NAPC Gyroscopic Moment Test Facility

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Since 1949, military engine specifications have required engines to operate satisfactorily under imposed gyroscopic moments. These reaction moments on the aircraft engine structural components occur in actual flight during the high angular acceleration rates experienced in aircraft maneuvers or in severe atmospheric disturbances. As an alternative to running a complex flight test program, a gyroscopic moment facility was conceived, designed, and constructed by Detroit Diesel Allison at Camp Atterbury, Ind. This paper describes the basic design features and capabilities of this unique test facility, which has been relocated to the Naval Air Propulsion Center Outdoor Test Site, Lakehurst, N.J., and is now operational.

Introduction

SINCE 1949, military gas turbine engine specifications have required engines to operate satisfactorily under imposed gyroscopic moments, but it was not until 1973 that the military engine specification, MIL-E-5007D,[1] specified an actual gyroscopic moment test up to 3.5 rad/s steady angular velocity. The traditional approach to turbine engine ground testing has been to emphasize performance characteristics (e.g., thrust and specific fuel consumption) of an operating engine at simulated flight conditions. In general, the structural integrity of the engine components was determined either analytically or by computed static equivalent load tests, as stipulated in earlier versions of the general engine specification and necessitated by the fact that no ground-based test facility existed that could simulate flight maneuver loads. These loads in combination with vibrations, temperature gradients, low and high cycle fatigue, etc., presented a complex structural design problem. Obviously, there was no alternative to verify engine structural integrity predictions other than complex, costly, and often time-delayed flight test programs.

It has long been recognized that the capability to test operating turbine engines under flight maneuver conditions in a ground test facility would be a valuable asset in any engine development program. This is especially significant recognizing today's trend toward engines that are lighter, have tighter internal clearances, and operate at higher rotor speeds and gas temperatures than their heavier and more rigid predecessors. Installed in high performance aircraft, these new generation engines may be seriously affected by gyroscopic moments and other load conditions resulting from high angular velocities (yaw/pitch) experienced in aircraft maneuvers (especially high stall departure) or severe atmospheric disturbances.

The Naval Air Propulsion Center (NAPC) acquired a gyroscopic test rig as surplus government equipment from the Detroit Diesel Allison Division. Allison designed and built the rig in the early 1970s to verify/fix a moment load structural problem with a high pressure turbine spacer ring in the TF-41 engine. The rig was removed from Camp Atterbury, Ind., and has recently been erected at the NAPC Outdoor Test Site (Fig. 1) in Lakehurst, N.J. Successful verification of rig capabilities was completed in December 1980 using a J52-P-8A turbojet engine, and the gyro rig is now available for future test programs.

This paper describes the basic design features of the facility, discusses the results of the facility shakedown tests, and details future plans for improving/increasing facility capabilities.

Facility Description

Basic Rig

The basic gyro test facility design specifications and capabilities are:

Engine thrust: 50,000 lb
Maximum gyroscopic moment: 4.5×10^6 in.-lb
Rig acceleration rate: 0.22-0.63 rad/s^2
Rig deceleration rate: 0.24-0.47 rad/s^2
Rotation direction: clockwise and counterclockwise
Speed of rotation: 0-3.6 rad/s
Plane of rotation: horizontal
Maximum rotation angle: 360 deg
Maximum engine diameter: 9 ft
Maximum live load: 25,000 lb

The facility, shown in Fig. 2, is located in an open field area with the basic rig structure mounted to an approximate 130-ft-diam, octagonally shaped concrete pad containing 700 yd^3 of concrete. The device contains 150 tons of steel plate and carbon steel pipe in even-inch diameters from 4-12 in.

A 12×12-ft engine mount platform is provided with a rotation axis passing through its center normal to and 15 ft above ground level. The engine mount and restraint are designed to accept a standard engine dolly. The engine platform and test unit are supported by a base structure containing the drive system and supporting thrust bearing, as shown in Fig. 3. Lateral motion of the platform from engine thrust and moment loads during rotation is restrained by self-aligning roller bearings in both the base structure and at the top of the engine platform. Support for the upper bearing is provided by a tower structure with a cantilever truss. This main truss is braced near the bearing mount at a 90-deg angle by a secondary tower and bracing truss structure. The bracing tower prevents lateral motion, or wobble, of the upper bearing assembly during platform rotation.

At the base of each tower, expansion rails are anchored. These rails extend parallel to each truss and connect with the base structure. Both the rails and base structure are mounted in guide plates and are free to move relative to each tower base. This provision minimizes misalignment between the upper and lower bearing due to thermal growth effects on the cantilever and bracing trusses.

Engine exhaust blast shields are located on each support tower to eliminate thermal effects and exhaust wake impact on the structure during rig rotation. The blast shields consist

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of tubular components which surround the main structural members, providing an air gap between each. The base shields are supported independently of the tower structure for vibration isolation.

The rig drive system (Fig. 4) comprises a 100-hp variable speed dc motor, a 2:1 belt drive reduction, and 25:1 helical gearbox reduction. This configuration provides a maximum rig rotational velocity of 3.6 rad/s. The maximum rotation rate can easily be altered by belt drive sheave changes to meet an increased test speed requirement. Drive motor control is by a rheostat located in the engine control room, and with acceleration and deceleration rates limited by the control systems within the motor-generator set. Rig rotation can be provided in either direction, depending upon the direction of the gyroscopic reaction moment desired for a particular test. An air actuated disk brake is provided for emergency stops and rig parking. Normal rig stops utilize the dynamic braking characteristics of the drive system.

Electrical System

Electrical service at the test site includes 460- and 200-V, three-phase, ac power. Both 110-V ac, single-phase and 28-V, 400-cycle power are available on the rotating portion of the rig.

A set of 33 propeller slip rings, mounted above the upper bearing assembly, are used to provide power and control circuits to the engine and instrumentation power supplies. Each slip ring has dual contact brushes rated at 60 A. Rig drive motor power is provided by a motor-generator set rated at 250 V dc and 360 A output. Facility operating data (e.g., power lever control, fire extinguishing systems, etc.) are transmitted through an 11-conductor slip ring assembly, shown in Fig. 5, located below the lower rig bearing. Amplifier signal conditioning and multiplexing equipment, located on the engine platform, enables considerable flexibility in utilizing available slip rings. For example, 16 of the 33 upper slip rings are submultiplexed to switch 96 signal leads. Future capabilities will include a 240-conductor slip ring assembly.

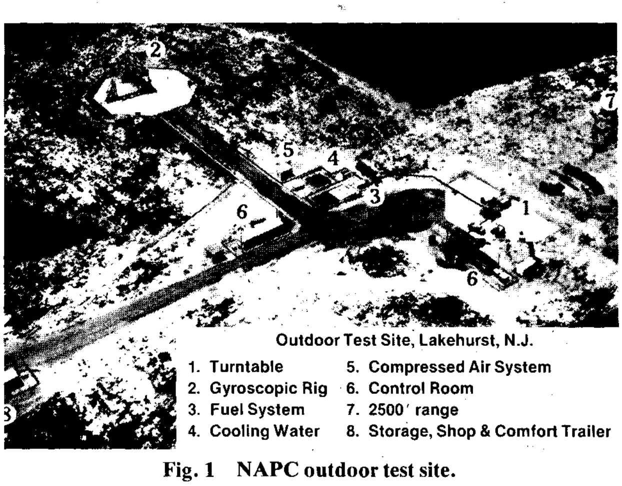

Fig. 1 NAPC outdoor test site.

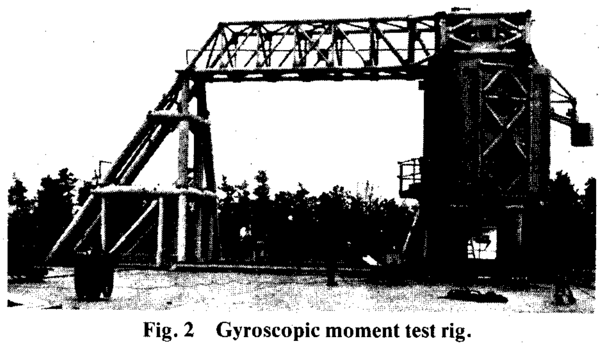

Fig. 2 Gyroscopic moment test rig.

Data Acquisition System

Current data acquisition capabilities include 1) gages and meters manually read in the control trailer (Fig. 6); 2) a leased two-module scanivalve for pressure measurement (40 pressures—20 each in two ranges); and 3) a total of 58 temperatures, millivolts, and frequency readings. Future instrumentation expansion plans include a) at least a four-pressure range scanivalve system, with an increased number of pressure lines to double current capabilities; b) procurement of a PDP 11/60 computer to process data; and c) installation of a more accurate sampled frequency measurement system similar to that used in the NAPC test cells.

Support Systems

The fuel supply system to the test site consists of a fuel pumping station with two 5000-gal capacity tank trucks and three pump/motor assemblies. The pumps include one 55-gal/m pump with a 50-150-psig discharge pressure, one 60-gal/m pump with a 28-psig discharge pressure, and one 200-gal/m pump with a 125-psi discharge pressure. The pumps are connected in parallel to a 3-in. iron pipe size (IPS) pipe main feeding the site. Fuel transfer to the rotating platform is via a 2-in. i.d. rotary union. An Adel operated emergency fuel shutoff valve is also provided in the supply system.

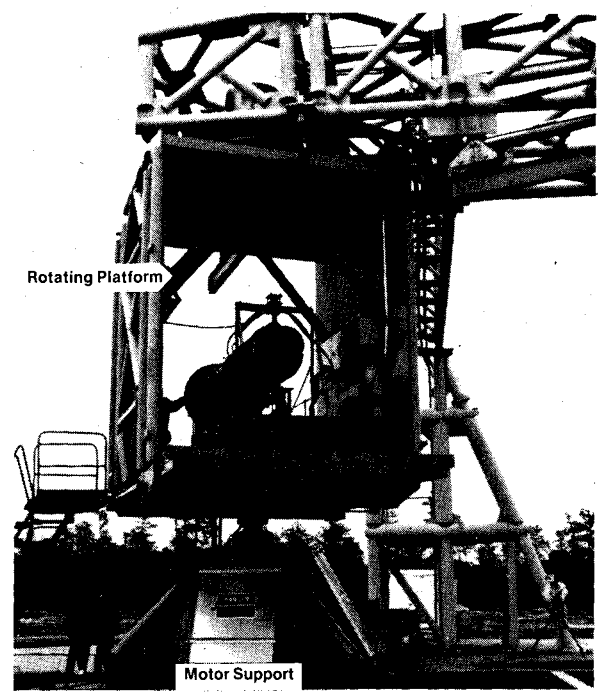

Fig. 3 Rotating platform and motor support.

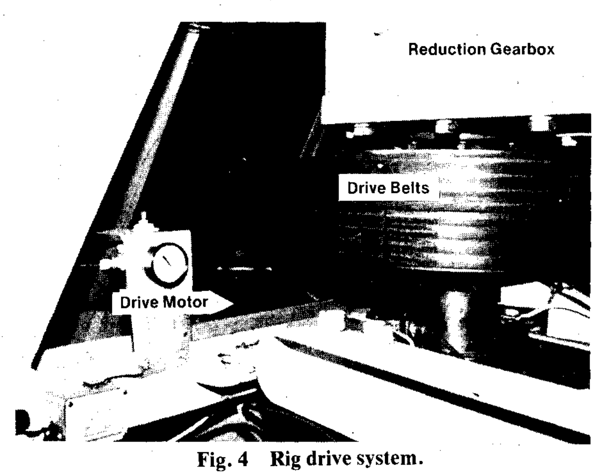

Fig. 4 Rig drive system.

The pumping station, required to supply water to the water brakes at the turntable facility (see Fig. 1), is of the recirculating type consisting of a shallow well, pond, two pump/motor assemblies, and a pond spray system. The capacity of the well is 60 gal/m. The pond capacity is 10,000 gal, of which 7000 gal are usable. The pumps each have a capacity of 123 gal/m and a discharge pressure of 60 psig. The well pump automatically maintains the level of the pond water between 5500 and 7000 gal. The pond is connected in parallel to the two pumps. The pumps are connected in parallel to a 4-in.-diam copper tube main which feeds the test site. A 4-in.-diam copper tube main also returns the water to the pond from the facility through a pond spray system.

An external air supply is provided to the engine platform via a rotary union through the upper rig shaft. Compressed air is furnished by a 210 ft^3/m, 90 psig, air compressor, and receiver system. The receiver is connected to a 2-in. IPS pipe main. Air is used to provide the cooling required for special engine instrumentation. Air to drive the engine starter is provided by a GTC-100 gas turbine compressor (Fig. 7) through a flexible hose to a quick-disconnect fitting under the engine rotating platform.

Miscellaneous Systems

Engine power lever movement and control is accomplished using a dc servo control motor with digital input capability and a gear reduction drive unit. An air-operated fail-safe system automatically closes the throttle in the event of a loss of electrical power.

A closed circuit TV system is used to monitor the engine during operation for fuel and/or oil leaks. In the event of an engine fire, fire extinguishing capability is provided by two large spherical bottles, each containing 100 lb of freon, mounted on one wall of the engine platform. Actuation of a solenoid valve from the control trailer discharges the freon from the bottles through a manifold system on both sides of the engine.

Discussion

Capabilities and operational procedures and characteristics of the NAPC gyro rig were verified in a two-phase test program. The first phase consisted of rig operation with dead weights only. The second phase was with an operating J52-P-8A turbojet engine installed, as shown in Fig. 7. It should be emphasized that the rig was designed specifically to meet the military engine specification requirement of 3.5-rad/s angular velocity in yaw. It was never intended to be used to demonstrate linear acceleration (g), or inertial forces. It was intended instead to be a reasonably low cost approach to testing an engine at extreme gyroscopic moments on the ground in the place of the complexity, cost and potential safety problems associated with an in-flight test program. Although the turntable concept does have the linear acceleration limitation, the effects of pure gyroscopic moments are important, especially in development testing, where it is desirable to separate and study gyroscopic moment effects independent of linear acceleration effects.

The dead weight check-out phase consisted of operating the gyro rig in the clockwise (CW) and counterclockwise (CCW) directions at angular velocities up to 3.5 rad/s. The rig was operated unloaded first, then was loaded up to 8500 lb and finally operated with eccentric (unbalanced) dead loads. Rig deceleration rates were established by bringing the rig up to the desired rotational speed, then rapidly returning the speed control rheostat to zero (stop position) and recording the time to stop. The rheostat was then set at the previously determined speed setting and the rig was started and allowed to accelerate to the predetermined speed to establish acceleration rates. Typical accel times with 1700 lb of dead load from rest to 3.5 rad/s were 29 s for CW rotation and 34 s for CCW rotation; decel times from 3.5 rad/s to rest were 5 and 7 s, respectively, for CW and CCW rotation. Similar times were measured with

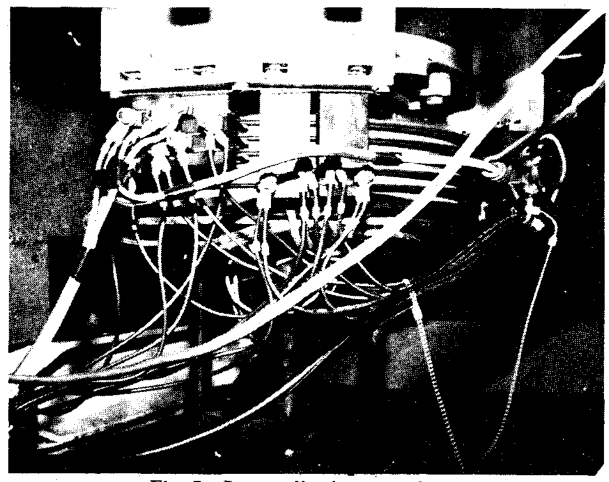

Fig. 5 Lower slip ring assembly.

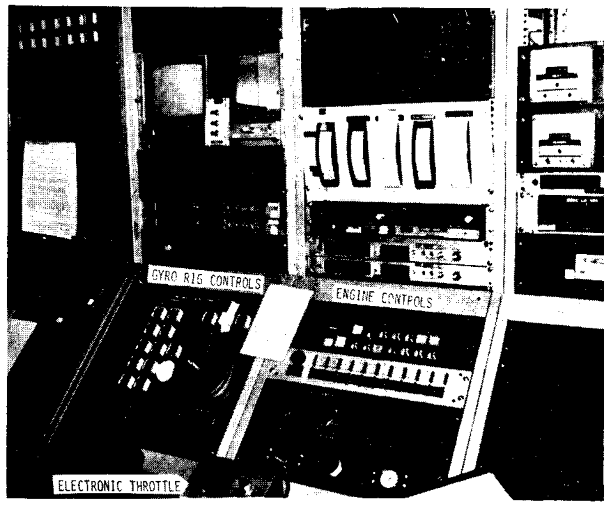

Fig. 6 Control room instrumentation.

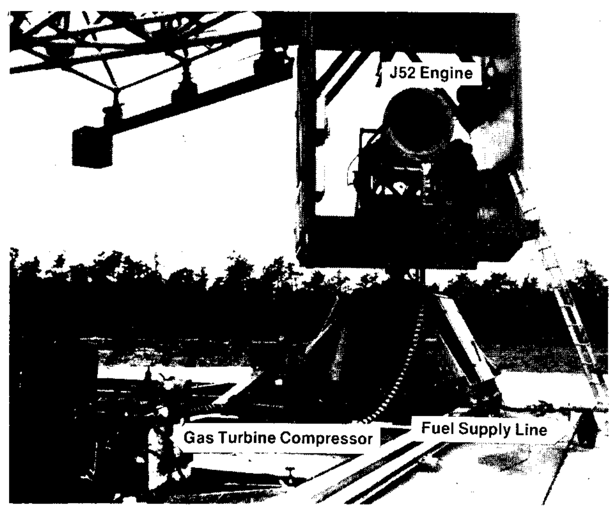

Fig. 7 J52 engine installed in gyro rig.

8500 lb of dead load. Gyro rig operation was satisfactory in all cases except for speed overshoots that occurred when accelerating the rig in the CW direction. This appears to be an inherent characteristic of the rig design and can be overcome by modifying speed control rheostat operating procedures.

The second phase of the gyro rig check-out consisted of operating the rig with a running J52-P-8A test engine up to 1.7 rad/s in a CCW direction and 0.2 rad/s in a CW direction between idle and normal rated engine power. The rig rotational speeds were limited to the precalculated stress limits of the NAPC engine test stand. A total engine accumulated operating time of 4.7 h was recorded, of which 1.6 h were under gyroscopic loads. In addition to the steady-state testing, engine throttle bursts and chops between idle and normal rated power were demonstrated at each of the gyro rotational speeds. The test successfully demonstrated the capability of the facility to 1) measure and record pressure, temperature, frequency, and millivolt data transmissions, and 2) control the engine throttle and ignition systems, all via slip rings during gyro rotation. The test also showed that gyro rig operating characteristics observed during dead weight testing were in no way altered by testing an operating engine.

Future Plans

NAPC personnel are continuing to improve/increase the capabilities of the gyroscopic moment test facility, particularly in the areas of quantity of data measurements and instrumentation/data acquisition system accuracies. A permanent building is being constructed at the test site to house the engine/rig control room with its associated equipment/computers, thus eliminating the need for the present space-limited portable trailers. To provide more realistic and effective simulation of a maneuver load test environment, a study will be made to determine the feasibility of incorporating a g load test capability into the gyro rig. In addition, some of the test facility support systems are being modified, such as the fuel and water supply systems. The improved water supply system will allow a water brake to be used to extract power from the test engine for customer purposes, thus more closely simulating realistic flight operation.

The most recent Navy engine to complete full-scale development is the F404-GE-400, used in the F/A-18 aircraft. When the F404 engine development contract and model specification were negotiated, the gyroscopic moment test requirement was replaced by a requirement for a gyroscopic moment analysis, only. During the early phases of the development program, one of the problems encountered included three confirmed failures of a bearing in the turbine area of the test engines. The gyroscopic moment analysis performed by General Electric to satisfy the specification requirement indicated that the bearing loads on static test stands may be less than one-tenth of that occurring during extreme flight maneuvers. (Also, analyses by the Navy and Air Force have shown that gyroscopic loads are especially critical on engine bearings.) Under consideration for the near future is an actual specification type gyroscopic moment test on a fully instrumented production F404 engine. The probable benefits of conducting such a test would be to uncover unknown potential problem areas related to gyroscopic moments (e.g., significant blade deflections, lube system performance, internal structural loading), thus avoiding possibly substantial engine retrofit costs which would occur if these problems developed later in fleet service operation. The test data would also be useful to verify the sophisticated analytical techniques used in the gyro moment analysis to predict structural integrity.

Besides rotational tests, other possible uses of this open-field ground facility include tests involving water, sand, and fuel ingestion; noise, infrared, smoke, pollution, and exhaust plume measurements; icing, corrosion, vulnerability, and humidity tests; test cell correlation effects, etc. The facility is available to government agencies and industry contractors in the United States and the NATO nations. The costs and scheduling of programs will be determined upon application to the Naval Air Systems Command.

Summary

The addition of maneuver loads testing to the military engine specifications[1] has constituted an important step toward more timely and cost effective engine development philosophy. Stress and relative deformation between moving and stationary parts, regardless of the cause, parallel the importance of fluid and thermal dynamic design aspects. Simulating gyroscopic moment loads is not the ultimate test, but it does represent a significant advancement in providing realistic test conditions.

The NAPC gyroscopic moment test facility, the only facility of its kind in the United States, and perhaps the world, is now operational. Its application to future engine development programs should overcome the current lack of analytical design confidence and provide additional assurance that engines which reach service operation will not be adversely affected by gyroscopic moments.

Reference

[1]Military Specification, "General Specification for Engines, Aircraft, Turbojet and Turbofan," MIL-E-5007D, Oct. 19, 1973.