to measure the response with strain gauges applied on subject blades during engine testing. Then maximum stress values were calculated by combining of measurement and analysis results. All plotted responses within the operation range are below the material fatigue limits. Thus, the evaluation demonstrated that the design complies with the FAR.

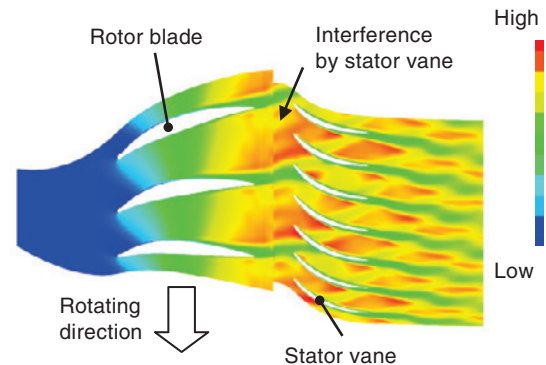


Fig. 7 Total pressure of fan flow

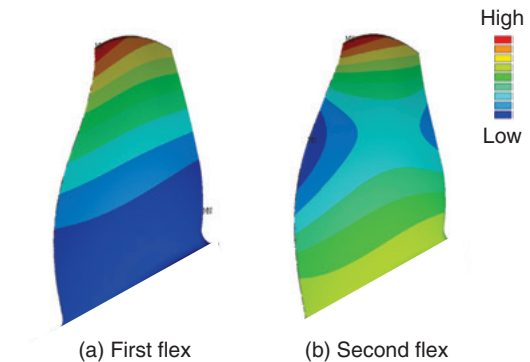


Fig. 8 Fan rotor displacement of typical modes

3. LPT1 Nozzle Structural Design

3.1. LPT1 Nozzle Configuration

The HF120 LPT is composed of two stages as illustrated in Fig. 9. The LPT1 nozzle design is a monoblock casting feature intended to be light-weight and compact, and to result in low-fuel consumption.

3.2. Vane Monoblock Casting Configuration

The turbine nozzle has high thermal load due to high

temperature conditions. In other designs, segmented vanes may be used to alleviate the thermal effect. This HF120 engine, however, adopted vane monoblock casting configuration. The advantages of monoblock casting include a light-weight, compact configuration and eliminating fuel gas leakage from the joints between separate pieces. As a result, the fuel consumption improves. At the same time, countermeasures against high thermal load were introduced.

The vanes are exposed to high-temperature and high-pressure gas after combustion in the combustor. The metal temperature of the vanes reaches the same level as the gas, while the metal temperature of the platform is kept relatively low by cooling air. Two countermeasures were adopted to address the high stress that could result from the temperature gradient. One was to adopt variable fillet curvature on span and chord directions (Fig. 10). The other countermeasure was to adopt a heat shield on inside of platform (Fig. 11). This heat shield helps form an intermediate temperature layer of which relieves the thermal temperature gradient from vane to platform (Fig. 12) and reduces the thermal stress.

The turbine layout is composed of the nozzle holder, outer and inner gas passages, seal holder, and heat shield.

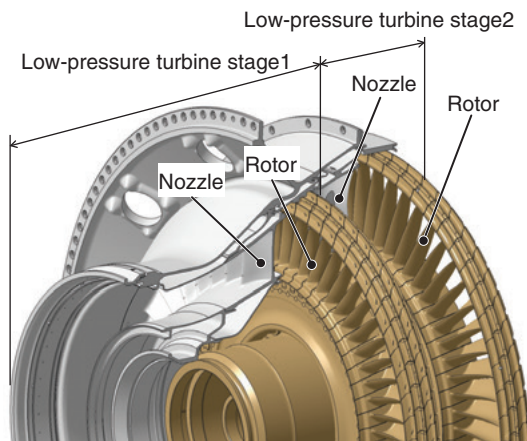


Fig. 9 Turbine module layout

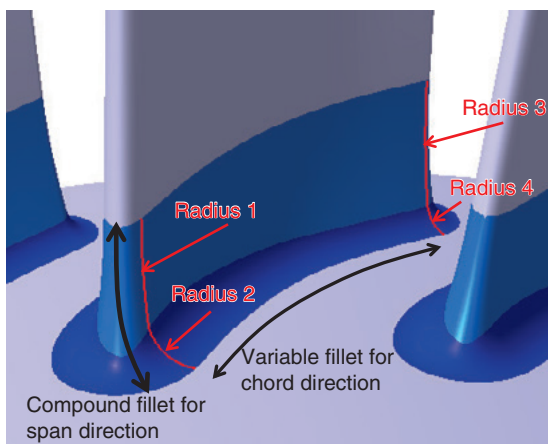


Fig. 10 Vane compound fillet

These features were integrated into the monoblock casting vane configuration. As a result, the gas leakage was avoided, and the design enabled a light-weight and compact LPT1 structure.

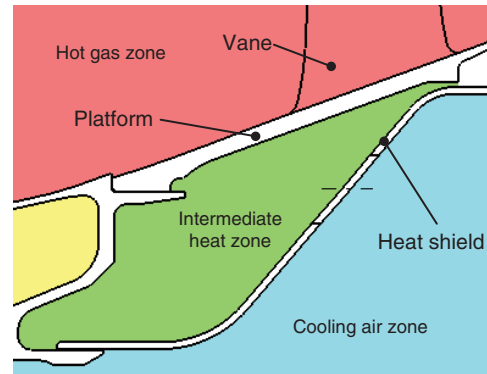


Fig. 11 Heat shield layout

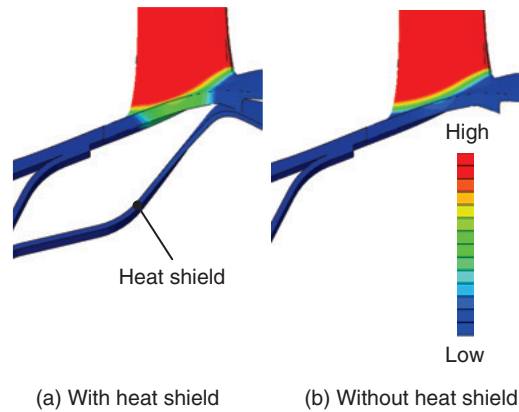


Fig. 12 Metal temperature distribution

4. Parts Life Management

Chapters 2 and 3 described designs and verification methods for specific parts. This chapter explains the general design concept commonly applied to turbofan engine composition parts. A turbofan aircraft engine has the following characteristics: management of the engine in-service time, definition of the Time Between Overhaul (TBO) and the repair or maintenance procedures on manual. These characteristics are incorporated into life-limited part design. In general, major parts comprising a turbofan aircraft engine are life-limited to make the engine more efficient and light in weight. These parts have life requirements that include crack initiation and propagation. Thus, the design must consider how the subject parts comply with these requirements based upon their features, material, interfaces, manufacturing process, and proper use of the engine. Parts life requirements vary depending on their criticality and environment. Figure 13 outlines the relationship between life-limited parts, non-life-limited parts, and TBO during

part in service. Most static parts are designed not to be life-limited, but instead to be continuously used until the engine is removed from service. On the other hand, some parts that operate under high temperature and high stress conditions are designed to satisfy a specified life. These parts' in-service histories are managed by the recorded flight operation log. An engine must undergo regular inspections and overhauls at designated times defined by the operation manual to determine if the subject parts maintain their integrity for continuous service. Any parts that reach their life limit must be replaced with new parts during the overhaul.

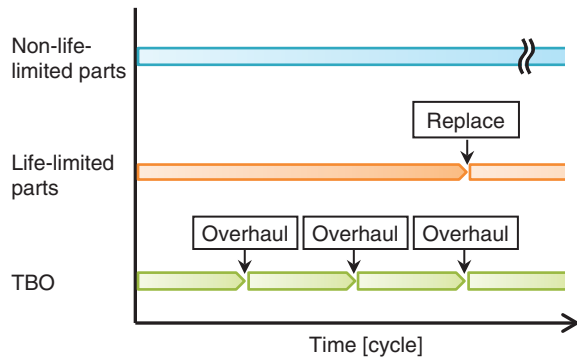


Fig. 13 HF120 life management

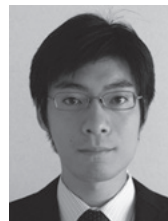
5. Conclusion

This paper describes HF120 turbofan engine design characteristics with a general perspective of engine structure, as well as two representative components, the fan rotor and the LPT1 nozzle. The fan rotor demonstrated compliance with internal design requirements and FAR for FBO, FOD, and HCF by a combination of CAE analysis and substantiation testing. The LPT1 nozzle configuration is light-weight, compact, and highly efficient nozzle with an optimized configuration feasible under high thermal load environments. In addition, the life-limiting concept was adopted on major engine parts design. The life requirement of each engine part was defined in accordance with criticality and characteristics, and parts are designed to meet these life requirements.

References

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- (2) Bird ingestion, 14 Code of Federal Regulations Part 33 Amendment 30 Section 33.76
- (3) Vibration test, 14 Code of Federal Regulations Part 33 Amendment 30 Section 33.83

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