Keynote Address

Structural Integrity for Propulsion Systems

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I. Introduction

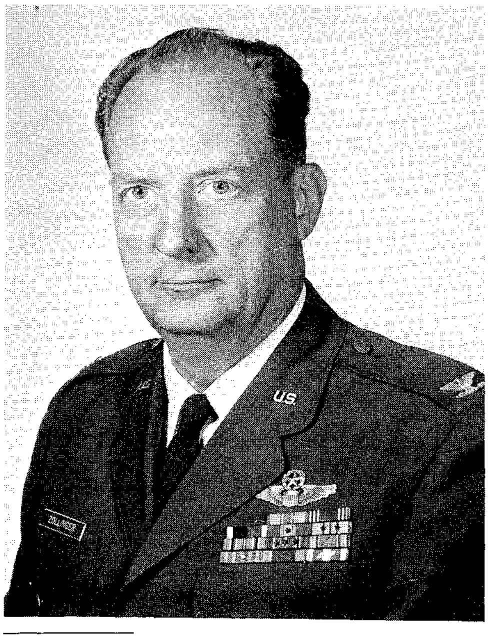
THE basic goal of this Symposium is to exchange information and, as individuals, become more enlightened on the nature of a very complex problem which affects us all. During the recent past, commercial and military propulsion system problem events have been noticeably on the increase, both in frequency and in severity. A large portion of these events have involved the mechanical and structural integrity of engine components. It is that collection of events that has become the main stimuli for this Symposium.

In presenting the Keynote Address for this Symposium, I will give you some insight into why we in the Aeronautical Systems Division consider the development and application of better structural tools, specifications, and tests appropriate for highest consideration. This effort includes both our advanced propulsion systems and our current operational engines. I would also like to express how this thinking is being applied as an integral part of the total propulsion system development process and how it emerges as a major feature in our revised concepts of engine development.

II. Summary of Problem Areas

First, to set the stage, let us consider some of the most recent modern engines that have experienced structural integrity problems. These have occurred either during the development phase or during operational use.

The J85-21 engine had a compressor blade flutter problem which was discovered after the engine had successfully passed qualification testing and after engine production had started. The problem was of such severity that it nearly resulted in delaying delivery of new production aircraft. Structural failures during F-100 engine qualification testing threatened the existence of the weapon system program and raised serious questions about military engine procurement techniques. Fatigue failures in the TF-41 engine have caused loss of life and aircraft. Cracking of expensive turbine blades in the TF-30-P-100 engine produced serious support problems through excessive replacement rates during engine overhaul. The commercial engine business has had its problems: JT-9D engine case ovalization delayed aircraft deliveries. Other significant problem events have been CF-6 engine turbine case separations, RB-211 engine fan blade and disk failures, JT-



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Colonel Joe E. Zollinger is the Director of Aeronautical Systems Division's Directorate of Propulsion and Power Engineering, located at Wright-Patterson Air Force Base, Ohio. He received his BSME degree from Kansas State University of Agriculture and Applied Science, Manhattan, Kansas, in 1948 and his MSME degree (Propulsion Options) from Purdue University, Lafayette, Ind., in 1953. He holds a professional engineering license from the State of Kansas. Beginning with the F-86 fighter in 1953, Colonel Zollinger has had extensive experience in the engineering, development, and production phases of numerous fighter and trainer aircraft weapon systems currently operational in the USAF inventory. As ASD's Director of Propulsion and Power Engineering, he has emphasized the importance of the propulsion system/airframe interface and improving the development cycle for aircraft engines as related to the total weapon system. He is an active member of the AIAA Dayton-Cincinnati Section.

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9D-3 engine initial low overhaul times, and large cost overruns on the RB-211 engine program. This listing is a significant collection of problems, no one of which is common to any particular engine manufacturer. There are others, but within the past two years, these engines have had difficulties involving structural integrity which had significant impact on aircraft. In each case, the basic problem has been that something did not last as long as somebody wanted. This created no end of difficulty for the development agencies, the development contractors, and the logistic and using agencies.

Taking the military examples in turn, I will give a brief discussion of the underlying factors leading to the problem and the steps the Air Force used to resolve the situation. This is not a finger pointing exercise, but an honest attempt to show what we have learned. I might also note that finger pointing sometimes turns out to be at a mirror.

Two J85-GE-21 engines are used in the highly maneuverable F-5E Tiger II aircraft. This fighter is for the export market as a replacement for the earlier F-5A aircraft. The "21" version of the J-85 engine was developed by General Electric with what is now recognized to have been at a very low funding level.

Early in the production run, failures of the fourth- and sixth-stage blades in the compressor necessitated a production line stoppage. In order to identify the cause, an extensive test program was initiated to obtain data. The failure mechanism was identified as a compressor blade instability during off-schedule operation which resulted in high cycle fatigue. Redesign was accomplished and deliveries resumed after significant and expensive verification testing. This verification testing involved extensive strain gauge instrumented compressor running over the complete operational flight envelope.

In the case of the F-100, a similar type of blade instability occurred in the first-stage fan blade. This led to blade tip cracks. A second problem in this program was the severity of the edurance test due to extensive running at maximum flight conditions when compared to expected engine usage. The 150-hr endurance test was essentially equivalent to the total required blade life. You will hear specific papers on both of these subjects during this Symposium.

The TF-41 engine is used in the A-7D/E aircraft by both the Air Force and the Navy. This is a single engine attack aircraft and, therefore, subject to somewhat higher attention whenever an engine failure occurs. The first serious problem that reared its head was a failure of the spacer separating the hubs of the two high-pressure turbine stages. This failure was due to low-cycle fatigue occurring during maneuvering flight. The solution is one that appealed to me and is one which I wish we could use more often. We simplified the engine and reduced weight; that is, the spacer was simply removed—or as Dr. Eugene Covert, Air Force Chief Scientist Emeritus, would put it, "we simplicated and added lightness."

Two TF-30-P-100s are installed in the F-111F aircraft. This engine's major operational problem was failure of the first-stage turbine buckets in the shank area. The failure was due to local hot gas flow past the seal plate into the fir tree area. The resulting reduction in material strength capability was sufficient to lead to high-cycle fatigue cracking and ultimately in separation of the airfoil. A major logistic problem was caused by cracking of the blade coating due to its thermal incompatibility with the directionally solidified parent material.

III. Summarizing

In all of these cases, the end result was that the part just did not last long enough. This can be the result of inadequate structural tools, improper specifications, inadequate testing, or just not enough emphasis on what is wanted. It is important that we identify and understand the sources of these problems and develop the means by which to predict and avoid them in future systems.

Today's engines are designed to be more efficient, possess a higher thrust-to-weight ratio, and are more tolerant to inlet distortion than their predecessors. To achieve this desirable propulsion system performance, the complexities are greater than ever because of the use of higher stage loadings, tighter tip clearances, and utilization of extremely complex materials and manufacturing techniques. A "thoroughbred racehorse" temperamental to its surroundings has evolved.

The foregoing examples all relate to the key point of any structural design. I think it can be boiled down to answering two questions. What do you want the part to do and how long should it last while it is doing it?

Another way of stating it is, what is the mission and how long can you perform it without incurring a failure? Important to our future efforts is an understanding of the mission for which the propulsion system is expected to support the weapon system. Obviously, the end engine product is affected by the type of aircraft and the mission involved. As an example, low-cycle fatigue places a need for us to determine how often, how fast, and how far the pilot moves the throttle. Almost everyone figures the fighter jockey is the toughest guy to satisfy. Perhaps, but rest assured that low-level terrain following with the B-1 aircraft requires a hard look accompanied by careful analysis of the mission. Strangely enough, for some weapon systems, the training mission often proves to be the toughest to handle.

IV. Current Analytical Capability

It is intended that this Symposium give a fresh look at the methods we have at our disposal to cope with durability problems. A fresh perspective should evolve on basic engine structural failure modes. These failure modes include deflections under overloads, high-cycle and low-cycle fatigue, and creep and stress rupture plus oxidation and corrosion.

How do we do it? Among the most valuable tools we have at our disposal is the computer. Computers make feasible involved calculations for loads, stresses, and deflections. Computer programs, which have been and are being developed, provide valuable insight to potential problem areas and greatly facilitate the design process. Finite-element techniques have added a new dimension for the structural designer and analyst. But the tool is no good without the man. Improper inputs or incorrect interpretation of the results can give you a bad part. Therefore, testing is still a must!

Computer programs are available to predict reasonably well the stresses, loads, and deflections. Current programs provide a capability for both macroscopic and microscopic examinations of structural displacement and stress response to a virtually unlimited spectrum of thermomechanical inputs. The constraint of central processor core size on stiffness matrix bandwidth has been circumvented even for machines of moderate size by programs such as NASTRAN which incorporate a substructuring feature. Material and geometric nonlinearities can be accommodated with less general purpose programs. These permit analyses of cyclic plasticity with a choice of hardening laws, crack tip singularity effects, and temperature-dependent plasticity known simply as "CREEP." Current capabilities fall somewhat short in life prediction techniques and in the transient temperature predictions area. Elastic or plastic analytical techniques are available, but need refinement. Low-cycle fatigue prediction techniques need refinement particularly in the area where temperature effects dominate. A better understanding of interactive effects of hold time, creep, and vibratory stresses on low-cycle fatigue life is needed. Three-dimensional analysis to better predict load distribution of complex shapes is needed. The use of fracture mechanics in engine design and life determination as well as materials selection, needs to be expanded. Several programs exist to generate coupled-stress-intensity factors for damage tolerance studies of two-dimensional linear elastic geometries. Much work is still required to attack three-dimensional fracture problems and the additional difficulties of propagation direction and retardation.

V. Experimental Techniques

Testing techniques and philosophy have been changing and are slowly becoming more mission-oriented. Engine endurance test cycles are changing to reflect basic mission-related engine failure modes, such as stress rupture and low-cycle fatigue. More structural component tests are being conducted on basic engine structure, both rotating and static. These tests encompass both strength and life tests, thereby, giving us more confidence in the engines' structural integrity early in development.

New tests and test facilities are evolving. We have the gyro rig test facility where operating engines the size of the TF-39 and JT-9D can be roted up to 3.5 rad/sec to assess gyro-moment effects. High-energy X-ray facilities capable of photographing and measuring axial and radial clearances on running engines are being used. Tip clearance measuring devices, using laser technology, are being used on running engines under steady-state and transient conditions. Properly utilized, these devices and techniques will help the engineers to identify, understand, and eliminate or prevent structural problems in the future.

The real world usage and real time loading of our modern turbine engines are next to impossible to simulate by analysis and ground test facilities. This results from our imperfect understanding of the total environmental loading which the various engine components experience in flight and our ability to duplicate them in concert in a real time manner. In the future, greater emphasis must be placed on obtaining more informative flight information relative to the true loading and usage of the engine in flight. This must be done in order close the loop on our structural and life assessment analyses and ground test simulations.

We must discard our old concept that "the engine held together during the category tests so it must be durable and reliable." Our challenge in the future will be to develop the data measurement and telemetry systems which will provide us with the necessary quality and quantity of data in a timely manner to validate our theoretical and empirical understanding. This will be a most formidable endeavor!

VI. Outline for Future Research and Development Efforts

In summary, I believe our future efforts should concentrate in several areas.

1) The derivation of better analytical tools.

2) Further exploration of the role of fracture mechanics in engine design

3) Increased emphasis on low-cycle fatigue life prediction techniques, particularly, for the engine hot sections.

4) Development of a cyclic hot section test facility or turbine test rig configured to control boundary conditions. A facility of this type can evaluate existing and new analytical tools, conduct sensitivity studies, and be used as a life verification tool for new engines.

5) Further development of instrumentation technology. This includes data transmission systems such as telemetry and slip rings and sensors capable of surviving in high-temperature, high-vibration environments.

6) A most important, but sometimes overlooked, item vital to the effective use of our inventory is the nondestructive test equipment to accurately find the bad areas, once we discover how bad is bad. (This must be closely integrated with predictions so we avoid the death spiral. That is, we cannot afford to scrap parts with smaller and smaller defects that mean less and less until we scrap new production parts.)

Again, the goal of this Symposium is to exchange information and, hopefully, to allow each attendee to obtain a better perspective on where we are and where we should go in pursuit of structural integrity in our propulsion systems.

Improved structural integrity means longer life and an improved life cycle cost factor. It is a tough, but not an insurmountable, challenge. Closer communication between organizations and people in the know will greatly enhance understanding and progress.