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Effects of Ambient Temperature and Shaft Power Variations and Compressor Degradation on Creep-Fatigue Interaction Life Consumption of Industrial Gas Turbine Blades

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Abstract: This work centres on the investigation of the effects of ambient temperature, shaft power level and compressor degradation (in the form of reduction of health parameter indices including flow capacity index, isentropic efficiency index, and the pressure ratio index) on the creep-fatigue interaction life consumption of the high pressure turbine blades of LM2500+ engine. The aim is to ascertain how the different effects affect engine creep-fatigue interaction life consumption so that engine operators will be properly guided. The Larson-Miller parameter method was used for creep life tracking while the modified universal slopes method was used for the fatigue life analysis. Creep and fatigue damage parameters were obtained at each engine operation point and the linear damage accumulation model was used for the creep-fatigue interaction life analysis. The life analysis models were implemented in PYTHIA, Cranfield university's in-house gas turbine performance and diagnostics software where an engine model was developed and creep-fatigue interaction life was investigated at different ambient temperatures and shaft power levels. In the compressor degradation, 1% and 2% reduction in the health parameter indices were implanted in the developed engine model and the effects of the degradations were investigated at different shaft power levels and ambient temperatures. It was observed that at a given shaft power level, creep-fatigue life expressed in terms of creep-fatigue factor decreases with increase in ambient temperature while at a given ambient temperature, creep-fatigue life decreases with increase in shaft power. For the degraded engine, the percentage decrease in creep-fatigue factors increases with both shaft power increase and ambient temperature increase. Doubling the compressor health parameter indices reduction nearly doubles the impact on creep-fatigue life consumption. For instance, at 70% power level, the 1% and 2% degradation cases gave percentage reductions in creep-fatigue interaction life as 10.84% and 21.16% respectively while the respective results at 90% power level are 16.05% and 30.10%. The methodologies developed could be applied to other engine types and the results will serve as useful guides to engine operators.

Keywords: Creep-Fatigue Interaction, Health Parameter Indices, Flow Capacity Index, Isentropic Efficiency Index, Pressure Ratio Index

1. Introduction

The creep-fatigue interaction life tracking of the compressor turbine blades of LM2500+ engine has been investigated as presented in [1]. Creep-fatigue interaction life can be modelled considering the creep part and the fatigue part separately and adding the two contributions together. Creep life is temperature dependent and the rate of creep life consumption is affected by several factors. Fatigue life on the other hand is affected mainly by the load amplitude and the rate of fatigue life consumption of a given component may be affected by a number of factors. Since creep-fatigue interaction life has contributions from creep and fatigue, any factor which affects either failure modes will definitely influence their combined mode of failure.

There are several works which examine the effects of different factors on creep life consumption [2–5]. For gas turbine engine components, the power level, ambient temperature and engine degradation are among the factors that affect creep life. Fatigue failure usually starts with crack initiation followed by crack growth. Aside the load amplitude, the microstructure of the material has great influence on the fatigue life and this and other effects have been investigated by several researchers [6–10]. Creep-fatigue interaction life of gas turbine components whether modelled from crack growth consideration [11–14], or any other approaches [15, 16] will be affected by the conditions of the engine operation which include the power level, ambient temperature and degradation of engine components. Works on creep-fatigue interaction life are usually concerned with the methodology employed and the accuracy of results rather than different factors affecting the creep-fatigue interaction life consumption of the components considered. In this work therefore, the effects of ambient temperature, shaft power level and compressor degradation on the creep-fatigue interaction life consumption of the compressor turbine blades of LM2500+ engine were investigated.

2. Methodology

To investigate different effects on creep-fatigue interaction life consumption, an engine model and a platform for the creep-fatigue interaction life estimation must be developed first. One of such platforms has been developed in [1] and the LM2500+ engine model could be found in [17]. The linear damage accumulation model is adopted here where creep life is investigated with Larson-Miller parametric method, fatigue life with the modified universal slopes method and the individual damage parameters are added together to obtain the creep-fatigue interaction life consumption. The basic relations are presented in Equations (1) to (6);

Creep Life Model

$$t_f = 10^{\left(\frac{LMP}{T} - C\right)} \quad (1)$$

t_f is the time to creep failure, T is the temperature of blade material in Kelvin (K), LMP is the Larson Miller parameter obtained from a Master curve and C is material constant usually of the order of 20. The creep life fraction $D_{c,i}$ consumed at a given engine operation point is,

$$D_{c,i} = \frac{t_i}{t_{f;i}} \quad (2)$$

t_i is the time spent at a given stress-temperature combination, $t_{f;i}$ is creep fracture life at same stress-temperature combination

Fatigue Life Model

$$\sigma_a = 0.623\sigma_u^{0.832} E^{0.168} \left(2N_f\right)^{-0.09} + 0.0196\varepsilon_f^{0.155} \sigma_u^{-0.53} E^{1.53} \left(2N_f\right)^{-0.56} \quad (3)$$

σ_a is the nominal alternating stress amplitude, σ_u is the ultimate tensile strength of the material, E is the Young's Modulus of the material, ε_f is the true fracture ductility, and N_f is the number of stress cycles to failure. The fraction of life consumed $D_{f,i}$ due to fatigue at each stress-temperature combination is given as,

$$D_{f,i} = \frac{N_i}{N_{f,i}} \quad (4)$$

N_i is the number of cycles accumulated at stress amplitude $\sigma_{a,i}$ and $N_{f,i}$ is the number of cycles to failure at stress amplitude $\sigma_{a,i}$.

Creep-Fatigue Interaction Life Model

The creep-fatigue damage parameter D_{c+f} given by Equation (5),

$$D_{c+f} = \frac{t_i}{t_{f,i}} + \frac{N_i}{N_{f,i}} \quad (5)$$

The time to creep-fatigue interaction failure $t_{f,c+f}$ is expressed as in Equation (6) and other failure terms such as equivalent creep-fatigue failure and equivalent creep-fatigue factor could be obtained as in [1].

$$t_{f,c+f} = \frac{t_i}{D_{c+f}} = \frac{t_i}{\frac{t_i}{t_{f,i}} + \frac{N_i}{N_{f,i}}} \quad (6)$$

The creep-fatigue interaction life estimation algorithm is implemented in PYTHIA [18] and the procedure for investigating different effects on creep-fatigue interaction life consumption is presented in Figure 1. The creep life analysis, fatigue life analysis and creep-fatigue interaction life analysis could be carried out at a given condition of engine operation. The required effect can be planted in the engine model. This effect may be any of differing ambient temperature or shaft power level or implanting degradation in the compressor.

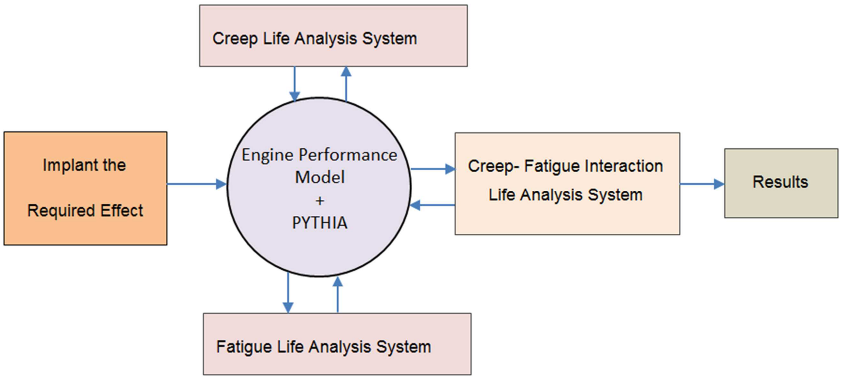

Figure 1. *Algorithm for Estimating different effects on creep-fatigue interaction life consumption.*

Three effects are investigated in this research. The creep-fatigue interaction life can be estimated at given engine operation conditions. To investigate each effect, say ambient temperature on creep-fatigue interaction life, the shaft power level will be fixed and the ambient temperature is increased. The creep-fatigue interaction life is then estimated at the new ambient temperature level. The responses of creep-fatigue interaction life to the various effects are considered in turn.

3. Effect of Ambient Temperature Variation on Creep-Fatigue Interaction Life

The effect of ambient temperature on creep-fatigue interaction life analysis is carried out at 70% to 100% power levels and ambient temperatures of 5°C to 30°C (expressed in terms of deviations from ISA condition). The shaft power level is fixed while the ambient temperatures are varied and the creep-fatigue interaction life estimated at the various ambient temperatures for each fixed power level. The creep-fatigue interaction life estimated in each case is expressed in terms of creep-fatigue factor (CFF) which is a relative life [1]. At a particular power level, the percentage decrease in CFF due to increase in ambient temperature PD_{CFF} is given by Equation (7),

$$PD_{CFF} = \frac{CFF_{T,i} - CF_{T,i+1}}{CFF_{T,i}} \times 100 \quad (7)$$

$CFF_{T,i}$ is the CFF at the initial temperature value, and $CFF_{T,i+1}$ is the CFF evaluated at the next temperature level. The average percentage decrease in CFF at a particular power level due to unit increase in ambient temperature for the entire range of temperatures $PD_{CFF,m}$ is given by Equation (8),

$$PD_{CFF,m} = \sum_{i=1}^{n-1} \left(\frac{CFF_{T,i} - CFF_{T,i+1}}{CFF_{T,i}} \times 100 \right) \times \frac{1}{n-1} \quad (8)$$

n is the number of ambient temperature levels where creep-fatigue factors are estimated.

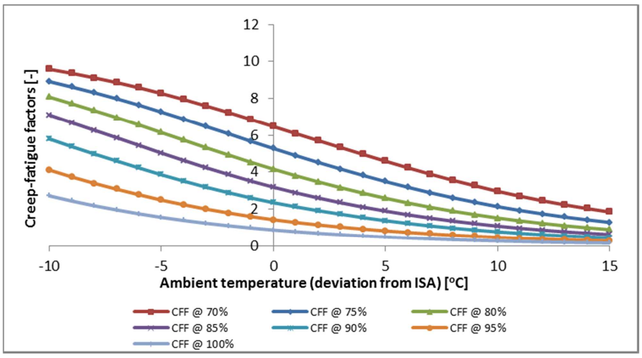

Figure 2. *Effect of ambient temperature on creep-fatigue interaction life.*

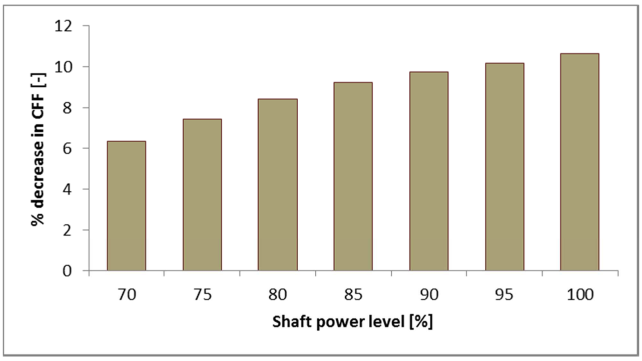

Figure 3. *Average percentage decrease in CFF with ambient temperature at different power levels.*

Figure 2 shows the effect of ambient temperature variation on creep-fatigue interaction life at different power levels. The creep-fatigue factors decrease with ambient temperature increase at all power levels. This is because the creep failure contributes majorly to creep-fatigue interaction failure. At higher ambient temperatures, the creep-fatigue factors trend is similar to the creep trend as creep contribution to creep-fatigue failure is more in higher ambient temperatures [1]. At lower ambient temperatures, the fatigue contribution increases but still far less than the creep contribution; the creep-fatigue factors trend is less similar to the creep factors trend in this low temperature band. Both creep and fatigue contributions to creep-fatigue interaction failure at a given ambient temperature increases with increase in shaft power, but creep contribution increases faster; the creep-fatigue factors trend thus behave like the creep trend more closely at higher shaft power levels. Higher values of percentage decrease in creep-fatigue factors due to increase in ambient temperature for the specified ambient temperature range occur at higher shaft power levels as shown in Figure 3. This is because at higher shaft power levels, the contributions of both creep and fatigue to creep-fatigue life increases, and increase in ambient temperatures thus has more impact on the creep-fatigue interaction life at higher power levels.

4. Effect of Shaft Power Variation on Creep-Fatigue Interaction Life

To investigate the effect of shaft power on creep-fatigue interaction life consumption, the ambient temperature will be fixed while the engine is operated at different power levels before shut down. 70% part load to peak power levels are considered for the analysis. The power level is varied at the different ambient temperatures considered (5^{o}C to 30^{o}C). The decrease in CFF with power level increase at a given ambient temperature and the average percentage decrease in CFF can be estimated with relations similar to Equations (7) and (8) respectively. At a given ambient temperature, the creep-fatigue factors decrease with increase in shaft power. This is shown in Figure 4 for ambient temperatures of 13^{o}C and 17^{o}C respectively.

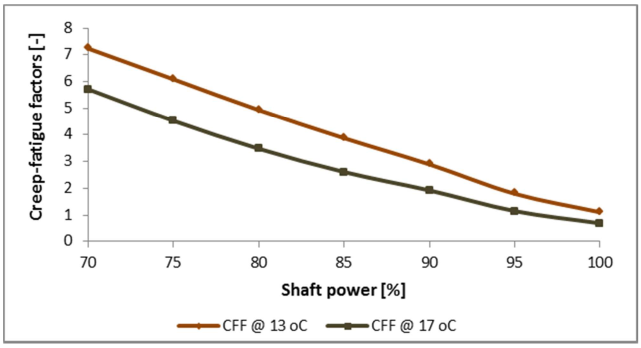

Figure 4. *Effect of Shaft power variation on creep-fatigue interaction life.*

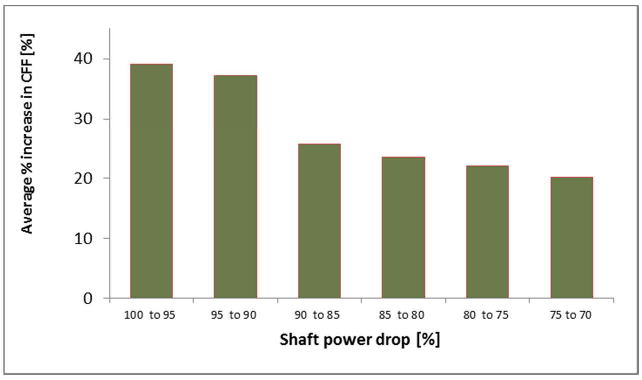

Figure 5. *Average percentage increase in creep-fatigue factors with shaft power drop.*

At a given ambient temperature, increase in shaft power leads to decrease in creep-fatigue factors as in Figure 4. On the other hand, increase in creep-fatigue factors occur with power drop, in the same magnitudes as increase in shaft power does to creep-fatigue factors decrease. Greater values of percentage increase in creep-fatigue factors are obtained when power drop occurs at higher power levels. The increase in creep-fatigue factors with power drop at different ambient temperatures was estimated and the mean value is obtained at each power level and presented in Figure 5. These results are a bit similar to those obtained in creep life analysis where larger increase in creep factors is obtained when power drop occurs at higher power levels. This similarity is due to the large contribution of creep to creep-fatigue interaction failure at all ambient temperatures and shaft power levels.

5. Effect of Engine Degradation on Creep-Fatigue Life Consumption

The effect of compressor degradation on creep-fatigue interaction life consumption of the low pressure turbine blades is considered here. The degradation of engine components is expressed in terms of degradation scaling factors or health parameter indices [19]. The indices for a compressor include the flow capacity index, isentropic efficiency index, and pressure ratio index, but the pressure ratio index is assumed to be equal to the flow capacity index hence flow capacity and isentropic efficiency indices are used to represent compressor degradation. Degradation of any engine component affects the properties of the gas path properties and hence the life of the hot section components. Two cases of compressor degradation are considered: 1% and 2% reductions respectively in compressor health parameter indices and these are shown in Table 1. The effect of each case of engine degradation on creep-fatigue life consumption is examined at different power levels (70% to 100% power levels) and various ambient temperatures (10°C to 30°C).

Table 1. *Degradation cases for creep-fatigue interaction life analysis.*

Case	Component	Degraded Parameter	
		Efficiency Index (%)	Flow capacity Index (%)
I	Compressor	-1	-1
II	Compressor	-2	-2

The extent to which engine compressor degradation affect creep-fatigue interaction life consumption is revealed by examining the sensitivity of creep-fatigue interaction factors to compressor degradation at different engine operating conditions; that is, the response of creep-fatigue interaction factors to compressor degradation will be investigated at different conditions of engine operation. This is best presented in terms of the percentage decrease in creep-fatigue factors due to compressor degradation, and it is given by Equation (9),

$$PD_{CFF,i} = \frac{CFF_{CE,i} - CFF_{DE,i}}{CFF_{CE,i}} \times 100 \qquad (9)$$

$PD_{CFF,i}$ is the percentage decrease in creep-fatigue factor at each power level and at the various ambient temperatures, $CFF_{CE,i}$ is the creep-fatigue factor for the clean engine at a given power level and ambient temperature counter i, while $CFF_{DE,i}$ is the creep-fatigue factor for the degraded engine at same power level and ambient temperature. The value of the percentage decrease in creep-fatigue factor indicates how engine creep-fatigue life responds to engine degradation at the given power level and ambient temperature. Higher values of percentage decrease in creep-fatigue factor indicate greater impact of degradation on creep-fatigue life and vice-versa. Results of the creep-fatigue factors of the clean and degraded engines at different power levels and ambient temperatures are presented for comparisons.

Case I: Reduction in Compressor Health Parameter Indices by 1%

When the compressor health parameter indices are reduced by 1% each, the creep-fatigue factors are reduced at each condition of engine operation. Here, the creep-fatigue factors are presented at 90% and 100% power levels and at different ambient temperatures for both the clean engine (CE) and the degraded engine (DE) for the purpose of comparison as in Figure 6.

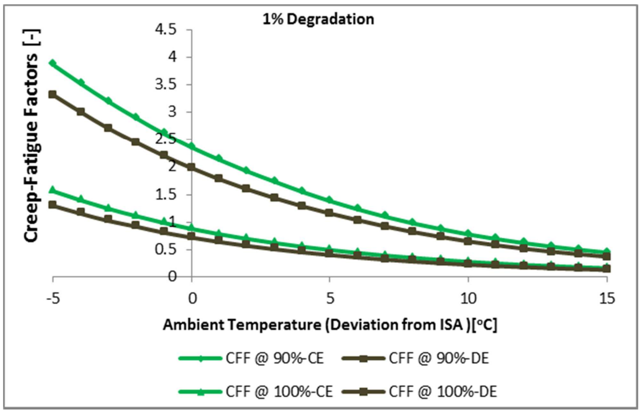

Figure 6. *Creep- fatigue factors of CE and DE at 1% reduction in compressor health parameter indices.*

The creep-fatigue factors of the CE are greater than those of the degraded engine at the two power levels and the different ambient temperatures. The difference between the creep-fatigue factors for the CE and DE becomes smaller at higher power levels and higher ambient temperature because smaller values creep-fatigue factors are recorded at higher power levels and higher ambient temperature. But, in terms of percentage decrease in creep-fatigue factors, larger values are recorded at higher power levels and higher ambient temperatures. This is because at the higher power levels, the compression process is less efficient and compressor degradation leads to greater percentage increase in the temperature of gases at the turbine entry. Since creep-fatigue interaction life consumption is dominated by creep which is temperature-driven, compressor degradation has greater impact on creep-fatigue life consumption at higher power levels. Thus at a given power level, the percentage decrease in creep-fatigue factors increases with ambient temperature forming no regular trend as in Figure 7 for 70% and 85% power levels. In the same vein, at a given ambient temperature, the percentage decrease in creep-fatigue factors increases with increase in shaft power (forming no regular trend) as shown in Figure 8 for two different ambient temperatures.

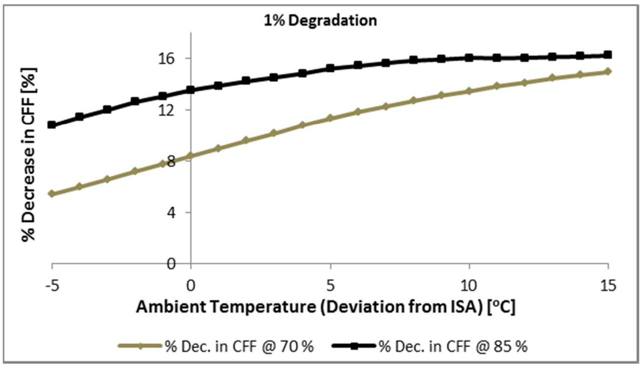

Figure 7. *Percentage decrease in CFF for 1% reduction in compressor health parameter indices.*

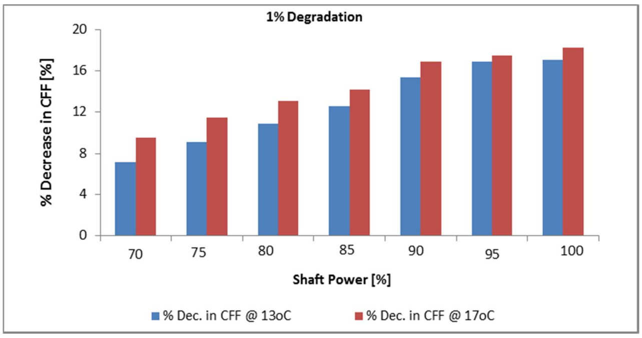

Figure 8. *Percentage decrease in CF with shaft power at different ambient temperatures for 1% reduction in compressor health parameter indices.*

Figure 9 shows the average percentage decrease in creep-fatigue factors evaluated at each power level and ambient temperatures between 10°C to 30°C. Compressor health parameters indices reduction thus has more impact on creep-fatigue life consumption at higher ambient temperatures and at higher power levels.

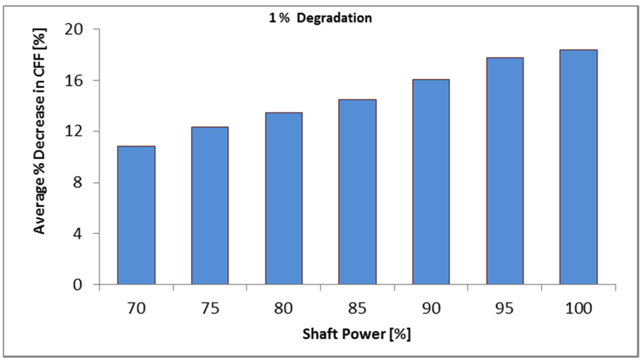

Figure 9. *Average percentage decrease in CFF at different power levels for 1% reduction in compressor health parameter indices.*

Case II: Reduction in Compressor Health Parameter Indices by 2%

The creep-fatigue interaction factors obtained for 2% reduction in compressor health parameter indices are similar to those of both the clean engine and the engine with 1% reduction in compressor health parameter indices in terms of trend, but less than those of 1% compressor degradation in terms of magnitude as shown in Figures 10 to 13. The average percentage decreases obtained at the various power levels for 2% reduction compressor health parameter indices are greater than those obtained at 1% reduction in compressor health parameter indices.

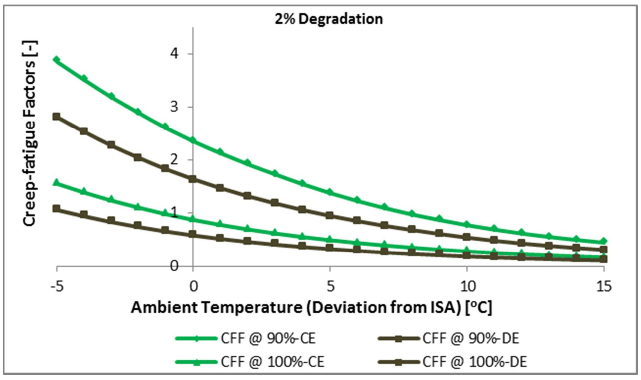

Figure 10. *Creep- fatigue factors of CE and DE at 2% reduction in compressor health parameter indices.*

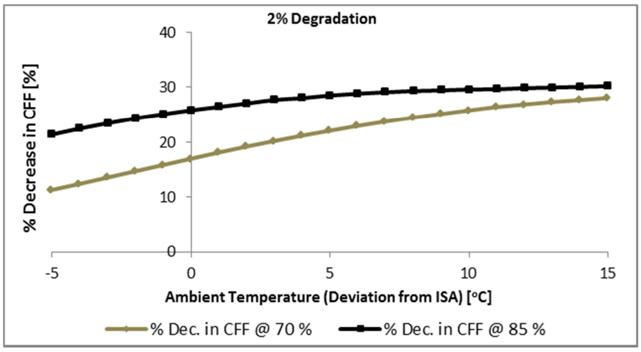

Figure 11. *Percentage decrease in CFF for 2% reduction in compressor health parameter indices.*

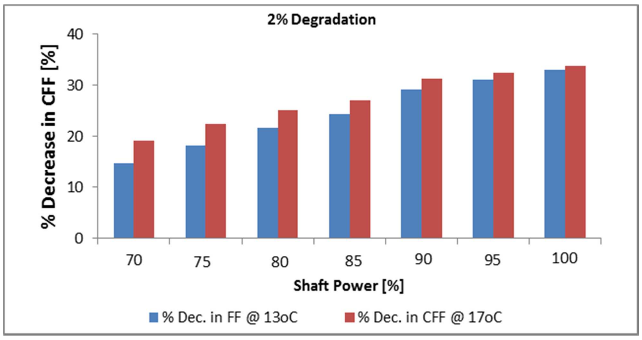

Figure 12. *Percentage decrease in CF with shaft power at different ambient temperatures for 2% reduction in compressor health parameter indices.*

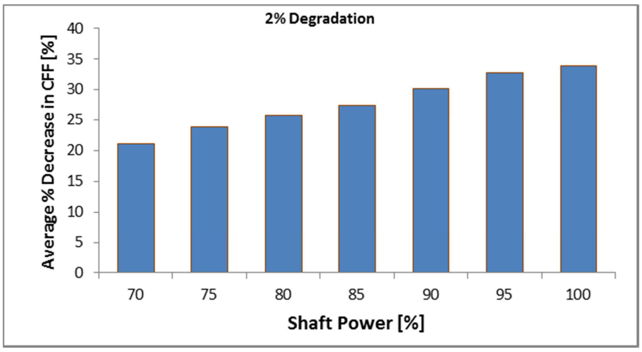

Figure 13. *Average percentage decrease in CFF at different power levels for 2% reduction in compressor health parameter indices.*

Comparison of the Impacts of the two Degradation Cases on Creep-Fatigue Interaction Life Consumption

In both cases of degradation, the creep-fatigue factors behave like the creep-fatigue factor of the clean engine in terms of trend but of lower magnitude at all temperatures and shaft power levels. The creep-fatigue factors for both the clean and degraded engines decrease with increase in ambient temperature for a given power level; they also decrease with increase in shaft power for a given ambient temperature level. Figure 14 shows the creep-fatigue factors for the two cases of degradation at 13°C (-2°C deviation from ISA) and different power levels. Figure 14 also shows that the engine with 2% reduction in compressor health parameter indices has creep-fatigue factors lower than the engine with 1% degradation case at a given ambient temperature and at all power levels. More noticeable difference between the creep-fatigue factors is obtained at lower power levels because high values of creep-fatigue factors are gotten at lower power levels.

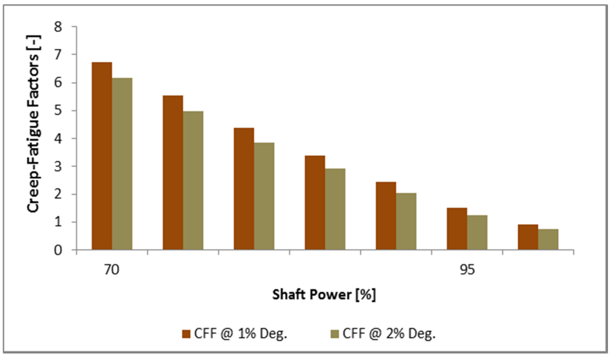

Figure 14. *Creep-fatigue factor variation with shaft power for degraded engines at a given ambient temperature.*

Increasing the compressor health parameter index reduction from 1% to 2% nearly doubles the impact of the degradation on creep-fatigue interaction life at all ambient temperatures and shaft power levels judging from the values of the average percentage decrease in creep-fatigue factors. This means doubling the compressor health parameter indices nearly doubles impact on creep-fatigue life consumption. Table 2 shows the average percentage decrease in creep-fatigue factors for the 1% and 2% degradation cases at 70% and 90% power levels.

Table 2. *Average percentage decrease in creep factors at two degradation cases.*

Power Level (%)	Average Percentage Decrease in CFF (%)	
	1% Degradation Case	2% Degradation Case
70	10.84	21.16
90	16.05	30.10

6. Conclusions

The effects of ambient temperature variation, shaft power variation and compressor degradation in the form of reduction in health parameter indices on creep-fatigue interaction life consumption of the high pressure turbine blades of LM250+ engine were investigated in this work. The study shows that at a given shaft power level, creep-fatigue factors decrease with increase in ambient temperature while at a given ambient temperature, creep-fatigue factors decrease with increase in shaft power. For an engine with compressor health parameter indices reduction, the trend of the creep-fatigue factors is similar to that of the clean engine, but lower in terms of magnitude at all ambient temperatures and shaft power levels. The percentage decrease in creep-fatigue factors due to compressor degradation increases with both shaft power increase and ambient temperature increase. Doubling the compressor health parameter indices reduction nearly doubles the impact on creep-fatigue life consumption. In both degradation cases (1% and 2% reduction in compressor health parameter indices), the percentage decrease in creep-fatigue factors increases with shaft power at a given ambient temperature, and at a given ambient temperature, the percentage decrease in creep-fatigue factors increases with shaft power level. The values of the percentage decreases in creep-fatigue factors with ambient temperature variation, shaft power variation and compressor degradation obtained in this research are specific to the engine model, different engine models will give different results but the trends will be similar. Thus, the results could serve as guides to different engine operators. Also, the methodologies applied in this research could be applied to different engine configurations. This should be carried out in future researches to see how the different effects studied in this work lead to engine creep-fatigue interaction life consumption.

Nomenclature

C	Material constant
CE	Clean engine
CFF	Creep-fatigue (interaction)factor
DE	Degraded engine
LMP	Larson Miller parameter
T	Temperature of blade material
$CFF_{CE,i}$	Creep-fatigue factor for the clean engine
$CFF_{DE,i}$	Creep-fatigue factor for the degraded engine
$CFF_{T,i}$	Creep-fatigue factor at the initial temperature level
$CFF_{T,i+1}$	Creep-fatigue factor evaluated at the next temperature level
$D_{c,i}$	Creep life fraction consumed
$D_{f,i}$	Fatigue damage parameter
D_{c+f}	Creep-Fatigue interaction damage parameter
E	Young's Modulus of the material
N_f	Number of stress cycles to failure
$N_{f,i}$	Number of cycles to failure
$N_{f,c+f}$	Number of cycles to creep-fatigue interaction failure
$PD_{CFF,i}$	Percentage decrease in creep-fatigue factor at each power level
$PD_{CFF,m}$	Average percentage decrease in creep-fatigue factor at a particular power level
N_i	Number of cycles accumulated
t_f	Time to creep failure
$t_{f,i}$	creep fracture life at same stress-temperature combination
$t_{f,c+f}$	Time to creep-fatigue interaction failure
t_i	Time spent at a given stress-temperature combination
ε_f	True fracture ductility

σ_a	Nominal alternating stress amplitude
σ_u	Ultimate tensile strength of the material

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