Analysis of Engine Usage Data for Tactical Systems

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Turbine engine field experience has demonstrated a need to consider realistic engine usage profiles and duty cycles in the preliminary design phase of development. The increased emphasis on understanding usage is a result of hardware failures in today's engines brought on by aircraft/engine usage that is considerably different than design. Recognizing this need, the Aero Propulsion Laboratory recorded a limited amount of data and used it to identify driving parameters on engine usage. This paper presents results of data analysis from continuously recorded engine/aircraft parameters on F-15, F-5E, and A-10 aircraft. These aircraft were flown in Red Flag combat training exercises, normal training, and check flight sorties. Pilot debriefs were obtained. These identify specific flight events which impact usage.

Introduction

THE U.S. Air Force is placing emphasis on durability and reliability in the development and transition of advanced technology into the design of new propulsion systems for the next generation aircraft. The result will be engines with reduced operating and support costs as well as improved operational readiness capability. One of the key elements in achieving these goals is to understand how the engine will be used in the field in order to establish realistic structural design criteria.

Although the problem is not unique to the F100 engine in the F15, the F100 serves as a good example of the problems that can occur if the engine is designed to the steady state (or stick mission) rather than for realistic usage. The F100 was designed to spend about 1050 h out of its 4000-h mission life at intermediate power and above. In actual field use, however, the average sees only 400 h at these conditions. On the other hand, the average field engine experiences nearly 12,120 idle-to-intermediate-to-idle cycles in its 4000-h life and yet none of these cycles were included in the design criteria. This does not necessarily mean that none of these cycles were expected, but that the number would be low enough that the life limiting failure mode would still be stress rupture and not a throttle excursion induced low-cycle fatigue failure. This unfortunate miscalculation has cost many millions of dollars in Component Improvement Program (CIP) funds and additional spare parts expense as well as hindered the operational effectiveness of the system. In order to avoid this problem in future engines, the major drivers affecting system usage must be understood so that realistic design criteria can be established which are tied to the characteristics of the system. This information must also be made available to the designer early in the design process while necessary design changes can still be easily made. Once the system is in the field possible modifications are limited.

The Aero Propulsion Laboratory has funded the development of several engine usage prediction procedures as part of the Life Utilization Criteria Identification in Design Program.[1,2] McDonnell Douglas has developed an analytical approach, while Boeing has made use of some existing usage data to develop an empirical based model. Both of these models predict throttle time histories for advanced tactical systems for any appropriate mission or mix. This throttle history can then be used to establish engine structural design criteria for use in conceptual and preliminary design. The Aero Propulsion Laboratory also sponsored an in-house program called the Engine Usage Data Acquisition Program (EUDA) to obtain data to aid in understanding the usage of current tactical systems and to provide more data for model development and verification. Very preliminary results from the A10 and F5E analysis were reported by the authors in Ref. 3. This paper is an update of these results and includes the analysis of a larger data base of A10 and F5E flights and the addition of the F15 results. For the sake of completeness, a brief summary of the EUDA program background will be presented.

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Background

Prior to the EUDA program only a very limited amount of continuously recorded engine usage data was available. Some "snapshot" or "gate crossing" data such as from the engine time temperature recorder (ETTR) on the A10 and the events history recorder (EHR) on the F15 existed. These data have the disadvantage of a predetermined definition of a damaging event and do not allow a correlation of engine usage with individual mission profile segments (i.e., combat, touch and go's, etc.). The objective then of the EUDA program was to obtain a data base of continuously recorded engine parameters from several different tactical systems in a simulated combat environment. Combat was emphasized since this was believed to be the most important data and also information on this usage was the least available. The approach was to instrument one operational A10, F5E, and F15 and record engine data during Red Flag combat training as well as normal training flying at the home base. Red Flag is held several times annually at Nellis Air Force Base and provides a realistic threat environment to operational flying units. The systems were selected to give a difference in design mission (air-to-air and air-to-ground) as well as a range in design variables (thrust-to-weight, wing loading, etc.). F4 and F16 aircraft were also considered for the study but were not included owing to either aircraft or recorder nonavailability. The restriction to one aircraft of each type resulted from Tactical Air Command readiness and flying requirements. This limited the availability of operational aircraft for modification and instrumentation installation and resulted in a limited sample size. However, the requirement for realism dictated that data be recorded from operational aircraft with operational pilots flying in their normal role rather than special test aircraft with test pilots flying specified maneuvers. Thus the limited sample size was deemed a necessary compromise.

The A10, F5E, and F15 are all part of the Air Frame Structural Integrity Program (ASIP), which equips about 20% of each system with a continuous recording system to record data used to monitor airframe fatigue. The Signal Data Recording System (SDRS) is manufactured by Conrac

Corporation. The A10 and F5E systems consist of an MXU553/A recorder with removable 15-h tape cassette and an ECU68/A multiplexer which are set up to record 16 channels of data at a rate of up to 15 times/s. The F15 recorder is an AN/ASU-28 with a removable 25-h tape cassette and has a sampling rate of 240 samples/s. These recorders could be used without alteration to record desired engine parameters, although certain existing airframe parameter input had to be replaced.

The desired engine parameter signals were already available either as normal cockpit instrumentation or as input to the fuel control. A Class II aircraft modification was required to install a small signal conditioning box to make these signals compatible with the SDRS recorder. This modification was performed by the 4950th Test Wing from Wright-Patterson Air Force Base.

The A10 SDRS was modified to record fan speed, core speed, interturbine temperature, and power lever angle. The F15 SDRS was modified to record fan speed, core speed, and power lever angle. The F5E SDRS was modified to record engine speed, exhaust gas temperature, and power lever angle, although the transducer for this signal was defective and no useful PLA data were obtained. Already recorded were altitude, airspeed, and normal load factor. This is all shown schematically in Fig. 1.

Figure 2 shows the steps in the data acquisition and processing procedures. The various parameters were recorded on 9-track cassette tapes using the onboard recording system. These cassettes were then sent to Oklahoma City Air Logistics Center at Tinker Air Force Base, where the data were edited and transcribed to computer compatible tapes and sent to the Aero Propulsion Laboratory at Wright-Patterson Air Force Base. They were then processed on a CDC 6600. Copies of the tapes were made for shipment to interested contractors and other government agencies. Calcomp plots and hard copies of the data were made and the data were also stored on disk for in-house analysis. The data were sampled at a once per second rate and the following types of analyses were performed: altitude/velocity flight profile distributions, power setting distributions, rainflow cycle counting, "level crossing" cycle counting, and *g* loading distribution.

The A10 which was part of the EUDA program was assigned to the 354th Tactical Fighter Wing stationed at Myrtle Beach Air Force Base, South Carolina. The aircraft was modified on March 31, 1980 and demodified on December 10, 1980. During this time approximately 86 h of edited data were recorded. Twenty-seven of these hours were from normal training flights at the home base. The remaining time was recorded when the aircraft participated in Red Flag 80-4, a Rapid Deployment Force exercise. During Red Flag the A10 flew from a "bare base" established at Indian Springs Auxiliary Air Field, Nevada, where its missions were close air support and battlefield interdiction.

The F5E was modified on May 23, 1980. It remains modified and data are still being recorded. The aircraft is assigned to the 57th Fighter Weapons Wing at Nellis Air Force Base, Nevada. To date, a total of 87 edited hours of data have been recorded which include participation in several Red Flag exercises. In addition, basic flight maneuver and pilot familiarization training data were also recorded. During Red Flag the aircraft is part of the aggressor unit and flies combat air patrol missions. Data yield from the F5E was significantly reduced owing to a series of recorder, tape, and transducer failures.

The F15 in the EUDA program was assigned to the 49th Tactical Fighter Wing at Holloman Air Force Base, New Mexico. It was modified on November 12, 1980 and demodified on May 29, 1981. It participated in Red Flag 81-2, flying combat air patrol out of Nellis Air Force Base, Nevada. Approximately 57 edited hours of data were recorded during this exercise and included several flights with air-to-air refueling. In addition, approximately 10 h of normal training flying were recorded at the home base.

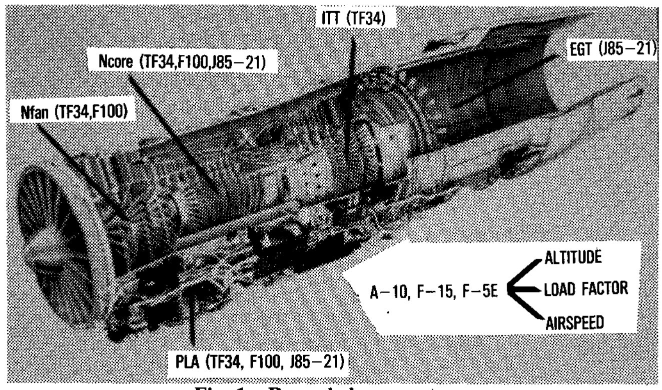

Fig. 1 Recorded parameters.

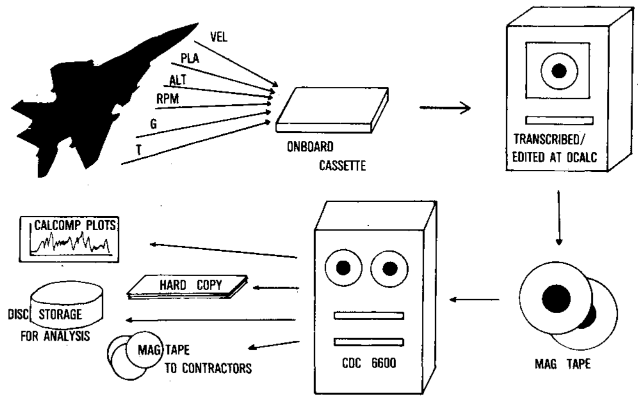

Fig. 2 Data acquisition and processing.

Personnel from the Aero Propulsion Laboratory were on-site to conduct verbal pilot debriefs for all sorties flown by the instrumented aircraft during the Red Flag exercises. In addition, written Red Flag evaluations were obtained which described threats, maneuvers, targets, and mission effectiveness.

Data Analysis

Figures 3 and 4 present sample time history traces recorded from a typical A10 ground attack mission, and Figs. 5 and 6 show typical F5E and F15 combat air patrol missions flown during Red Flag. The traces for the A10 contain plots of altitude (ALT, ft MSL), velocity (VEL, KCAS), normal load factor (*g*), low-pressure rotor speed (N1, rpm) power lever angle (PLA, deg), interturbine temperature (ITT, °C), high-pressure rotor speed (N2, rpm) as a function of time. The F5E time history traces include altitude (ALT, ft MSL), Mach number (MACH), normal load factor (*g*), exhaust gas temperature (EGT, °F) and compressor speed (N1, rpm). The F15 data consist of plots of altitude (ALT, ft MSL), normal load factor (*g*), power lever angle (PLA, deg), and high-pressure rotor speed (N2, rpm) as a function of time. Velocity (KCAS) and low-pressure rotor speed (rpm) from the F15 are not shown because of space limitations. The A10 and F15 recorders were started and stopped when the engine was started and stopped. Hence they recorded pre- and postflight ground time. However, most of this ground operation was eliminated from the sample trace. The F5E recorder, on the other hand, started with "weight off wheels" and shut off with "weight on wheels" and therefore only recorded flight time.

The A10 trace is very representative of an average Red Flag ground attack mission. Analysis of these data shows that the aircraft spent most of the mission at very low levels above the ground, with the major changes in altitude, a result of "terrain-masking" maneuvering through the mountains both into and out of the target area and "pop-up" bombing maneuvers over the target. The mission was flown at near

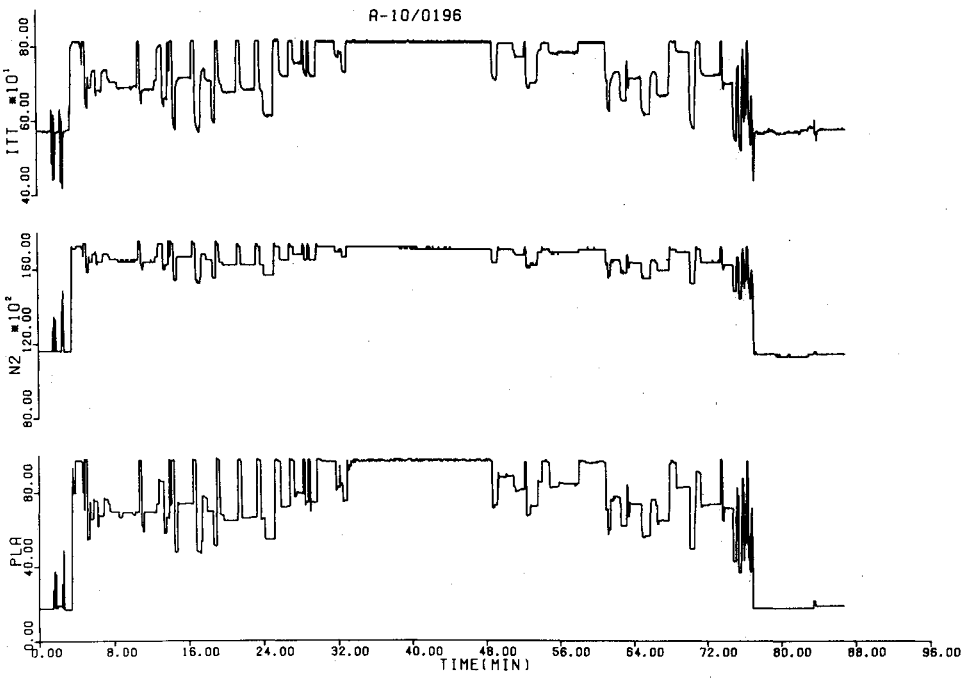

Fig. 3 Sample A10 data trace.

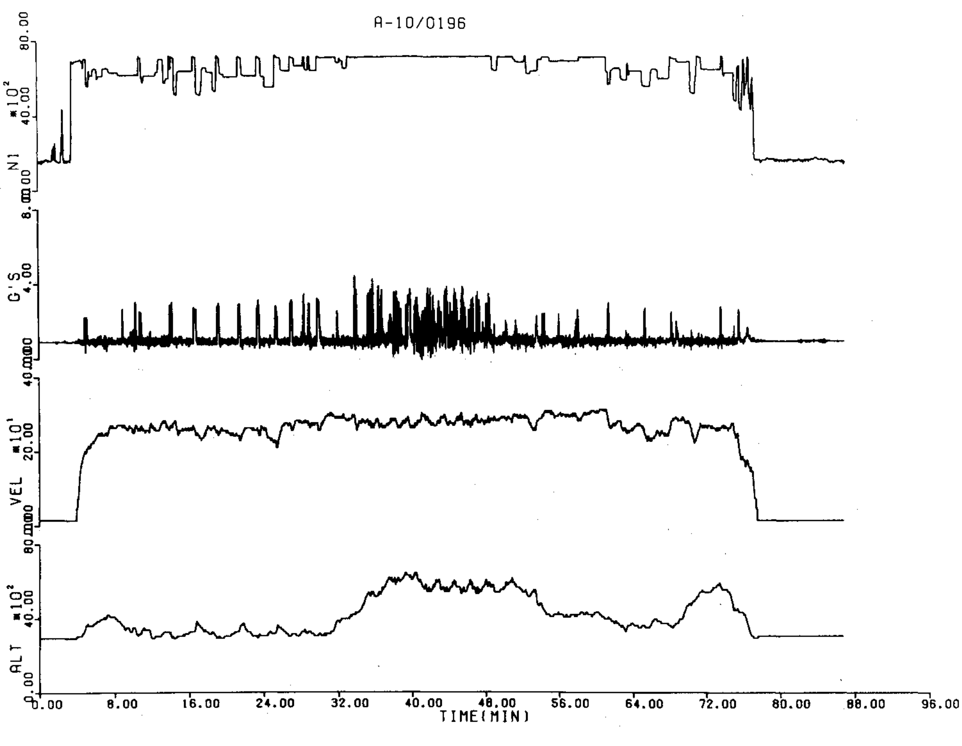

Fig. 4 Sample A10 data trace.

constant maximum airspeed, with the variations in airspeed resulting from extreme maneuvering. The load factor trace indicates many exercises to near maximum g condition, again probably due to the low-level "terrain masking" flying as well as evasive maneuvers over the target. The PLA time history shows that the throttle spends a large portion of the mission at maximum power, makes several excursions between part power and intermediate, but no major idle-to-intermediate cycles.

The F5E and F15 traces are representative of a typical Red Flag combat air patrol mission and are both very similar except that the F15 mission was considerably longer because of the air-to-air refueling which occurred during this flight. Unlike the A10, both the F5E and F15 spend most of their mission at higher altitudes and only spend about one-third of the mission maneuvering. Combat occurred at the lower altitudes and at subsonic Mach numbers. The engine parameter traces are characterized by a number of major and minor speed excursions and less time at maximum power condition than the A10. The F15 PLA trace also shows that the afterburner is used a number of times but only for very short periods. The constant altitude portion of the F15 trace occurring at the 44 min point of the mission is the air-to-air refueling trace.

One of the more interesting discoveries from analysis of the data is the large amount of engine operating time that is spent in ground operation. The ratio of engine total operating hours to engine flying hours is shown in Fig. 7 for the three different aircraft. The F15 results are from a sample size of 22 flights, the F5E data represent 21 flights, the A10 data base is 31 flights, and all flights are from Red Flag. The A10 engines run approximately 1.3 h for every hour of flying, the F5E engines

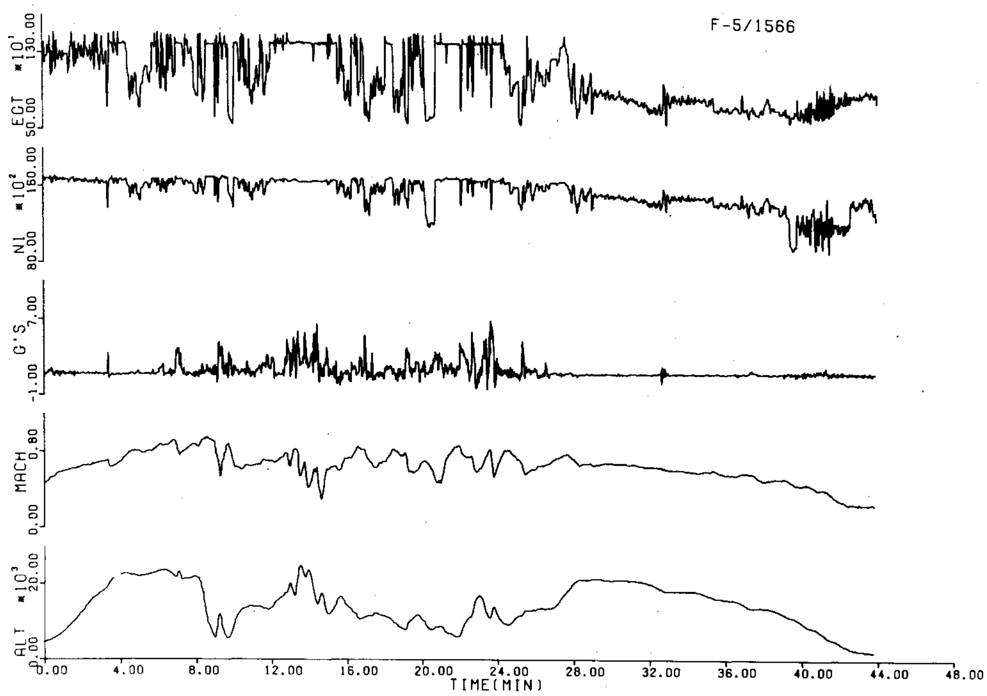

Fig. 5 Sample F5E data trace.

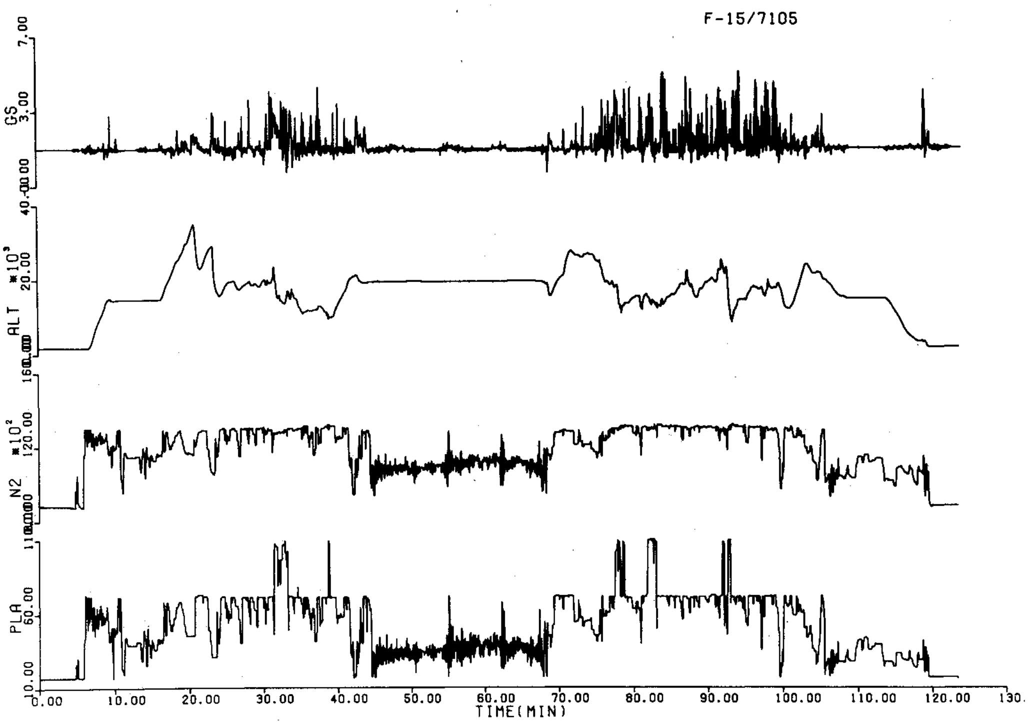

Fig. 6 Sample F15 data trace.

operate about 1.5 h for every hour of flying, and the F15 engines operate about 1.5 h for every hour of flying. In other words, between 23 and 33% of the engine operating time is spent in ground operations. Ground operation is usually spent at low-power settings and is the time accumulated during avionics warmup, pre- and postflight maintenance and inspections; arming, disarming, and safing of external stores and weapons; and time spent waiting for takeoff clearance. While this near-idle operation is probably not damaging to the gas path components, it can be important if the engine is designed for maintenance and/or removal based strictly on operating time. In addition, some parts consume some of their useful life at low power. Another impact of the long ground operations time on usage is that significant amounts of fuel are being consumed, which limits the flight length and hence reduces the number of damaging events that the engine encounters (i.e., passes on target or touch and go's, etc.). The point is that tactical weapon systems accumulate a large amount of time at idle power on the ground and this should be included in structural design criteria when appropriate and accounted for in usage prediction procedures.

Figure 7 also presents the number of start cycles per engine flying hour for each system. This is the most damaging cycle that the engine encounters because it encompasses the full speed range from off-to-maximum rpm and back to off. This type of cycle is strictly related to mission length. The A10 did not fly with a full fuel load during Red Flag and it accumulated less than one of these cycles per flying hour. From the standpoint of off-to-max-to-off cycles, the F5E usage was most severe because it flew the shortest missions and accumulated nearly 1.38 of these cycles per flying hour. The F15 had the lowest rate at 0.75 per flying hour. These results are

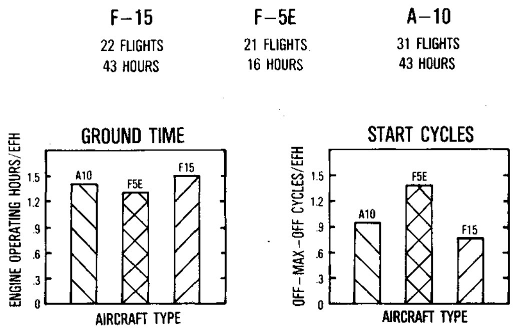

Fig. 7 Engine starts and ground operations—Red Flag usage.

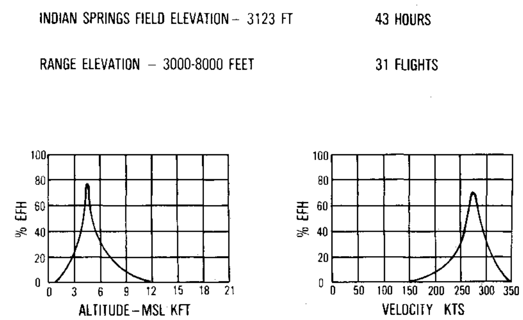

Fig. 8 A10 flight profile distribution—Red Flag usage.

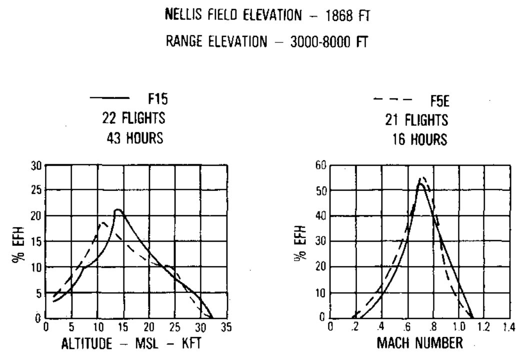

Fig. 9 F15/F5E flight profile distributions—Red Flag usage.

probably biased to the low side because of the large number of long refueled missions flown during Red Flag.

Figure 8 presents the A10 flight profile distributions based on 31 flights (43 h of recorded data) of Red Flag missions. The percent of engine flying time spent at the different altitudes and velocities during the average mission is shown. The A10 spent nearly 80% of its time at altitudes between 3000 and 6000 ft MSL. Realizing that the Indian Springs field elevation is over 3000 ft and the range elevation generally higher, it is apparent that the missions were flown at very low altitudes above the ground. The velocity data also show a very predominant airspeed of between 270 and 300 knots, where the A10 spent over 70% of its mission. In other words, A10 ground attack missions were flown at very low levels, and at near constant airspeed, close to the maximum aircraft capability.

Similar flight profile distributions for the F5E and F15 are shown in Fig. 9. These distributions represent average combat air patrol missions during Red Flag based on 43 h of F15 data and 16 h of F5E data. The profiles are very similar. The altitude profiles are much more evenly distributed than the A10 and show that on the average both systems spend most of their missions at higher altitudes. The F15 distribution peaks at a slightly higher altitude than the F5E. This is primarily due to the large amount of time spent at from about 15,000 to 18,000 ft during air-to-air refueling which occurred during approximately one-third of the missions. The Mach number

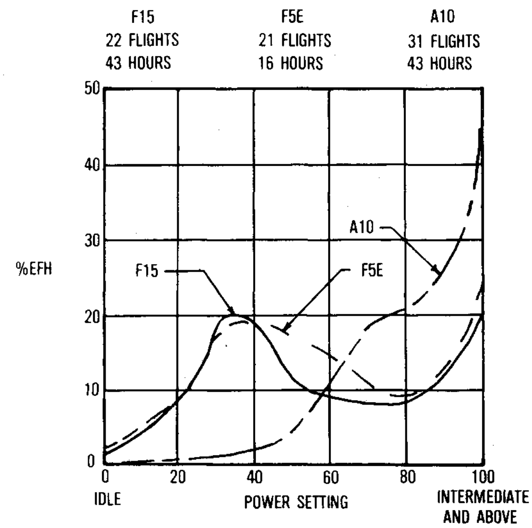

Fig. 10 Power setting distribution—Red Flag usage.

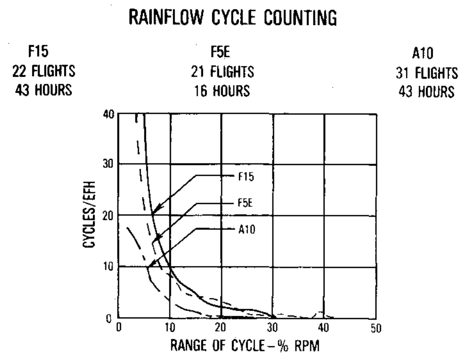

Fig. 11 Cyclic usage distribution—Red Flag usage.

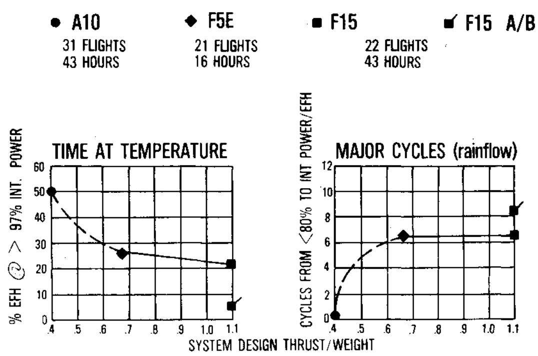

Fig. 12 Summary of damaging events—Red Flag usage.

distributions in Fig. 9 are remarkably similar on the average. Both systems spend over 50% of their missions at a subsonic Mach number between 0.6 and 0.8 and see very little supersonic operation.

Figure 10 investigates the average power setting distribution for the three systems for Red Flag flights. For this plot, power setting is defined by assigning idle a power setting of 0, intermediate and above a power setting of 100, and assuming a linear variation in between. This normalization procedure was applied to the power lever angle data from the A10 and F15 flights and the exhaust gas temperature data from F5E flights (the F5E PLA channel was inoperative). The power setting range was divided up into ten equal parts and the amount of flying time spent in each interval was summed and then converted to the percent of total mission flying time. The data were then plotted at the midpoint of each interval. For the F5E and F15, time in afterburner was included with time at intermediate power.

It is very difficult to make exact comparison between the A10 data and F5E and F15 data since the TF34 is a dry engine, while the J85 and F100 are both augmented. The A10 data do show that during Red Flag very little time was spent at part power conditions. The predominate power setting is near intermediate power. The F5E and F15 power setting distribution for Red Flag flights are remarkably similar. Both systems spend nearly 20% of their flying time at part power cruise condition, very little time near idle power and between 20 and 25% near intermediate power and above.

Low-cycle fatigue (LCF) is one of the major consumers of engine parts life and is directly a function of the number and magnitude of the rotating component speed changes. A number of cycle counting techniques are available to count the various speed excursions seen in the time history traces. Based on the work of Dowling,[4] a "rainflow" cycle counting technique was employed because it was found superior to the other techniques when applied to complicated time histories. The rainflow method defines cycles as closed hysteresis loops and hence corresponds closely to the cyclic response of metals. The rainflow algorithm developed by Richards et al.[5] was employed in this study.

The rainflow cycle counting was applied to the time histories of high-pressure compressor rotor speed for every flight and then arithmetically averaged for each system. The data were first filtered to eliminate speed changes of less than 1%. The cycle counting algorithm used requires the amplitude of the time history to be divided up into a number of bands. The larger the number of bands, the more accurate the cycle count. In this analysis 49 bands were selected as a good compromise between accuracy and computer storage and eccentric time requirements. Reference 5 estimates this introduces a possible error of 4% into the cycle count.

Using rainflow procedures, all cycles of at least 2% magnitude were counted and the average results are shown in Fig. 11. The number of each type of cycle per engine flying hour is plotted vs the range of that particular cycle in percent rpm for the A10, F5E, and F15 Red Flag missions. The data show that for all three systems, as the range of the cycle decreases, the number of these types of cycles per engine flying hour increases dramatically. It also indicates that the A10 usage has a lower cyclic content than either the F5E or the F15. The F15 flights contain more cycles of less than 15% magnitude, but the F5E seems to incur more cycles of greater than 15% magnitude.

A simple level crossing type counter such as the EHR on the F15 would only count one range of cycle and all the other cycles would be lost. There is a considerable amount of controversy over what constitutes a damaging cycle. Typically rotor speed changes of less than 15-20% are considered nondamaging and are usually neglected in most analyses. However, as pointed out in Ref. 6, small partial cycles can be important if changes in the cooling circuit are induced owing to mismatch between rotating and stationary parts. In addition, some of the newer advanced materials are possibly more susceptible to damage from smaller speed excursions and hence they must be included in design criteria. The significance is that a large number of relatively small cycles occur in both air-to-air and air-to-ground missions and, depending on the particular engine design, they should be included in the structural design criteria as appropriate.

One of the most important criteria in hot section design, because of its dramatic impact on stress rupture and creep life, is the engine operating time spent at near maximum temperature conditions. For this analysis, time spent at power settings greater than 97% of intermediate was considered damaging. For low-cycle fatigue and thermal fatigue life limited parts the major damaging event is large speed excursions which in this analysis was defined as a cycle from less than 80% of intermediate power. Throughout this paper, 0-max-0 cycles are counted separately and are not included in the summaries of damaging events. A summary of the average occurrence of these damaging events per engine flying hour is presented in Fig. 12 as a function of the system design thrust-to-weight ratio. Despite the fact that the results are plotted vs thrust-to-weight, it is unclear whether the major influence affecting the difference in usage between the A10 and F5E/F15 is system thrust-to-weight or design mission (air-to-air vs air-to-ground). Hence the A10 data point is connected with the other data points using a dashed line.

The data in Fig. 12 show that on the average the A10 spends over 50% of its time within 97% of intermediate power during a Red Flag ground attack mission. This is significantly higher than the F5E (25%) or the F15 (20%). The data also show that time at temperature is only a weak function of system thrust-to-weight for relatively high-thrust loaded air-to-air fighters. These data also confirm the general trends indicated by Finger,[7] although the A10 spends much more time at intermediate power than Finger would anticipate for an air-to-ground aircraft of about 0.4 thrust-to-weight (50 vs 30%). This could be the result of the extreme amount of very low-level flying and the very high ambient temperatures encountered while flying Red Flag missions out of Indian Springs Auxiliary Air Field.

The flagged symbol represents the average amount of afterburner operating time for the F15. It is a relatively low 5% of the mission. Comparable data for the F5E were not available owing to the power lever angle transducer failure.

The trends in cyclic usage from Fig. 12 also confirm the estimates of Finger. The average A10 usage included less than one major cycle per flying hour from less than 80% to intermediate and back, while both the F5E and F15 usage included nearly 6.5 of these damaging cycles per flying hour. Cyclic usage appears to be nearly independent of system thrust-to-weight for highly loaded air-to-air fighters.

Again, the flagged symbol represents the number of augmentor transients for the F15. The augmentor is used on the average of 8.5 times per flying hour during a typical F15 Red Flag combat air patrol mission.

Summary

Durability problems associated with the introduction of several recent high-performance tactical weapon systems into field operations have in general been attributed to the selection of structural design criteria not adequately reflecting actual engine usage. To provide a data base of usage data to quantify damaging events, to be used to identify important drivers and to aid in usage model development and verification, the Aero Propulsion Laboratory instrumented and recorded engine usage data from an A10, F5E, and F15. A total of nearly 240 h of edited data were recorded during Red Flag combat training and home base flying.

Conclusions

The results of the analysis of the data from the A10, F5E, and F15 Red Flag missions are summarized below:

1) All three systems spend considerable amounts of time in ground operation at near-idle power.

2) All three systems have usage which includes a large number of small amplitude throttle cycles.

3) F15 and F5E usage is very similar for combat air patrol missions in terms of flight profile, number of major cycles, and time at maximum temperature conditions.

4) The low-thrust-to-weight, air-to-ground system (A10) usage includes very few major throttle cycles (<1/EFH), but an extremely large amount of time at maximum temperature conditions (50% EFH).

5) The high-thrust-to-weight, air-to-air systems (F5E/F15) usage includes many major throttle cycles (6-7/EFH), but reduced time at maximum temperature (20-25%) conditions.

Recommendations

A certain amount of continuously recorded engine data would be very useful to augment the "level crossing" data from recorders which are currently in widespread use in the field. Obviously not every engine in the fleet needs such a sophisticated system. The success of the limited Aero Propulsion Laboratory data acquisition program demonstrates the feasibility of such an approach to provide data for monitoring usage trends in current systems as well as providing a data base for usage prediction for future systems. The EUDA data could be incorporated into MIL-E-5007 to achieve a more useful engine specification for military procurement. The EUDA data should be expanded to include other systems and other operational environments. The ASIP recorder is already in place on a large number of systems, will be included in future systems, and can be easily adapted to record engine data. The data processing procedures are also well established. The British currently have such a continuously recorded engine usage monitoring system. The American engine community should follow the example of their airframe counterparts and the British engine community to provide the necessary data base which, in addition to other uses, is necessary to avoid serious usage related structural deficiencies in future systems.

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