Lessons Learned to Improve HCF Demonstration Tests*

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Abstract

New turbine engine component designs are subjected to structural characterization tests to verify that vibratory stresses are below high-cycle fatigue (HCF) limits at various engine operational conditions. These tests are sometimes conducted in an altitude test chamber with a heavily instrumented engine where a limited number of altitude/Mach number test conditions are simulated to characterize component vibratory stresses. If the vibratory stress measurements from these characterization tests are below predefined limits (usually 60 percent Goodman limit), the part "passes" and the component development process will often continue to a durability demonstration phase. The engines that are used for durability demonstration tests, such as Accelerated Mission Testing (AMT), usually don't have instrumentation to measure component vibratory stresses. The durability demonstration tests are often designed to accumulate low-cycle fatigue (LCF), creep, and wear mode damage that is caused when the engine cycles between low- and high-power settings. Some tests might be performed specifically to demonstrate that the engine components will not experience HCF damage during field us, (for instatnce, an HCF stair-step test), but comparison between test and field vibratory load spectra is often limited because of the lack of instrumentation of the test engines.

This paper presents some lessons learned during past HCF characterization and demonstration tests. Based on these lessons learned, suggestions are made to improve demonstration testing to increase the probability of revealing HCF deficiencies. Results are presented that compare the estimated vibratory load spectrum components experienced during AMT and HCF stair-step tests with field usage. Comparisons are also made between different test scenarios to identify potential improvements to the HCF demonstration test process. These evaluations consider multiple components to identify potential test methods that could be standardized and could provide some benefit over current HCF demonstration test methods.

1.0 HCF CHARACTERIZATION TEST

High-cycle fatigue (HCF) characterization tests are performed during engine development with the intent of defining and evaluating turbine engine component vibratory response characteristics for a wide range of engine operational conditions. The engine characterization tests are performed after extensive component-level analysis and evaluation through modeling, simulation, and rig testing. Figures 1 and 2 are representative test matrices from the characterization test performed on the General Electric F101 core and engine during the 1970s.[1] The core consisted of the high-pressure compressor, combustor, and high-pressure turbine. The parameters that were known to influence core component vibratory response include compressor inlet pressure and temperature, variable stator vane (VSV) position, and compressor inlet total pressure distortion. Considerations were made for the operational extremes, such as VSV-control failure modes and flight maneuvers that caused maximum inlet distortion when defining the test sequence. After the core module was tested, a test

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matrix for the full engine was selected and performed. These tests were designed to verify that component vibratory stresses would be below material limits for any operational condition experienced in the field.

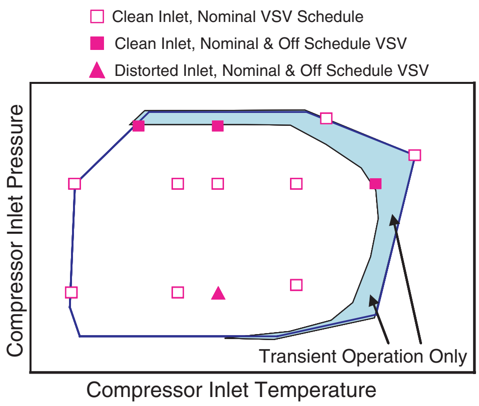


Figure 1. F101 Core Stress Survey Test Matrix

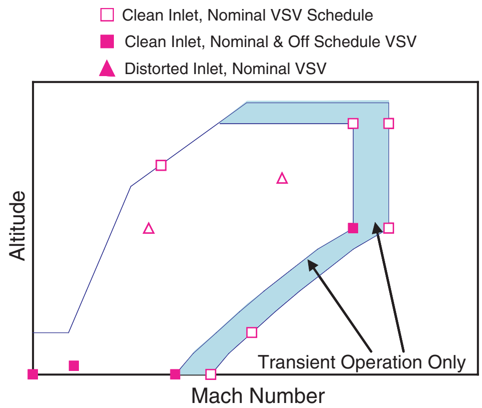


Figure 2. F101 Engine Stress Survey Test Matrix

2.0 ACCELERATED MISSION TESTING

Accelerated Mission Testing (AMT) is a common test performed on military aircraft turbine engines to demonstrate component durability after the HCF characterization test. AMT missions are designed on the basis of analysis of expected operational usage for development engines or by the throttle profiles recorded during flights for field engines. To reduce the amount of time and cost associated with performing the tests, the throttle histories of field engines are analyzed, and portions of the histories that are considered not to be damaging to the part are removed. Damage for some modes, such as creep or erosion, is driven by high turbine temperature operation associated with engine high power, or "hot" time. The damage for other failure modes, such as low cycle or thermal fatigue, is accumulated as the engine cycles between low and high throttle settings. For the failure modes of concern, some of the portions of the throttle histories that are considered to be damaging and that are therefore matched between AMT and operational missions include:

1) Time at high power
2) Number of large throttle excursions
3) Time at elevated inlet pressure/temperature conditions (RAM)
4) For augmented engines, the time in augmentation and the number of augmenter lights
5) The mix of mission types (air-to-air, air-to-ground, etc.)

AMT missions do not include many small throttle transients in the part-power region (Fig. 3) because these are considered to have little effect on many of the failure modes of concern.[2]

Removing the extended dwells and small throttle transients results in a reduction of time required to perform the AMT by a factor of 2 to 10 compared to the equivalent operational time.

One method used to quantify engine usage is based on defining and tracking different types of throttle excursions on the basis of their relative severity. Definitions commonly used for engines used by the U.S. Air Force include the following throttle cycle types:[3]

Type I - Cutoff (0 RPM) - to High power – return to Cutoff
Type III - Idle power – to High power – return to Idle power
Type IV - Cruise power – to High power – return to Cruise power

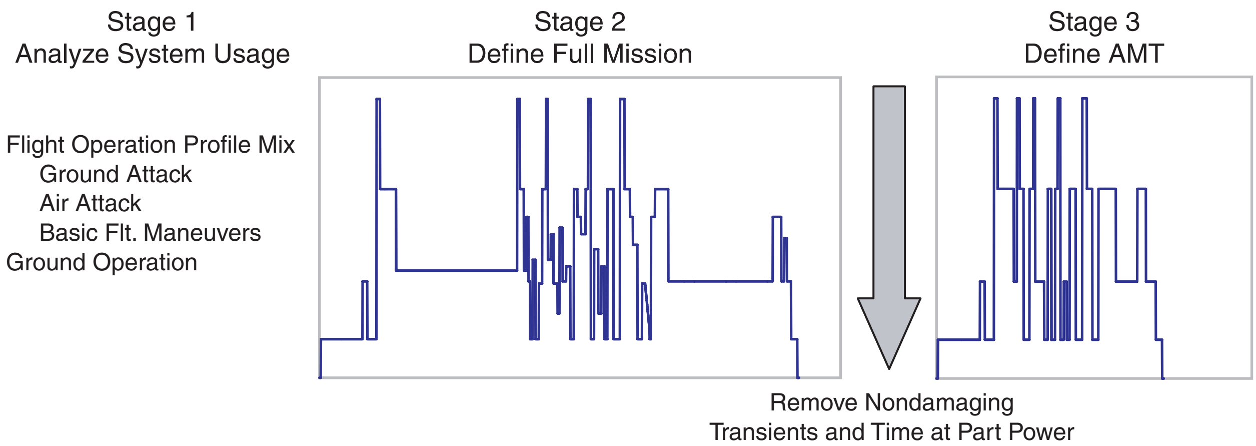


Figure 3. Defining Accelerated Mission Throttle Profile from Field Recordings

The Idle, Cruise, and High power settings can be defined as rotor speeds or throttle positions. These different types of throttle cycles are input to the Total Accumulated Cycles (TAC) by the following equation:

$$TAC = \text{Type I} + \text{Type III} / 4 + \text{Type IV} / 40$$

This definition of TAC permits comparison of AMT to operational usage and permits tracking engine usage during operation to determine when the engine should be removed from the aircraft for major maintenance intervals.

HCF damage is accumulated by extended operation at critical speeds where component vibrations occur. As shown by the representative Campbell diagram in Fig. 4, the critical speeds at resonant responses may occur over small RPM regions in the part-power region where AMT missions do not spend much time. Because it is known that AMT missions might not include extended dwells at critical speeds, many AMT programs include a stair-step test to verify that HCF failure modes do not occur in the operational speed range. The stair-step test is performed by operating the engine for extended dwells at small rotor speed intervals in an attempt to expose all components to all potential modes of vibration (Fig. 5). This standardized test is designed to operate the engine at rotor speed intervals for enough time to accumulate a predetermined number of cycles for lower frequency fundamental modes or at low integer engine order excitations. For a stair-step test where the dwells are performed at small rotor speed increments, the entire test can require between 10 and 100 hours of engine operation time.

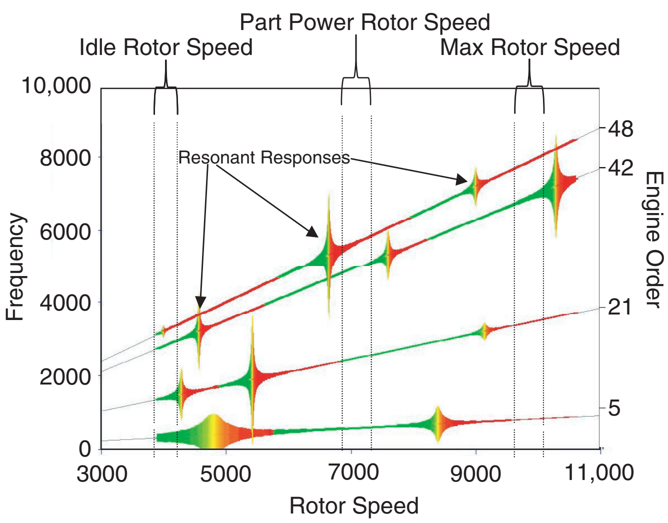


Figure 4. Campbell Diagram with AMT Speed Ranges

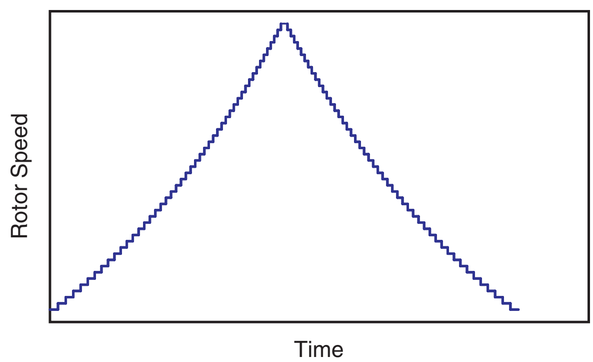


Figure 5. HCF Stair-Step Test

3.0 LESSONS LEARNED

HCF characterization and demonstration tests have been performed on military engines in a similar manner for several decades. Lessons learned from these tests can be used to improve the testing of future military engines. Below are some lessons learned and their application to improve future HCF demonstration tests.

3.1 Current AMT and HCF Stair-Step Tests Do Not Reveal All HCF Deficiencies

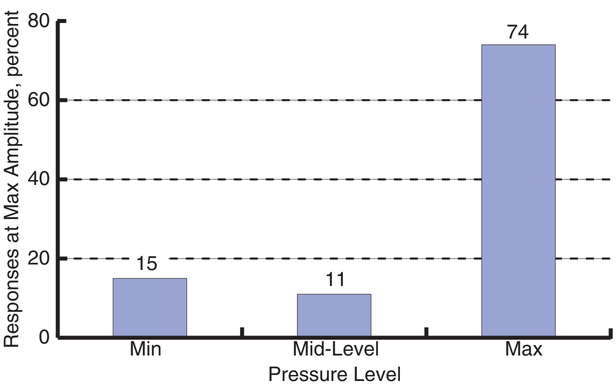
When the AMT and HCF stair step tests were initially developed in the 1970s, it was thought that they could reveal up to 50 percent of the potential HCF problems[2] that were not identified during early development or by the characterization tests. Between 1982 and 1996, however, HCF accounted for 56 percent of all class A engine related failures.[4] In the mid 1990s, the cost of HCF to the Air Force was estimated at $400 million per year. These statistics indicate that there is a need for improved testing, both for the characterization and demonstration phases, to reduce the probability that components will experience HCF failures when fielded.

3.2 Endurance and Durability Tests Need To Have a Direct Relationship To Field Usage

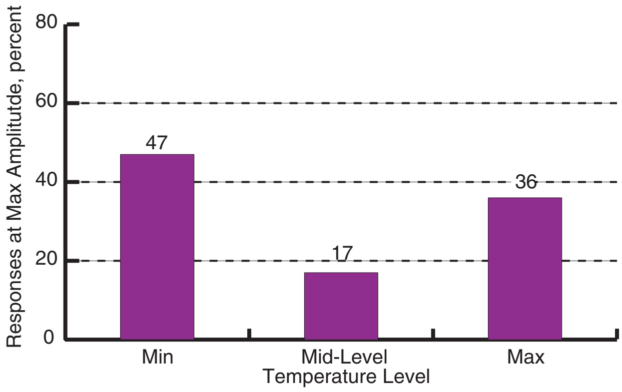
Before the development of the AMT test, endurance tests (such as the Military Qualification Test, or MQT) were employed to demonstrate engine durability prior to engine field operation. The emphasis of the MQT tests was testing at intermediate and afterburner power to evaluate the creep characteristics of new materials.[5] The MQT tests were limited in that test results could not be directly related to field usage and structurally related problems. The AMT was the next step in the development of the endurance test. Compared to the MQT, the AMT included more throttle excursions. The amount and order of the AMT throttle excursions could be directly related to the field operation. Based on this lesson, improved HCF demonstration tests should be representative of and directly comparable to field usage.

3.3 Component Vibratory Responses Are Sensitive To Environmental and Operational Extremes

A review of the change in component vibratory response with changing influence parameters indicates that the maximum vibratory response is likely to occur at the extreme of the parameter of interest. For example, fan and compressor blades that are sensitive to variable vane position are likely to have the maximum response at the full cambered or full axial position for a given rotor speed. Likewise, a review of the vibratory responses for several different components that were subjected to changes in engine inlet pressure and temperature revealed that higher vibratory responses are most likely to occur at the extreme temperatures and pressures (Fig. 6).[6] At constant temperature, most components experienced maximum responses at elevated pressure because of the increased excitation force with increased density. A few components, however, expe-



a. Pressure



b. Temperature

Figure 6. Historical Max Response Trends

rienced maximum response at reduced pressure, resulting in reduced aerodynamic loading. Components that were subjected to temperature changes while maintaining constant pressure also were more likely to have the highest response at the extreme temperature. This lesson indicates that component vibratory stress exposure could be accelerated for most components by using extremes in environmental conditions and operational scenarios during HCF demonstration testing.

3.4 Component Vibratory Responses Can Be Path Dependent

It has been observed that component vibratory response amplitudes can be dependent on the path of approach and the previous operational history. During characterization tests, stress surveys typically are performed during slow engine accelerations and decelerations between idle and intermediate speed. The slow throttle transients are performed to ensure that vibratory responses reach steady-state levels when traversed. For some cases, the vibratory response amplitudes measured during the deceleration were more than twice the amplitude of the acceleration. The path of approach affects material thermal state and mechanical fits that result in changes to system vibratory response characteristics. Also, engine control logic that is a function of previous state can greatly influence the excitation source. At a given flight condition and rotor speed, variable vane position or operating line might be dramatically different for different throttle scenarios. For example, on a rapid engine deceleration, variable vanes can be cambered from the nominal schedule, and exhaust nozzle area scheduling can be modified to reduce high compressor rotor speed excursions and improve engine reacceleration characteristics.[7] Most of the possible scenarios of structural/thermal and engine control states probably were not tested during the characterization test. Ideally, the demonstration test would replicate many of these scenarios in a test that represents field usage so that components might be subjected to more of the potential variations in vibratory response.

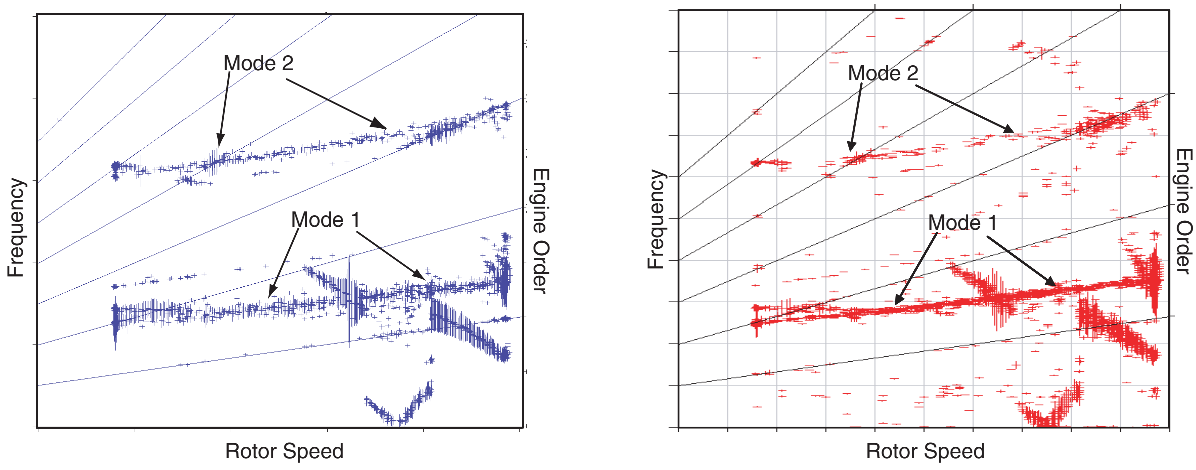
3.5 Testing Can Be Expensive

RAM AMT that requires a plant to compress, heat, and condition air can cost over $10,000 an hour.[8] Sea-level AMT that does not require conditioning of the inlet air can also be expensive, with costs exceeding $4000 an hour. Also, the time required to perform a complete AMT can be several months. Any increase in development time translates directly into increased cost. Based on this lesson, it would be preferable that improved HCF testing not increase the overall development test cost or time.

3.6 Measurements of Component Vibration That Lead to HCF Failures Are Rarely Made on Durability Demonstration or Flight Engines

As mentioned previously, test results should be directly comparable to field operation. Ideally, this would be done using instrumentation on both test and field engines, and a direct comparison of load spectra could be performed. Traditional methods used to measure component vibrations, such as strain gages through telemetry or slip rings, often have limited life and prohibitive cost, both of which prevent them from being used on test programs that might last several months or on field engines that might operate for several years. Noncontact stress measurement systems (NSMS) are being developed with improved sensors and algorithms that have extended life and reduced costs compared to the traditional strain-gage measurements. Figure 7 displays the comparison of the vibratory stresses measured with strain gages and NSMS during a recent HCF characterization test.[9] This system was developed under a cooperative effort between the U.S. government and industry to advance the state of the art for all participants. Additional advances have been made with sensors, such as the sensors developed that can measure blade tip time of arrival through fan and compressor cases.[10]

While additional advances to NSMS sensors and algorithms might be used on future development test programs to regularly perform comparisons between field and test engines, the comparison of load spectra



a. Strain Gage b. NSMS

Figure 7. Comparison of Strain-Gage and NSMS Measurements

between test and field engines can be performed present day using empirical relationships derived during HCF characterization tests. The method is similar to a method developed to use common engine control measurements (P2, T2, rotor speed, etc.) to approximate steady stresses caused by thermal, centrifugal, and aerodynamic loads.[11] A similar approach was extended to the frequency domain to estimate component vibratory response amplitude and frequency for any operational condition.[12] Figure 8 demonstrates some of the steps for a case where the empirical relationship derived with characterization test data could be used to estimate component vibratory response and load spectra using altitude, Mach number, and throttle inputs to a math model. A similar approach can be used to compare field and test engines for multiple parts where characterization test data are available.

3.7 HCF and LCF Interaction Affects Fatigue Life

Recent research has demonstrated there is an HCF-low-cycle fatigue (LCF) interaction that affects material fatigue life.[13,14] This research further supports the need for HCF tests that are performed in conjunction with LCF tests in an operational scenario that reflects field usage. In some current test programs, the stair-step test (designed to accumulate HCF cycles) might be performed after all AMT missions (designed to accumulate LCF cycles) are completed. This approach would not provide load spectra or damage accumulation that is representative of field usage. An improved method that intersperses HCF and LCF cycles in an order and magnitude representative of field use will more likely accumulate stresses and the associated damage in a manner that is similar to operational engines.

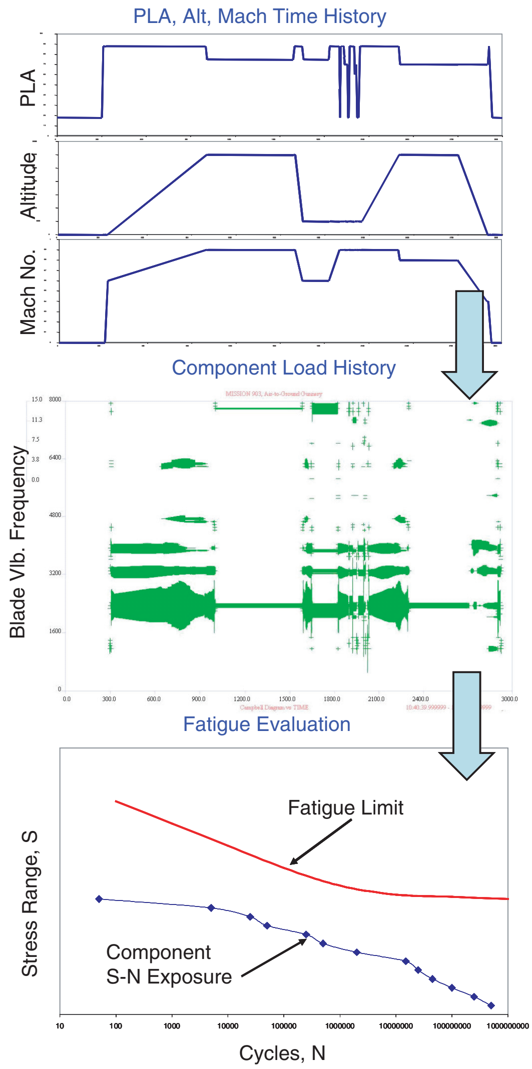


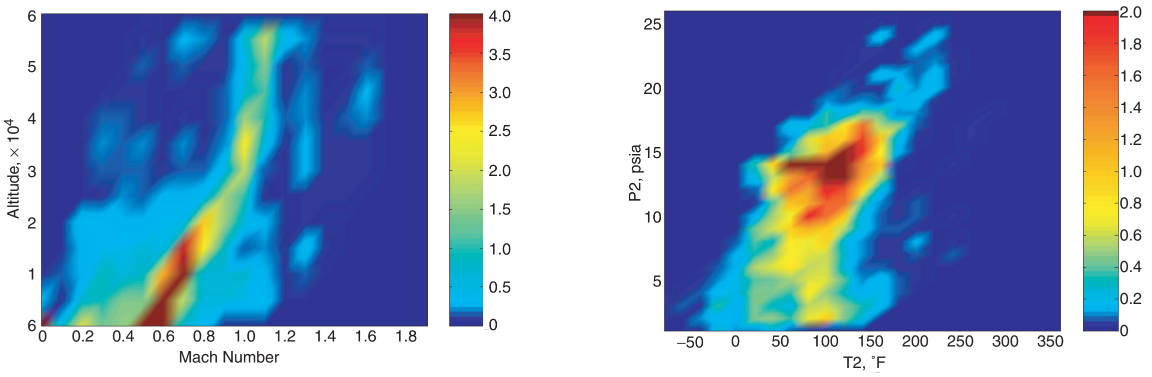
Figure 8. Component Vibratory Response from Altitutde, Mach No., and PLA Time History Estimated

3.8 AMT Tests Usually Accumulate Time at Limited Rotor Speed Ranges

The throttle profiles used during AMT often have only three or four different settings. The idle, cruise, intermediate, and maximum augmentation settings might be the only throttle settings defined for composite missions. The idle and cruise power settings might be defined based on definition of the Type III and Type IV throttle sequences. Because of this, extended engine operation might occur only at a limited number of rotor speeds during the AMT. However, advances in computerized throttle controls now permit small changes and variations in the defined idle and cruise points used between missions; thus extended time can be allotted to a wider range of rotor speeds during the AMT. This would increase the probability that all vibratory modes would be excited under conditions representative of field usage.

4.0 APPLYING LESSONS LEARNED TO IMPROVE HCF DEMONSTRATION

A case study was performed to evaluate the effectiveness of the AMT and HCF stair step and to consider improvements to the process from the previously described lessons learned. A Monte Carlo simulation was performed using a turbine engine transient cycle deck representative of a current nonaugmented military engine that operates for one maintenance cycle defined as 5000 TACs. The throttle range for the engine model was from 18 to 90 deg. For tracking Type III and IV throttle cycles, idle power was defined as being between 18 and 30 deg, cruise power was between 30 and 58 deg, and high power was above 78 deg. Variable inputs into the Monte Carlo simulation included length of mission, altitude, Mach number, ambient temperature, throttle position, and throttle dwell time. For the variable distributions input, the model reached 5000 TACs after 978 missions. The average mission length (including time on the ground) was 127 minutes. The resulting distribution of engine operation time at altitude/Mach number and P2/T2 conditions is shown in Fig. 9.



a. Altitude/Mach Number **b. P2/T2**

Figure 9. Time Distributions

The history of throttle excursions and time at flight condition were evaluated to define a composite mission for the AMT. The composite mission defined for the AMT matched the time at high power and the number of Type III and Type IV throttle excursions of an average mission. The resultant mission throttle history defined for the AMT is shown in Fig. 10. As is common with many AMT missions, only four throttle positions are defined: ground idle at 18 deg, flight idle at 29 deg, cruise power at 57 deg, and intermediate power at 85 deg. The length of this AMT mission is 49 minutes, which represents an

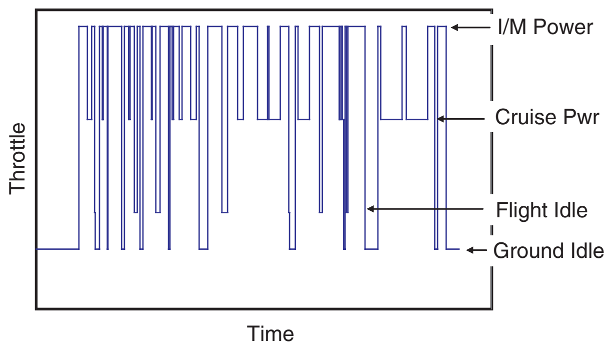


Figure 10. Composite AMT Mission Throttle Profile

acceleration factor of 2.6 compared to the average field mission. It was also determined that, for the AMT, 15 percent of the AMT would be performed at two standard-day RAM conditions (Alt = 1000 ft, Mach = 0.57, and Alt = 5000 ft, Mach = 0.95) to replicate the amount of elevated pressure and temperature time the engine was expected to be subjected to in the field.

The composite mission was used as input to the engine cycle model for 978 missions using a mix of 85 percent ambient inlet and 15 percent RAM. For the ambient missions, the range of inlet temperatures used was representative of seasonal temperature changes over a six-month period, the time period typically required to perform a complete AMT.

The model output of engine rotor speed, P2, and T2 were used to estimate field and AMT component load spectra for three different fan parts using the component vibratory estimating algorithm described previously. A comparison of the load spectra for one of the parts is shown in Fig. 11. For the parts evaluated, the number of HCF-type cycles accumulated during the AMT was between 4 and 100 times less than the cycles accumulated during the field usage.

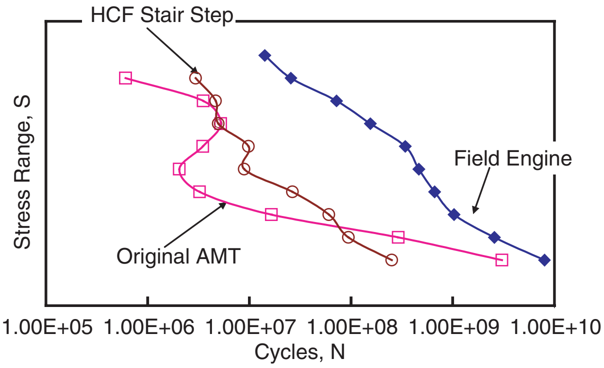


Figure 11. Comparison of Field Engine, AMT, and HCF Stair-Step Load Spectra

Ideally, the maximum difference in AMT and field HCF-type cycles should be only the 'acceleration factor,' the ratio of the operational flight hours divided by the time required to complete the AMT missions (2.6). A comparison of the field and AMT fan rotor speed histograms (Fig. 12) partially explains why the difference between HCF cycles is much greater than the acceleration factor. Only four speed regions for the AMT accumulate the amount of time that is within a factor of 10 of the field rotor speed time distribution. The ground idle, flight idle, cruise, and intermediate rotor speeds are within a factor of 10 of the field time distribution. The time accumulated for several other rotor speeds is more than 200 times less during the AMT than during field usage. The difference in time at rotor speed is a major contributor to the discrepancy in the field and AMT missions.

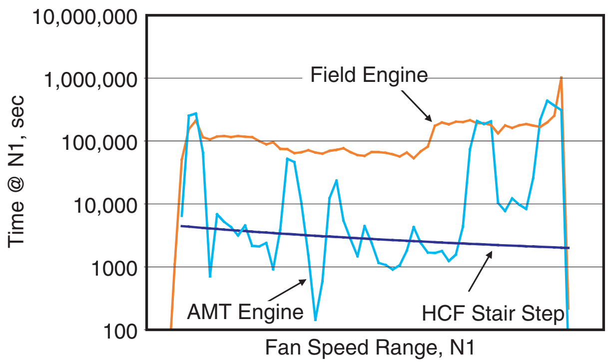


Figure 12. Time at Fan Speed for Field, AMT, and HCF Stair Step

Because the HCF stair-step test was intended to compensate for known HCF exposure deficiencies, an evaluation of the HCF cycles accumulated during an HCF stair-step test at the highest pressure RAM AMT conditions was performed. The evaluations for the three parts were similar. The HCF cycles accumulated during the HCF stair step were in some cases as much or more than the cycles accumulated during the AMT missions (Fig. 11). This was despite the fact that the stair-step tests took only 6 percent of the time of the AMT missions. Figure 12 displays the time distribution at different rotor speeds for the HCF stair step compared to the AMT and field distributions. The stair-step test, however, still accumulated up to 100 times fewer HCF cycles than the components experienced during field usage.

The large difference between the field- and AMT-accumulated HCF cycles indicates that more HCF problems could be identified during the test if the number of HCF cycles accumulated during the demonstration were closer to field usage. For the case studied, a modification to the AMT missions was considered to increase the

HCF cycles. The difference was based on defining flight idle as being between 18 and 30 deg instead of the set value of 29 deg. Also, cruise was defined as being above 30 deg but less than or equal to 58 deg, instead of the set value of 57 deg. With this range of PLAs instead of discrete values, the AMT missions were performed in the same sequence, but on successive AMT missions, the flight idle and cruise throttle positions were decreased 1 deg before the next mission was performed. This is easily accomplished with computerized throttles that permit user definition of set points within a throttle sequence. The flight idle and cruise PLAs were decreased for each subsequent mission until the minimum PLA was reached within the flight idle or cruise band, and then the next mission was performed at the top end of the throttle setting for the particular band. These changes to the cruise and flight idle settings during AMT missions permitted an increase in the time accumulated for more rotor speed regions without increasing the overall amount of test time or the number and type of throttle cycles accumulated.

The model was run using the varying cruise and flight idle PLA scenarios. A comparison of the accumulated time at rotor speed ranges for the varying cruise and flight idle PLAs versus the fixed PLA AMT and flight operations is provided in Fig. 13. This figure indicates that more rotor speed ranges have time at speed within a factor of 10 compared to the flight distribution, and the 'valleys' with minimal time have been reduced significantly so that the speed distribution more closely resembles the flight trend.

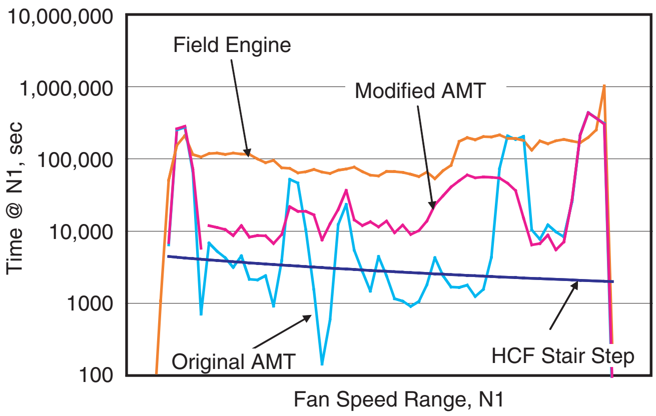


Figure 13. Time at Fan Speed with Modified AMT

The HCF cycles accumulated for this modified AMT were then calculated using the component vibratory estimating algorithm described previously and compared to the original AMT and field usage. Figure 14 is typical of the results observed during the comparisons for different components. In all cases, the accumulated HCF cycles for the modified AMT were more than two times greater than the HCF cycles accumulated with the initial AMT. In most cases, the HCF cycles were increased by more than 20 times. Another indicator of the improvement in HCF exposure using the modified AMT is quantified by comparing the stress level that exceeds a given cycle exposure (10^7 cycles, for example) for the flight, initial AMT, and modified AMT spectrums. Figure 15 displays normalized stress levels accumulating 10^7 cycles or more for three different fan components using the three different test scenarios. The stress level exceeding 10^7 cycles or more during the initial AMT was only 40 to 65 percent of the stress magnitude

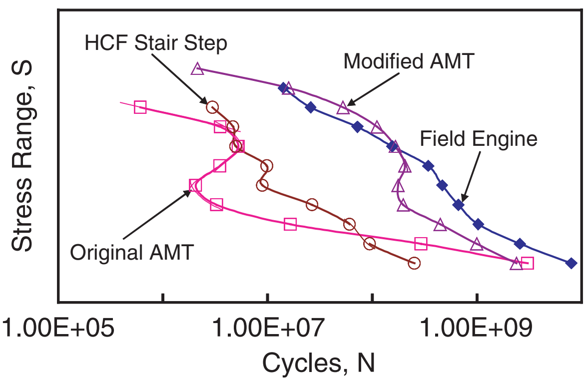


Figure 14. Comparison of Load Spectra with Modified AMT

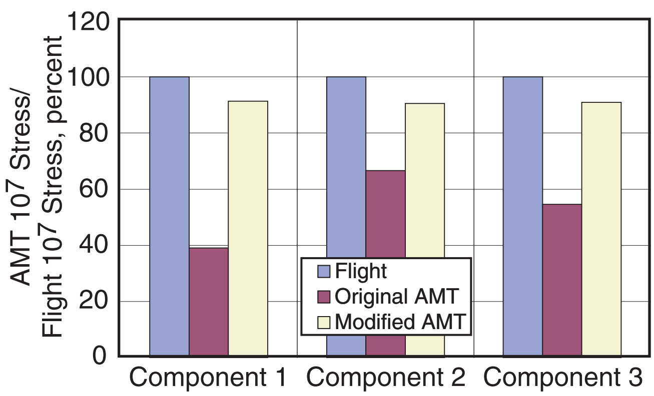


Figure 15. Comparison of 10^7 Stress Range for AMT and Flight

that saw over 10^7 cycles during flight operations, but for all of the modified AMT cases the stress amplitude's more than 10^7 cycles was at least 90 percent of the stress for flight operations.

Additional modifications to the AMT might be performed to increase the probability of identifying HCF-deficient parts. The effects of nonstandard temperature, distortion, and other influences parameters can be evaluated to quantify the change in HCF exposure for different scenarios. This information could be used to define a standard durability test that increases the probability that components with HCF deficiencies will be identified as early as possible during the development process.

5.0 SUMMARY

Several lessons have been learned from the past decades of HCF characterization and demonstration tests performed on military turbine engines. These lessons were applied to define a modification of the current AMT test method to improve the probability of revealing HCF deficiencies. A case study indicated that some parts during an AMT are exposed to only 50 percent of the stress amplitude that is experienced during operational flight. The modified AMT increased the stress magnitude exposure to 90 percent of the HCF-type stresses that are experienced during flight. This was done without increasing test time or cost. Also, the number and type of throttle excursions and the time at high power were unchanged between the initial and modified AMT. Other potential modifications, such as increasing time at nonstandard day temperatures, could be evaluated using a similar process. These modifications to the AMT could be used to increase the likelihood of identifying HCF problems during development without significantly increasing the cost and time of testing.

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SYMPOSIA DISCUSSION – PAPER NO: 20

Author's name: S. Arnold

Discussor's name: A. Abate

Question: To obtain the HCF/LCF effects, why not do RPM sweeps (accels & decels) as opposed to 200rpm stair case stepping which could be too coarse and miss the resonances? How would costs compare?

Answer: Agree but this would increase test time (and cost).

Discussor's name: A. Flotow

Question: A typical AMT Test runs the engine for 800rs or more. This runs day and night for several months, with automated test control and automated data acquisition and date reduction.

Answer: Automation of the whole process is important and is increasing.