Turbine Airfoil Life Prediction by Mission Analysis

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Increasing design complexity and cost have required an accurate life-prediction technique which would possess rapid computation time and still account for the life-determining variables. A method is described which analyzes the life expectancy of turbine parts by simulating airplane and engine performance, and incrementally calculating heat transfer and loading on those parts. This method has been successfully used to predict life in field service and to develop turbine hardware through accelerated endurance testing. Future applications of the mission analysis are described for real-time prediction systems and maintenance planning.

Introduction

GAS-turbine designers and analysts have long been faced with the problem of determining the life of a turbine airfoil. Historically, it has been realized that life must certainly be dependent on time, temperature, and load—although exactly which time, temperature, and load as not been previously reported. It has been sufficient to consider the maximum conceivable temperature/load condition, determine the life there, and multiply that value by an emprical constant to determine the expected service life. The maximum condition life is usually referred to as the hot life for obvious reasons. Needless to say, considerable art is required to develop a satisfactory multiplier to arrive at expected service life. This method has proved to be generally acceptable in the past for two reasons: 1) the failure modes usually considered were either erosion/corrosion/oxidation or creep caused by a very small amount of the service life; and 2) more emphasis was placed on having at least a prescribed life than upon determining the specific value. In today's turbine designs, the complex cooling configurations and related high replacement costs dictate a more accurate life calculation for adequate economic evaluation of the engine.

Life Prediction Problem

In today's turbine, two problems occur which were not present in older engines. These are the high amount of cooling air used and the interaction of low cycle fatigue (LCF) with creep. The cooling-air levels used to reduce metal temperatures to acceptable values also have the effect of reducing the range of those temperatures observed for the operational spectrum of the engine. As illustrated in Fig. 1, the life values calculated for various operational modes tend toward a uniform value as the cooling-air flow rate is increased. This phenomenon requires that life calculations now be made at engine-operating conditions which had previously been ignored with the "hot life" approach.

The second problem which has become significant in life prediction is the interaction of LCF and fatigue which has been explored by many other authors in the past five years. The occurrence of the interaction is closely associated with cooled designs which undergo thermo/mechanical cycling with operational excursions from steady-state conditions. The magnitude of these cycles is dependent upon the end-point temperatures as well as the method of translating between them. Clearly, an accurate life prediction cannot rely on an a priori assumption of maximum temperatures as might be used in computing "hot life."

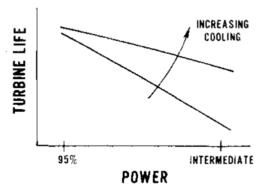

Fig. 1 Increased cooling reduces life variation with power.

Mission Life Analysis

It becomes obvious from the discussion so far that a satisfactory (i.e., accurate) life-prediction method is one which accounts for all portions of the operational spectrum in creep as well as LCF. Such a technique has been established to fill this need and is referred to as "mission life analysis." This method has evolved over many years to the form described in this report and has been used in its present form since 1971 at Pratt and Whitney Aircraft. It was initially applied primarily to the commercial JT9D series of engines, but it has since been applied to a wide variety of commercial and military engines.

The development of mission life analysis for turbine airfoils was subject to several philosophical constraints: it was to be as general as practically possible so that future parts could be easily analyzed, it was to be modular in construction to permit technical advancements to be added, and it must use separately correlated physically related calculations and not a completely empirical technique. With these restrictions, it was planned that important parameters would not be overlooked and also that

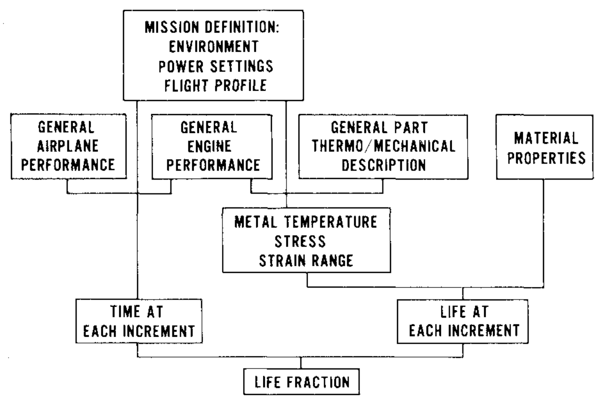

Fig. 2 Mission analysis block diagram.

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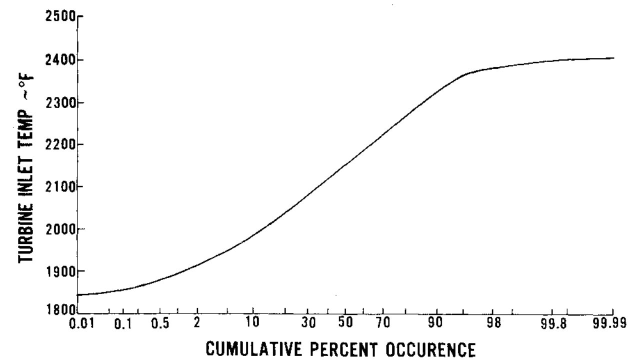

Fig. 3 Typical sea level static turbine inlet temperature variation due to ambient temperature.

designs could be evaluated long before testing occurs. The block diagram for the mission life analysis shown in Fig. 2 illustrates that life prediction combines the attributes of airplane and engine performance with a heat transfer-/stress analysis. Fundamental to the analysis is the definition of the mission itself and the environmental conditions which are experienced on that mission.

The mission definition requires specification of a flight profile in the sense of identifying flight Mach numbers, altitudes, and engine operations (e.g., intermediate power, 95% power, etc.) for the entire mission. Normally, an initial aircraft gross weight must also be specified and would reflect the payload, fuel, or other weight-contributing items expected at the beginning of the mission. Also very important in defining the mission is the identification of ambient temperatures expected on the mission. An illustration of the ambient-temperature impact on turbine-inlet temperature is given in Fig. 3 for a typical military turbofan-powered fighter. Here it can be seen that the inclusion of variability in ambient temperatures allows the quantification of the qualitative observation that hot external environments are detrimental to turbine durability, and also allows an analyst to distinguish between operations in various geographical areas. To permit easy access to what is essentially weather data, the mission life analysis has stored information for the world by latitude and longitude, for each month, and for altitudes up to 53,000 ft. The data are in the form of a statistical distribution of probable ambient temperatures at each coordinate and reflects historical occurrences over a 30-yr time period. These data are available from many sources, the most valuable of which is Ref. 1. Care must be taken in acquiring the data so as not to lose the variability since occurrences of high ambient temperatures, even though infrequent, have the largest influence on the resultant life.

The general airplane performance block consists of lift-/drag curves for each configuration and is a simulation of internal engine performance as a function of the performance-controlling parameter, e.g., engine pressure ratio. The engine data ordinarily provided would include thrust and fuel flow for interaction with the airframe as well as temperatures, pressures, and rotational speeds for the part life analysis.

The results of a detailed heat-transfer and stress analysis are obtained for a standardized flight. An adequate analysis at this stage is critical to the overall life analysis so that metal temperatures and stresses for steady-state and transient operation may be evaluated. This step would determine critical areas on the part which would be expected to be the failure locations. These locations would ordinarily be evaluated for several potential modes such as creep, LCF, and erosion/corrosion/oxidation. For each of these potential failure locations, a metal temperature, local coolant temperature, and local external hot-gas temperature are provided for a specific engine performance point, along with steady-state stress and transient strain range. The overall approach to the solution of determining turbine life is to break up the flight profile into small increments, to determine the life for each increment, and to combine these lives by the well-known Miner's rule.[2] In order to make this final step, however, the time spent and life expected for each increment must be determined. The time spent is calculated in the traditional way from lift-/drag relationships, engine thrust, and airplane weight for the Mach number, altitude, and ambient temperature in the increment. An elementary text on aerodynamics will provide background information and the necessary equations for these calculations.

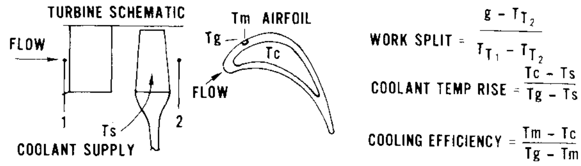

Fig. 4 Thermal similarity parameters.

The calculation of the steady-state stress is routine after recognizing that the stress is comprised of portions proportional to the rotational speed squared (for centrifugally loaded blading) plus portions proportional to the airflow loads. Then the steady-state stress may be calculated from

$$\sigma = \left(\frac{\sigma_N}{N_R^2}\right)N^2 + \left(\frac{\sigma_L}{L_R}\right)L \tag{1}$$

where σ = stress, N = rotational speed, L = aerodynamic load, σ_N = stress caused by N_R rotational speed, and σ_L = stress caused by L_R load. The calculation of metal temperature is made by assuming that the three thermal ratios defined in Fig. 4 remain constant during the mission. The calculation of the strain range for the increment (if any) would be computed from

$$\Delta\epsilon = \frac{\Delta\epsilon_R}{\Delta T_R}\,\Delta T \tag{2}$$

where $\Delta\epsilon$ = strain range experienced, ΔT = thermal excursion experienced, and $\Delta\epsilon_R$ = strain range at ΔT_R thermal excursion. Combining the metal temperature and steady-state stress for this increment with the Larson-Miller materials property representation for the failure level (e.g., 1% creep) to determine the life for that increment from

$$\log t = \frac{P}{T_m} - C \tag{3}$$

where t = life, P = Larson-Miller parameter (stress dependent), T_m = metal temperature (°R), and C = Larson-Miller constant. These creep lives are similarly calculated throughout the mission and combined via Miner's rule to arrive at the average life for the mission.

$$\text{Life} = \sum_i \delta_i \Big/ \sum_i (\delta_i/t_i) \tag{4}$$

where δ = incremental time spent and t = incremental life. At this point, a mission life for creep failure is determined. In the event that LCF is also present, creep and fatigue are interacted through the use of the exhaustion-of-ductility model[3] to determine the life to interactive failure. Erosion/corrosion/oxidation life is determined in a manner similar to that used in determining creep life.

Substantiation of Mission Life Analysis

Before discussing examples of the validity of this technique, a short explanation is necessary so that the calcutated life is correctly interpreted. The predicted life is not a single value, but rather a probability distribution of lives usually in the form of a Weibull analysis line.[4] This

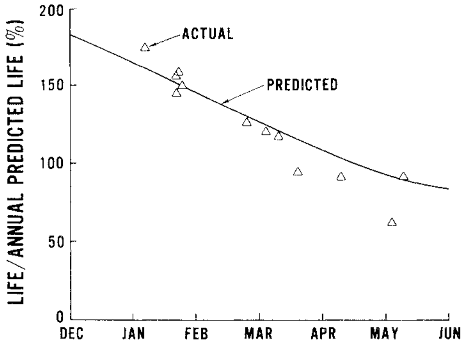

Fig. 5 JT9D-3A U-700 first turbine-blade experience.

line is a graphical probability description with two identifying parameters: slope and life, for some probability. The slope is interpreted as a measure of the variability of the distribution. The predicted life occurs at the 50% cumulative probability level which should not come as a surprise since the average mission, average engine performance, and average tolerance heat transfer/stress analysis were used. The Weibull slope has been determined empirically and is currently not within our prediction system.

Two examples of the correlation achieved between analytical prediction and actual experience are given here. In each case, the specific types of missions experienced by each engine are not known. The individual engine deterioration characteristics are also unknown. However, the mission types and engine deterioration are known on an overall average basis.

During 1971, an attempt was made to relate a U.S. based airline's life experience to their life prediction on the JT9D-3A first-stage turbine blade. This blade, made of Udimet 700 nickel-base alloy is convectively cooled, and shroudless. At that time the airline's route structure, ratings practices and operational characteristics were known. Based on that information, a mission life analysis was performed for the airline's fleet of aircraft, with the assumption that engines would experience every route on a frequency-weight basis and that engines would have the same average deterioration characteristics. In order to illustrate the influence of ambient temperature, the results of this analysis are given in Fig. 5 in terms of time-to-failure (a visible crack or a fracture of one blade in an assembly of 116 blades) as a function of installation date. The failure mode was determined as being a result of the interaction of creep and LCF. The engines generally were used 300 hr/month on the average. It may be seen that the data falls generally within a ±10% band about the prediction.

The second example of correlation is a forecast of expected failures for an Asian-based airline operating the JT9D-7 engine. In this case, the part analyzed was the second-stage turbine blade where a failure was considered as a visible crack or fracture of one blade in an assembly of 138 blades. The cause of the failure was creep-rupture. The forecast was made during 1972 for the next two years and reflected the expected operations of this airline. The results of the analysis and subsequent failure data are shown in Fig. 6 in terms of removals expected at various times.

Applications-Present and Future

The mission life analysis currently is being applied in three general areas: design, testing, and service. In the design phase, the analysis translates the known or estimated mission applications of an engine into critical design parameters (e.g., metal temperatures, stresses) and

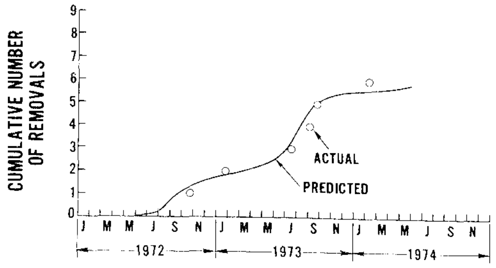

Fig. 6 JT9D-7 PWA 1455 second turbine-blade experience.

so provides a rational approach to the trade studies implicit in the design process, particularly those regarding compromises in design parameters or those considering cost/life influences.

During testing, critical parts have their "life processes" accelerated through carefully constructed tests which attempt to minimize test time while maximizing useful data. Closely related to testing is the forecasting and evaluation of service data. Here the analysis provides maintenance requirements (both timing and actions) as well as providing an early warning of unexpected behavior by the continuous comparison of prediction and experience. One of the more interesting programs being undertaken at this time is the attempt to predict an individual engine's maintenance requirements. If successful, this feature will enable engine owners to optimize their maintenance actions by knowing the timing and type of maintenance required. Work to data has shown that the concept is sound and will be described in a later report. A second area in which work is underway involves the extension of the life prediction method developed for turbine airfoils to other critical engine parts (e.g., burner, bearings etc.) so that a more complete maintenance and design definition is acquired. A third area for investigation is the incorporation of more sophisticated life analysis methods, such as fracture mechanics, to this process. While work is just getting started in this area, future life predictions can be made with this approach as the necessary data become available.

Conclusions

It may be seen that a method has been developed and used to enable an analyst to determine future service life for a turbine airfoil from a stated mission. This analysis provides a unified method for evaluating a design in terms of expected operation, optimizing test information, and providing maintenance direction for individual users. Good correlation has been shown for this incremental life analysis in the previous examples as well as in numerous other life calculations frequently made for various engine operators. These calculations assist in the evaluation of alternate engine operations so that durability impact may be properly assessed. The mission life analysis provides a rational approach toward understanding engine operation and in providing information for economic evaluation of life-limited parts.

References

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