Turbine Engine Structural Integrity Program (ENSIP)

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The Turbine Engine Structural Integrity Program (ENSIP) was established by the Air Force to provide the framework from which an engine contractor can derive a well-ordered structural development program to meet Air Force needs. ENSIP's background and highlights are presented as well as the concept details. Some effects of the concept on existing programs are discussed. The paper is concluded with a brief list of new criteria which are under consideration to refine or update the present program.

I. Introduction

FOR some time considerable attention has been given to the performance aspects of turbine engine development. Relative to the past, today's turbine engines operate at high thrust-to-weight ratios, higher pressure ratios and higher turbine inlet temperatures. Moreover, complex materials employing as many as 16 different alloying elements resulting in multiple hardening mechanisms are being extensively utilized, as well as exotic manufacturing techniques including directionally solidified castings, laser drilling, and inertia welding. Lately, turbine engine structural problems have noticeably increased, both commercial and military, causing an increased emphasis to be placed on structural integrity during engine development.

This paper will present the United States Air Force efforts to minimize new and future turbine engine structural problems through the development and application of an engine structural integrity program called ENSIP. The paper will also include refinements currently under consideration for future versions of ENSIP.

II. Background

Increased interest in engine structural integrity began in 1968 when two of our new generation, high pressure ratio, high-bypass turbofans experienced combustor case structural failures. These engines failed on the test stand within a month of each other after thousands of hours of engine testing had been accumulated. As a result of these failures, an in-depth structural audit was performed by the Government. This detailed review of the entire engine structural design revealed many life limited components, and it became apparent that limited structural life would be a characteristic of high thrust-to-weight, high performance engines. A review of the then existing (1968) Air Force and Navy Specifications requirements showed that no viable structural criteria existed for engine design. It also became evident that an organized and systematic approach to engine structural development was needed. Air Force recognition of potential engine structural problems resulted in the formulation of the ENSIP program.

ENSIP philosophy was first incorporated into the B-1 engine (F-101) "Request for Proposal" (RFP) and has since been utilized in the A-10 (TF-34-100) and SCAD engine programs. Because of timing, only the combustor case on the F-15 engine (F-100) had ENSIP criteria applied.

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III. ENSIP—The Concept

ENSIP is in concept similar to the Aircraft Structural Integrity Program (ASIP)[1] in that it provides the framework for, and a unifying approach to, the engine structural development process through four basic program elements: structural design criteria, structural test requirements, structural data requirements, life monitoring requirements. The major constituents of ENSIP are contained in the latest Military Specification MIL-E-5007D[2] which has been applied to the latest turbine engine development programs.

Even though ENSIP is still being developed, it does provide industry with the design and test guidance it needs to provide the Air Force with sound turbine engine structural development programs. The result is more durable engines which meet the Air Force mission requirements.

ENSIP Structural Design Criteria—The Need For a Defined Duty Cycle

A major point of the ENSIP design criteria is the structural design philosophy employed to guide the contractor in derivation of the engine structural design duty cycle. The philosophy divides the engine into "hot" and "cold" parts for life definition purposes. (Life is the time before failure by excessive creep deformation, stress rupture, and high cycle or low cycle fatigue cracking.) Hot parts are defined as those in the hot gas stream such as liner, turbine blade, and nozzle. Cold parts are all the remaining structural parts of the engine, e.g., disks, shafts, casings, blades, etc. The cold part structural design life of the engine shall be the same as the *airframe operational structural life requirement with 100% margin in design fatigue life utilizing minus three sigma material design properties.* Hot parts are to possess *one half the cold part life* again using minus three sigma material properties. The philosophy of 100% margin provides for uncertainty in design and experimental scatter as well as mission usage.

The ENSIP structural life definition allows the contractor to evolve the number of low-cycle fatigue cycles, stress rupture, and creep life required for engine structural design assuming the system mission profiles and mission mix are made available. However, the correct mission profiles and mix often are not available during early development. ENSIP, therefore, provides model structural preliminary design duty cycles for each class of aircraft, i.e., fighter, bomber, cargo, etc. (see Table 1 for example). These are used in preliminary design until sufficient mission profile data are available.

The need for the aforementioned guidance criteria is obvious. Past engine structural designs were evolved based on design duty cycles which were often unrelated to actual expected service usage. These designs were based on 1000

Table 1 Sample ENSIP Preliminary Design Duty Cycle

		Low Cycle Fatigue Requirements[b]				Stress Rupture and Creep Requirements				
System category	Service life	SLTO ③ cycles	Touch & go cycles	Combat[a] subsonic cycles	Combat[a] supersonic	Power setting	Altitude feet	Mach number	Time %	Remarks
Fighter						Max ②	①	① Supersonic	1	① To be supplied by using agency
Cold parts	4000	3500	2000	2200[a]	400[a]	Max ②	①	0.9	4	
Hot parts	2000	1750	1000	1100[a]	200[a]	Immediate	10,000	0.9	30	② Full A.B.
						cruise loiter	35,000	0.75	60	
							SL	0.3	5	
									100%	③ Sea level take off

[a] Includes SLTO cycle—use as major cycle when more damaging.
[b] For design multiply these cycles by 2.

hr of some arbitrarily defined preliminary flight rating test (PFRT) cycle or two military qualification test cycles (MQT) which were totally independent from the system requirements. In some cases, close scrutiny of past engine designs has revealed that different components within the same engine were designed to different mission usages.

The duty cycle philosophy employed in ENSIP provides a systematic base for engine structural design and development and allows an "apples-to-apples" evaluation of competing engine designs to be made from the structural and durability standpoint. This has been a problem in past engine source selections.

ENSIP also contains the following additional structural criteria: ambient temperature exceedance curve (Fig. 1) to account for percentage of engine operating time on standard, tropical, and hot day conditions, and the specific design criteria shown in Table 2. Table 2 contains combustor case criteria because of the energy levels being contained, required minimum rotor burst speed; an infinite life criteria on gyromoment under expected maximum normal maneuver conditions, verification of the creep life prediction, a foreign object damage (FOD) requirement to assure a measure of fan durability under the field environment, critical speed margin, a design low-cycle fatigue (LCF) life margin and a fatigue monitoring system. A flight stress survey is included to insure that no detrimental fan blade vibratory stress exist in the installed condition in the field environment. The survey includes suitability of operation in crosswind conditions, thrust reverser operation or gun fire gas ingestion effects.

Table 2 Specific Design Criteria

Design Item	Requirement
Combustor case	No failure at 2× maximum operating pressure
Rotor burst speed	No failure at 122% maximum operating steady-state speed
Gyromoment	3.5 rad/sec for 15 sec Infinite life under maximum normal flight pitch rate and maximum g force
Creep analysis verification	Analysis versus actual growth in MQT test
Blade containment	All rotors
Critical speed	20% minimum margin above-operating range
Blade out	One blade at airfoil root
Flight stress survey	Required (fan only)
FOD	K_t of 3
Vibration survey	No detrimental responses in operating range
Design material properties	−3 sigma
Casting factor	1.25
Flight maneuver load	No failure at 1.5× maximum load
Design requirement	No yield at maximum normal load
Design LCF	100% margin
LCF recorder	On-board recording system, engine mounted counter or a paper count system

ENSIP Test Requirements

The purpose of the ENSIP structural test requirements is to verify that structural design requirements have been satisfied. Where practical, each structural design requirement is verified by a test using either component testing or engine running tests or both. Test scheduling philosophy is such that static strength tests on mounts, cases and frames and rotor burst tests are completed prior to PFRT to ensure safe early test flights. Life verification tests are to be completed by MQT.

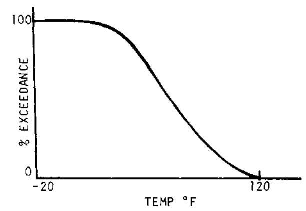

Fig. 1 Ambient temperature exceedance curve.

In the highly stressed components of today's high thrust-to-weight engines, low cycle fatigue plays a very important role in engine durability. ENSIP testing concentrates on both component and full scale engine fatigue tests (Fig. 2). Component tests, e.g., rotor spin pit tests and pressure case hydrocyclic tests demonstrate the engine design margin capabilities. They employ the two life-

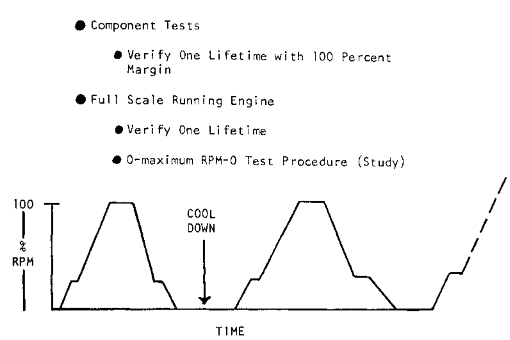

Fig. 2. ENSIP LCF tests.

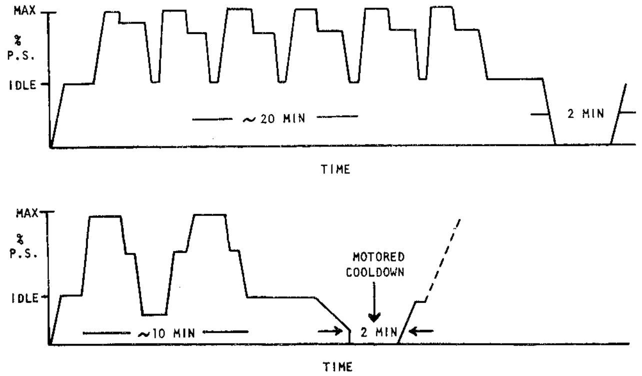

Fig. 3 Actual LCF test cycles after study.

time design margin requirements. A full scale running engine cyclic test, utilizing maximum strain range test cycle from 0-maximum RPM-0 with short cool down test procedure, is required to prove the engine structure for one lifetime. Provisions for a study are included in Military Specification 5007D to base the engine running test cycle and test procedure on realistic fatigue damage estimates with attention given to mission profiles, thermal transients, hold times at high power settings, and length of cool down times. Results of past studies have produced final LCF test cycles as depicted in Fig. 3. The test study usually focuses on sensitivity of the turbine disk and blade to damage from thermal cycling for guidance in selection of the final test cycles. The engine running low cycle fatigue test also evaluates the structural characteristics of the compressor and fan system through subjecting these components of their maximum mechanical induced strain ranges. From this test, realistic criteria for repair can be derived, and follow-on assessment of structural performance of redesigned components can be determined.

Specific tests are required in ENSIP to verify structural design requirements (see Table 3). These verification tests encompass both the strength and life aspects of the design. Component low cycle fatigue tests demonstrate the 100% design life margin. Scheduled (Technical Order) repairs are permitted during this second lifetime. Component life tests are performed on critical rotors, pressure cases, and shafts. FOD tests are conducted either as a bench test, rig test, or engine test.

Table 3 ENSIP Structural Verification Tests

Type Test	Requirement
Strength test	No permanent set at limit load
Cases	
Frames	
Mounts and support frames	No failure at ultimate load
Nozzle	
Pressure test	No failure at 2× maximum operating pressure
Rotor burst tests	No failure at 122% of maximum steady state speed
Low cycle fatigue	Components—2 lifetimes Engine running—1 lifetime
High cycle fatigue	
Vibration and stress survey	No detrimental vibration or stress in operating range Correlate with component tests
Flight stress survey	Fan
FOD	Infinite life with $K_t = 3$ and technical order blend limits

ENSIP Technical Documentation

ENSIP requires structural data in the form of a strength and life analysis to be submitted for approval. This documentation is analogous to the airframe stress analysis and fatigue analysis and is needed to ensure contractor compliance with ENSIP requirements. Previously, the structural strength and life analysis requirements were of limited scope and were contained as part of the structural data submitted to the program offices in the standard engine design development reports. It is felt that the depth of this structural data needs to be improved. This is the objective of the ENSIP documentation requirements.

ENSIP Life Monitoring

The ENSIP program requires that a means of monitoring engine service usage be utilized so that engine structural integrity can be preserved through critical part retirement to preclude the occurrence of a structural failure. Engine life monitoring identifies any abnormal service usage with respect to that used in design which affects safety of flight or engine structural integrity as well as identifying an unexpected lower usage rate which could lead to cost savings through a reduction in spare part requirements.

Engine life monitoring involves recording engine run times and counting low-cycle fatigue cycles. This can be accomplished manually by recording separately the number of take-offs, touch-and-go's, and in-flight power excursions as is currently being done in the C-141 and C-5 programs, or it can be accomplished by using on-board recording systems such as Madar on the C-5 or the CITS system on the B-1. Another alternative is a small LCF digital counter mounted on the engine similar to that used on the F-15 and A-10 engines.

IV. New Design and Test Requirements Under Consideration

ENSIP continues to evolve. During this evolution every effort is being made to not dictate details of design but rather to provide the basics to construct a more meaningful structural development program. New requirements under consideration that reflect the Air Force needs are as follows: 1) New requirement—permanent provision (space, temperature, and g field) for telemetry instrumentation shall be designed into turbofan engines (development and production). 2) Addition—add to existing vibration survey requirements that bowed rotor starts shall be investigated and maximum power stall stresses shall be measured. 3) New requirement—uncontained fan blade rotors shall be designed to 141% overspeed requirements. 4) New requirement—a test shall be conducted to confirm the creep and stress rupture capability of the engine hot parts. This test can be separate or a modification to an existing engine running test. 5) Addition—add a 1/4 in. depth minimum to the FOD $K_t = 3$ design and test requirement. 6) New requirement—a resonance search test on installed engine, plumbing and accessories shall be conducted to ensure detrimental resonances of external components are outside of operating range. 7) New requirement—an aero/mechanical stress survey under flight envelope conditions shall be performed to ensure that flutter and critical system excitations are not detrimental to engine life requirements. Investigation of rotor speed ranges and off schedule variable inlet guide vane operation is to be included. The use of multiplexed telemetry is encouraged.

V. Summary

ENSIP establishes the framework from which a contractor can evolve an engine structural development program that meets the needs of the Air Force. This is accomplished through four program elements: 1) structural design criteria, 2) structural test requirements, 3) structural data requirements, and 4) life monitoring requirements. Constituents of all four elements are contained in the latest military specification revision 5007D which has been applied to the latest Air Force turbine engine programs.

References

[1]Military Standard, "Aircraft Structural Integrity Program, Airplane Requirements," MIL-STD-1530 (USAF), Sept. 1, 1972.

[2]Military Specification, "Engines, Aircraft, Turbojet and Turbofan, General Specification for," MIL-E-5007D, Oct. 15, 1973.

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Residual Life Prediction for Surface Cracks in Complex Structural Details

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This paper reports on the development and application of an efficient technique for calculating the residual fatigue life for surface-cracked structures. The analysis treats the major three-dimensional aspects of the surface-crack problem including crack shape (planar crack with crack front curvature) and local stress variation in the structure. The surface crack is modeled with a finite number of shape-degrees of freedom in order that cyclic changes in crack shape are predicted. Necessary stress intensity factor computations are based on the use of a boundary-integral equation (BIE) model of the surface crack, together with an influence function technique for modeling the crack in an actual structure. The accuracy of the BIE crack modeling is verified with a series of buried and surface crack problems. The theoretical basis of the influence function technique is reviewed in the context of the general surface crack modeling problem. The combined residual fatigue life method is then employed to predict the life of an actual gas turbine engine disk subjected to flight-by-flight testing in a spin pit. A corner crack was initiated at the intersection of a disk bolt hole and the disk face; this crack led to the fatigue failure of the disk. The residual life analysis models this crack during the propagation phase of the disk life. Calculated residual life correlates well with the actual disk life determined experimentally.

I. Rationale

THE fracture mechanics fatigue life of engine disk structures generally may be defined so as to fall into two classes of problems: the growth of subsurface or buried cracks from intrinsic defects, or the growth of surface cracks initiated by fatigue loading of initially defect-free structural notches. The technology of stress analysis and fracture mechanics has reached the level where the fatigue life of components with buried cracks may be reliably and conservatively predicted. However, the complexity of the stress fields and crack geometry for surface-crack problems in engine structural details such as rim slots and bolt holes has precluded the use of fracture mechanics for such problems. Rather, the fatigue life of structural details with stress concentrations has been conservatively estimated by predicting the cycles to initiate a surface crack, ignoring the life which remains in the part until surface-crack growth causes failure.

Linear elastic fracture mechanics analysis forms the basis of predicting the residual fatigue life of a cracked structural element. The material is characterized in terms of its crack growth rate (da/dN) as a function of the cyclic change in the crack tip stress intensity factor (ΔK). The effects of the stress field, the crack size and shape, and the local structural geometry are enveloped by the parameter K. The primary difficulty in analyzing the growth of surface cracks is that no one value of K may be assigned to characterize the entire crack front; further, the stress state near the crack is three-dimensional due to crack front curvature and complex local geometry.

Two extreme approaches may theoretically be employed to model this three-dimensional cracking problem. An engineering approach might consist of replacing the surface crack by an "equivalent" two-dimensional, or line, crack created mathematically by combining suitable analytical models with correction functions. Unfortunately, the correction functions have been found to be unique for each problem and often can be selected only when the answer (life) is already known. The other extreme is to develop a special three-dimensional stress analysis model to reanalyze the crack geometry sequentially as it grows. This second approach requires a full three-dimensional solution for the crack at each increment in its growth history, and for each local stress distribution.

The residual life analysis procedure reported in this paper seeks to employ recent developments in fracture mechanics analysis technology to achieve the accuracy of

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