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Operational Environment of Naval Aircraft Gas Turbines

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Military aircraft engine usage is reviewed, with emphasis on a new technique for qualification testing. Future engines, including the F404 and T700, will be required to pass a Simulated Mission Endurance Test (SMET) prior to high production release. SMET details are highlighted by comparing design mission power required to actual mission time histories. In addition, time at maximum temperature and number of full and partial stress cycles is compared. Results show the operational usage has triple the cyclic content and one-quarter the hot time of the military specification.

Introduction

Two military specifications define the model qualification test (MQT) for aircraft engines. MIL-E-5007D pertains to turbojets and turbofans[1] while MIL-E-8593A applies to turboshafts and turboprops.[2] Figure 1 depicts a six-hour qualification test schedule which is repeated 25 times to accumulate specified endurance test hours. The primary goal is to meet "spec" performance and to have surge-free operation, hence this schedule contains a large amount of maximum power operation. As a result, military gas turbines have been designed to this goal and these operating conditions.

An historical view of aircraft engine development shows that after having passed MQT, Navy propulsion systems are plagued by numerous durability problems, especially where a high state-of-the-art level of performance is needed. As structural deficiencies surface during service introduction, product support programs enlarge to accelerate engine development while addressing component durability. Birkler and Coté[3] show that an exponential growth function applies to both test hours and expenditures during this phase of development. Thus qualification, in the past, was overly severe in terms of meeting performance and was deficient in terms of screening durability problems associated with service use. This paper reviews a new approach to qualification, some typical results, and some conclusions that may be drawn from this study.

Background

The traditional approach to test and evaluation is being challenged for not simulating actual service operation in the test cell. In 1975 typical TF41 engine parameters were recorded during several A-7D flights. Bauer, Peer, Holley, Kenne, and Onizuka[4] validated engine stall data while investigating different phases of flight. More importantly, they stated a concern about the large throttle movements occuring in the six sorties flown. A year later, Rapp, Montgomery, and Lail[5] reported on the YF-17/YJ101 flight test experience and observed almost constant throttle movements on an air combat maneuvers flight. They also stated that these changes in power have a significant effect on engine structural life and that these cycles are now being incorporated into endurance testing to simulate actual operational requirements. In 1976, Holl and Wilkins[6] developed a rather unique approach to engine usage monitoring. By recording each sortie on a real-time basis, low-cycle fatigue (LCF) cycles are computed. By 1978 Hurry and Holmes[7] described further refinements to this monitoring system by which they calculate material creep. These kinds of engine distress are being compared to on-going development bench testing to correlate engine structural conditions against usage.

New test techniques which incorporate fleet operations are evolving. A different approach has been presented in the development of the TF34-GE-100 turbofan accelerated mission test (AMT). In 1977, Taylor and Ogg[8] based their test cycle on pilot interviews which provide flight details, and test cell records which provide ground operations, trim runs, etc. Their composite test cycle has deleted steady-state part-power operation, and in a shorter test length they accomplish essentially the same usage as in real time. A merging of these two appoaches has been suggested by Coté, Birkler, and Byers.[9,10] Their approach to a SMET development also was based on a fleet survey. They highlighted the different types of flight profiles and used in-flight test data from these flights to derive a duty cycle. This resulted in a real-time representation of current fleet aircraft engine usage.

Thus, the true military engine duty cycle is a very important item in terms of turbine engine design and development. The Navy, recognizing this fact, has begun a new approach to engine development, in which a SMET has been added to the qualification requirements. Future engines, including the F404 turbofan and the T700 turboshaft, will be required to pass a SMET prior to qualification and high production release. Emphasis during this phase of development will be on durability, reliability, and maintainability, while meeting minimum levels of propulsion system performance.

SMET Methodology

To establish an engine duty cycle requires an understanding of fleet operations. There are two modes of operation used by the Navy today: installed engines flying mission profiles and uninstalled engines undergoing test cell trims or maintenance checks. Comprehensive squadron surveys are performed at Naval Air Stations to elicit information concerning mission profiles, ground runs, trim cycles, sortie frequency, ship to shore ratio, etc. Table 1 lists typical mission profile types for

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Table 1 Summary of naval aircraft operational missions

Aircraft	Mission profile types
A-4M	Familiarization, carrier qualification, formation, air combat maneuvers, ground attack
A-6E/EA-6B	Familiarization, navigation, tactics, tanker, ground attack, airborne electronic warfare, carrier qualification
A-7C/A-7E	Familiarization, formation, instrument, surface search, ground attack, air combat
AH-1J/AH-1T	Familiarization, ordnance delivery/ground attack, nap of the Earth
AV-8A	Navigation, air combat maneuvers, consolidation, ground attack, close air support
F-4J	Familiarization, intercept, air combat maneuvers, ground attack, carrier qualification
F-14A	Familiarization, air combat maneuvers, gunnery, intercept, carrier qualification
F/A-18	Familiarization, air combat maneuvers, interdiction/ground attack, intercept, carrier qualification
S-3A	Familiarization, anti-submarine warfare, surface search, carrier qualification
SH-2F/SH-60	Familiarization, anti-submarine warfare, search and rescue, carrier qualification
T-2C/TA-4J	Familiarization, instrument, formation, gunnery, carrier qualification, air combat maneuvers, ground attack

several different Naval aircraft, as determined from the interviews. It is significant that three profile types (familiarization, carrier qualification, and combat training) are common to each of these aircraft. The AV-8A and AH-1J/T are slightly different due to limited use aboard carriers. Both Navy and Marine pilots and navigators provide a wealth of operations data to explain fleet aircraft use. Shorebased missions and shipboard missions are obtained with the most frequent sortie and particular maneuvers assembled to represent a typical mission type.

To describe the engine environment accurately, it is necessary to instrument several aircraft and record performance parameters, such as power lever angle for fixed-wing aircraft and load demand angle for rotary-wing aircraft, turbine temperature, and rotor speed. These parameters show directly what demands are placed on an engine by the pilot. In addition to these engine parameters, airspeed, altitude, and ambient air temperature are recorded to establish the operational flight envelope.

An instrumented test aircraft is flown to each of the typical mission profiles defined in the fleet survey. In-flight monitoring is accomplished by the use of an on-board tape recorder or via FM-telemetry. In either case, each parameter is sampled at one point per second. This frequency is satisfactory for impulse power demands and normal engine temperature and speed response. For accuracy in the duty cycle, airframes are configured with weapon racks or fuel tanks, as specified in the fleet survey. It was observed that turbofan power aircraft had fewer stores or external fuel tanks in current fleet squadrons and that this was due to better fuel specifics offered by these engines. In the case of turbojet-powered aircraft, specifically the F-4J, additional fuel tanks were required to provide comparable mission time available.

Once the flight data acquisition is completed, the time history is reduced and analyzed. Several items of interest are computed on a routine basis. Time at maximum turbine temperature is important relative to creep and rupture phenomena. The number of starts and partial throttle cycles, idle to intermediate to idle, are recorded for subsequent comparison to the MQT reference and input to eventual low-cycle fatigue life calculations.

A SMET is formulated by summing the mission profiles weighted by their frequency of occurence. The total number of missions are randomly sequenced to generate a test schedule to which an engine may be run. A 1000-h test based on these missions will expose a gas turbine engine to a real-time fleet environment in the test cell before service introduction.

Discussion of Results

As a part of the propulsion design requirements, proposed missions are defined for industry which define aircraft capabilities. These mission profiles are similar to the MQT cycle in that each segment has an unperturbed power setting for a set time period. Examples are given in Figs. 2-4. In these figures, the relative power required is plotted against mission time for a fighter, attack and trainer aircraft, respectively.

In contrast to the above profiles, flight recordings were made from similar aircraft on the same type of missions. Figures 5-7 show relative power required versus mission time for the YF-17, A-7E, and TA-4J respectively. These missions are more representative of the repetition or cyclic nature found in the training environment. In all flights, a combat segment is performed repeatedly. The A-7E performs thirteen runs on target, a common occurence for fleet aircraft. Thus, the operational requirement or usage is distinctly different from the proposed design missions. In terms of structural life, an alternating stress pattern appears predominant over the steady-state stress requirements. Intuitively, therefore, one would expect field distress to be characteristic of fatigue rather than creep or rupture.

There are other typical missions which display fewer throttle excursions, e.g., an instrument or navigation sortie. These missions are a part of the fleet squadron operational environment but do not occur as frequently as those listed in Table 1. Their use and occurence must be factored into a SMET calculation. To illustrate the overall SMET results, ten engine SMET's are calculated and comparisons with respect to durability are made to the reference MQT baseline. The items of merit are the number of starts, partial cycles, and time at maximum turbine temperature. The number of starts (engine startup to intermediate or A/B to engine shutdown) is equivalent to the number of fatigue stress cycles that the engine experiences. Partial cycles (idle to intermediate to idle) are also fatigue stress cycles which can significantly influence component thermal fatigue life. Time at maximum turbine temperature is defined as a condition of intermediate power and A/B.

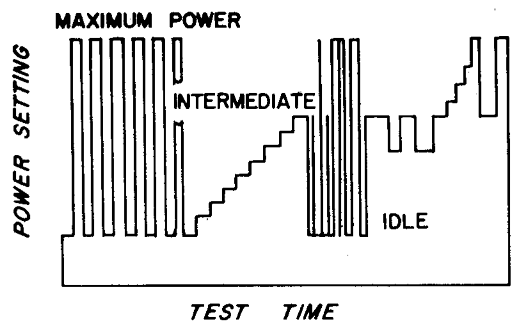

Fig. 1 Model qualification test (MQT) cycle for turbojet and turbofan engines.

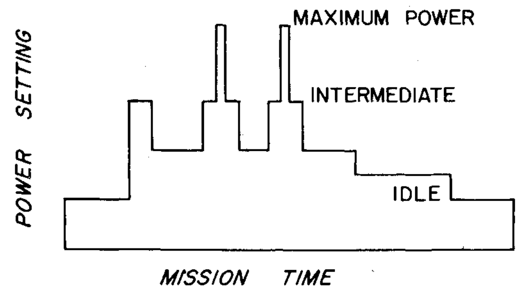

Fig. 2 Power required during air combat, proposed fighter aircraft design mission.

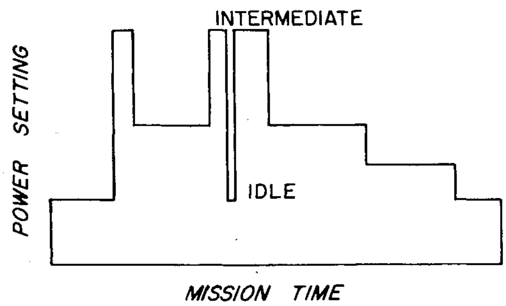

Fig. 3 Power required during ground attack, proposed attack aircraft design mission.

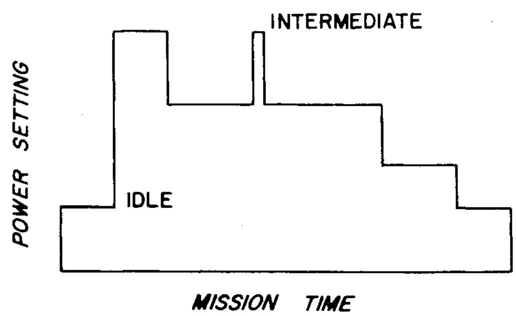

Fig. 4 Power required during air combat, proposed trainer aircraft design mission.

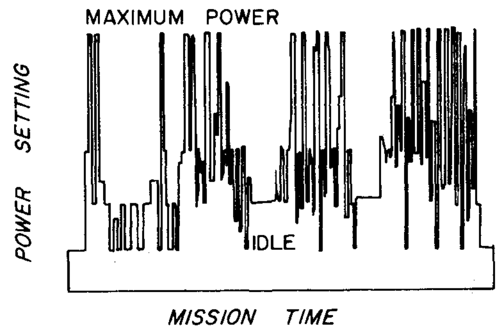

Fig. 5 YF-17 power required during a combat maneuvers flight, Rapp, Montgomery, and Lail.[5]

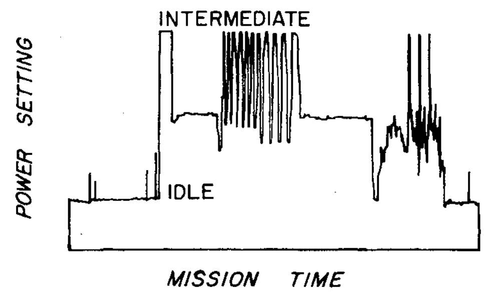

Fig. 6 A-7E power required during a ground attack flight.

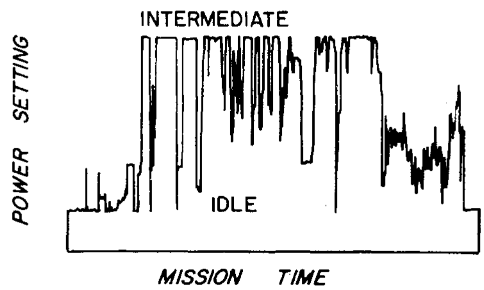

Fig.7 TA-4J power required during a combat maneuvers flight.

All comparisons are based on 1000 flight hours or equivalent engine test time. In Figure 8 all aircraft shown use significantly more starts than required by MQT. The differences range from twice to five times the reference value, with a mean value of 514 starts or three times that of MQT. The AV-8A aircraft had the shortest mission times, which accounts for its having the highest number of starts for a given number of flight hours. Conversely, the S-3A, SH-2F, and SH-60B had the longest mission times and the smallest number of starts.

Figure 9 compares the number of partial cycles for the same Navy aircraft with those required by MQT. Again all aircraft shown use more throttle cycles than the reference. It should be noted that the MQT for turbojets and turbofans contains 601 less partial cycles than the MQT for turboshafts and turboprops. For jet aircraft the differences range from 2.5 times to 4.3 times the reference. For helicopters the differences are approximately 1.4 times the reference.

The F/A-18A engine duty cycle was based on F-4J data, and thus the figure shows the same number of partial cycles. If two flight recordings (e.g., familiarization and air combat maneuvers) are substituted, the resulting partial cycles increase to 5990. These recordings were viewed as more consistent with the data base since the F-4J data was not based entirely on flight recordings. The reason for excessive partial cycles in the cases of the AV-8A, F-14A, and YF-17 may be their high thrust-to-weight ratio relative to the other aircraft. The other aircraft have landing practice as drivers of partial cycles. A significant amount of time is dedicated to field and carrier landing training within fleet squadrons because of flight safety.

Figure 10 compares the time at maximum turbine temperature for ten Navy aircraft with that of the MQT cycle. In each cycle, the operating aircraft uses less time than the reference. Values range from one-quarter to one-tenth of the MQT cycle. The mean value for fixed-wing aircraft was 10%, while the mean for the rotary-winged aircraft was just under 4%. The low values for the AH-1J and SH-2F systems are due to transmission limits which did not allow maximum turbine temperature during flight tests. Moreover with the assumption that an SH-60B would not be transmission limited, the usage is comparable with the rest of the aircraft shown.

Application

Pratt & Whitney Aircraft Group calculated much lower life for the TF30 components using the current F14A operational environment. Engine P-695048 recently was produced and considered healthy with respect to component improvements. To verify these component lives and correlate the SMET to field experience, the Navy decided to expose this engine to a 1000-h SMET.

After running approximately 500 h, nearly half the first stage turbine vanes were replaced after inspection. At 1000 h, the entire set, new and old, was badly cracked. The engine was

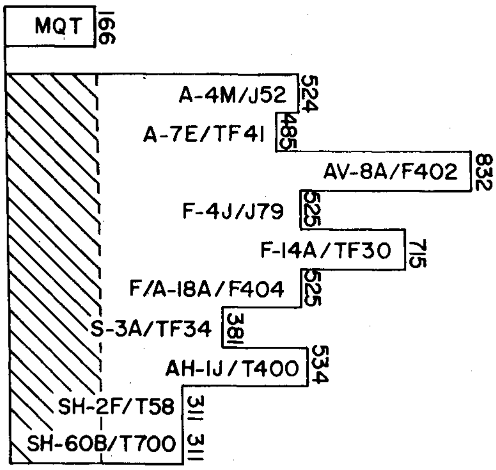

Fig. 8 Variation in number of starts required by MQT and 10 Navy aircraft.

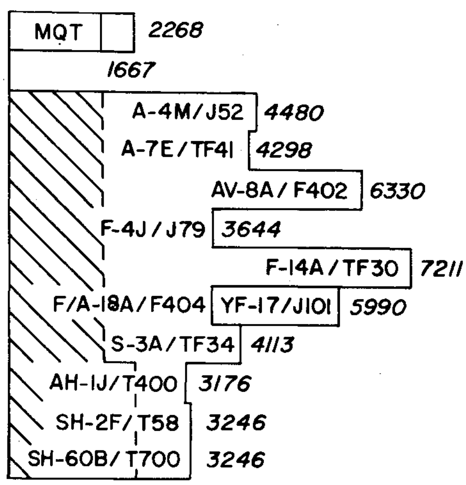

Fig. 9 Variation in partial stress cycles required by MQT and 10 Navy aircraft.

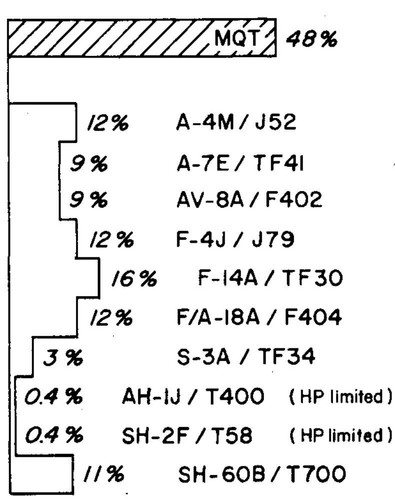

Fig. 10 Difference in time at maximum temperature between MQT and 10 Navy aircraft.

then submitted to a clean inspection where distress and wear were found in other components as well.[11] A list of worn components and their prognoses are provided in Table 2. Representatives from TF30 rework facilities attested to the similarity between parts exposed to SMET and those removed from fleet engines. Component lives were verified and suspected disks with life remaining will be tested in a spin pit to determine exactly how much life does remain. Moreover, the correlation to field experience is very good and thus supports SMET testing as a valid technique for substantiating engine design and durability.

Table 2 Status of SMET engine at 1000 hours

TF30-P-414 component	Recommended action
Fan inlet and exit guide vanes	Replace 2 inlet and all exit vanes
7th stage fan outer shroud	Weld repair cracked shroud
10th stage compressor disk	Exceeded life limit, replace disk
12th stage compressor spacer	Replace cracked spacer
16th stage inner airseal	Replace worn airseal
Burner diffuser case	Weld repair case
Fuel nozzle supports	Weld repair 7 of 8 supports
Burner cans	Replace 3 of 8 cans, recoat 5
Burner heat shield	Replace cracked heat shield
1st stage turbine vanes	Replace entire set of vanes
1st stage turbine disk	Replace cracked disk
1st stage turbine blades	Exceeded twist, growth and notch limits, repairable
2nd stage turbine blades	Replace 4, repair 87 blades
3rd stage turbine blades	Repair 78 blades
4th stage turbine blades	Repair 45 blades
A/B flameholder and tailcone	Repair cracked flameholder and tailcone
Gearbox carbon seal, de-aerator gear	Replace seal and gear

Conclusions

The study on which this paper is based has investigated current Navy and Marine aircraft engine usage. A result of this investigation has been the establishment of a data base of engine duty cycles for a broad range of aircraft missions. Simulated mission endurance tests have been formulated for ten unique aircraft systems. Results show usage to be dramatically different from original MIL specifications in most respects. When coupled with other tests required during new engine qualification, SMET will be an excellent indicator of expected engine durability. The data base also can serve as a basis to evaluate changes to or redesign of existing components in engines presently qualified. Constant updating of usage data is required to maintain currency with fleet operations.

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