Engineering Notes

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Simulation of Turbine Engine Operational Loads

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I. Introduction

THE Arnold Engineering Development Center (AEDC) has been working for five years on the definition and optimization of a new and unique test facility concept which will simulate flight maneuver loads on aircraft propulsion systems. This paper is intended as a progress report to interested parties and summarizes the planning and rationale which have led to the proposed facility performance and conceptual design.

The major aircraft turbine engine test facilities in the U.S. were designed following World War II and have been in operation about 25 years. Modernization and repair programs have kept the facilities operating and marginally adequate for basic turbine engine development testing.However, the very significant increases in engine performance and complexity during the past two decades have demanded that the test facility simulate flight environments which were not anticipated during facility conception and which are impossible or infeasible to achieve by modification.

High-performance gas turbine engines are sensitive to not only self-induced loads but also to externally induced loads which result from aircraft maneuvers. These external loads cannot be simulated on the ground with any existing facility. Analytical techniques are also inadequate for prediction of the complex force interactions and the resultant repositioning of engine components, case distortions, etc. Experimental data which are obtained from flight tests are neither timely nor sufficiently definitive. The continuing trend toward more maneuverable aircraft, lighter and more flexible engines, faster rotors, and closer operating clearances between moving parts will increase the susceptibility of future turbine engines to performance deterioration from externally applied forces.

The proposed Turbine Engine Loads Simulator (TELS) facility will uniquely simulate maneuver-induced gyroscopic and inertial loads experienced by operating turbine engines. Various diagnostic techniques (including x-ray) will be used to determine the reaction of internal engine parts to the combined operational and maneuver loads. This new test capability will provide the engine designer with previously unavailable information very early in the development cycle to permit design optimization and innovation and to serve as a basis for judicious tradeoffs between engine performance and long-term wear.

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II. Definition of the Operational Environment

The structure of gas turbine engines results from a complex combination of aerodynamic, thermodynamic, mechanical, and metallurgical design considerations and may be composed of over 40,000 precision parts. The engine is expected to operate in a very hostile environment, being exposed to extremes of temperature, pressure, vibration, and mechanical forces within the engine. In addition, the engine is exposed to a variety of accelerations in all directions, thus imposing large inertial and gyroscopic forces on an already complex loading environment. The engine is expected to function under all conditions with small clearances between rapidly moving and stationary parts and to exhibit little degradation in performance after long periods of operation.

Flight Maneuver Forces

Aircraft maneuvers produce a combination of *g* forces and gyroscopic moments that distort the engine case and rotor. The *g* forces from aircraft turns, pullups, hard landings, etc., act on the propulsion system and cause rotor displacement and rotor and case bending and may exceed 10 *g* in some maneuvers.

Large gyroscopic moments are created when a spinning body such as the engine rotor rotates about some axis other than its spin axis. The size of these moments is a function of the body spin speed, mass and distribution of mass of the spinning rotor about its spin axis, and the aircraft pitch/yaw rate. The resultant forces cause damaging cyclic bending of the rotor disks, blades, and rotor shaft. Gyroscopic moments of military fighter aircraft engines can exceed 200,000 ft-lb and may be even higher for the large fan engines. It should be noted that gyroscopic forces are generated not only by aircraft maneuvers but can also be induced on wing-mounted aircraft engines in steady flight.

Combined Force Environment

The complex combination of operating forces and flight maneuver forces presents a formidable obstacle to determining the distortion occurring in the engine during flight.

Because of rotor movement, case bending and ovalization, rotor shaft and blade bending, blade extensions, and thermal stresses, the engine designer cannot accurately predict the relatively movement of engine components under all operating conditions. Consequently, modern aircraft turbine engines experience interference, rubbing, and wear of parts with a corresponding loss in performance

III. Requirements for Combined Force Environment Simulation

The outlook for the future indicates that the sensitivity of turbine engine performance to maneuver-induced forces will increase. Propulsion systems are increasing in complexity, with more moving parts and more control systems, thus providing more opportunity for "force effects" to cause problems.

The trend toward higher thrust-weight ratio will continue and result in more flexible engine structures and more maneuverable aircraft. Larger or faster-turning rotors increase the inertia of the rotating mass. Closer tolerances provide increased opportunity for engine wear. "Soft" bearings permit greater movement of the rotating components which react to external forces. Continuing improvements in turbine engine performance appear incompatible with reduced life-cycle wear unless the engine designer has better information on which to base his "flexible" engine designs and the tools are available early in the engine development cycle to permit the necessary tradeoffs. TELS can provide the critical information to satisfy these needs.

The information to be derived from tests with TELS will satisfy the engine designer's requirement to know with precision the relative location of engine components under all operating conditions. The application of x-ray techniques to operating engines in test cells has already revealed unexpected deflections of engine components. Use of x-ray as a diagnostic tool to observe an engine experiencing its total force environment will be even more revealing and useful. With detailed knowledge of movement of parts, the designer can confidently "design around" potential problems by such techniques as using active seals.

TELS is the primary remaining test facility needed to permit performance tradeoffs and optimization of the propulsion system during the development cycle. The information provided via TELS will combine with that from other developmental test facilities to complete the spectrum of experimental data. Desirable tradeoffs between engine initial performance, life-cycle performance, reliability, and wear can then be made with a reasonable degree of confidence. Such tradeoffs are now made late in programs when flight data and aircraft operational experience expose undesirable engine features. The resultant changes are seldom optimal because of insufficient information, tight schedules, and/or large costs. The use of TELS, in conjuction with existing and approved engine test facilities, will permit a much more "mature" engine to be introduced into the operational aircraft and should significantly reduce the required engine changes and problems during the aircraft service life.

IV. Definition of the Turbine Engine Loads Simulator Facility (TELS)

Engineers at the Arnold Engineering Development Center have been consulting with government and civilian propulsion experts for over four years to determine the potential facility user's views of TELS' test and performance requirements. Two studies by Planning Research Corporation have complimented the AEDC studies to define the facility concept and cost.[1,2] Several approaches were considered and evaluated before the final TELS concept was accepted. Because the propsed radiographic system demands special technical and safety considerations, the Commercial Products Division of Pratt and Whitney Aircraft was contracted to define the radiographic and safety requirements and identify preliminary design requirements.[3] A second contract was awarded to a combined team of Pratt and Whitney, Lockheed, and Varian to develop the conceptual design of the x-ray system. A final contractor study is underway with the University of Dayton Research Institute to analyze existing aircraft operational maneuver loads data and to develop simulated maneuver profiles and typical test programs for the TELS facility.

The TELS is an imaginative concept that will provide realistic flight inertial (g) and gyroscopic loads to an operating engine using the capabilities inherent in a centrifuge design. Selected facility design requirements of 15-g inertial force and 3.5-rad/s aircraft rotation rate determined the 40-ft test arm length (see Fig. 1). The centrifugal force created by rotating the arm simulates the g force experienced by the engine in a maneuver. The engine, although fixed in a test position on the arm, experiences one complete revolution for each rotation of the centrifuge arm. The test arm is balanced by a shorter counterweight arm that has both removable solid weights and a liquid transfer balancing system. The centrifuge

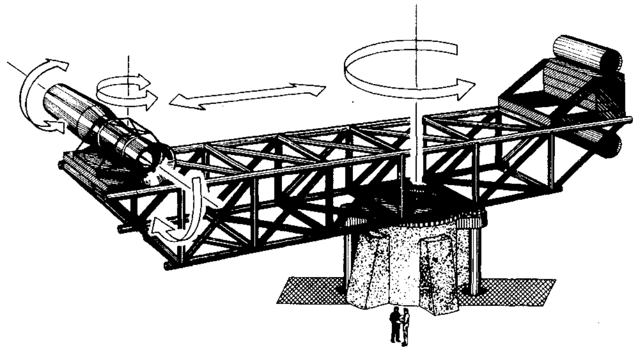

Fig. 1 Turbine engine loads simulator (TELS).

is driven by an electric motor and gear train. Engine thrust will be negated and the exhaust gas deflected using a splitter to divide the exhaust jet into equal and opposite streams directed away from the engine. The test engine can be positioned on the centrifuge arm at any radius.

To simulate the actual aircraft flight loads, a hinge-gimbal system was developed to provide pitch, roll, and yaw positioning of the test engine. The centrifuge test envelope is extended into the desired test area by pitching the engine mount about the hinge axis to provide the desired component of gyroscopic moment (a 90 deg pitch-up places the engine axis of rotation parallel to the centrifuge axis of rotation and the gyroscopic moment is zero).

V. Concluding Remarks

The TELS facility will provide the U.S. with a unique tool to attack engine deterioration and life-cycle performance problems. TELS will give the engine manufacturer previously unavailable information very early in the development cycle to permit design optimization before production design freeze occurs. In the present method of engine development, the effects of maneuver loads on an engine are never determined until flight test, when design changes are extremely difficult and costly to make. With TELS, an engine can be "flown on the ground" to verify its design and structural adequacy long before flight test.

The potential for dollar savings with information to be derived from TELS is enormous. The Air Force spends $1 million per day for jet engine spare parts and about one-half that amount for overhaul costs. TELS will provide information that the engine manufacturer can use to extend parts' life and increase time between overhauls. TELS should also aid in reduction of the $1.8 billion Air Force jet fuel bill by helping to lower the deterioration rate of in-service engines. Because TELS will permit a more mature engine to be entered into service, the Component Improvement Program expenditures should also be reduced. TELS will combine with other existing and approved propulsion system test facilities to give the U.S. propulsion community the necessary test facilities to maintain a pre-eminent world position.

References

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