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Technical Notes

Implications of a Military Turbofan's High-Pressure Turbine Erosion for Blade's Creep-Life Consumption

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I. Introduction

HIGH-PERFORMANCE aircraft, especially for military purposes, are complex in design and required to operate under severe stresses and temperatures [1]. Thus, designers and users of these aircraft continually seek greater reliability, increased availability, enhanced performance, and improved safety, as well as low life-cycle costs.

In-service costs consist mainly of those associated with [2] 1) the fuel consumed during the operation, and 2) the replacement of the system's components. Therefore, any extensions of life expectations or reductions in fuel usage of an aeroengine directly lower the life-cycle cost and depend upon the types of operation or mission undertaken, operating conditions experienced, and rate of in-service engine deterioration. Each type of the latter has an adverse effect on the performance and reliable operational life of the aircraft.

Several publications extensively mention performance deterioration of different components of an engine individually, as well as of whole engine. An earlier preliminary investigation established significant adverse impacts of aeroengine deteriorations. It also indicated that the extent of adverse impacts varies with the type of aeroengine component. Among the major aeroengine components, the low-pressure compressor (LPC) is the overall severest followed by the high-pressure turbine (HPT) [3]. This necessitated the need for a comprehensive investigation of the impacts of the LPC's fouling, as well as the HPT's erosion. Hence, this investigation was undertaken. The impacts of the LPC's fouling have been already investigated [4–6].

There are many components in a gas-turbine engine, but its performance is highly sensitive to changes in only a few. Among these, the HPT's blades are the most sensitive components, because they are subjected to both the highest rotating speeds and gas temperatures [3]; thus, they have been selected for the present investigation.

Because of the enormous effort required to carry out a comprehensive analysis regarding the implications of the HPT's erosion upon a military aircraft's fuel usage/weapon-carrying capability/combat duration, mission operational effectiveness, and life-usage aspects, separate inquiries have been undertaken for each aspect. This paper describes only the influence of the HPT's erosion upon the creep-life consumption of a HPT's blade.

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II. Performance Deterioration of Gas Turbines

In an ideal world, an engine would operate with the same performance from the time it enters service until it is removed. This of course does not happen in reality as the engine will deteriorate. There is very little reliable quantitative data on the magnitudes of performance deterioration of engine components as their service lives are extended, except for those in the papers written by Grewal [7], Sallee [8], Sallee et al. [9], Saravanamuttoo and Lakshminarasimha [10], and Zhu and Saravanamuttoo [11]. Sallee [8] produced several performance deterioration mathematical models for the JT9D engine's behavior. These models show that the performance-loss mechanisms associated with the compressors cause reductions in both flow capacity and efficiency and that those associated with the turbines result in a flow capacity increase and an efficiency fall.

Erosion, in the present context, is the abrasive removal of material from the flowpath components by hard particles suspended in the gas stream. Erosion of the aerofoil also occurs as a result of engine's ingestion of foreign particles, arising from ground debris or detritus, such as hail, volcanic ash, soot, and pollution. As a result, the gas turbine's aerofoil blades become eroded, some of the leading edges blunted, the trailing edges thinned, and the surface roughness increased. It also causes losses of the blades' camber and length, as well as of the seal material. These effects will be felt primarily at the tips of the rotor blades, and so result in increased blade-tip leakages [12], aerodynamic changes in the behavior of the blades, increases in pressure losses, permanent performance deterioration, and even blade failure [13].

III. Potential-Failure Modes

The major potential-failure modes for turbine components are creep, mechanical fatigue, thermal fatigue, oxidation, and sulphidation. At temperatures below approximately 800°C, mechanical fatigue is usually the dominant failure mode. At higher temperatures, that is, above about 1000°C, creep, oxidation, and thermal fatigue (acting alone or together) usually cause failure. In the intermediate temperature range, any of the several failure modes described can be dominant, depending on the structure, the material, and the engine cycle employed.

A. Creep

This is the progressive deformation of a material that occurs under mechanical load and a constant temperature. The resistance of a material to creep reduces as the temperature increases. Therefore, creep presents the largest potential problem in applications involving high temperature and high stress.

Accurately predicting the effects of creep in a gas-turbine engine is a complicated process. However, to obtain a reasonably conservative estimate of creep life, the problem can be simplified by examining creep as a simple function of uniform axial stress, time, and temperature [14].

The Larson–Miller parameter (LMP) is useful in understanding and quantifying the time versus temperature tradeoff for various materials and is given as [13,15]

$$\mathrm{LMP} = 10^{-3}T(\log t_f + C) = 10^{-3}T(\log t_f + 20) \tag{1}$$

or

$$\log t_f = 10^{3}(\mathrm{LMP}/T) - 20 \tag{2}$$

and, hence, the time to failure:

$$t_f = 10^{(10^3\frac{LMP}{T}-20)} \tag{3}$$

B. Mission-Creep Life

In carrying out mission-creep estimation, it is necessary to go through several stages. First, one determines the stress experienced by the component from knowledge of the engine's spool speed. Second, the metal temperature must be evaluated from what is known of the temperature distribution of the flowing-gas stream. Finally, the time spent at each of the separate operating conditions is tabulated. From these data, obtained from engine-duty cycles or mission profiles, it is possible to compute the total stress-rupture damage for the component [15].

C. Cumulation of Creep Damage

If the same amount of creep damage (CrpD) is done to a component at any stress level as a result of a given fraction of the number of cycles required to cause failure, then this may be described in a more general form (according to Minor's rule [15]) by

$$\Phi_C = t_h/t_f \tag{4}$$

or the cumulative damage is given as

$$\Phi_C = \sum \frac{t_{hi}}{t_{fi}} \tag{5}$$

When the LMP, as expressed by Eq. (1), is applied to determine the creep life, Eq. (5) can be rewritten to indicate the time to failure of each segment in a mission as described by Eq. (3). Then, the mission-creep life is calculated through use of Minor's rule for linear damage accumulation, viz.,

$$t_R = \frac{1}{\sum \frac{t_{hi}}{t_{fi}}} \tag{6}$$

D. Stress Analysis

The stresses that actually shorten life cannot be obtained directly from the performance data. To enable a reasonable assessment of the stress distribution for the rotating components in the engine, the method adopted assumes that the stress is proportional to the square of the spool speed. Therefore, given the spool speed at any time during the mission, the instant stress can be assessed using Eq. (7) [15]:

$$S = \left(\frac{N}{N_{\text{design}}}\right)^2 S_{\text{design}} \tag{7}$$

E. Temperatures of the Metal Blades

The temperature at any location in the considered blade is influenced by the temperatures of 1) the gas flow around the outside of the blade, and 2) the coolant at the inlet to and the outlet from the blade [15].

The rotor's relative gas temperature may be written as a function of the high-pressure spool speed [13], that is,

$$T_g = \text{TET} + \left[\frac{(\varpi r)^2}{2C_p}\right] = \text{TET} + \left[\frac{(\frac{2\pi r(\text{HS})}{60})^2}{2C_p}\right] \tag{8}$$

where TET refers to the turbine's entry temperature.

The metal temperature as a function of the gas and the coolant temperatures, and the cooling effectiveness (CEFF) (with a typical value of 60%) can be represented by the following simple equation [15]:

$$T_b = T_g - \text{CEFF}(T_g - \text{CT}) = T_g - 0.60(T_g - \text{CT}) \tag{9}$$

where CT refers to the coolant's temperature.

IV. Computer Modeling and Simulations

Because of the enormous cost reductions and rapid results achieved relative to experimental/trial techniques, the use of validated computer-simulation techniques has recently attained the status of an advanced engineering procedure. Many scenarios can be simulated without incurring the major difficulties and expenses of preparing and testing engines. The more accurate the simulation is, that is, preferably being based on actual measured data, the more realistic the predictions achieved.

For the purpose of present investigation the Engine's Performance-Simulation Program (NaeemPak), Aircraft's Flight-Path and Performance-Simulation Program, Aircraft & Engine's Performance-Simulation Program (NaeemPakA), and Creep-Life-Usage Prediction Program (NaeemPakBCRP) have been used. These programs were developed by the first author while completing his Ph.D. at Cranfield University, United Kingdom, and are proprietary to the author. The programs have been extensively used for previous investigations [2–6,16–18] and were further enhanced and tailored to accomplish the present task.

NaeemPak is an updated version of the engine-performance-simulation program TURBOMATCH [19]. The TURBOMATCH program is an authentic simulation tool and has been used widely at Cranfield University for many years. Performance predictions from NaeemPakA (using the simulation of an F-18 aircraft's behavior powered by two nominally identical F404-GE-400 aeroengines) are reasonable, compared with published values [2–6,16–18]. Based on the comparison of results of NaeemPakBCRP with analytical calculations and previously published results, the model is considered capable of achieving a level of accuracy appropriate to the aims of the model, which were to be simple and generic, rather than definitive and specific to type. The use of the model also confirmed the basic features affecting the HPT blade's CrpD as detailed in the literature.

In general, unlike those for civil aircraft, the mission profiles for military aircraft can be relatively complex. However, for the purpose of the present analysis, a relatively simple military aircraft mission profile as used in previous investigations [18] has been assumed.

When undertaking the computer simulation, the basic methodology is to fly the aircraft through a complete mission profile with 1) both engines functioning properly, and 2) both engines suffering identical prescribed degrees of HPT deterioration. Subsequently, the NaeemPakBCRP is run using the results of the NaeemPakA along with relevant material data as inputs. Thus, the creep-life usage is predicted for each flight, so determining the impacts of the HPT's deterioration on the creep-life usage as a function of the aircraft's flight path.

The relationship between physical degradation and simulated degradation is realized by choosing certain ratios between component efficiency and mass flow capacity deteriorations. Sallee [8] and Sallee et al. [9] have described how the efficiency and mass flow capacity are affected by the engine configuration and deterioration. Although several publications have described different HPTs' efficiency to mass flow capacity deterioration ratios, as yet, precise performance parameter changes due to typical faults in the engine's components and their interrelationships are not known accurately [20]. The exact ratios chosen can be open to some individual subjectivity and so it was worthwhile to establish the values of their ratios as commonly concluded from previous research [2]. Thus, for this assessment, a single-term empirical "erosion index" (EI) was defined to describe the effect of the reduction in efficiency as well as the increase in mass flow capacity of the HPT. For example, for an erosion model (EM) 1:0.5 (i.e., HPT's efficiency (%) to mass flow capacity (%) deterioration ratio), an efficiency of 96% and a flow capacity of 102% of those for a clean engine may be described as a 4% EI. As such, for the purpose of the present analysis, the effects of EM 1:0.5 for the following set of engine conditions have been assessed: 1) clean engines (i.e., an HPT's EI of zero for both engines), and 2) an HPT's EI of 1, 2, 3, 4, 5, and 6% for both engines.

The effects of varying the proportion of the HPT's mass flow capacity deterioration for a given HPT's efficiency deterioration (ED) level have been also assessed by considering EMs 1:0.25, 1:1, 1:2, 1:3, and 1:4.

For the purpose of present analysis, an HPT's EI of 6% is considered an outage for military operations, that is, the breakdown/deformation of a component and subsequent stoppage in the further use of the machine (aeroengine in this case) until an appropriate replacement or repair is undertaken [2].

V. Discussions and Analysis of Results

The aim of the present investigation is to quantify the impacts of turbine erosion upon a military aircraft's turbofan's HPT blade's creep-life consumption for a specified mission profile. An important factor, which needs to be realized when examining the results, is that the numerical values for the effects of the HPT's erosion are not definitive, but nevertheless are considered good ballpark figures. In addition, the trends of the effects are important as they provide an insight into how the engine behaves.

Besides time spent at higher temperatures, the prime factors responsible for any change in the HPT blade's creep-life consumption are the variations in the HS, TET, and CT. Higher values for these will result in greater CrpD and thereby higher blade's creep-life consumption. The variations of the HPT's erosion levels would require the engine(s) to run at different HSs and/or TETs and CTs to meet the thrust requirement for achieving the same aircraft's performance.

A. Aeroengine's Behavior

Any mission profile would always be a combination of altitude (alt), M, and engine settings. Therefore, before an overall analysis of the HPT blade's creep-life consumption, it was considered appropriate to see how the concerned engine parameters are affected with any variation in alt/M/day temperature/engine power setting, or any combination of these. For the purpose of the present investigation, day temperature variations have been expressed in terms of international standard atmosphere deviation (ISAD) (i.e., an ISAD of 0 K for a standard day temperature of 15°C and an ISAD of −15 and 35 K for day temperatures of 0 and 50°C, respectively). All high-pressure spool speed (HS) and maximum high-pressure spool speed (MHS) values have been expressed as a percentage of its design point value.

Table 1 shows the variation in CT with increasing alt/M/ISAD/TET/HPT erosion, whereas Figs. 1 and 2 illustrate the variation in CT and TET at constant low-pressure spool speed/constant net thrust (CLS/CNT) conditions (with increasing HPT erosion) for stipulated HPT erosion models, respectively. For similar conditions, variation for HS has been established by an earlier investigation [18]. An overall critical analysis established the significant and clear variation trends of HS, CT, and TET for different sets of stipulated conditions. For example, for the same levels of M, TET, and ISAD, the HS and CT change significantly with increasing alt. Both increase very slightly but linearly within the stratosphere. However, within the troposphere HS follows a clear variation trend (i.e., an almost linear increase until reaching its peak at about 6000 m alt and subsequently an almost linear reduction until the end of the troposphere), whereas CT reduces almost linearly. At any set of the aforementioned different conditions, HS, TET, and CT, as applicable, are significantly higher for a higher HPT's flow capacity deterioration (FCD) for a given HPT's ED. However, with increasing FCDs, HS's peak value slightly drifts toward the left with increasing altitude whereas it slightly drifts toward the right with increasing M and ISAD.

B. Aeroengine–Aircraft Combination's Behavior

For the purpose of subject investigation, when an aircraft flies through the assumed mission profile (AMP), in addition to the behavior of fitted aeroengines in isolation, the behavior of the aeroengines' and aircraft's aerodynamic structure combination as a whole is of greater importance. During flight segments such as takeoff (TO) and combat/reheat (RH) phases, the aeroengines' peak performance plays the dominant role and the aircraft performs

Table 1 Variation in CT with increasing alt/M/ISAD/TET/HPT erosion

		CT for stipulated EMs, K				
Stipulated condition		EM 1:0.25	EM 1:1	EM 1:2	EM 1:3	EM 1:4
At $M = 0.95$,	0	825.9	828.0	831.5	832.8	835.6
TET = 1555 K,	3	800.5	802.6	805.8	807.7	810.6
ISAD = 0 K and	6	777.2	779.3	782.5	784.4	787.3
stipulated alt ($\times 10^3$)	9	755.5	757.7	761.0	763.1	766.1
	12	741.7	743.9	747.3	749.5	752.6
	15	742.0	744.3	747.7	749.8	759.2
At alt = 10,000 m,	0	717.3	719.3	722.2	725.0	727.8
TET = 1555 K,	0.3	721.0	722.9	725.7	728.6	731.5
ISAD = 0 K and	0.6	732.6	734.5	737.3	740.0	742.8
stipulated M	0.9	750.5	752.3	755.3	758.0	760.6
	1.2	775.7	777.4	780.0	782.7	785.5
	1.5	811.8	813.6	816.1	818.6	821.2
At alt = 10,000 m,	−15	733.8	736.7	739.2	741.5	744.9
$M = 0.95$,	−6	743.1	745.4	748.8	750.9	754.0
TET = 1555 K, and	6	755.7	757.9	761.3	763.4	766.7
stipulated ISAD	15	765.1	767.3	770.7	772.7	775.8
	25	776.8	778.8	782.0	784.0	786.6
	35	787.7	789.9	793.1	795.0	797.9
At $M = 0.95$,	1400	720.8	722.7	725.4	728.0	730.6
alt = 10,000 m,	1500	754.3	756.4	759.2	762.0	764.9
ISAD = 0 K, and	1600	786.4	789.6	791.9	794.2	797.6
stipulated TET, K	1700	817.8	821.5	821.9	822.9	830.6
At $M = 0.95$,	1	749.9	752.1	755.4	757.5	760.8
alt = 10,000 m,	2	745.6	750.0	755.6	761.2	767.3
TET = 1555 K,	3	741.2	747.7	756.7	762.5	772.7
ISAD = 0 K and	4	738.4	746.0	754.6	768.2	777.2
stipulated HPT's EI, %	5	733.4	742.0	752.9	770.1	780.0
	6	729.1	738.9	750.3	761.3	779.3

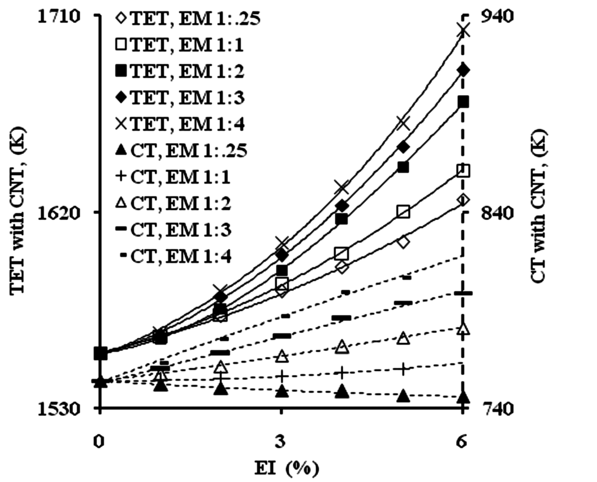

Fig. 1 TET and CT with CNT (at same alt, M, and ISAD) for stipulated EMs with increasing HPT erosion.

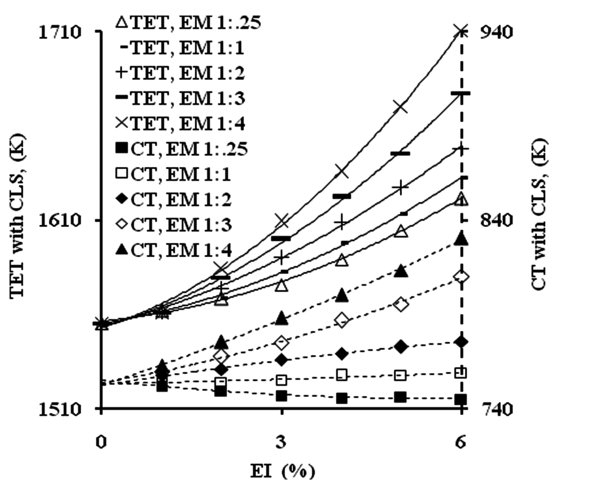

Fig. 2 TET and CT with CLS (at same alt, M, and ISAD) for stipulated EMs with increasing HPT erosion.

according to the maximum available NT from the engines. Whereas during other flight segments, for example, cruising at a specified alt and M, the aircraft's aerodynamic characteristics play the dominant role and the aeroengines are run at a power setting such that the NT available from the engines balances the aircraft's drag. Therefore, the engine parameters of concern, that is, HS/MHS/TET/MTET/CT/MCT (where MTET and MCT refer to the maximum turbine entry

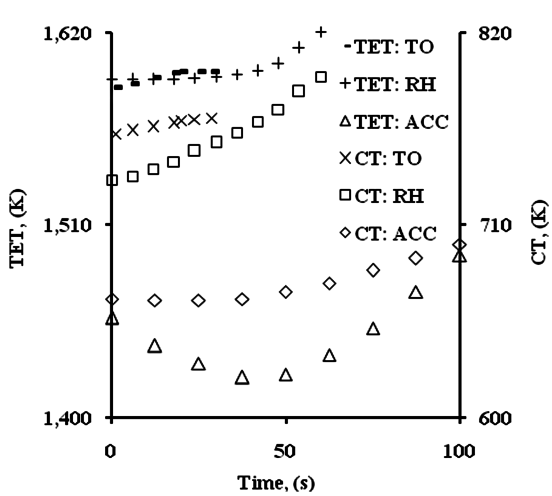

Fig. 3 TET and CT during stipulated flight phase.

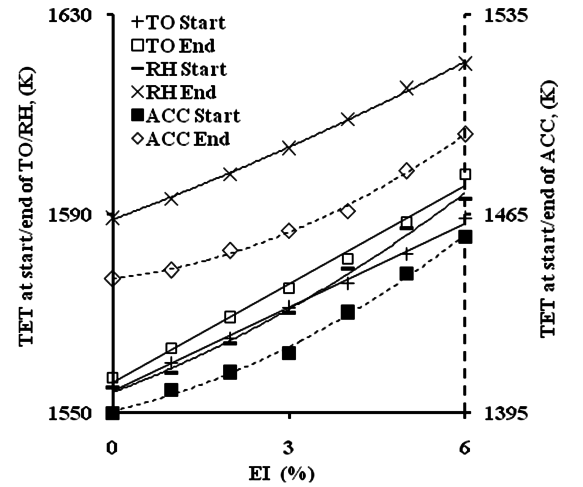

Fig. 4 TET at stipulated conditions with increasing HPT erosion.

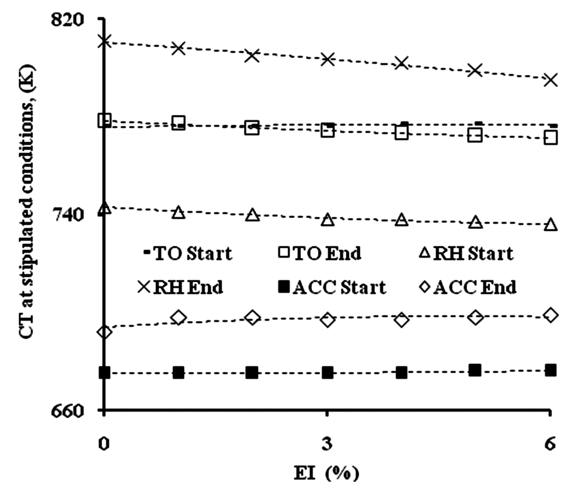

Fig. 5 CT at stipulated conditions with increasing HPT erosion.

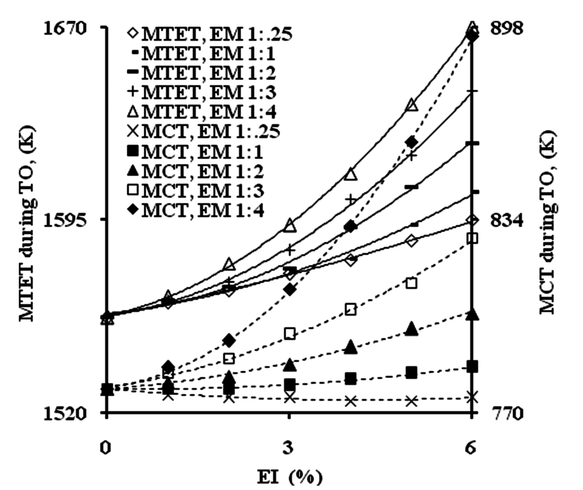

Fig. 6 MTET and MCT during TO with increasing HPT erosion.

temperature and the maximum coolant temperature) have been also observed during some important flight segments. Finally the aeroengine's HPT blade's creep-life consumption has been predicted for the complete mission profile.

Figures 3–8 illustrate, respectively, 1) TET, and CT during the TO, RH, and acceleration (ACC) phases for a given EM and HPT erosion; 2) TET, and CT at the start and end of the TO, RH, and ACC phases

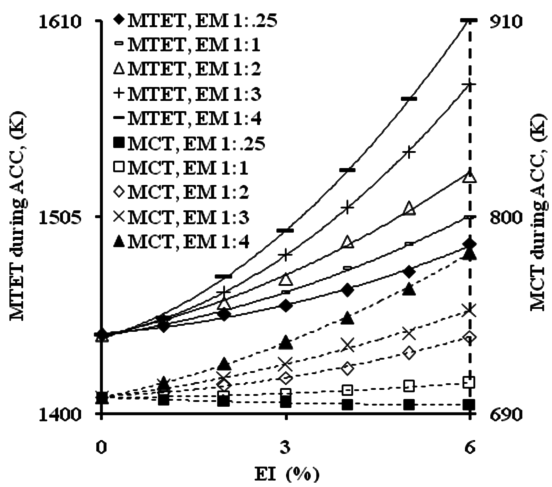

Fig. 7 MTET and MCT during ACC with increasing HPT erosion.

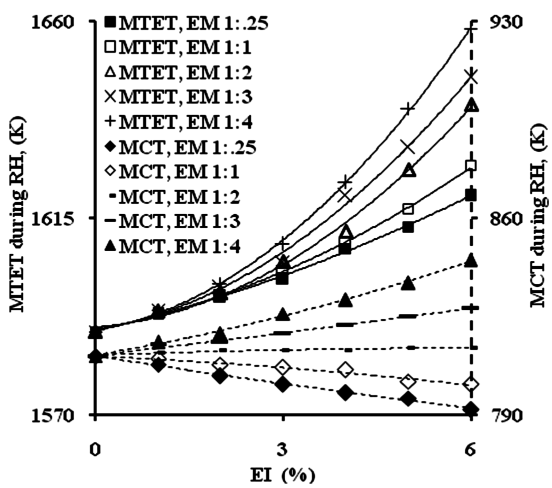

Fig. 8 MTET and MCT during RH with increasing HPT erosion.

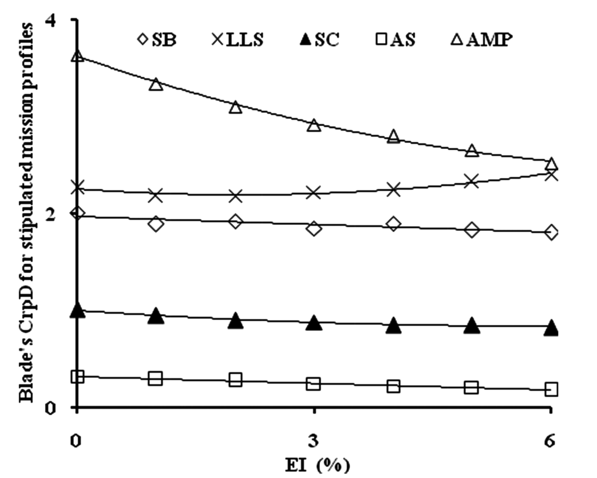

Fig. 9 HPT blade's CrpD (for stipulated mission profiles) with increasing HPT erosion.

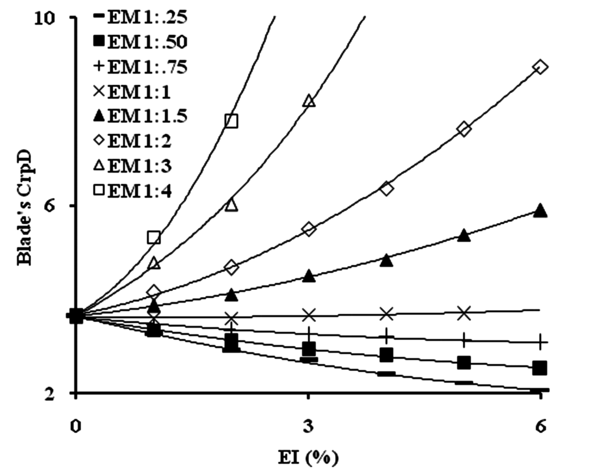

Fig. 10 HPT blade's CrpD (for AMP) with increasing HPT erosion.

for a given EM but with increasing HPT erosion; and 3) MTET, and MCT during the TO, ACC, and RH phases for the stipulated EM but with increasing HPT erosion. For similar conditions, the variation trend for HS/MHS has been established by a previous investigation [18]. An overall critical analysis establishes a significant variation (with differing variation trends) in HS/MHS, TET/MTET, and CT/MCT during different flight phases as well as for different points on the mission profile with varying EMs and HPT erosion levels. For example, with increasing HPT erosion, for various EMs, a clear variation trend is observed for MHS, MTET, and MCT during TO. At lower FCDs for a given ED, for example, EM 1:0.25, the MHS reduces almost linearly with increasing HPT EI. Whereas with increased FCDs, the reduction in MHS no longer remains linear; rather, it reduces with a slightly increasing rate. Also with rise in FCDs, the extent of reduction in MHS reduces with increasing EI. As a result, for an EM 1:2, the MHS remains almost invariant from an EI of 0–2%, whereas for an EM 1:4, the MHS even increases from 100 to 100.85% for an increase in EI from 0 to 3% and, subsequently, MHS starts reducing with a slightly increasing rate. However, at any given EI, MHS, MTET, and MCT are significantly higher for higher FCDs for a given ED. An almost similar trend to that of the TO phase with only one exception is observed during the acceleration phase. Unlike TO, during acceleration MHS reduces with a slightly increasing rate with an increasing HPT EI.

C. HPT Blade's Creep-Life Consumption

An overall rise in the HS, TET, and CT with increasing HPT erosion levels affects the HPT blade's CrpD adversely. For the AMP, with increasing HPT erosion levels, for HPT EM 1:0.50, the blade's CrpD and thereby creep-life consumption reduces with a slightly reducing rate (see Fig. 9). However, for various EMs, a clear variation trend is observed for the blade's CrpD. With increasing HPT erosion levels, at lower FCDs for a given ED, for example, EM 1:0.25, the blade's CrpD reduces with a slightly reducing rate. With increased FCDs, the extent as well as the rate of reduction in the blade's CrpD reduces. As a result, for EM 1:1, the blade's CrpD remains almost invariant. At further higher FCDs, the blade's CrpD starts increasing with a significantly increasing rate, becoming exceptionally high with EM 1:4 (see Fig. 10).

Among the four representative mission profiles of a military aircraft [5,18], low-level strike (LLS) is the severest in terms of the blade's creep-life consumption (see Fig. 9). The significant variation in the levels of the blades' creep-life consumption as well as the differing variation trend for different mission profiles are due to the reason that these vary with any change in the nature/extent of flight segment(s) as well as their interarrangement in any given mission profile.

For different conditions, the variation in HS/MHS is usually accompanied by a significant variation in TETs and CTs. A rise in TET/CT leads to greater thermal fatigue damages of the HPT's blades (an area of future investigation).

For EMs with lower FCDs for a given ED, the reduction in the blade's CrpD with increasing HPT erosion is because of the much greater reduction in HSs with not much difference in the TETs/CTs as compared with that for clean engines. This favorable effect of the HPT's erosion on the blade's creep life seems illogical at first glance, because any deterioration of a component should have a negative effect. The reader should keep in mind that the erosion of blades will make them weaker because of thinning, thus resulting in a lowering of the creep-life upper limit. The effect due to a lowering of the creep-life limit may well exceed the effect of the reduction in CrpD caused by the blade's erosion.

VI. Conclusions

Computer simulations have been used to explore the relative implications of turbine erosion for an aeroengine's HPT blade's creep-life consumption. For the conditions assumed in this investigation, the effect of the turbine erosion on blade's creep-life consumption is significant (favorable and adverse with lower and higher HPT's FCDs, respectively, for a given ED). The blade's creep-life consumption varies significantly with the type of mission flown and is the severest for a low-level strike among the four representative peacetime training mission profiles considered.

The use of appropriate instrumentation to accurately monitor HPT erosion levels and the results of such an investigation as the present for a variety of mission profiles under various operating conditions/engine's deterioration levels will provide a wide database and can lead to managers making wiser decisions. However, greater benefits will be achieved if the present analysis is considered as an integral part of a more comprehensive analysis, including the aeroengine's low cycle fatigue and thermal fatigue life usages, fuel usage/weapon-carrying capability, and the aircraft's mission operational effectiveness, as well as life-cycle cost aspects.

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