

Development And Application Of Fatigue Cycles Accumulation Model For Industrial Gas Turbines Operation

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Abstract

This paper presents the development and the application of fatigue cycles accumulation model suitable for industrial gas turbines operation. The model is developed from a model used by the US Air Force for aircraft engines. In industrial gas turbines, one fatigue cycle is counted in operating the engine to peak power level and shut down; also, daily operation and shut down constitutes one fatigue cycle. But greater variation in engine speed within any period of engine operation leads to greater fatigue life consumption; The developed model takes cognizance of this. The fatigue cycles are estimated from the variation of total stress resulting from the centrifugal stress and the bending momentum stresses imposed on the component concerned. The model is applied to the high pressure turbine blades of the GE LM2500+ type engine using real engine operation data and the fatigue cycles are estimated at the blade mean section. More fatigue cycles are obtained from the model compared to the aircraft model since the developed model takes into account every transition of engine shaft speed. The developed is intended to replace the traditional one fatigue cycle per engine shut down being practiced and provide results which are in line with the nature of engine operation.

Keywords: fatigue cycles, turbine blades, centrifugal stress, bending moment stresses, fatigue failure.

INTRODUCTION

In low cycle fatigue life analysis of gas turbine rotating components, the number of fatigue cycles accumulated in a given period of engine operation has to be estimated using different models available. The number of fatigue cycles accumulated is often put in form of blocks of loads defined by the stress amplitude. This is followed by determining the number cycles to failure at a given stress amplitude using different strain-based total life relations such as the Coffin-Manson relation, Morrow's equation, Smith-Watson-Topper relation, Universal slopes method, Mitchell's method and the modified universal slopes method (Kim et al. 2002; Ince & Glinka 2011; Dowling 2004; Park & Song 1995; Suresh 2004); where the task in most of the methods is the determination of four fatigue parameters. The low cycle fatigue life consumption analysis is then carried out by estimating the magnitude of damage each block of load does exploiting the damage summation rule provided by Palmgren and Miner (Kim et al. 2002), (Hashin 1979).

The determination of the number of fatigue cycles accumulated in the course of engine operation is crucial in the fatigue life estimation process. In industrial engines, accelerating the engine from standstill to maximum engine rotational speed and then returning to standstill constitutes one complete low cycle operation (Sapsard 2000) . Also, peak operation of engine on daily basis constitutes a low cycle operation for each day. The manner of counting

the low cycles in industrial gas turbine operations is of concern to engine operators. Low cycle fatigue of gas turbine materials, the high pressure turbine blades of the GE LM2500+ type engine in this case stems from the cyclic nature of the forces the blades are exposed to. Although one low cycle is assumed per day for peak operation of industrial turbines, and the shaft speed level may be described as steady in many cases, but several different shaft speed values may be obtained within the engine operation period. Ambient temperature varies very often within a day and this alone leads to different shaft speed levels even if the range may be small. Thus operating the engine for a number of hours each day before shut down will have different effect on the fatigue life consumption in different days depending on how the shaft speed varied in each day operation of the engine.

There are instruments for recording the cumulative low cycle fatigue damage rotating members in turbines undergo such as that patented by Meyer (Hartung 1977). Most of such equipment finds usage in aircraft engine operations and their shortcomings could be easily identified. Knowing the history of engine operation, several methods of engine cycle counting for low fatigue life analysis are available. These include the peak count, mean crossing count, and rainflow cycle counting method; of all these methods, the rainflow counting method is predominantly used (Downing & Socie 1982; Glinka & Kam 1987; Hong 1991; Baek et al. 2008; Cookson

& Halsam 2013). The rainflow method and other methods are generally used for aircraft engines hence there is need to find an appropriate method for industrial gas turbine engines instead of counting one cycle per engine shut down.

Problem Statement

In industrial gas turbine operations, fatigue cycles are still counted depending on engine shut down. This method does not take into account the variations of the engine shaft speed within the period the engine is operated before shut down. Therefore, in this paper, an appropriate method of counting fatigue cycles in industrial gas turbine operations is proposed.

Limitations of Study

In this study, the field data of engine operation from a single engine is used to test the developed fatigue cycles counting model. There is need to use data from other engines to test the model but this was not possible as at the time the research was carried out.

FATIGUE CYCLES COUNTING MODEL FORMULATION

Operators of industrial turbines will likely have history of engine shaft power or compressor speed over time as against the stress values. The stress values could be obtained from the shaft speed values, blade data and other engine operation properties. In aircraft turbine engine operation, four sequences of engine operation are identified depending on transition from one speed level to another speed level. These are from zero to maximum speed (type 1 transitions), idle to maximum speed (type 2 transitions), intermediate to maximum speed (type 3 transitions), and transitions between any two speed levels except maximum speed (type 4 transitions) (Chachurski et al. 2011; Cookson & Halsam 2013). The equivalent number of fatigue cycles N_{eq} from the given shaft speed history is given by Equation (1),

$$N_{eq} = N_1 + \frac{N_2}{4} + \frac{N_3}{40} \tag{1}$$

where N_1 are number of the type 1 transitions, N_2 are number of the type 2 transitions, and N_3 are number of the type 3 transitions within the period of engine operation. Type 4 transitions do not contribute to the fatigue cycles for life analysis. This model is basically used by the US Air Force (Chachurski et al. 2011). The issue with the above model is neglecting the contributions of intermediate load transitions. Figure 1 shows the required compressor shaft speed level and the actual shaft speed levels for one day operation of an industrial gas turbine. The compressor shaft speed is expressed in terms of compressor relative rotational speed PCN . With respect to Figure 1, going by the above model, very few type 3 transitions could be obtained together with one type 1 cycle if the engine is eventually shut down. Several

type 4 transitions are obtainable in real engine operations and these will definitely contribute to the overall low cycles accumulated for a particular period of engine operation.

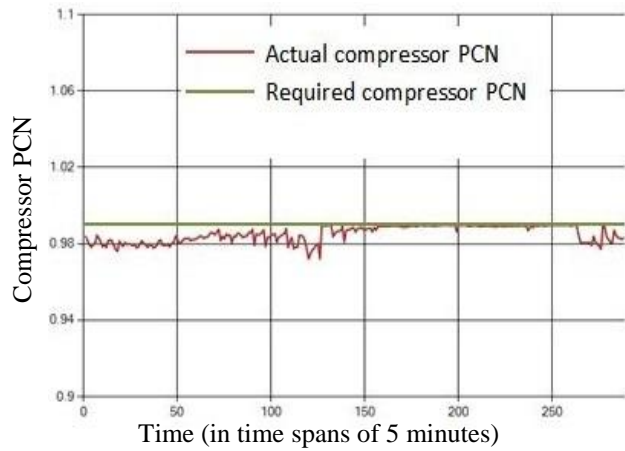


Figure 1: Actual and Required Shaft Speed Levels in a day Operation of an Industrial Gas Turbine

The method presented in Equation (1) is widely used for aircraft engines. Several variations of speed which will definitely contribute to low cycle fatigue failure are left out. In industrial gas turbine operations, a bit steady load is assumed, but the load actually varies with time usually influenced by changes in ambient conditions. The rain flow cycle counting method and the model presented in Equation (1) are ideal for estimating fatigue cycles undergone by aircraft engine rotating members. Though minor in most cases, the variation of each shaft speed from the set speed level contributes to fatigue failure and hence a fractional fatigue cycle is involved in such changes in shaft speeds. With shaft speed level set at N_s , when speed level changes from any level N_i to the next level N_{i+1} , the contribution to fatigue cycle is proportional to the difference between the two speed levels. Describing the contribution of each speed variation as a cycle contributing parameter (CCP), then, the cycle contribution parameter (CCP) is proportional to the difference between N_i and N_{i+1} given by Equation (2),

$$CCP \propto (N_{i+1} - N_i) \tag{2}$$

The set speed level about which the actual speed levels revolve has much influence on the cycle contribution due to speed variation. Equation (2) is put in dimensionless form by dividing with the set speed level and is given by Equation (3),

$$CCP' = \frac{N_{i+1} - N_i}{N_s} \tag{3}$$

CCP' is the dimensionless cycle contributing parameter. Considering the type 1 load transitions in Equation (1), several different speed levels might

have been traversed in raising the speed from 0 to maximum speed, depending on the time intervals in which the speed is recorded. Assuming n different speeds are recorded, 0 to maximum speed inclusive, then applying Equation (3) to the speeds, $(n-1)$ CCP' 's will be obtained:

$$CCP'_{i=1} = \frac{N_2 - N_1}{N_s}; CCP'_{i=2} = \frac{N_3 - N_2}{N_s}; \dots; CCP'_{i=n-2} = \frac{N_{n-1} - N_{n-2}}{N_s}; CCP'_{i=n-1} = \frac{N_n - N_{n-1}}{N_s} \quad (4)$$

Summing all the CCP' 's, we obtain,

$$\sum_{i=1}^{n-1} CCP' = \frac{N_2 - N_1}{N_s} + \frac{N_3 - N_2}{N_s} + \dots + \frac{N_{n-1} - N_{n-2}}{N_s} + \frac{N_n - N_{n-1}}{N_s} = \frac{N_n - N_1}{N_s} \quad (5)$$

But $N_n = N_s$, and $N_1 = 0$, therefore,

$$\sum_{i=1}^{n-1} CCP' = \frac{N_n - N_1}{N_s} = \frac{N_s - 0}{N_s} = 1 \quad (6)$$

The sum of the dimensionless cycle contributing parameters between successive speeds from zero to maximum gives one fatigue cycle, the same as type 1 load transition gives one fatigue cycle as given by Equation (1). Thus, intermediate speed transitions should be viewed as fractional contributions to the total fatigue cycles. Several different speed levels could be obtained in a given period of engine operation. The closer the difference between two adjacent speed levels, the smaller the cycle contributing parameter. The difference between two corresponding shaft speed levels may be positive or negative. Hence, the absolute value of the CCP' should be used for determining the equivalent fatigue cycles from the speeds obtained from engine operation. The equivalent number of cycles N_{eq} is as expressed by Equation (7),

$$N_{eq} = \sum_{i=1}^n \left(\left| \frac{N_{i+1} - N_i}{N_s} \right| \right)^k \quad (7)$$

where n is the number of different speed levels recorded in the course of engine operation, and k is the cycle determining exponent, which should be in the range $0.7 \leq k \leq 1$. In this range, the fractional cycle term in Equation (7) closely approximates the fractional cycles from the load transitions in Equation (1). In addition, the value of k chosen depends on the frequency of load recording. If the load is recorded in short time intervals, k value very close to 1 will suffice, but if the time interval is large, then smaller value of k should be used to have larger values of cycle contributing parameters to account for the 'unrecorded speeds'. In this work, several engine shaft speeds are recorded in a day operation of the engine, but in the case studies considered later $k = 0.9, k = 0.95$ and $k = 1$ are used and the

results are compared. Smaller values of k leads to more cycles and hence a bit conservative fatigue life analysis.

Expression Based on Stress Variations and Blade Locations

The fatigue cycles actually result from stress variations and are also referred to as stress cycles. In this light, the fatigue cycles should be accumulated from the stress history of the blades. Each blade could be divided into a number of sections, say n sections with $n+1$ nodes (Figure 2) and the centrifugal stress and the bending moment stresses the blades under study experience could be considered using the appropriate relations as in (Abdul Ghafir et al. 2011). The centrifugal stresses are viewed as steady stresses while the bending moment stresses transient in nature (Saravanamuttoo et al. 2009). Equation (7) is thus put in the form of Equation (8).

$$N_{eq,d} = \sum_{i=1}^n \left(\left| \frac{\sigma_{Tot,d}^{i+1} - \sigma_{Tot,d}^i}{\sigma_{Tot,d}^S} \right| \right)^k \quad (8)$$

$\sigma_{Tot,d}^i$, $\sigma_{Tot,d}^{i+1}$ and $\sigma_{Tot,d}^S$ are the total stresses at each node for the i^{th} data point, the next data point and the set speed level respectively. Although the cycles accumulated at each node $N_{eq,d}$ is evaluated, in this work this will be represented generally as N_{eq} .

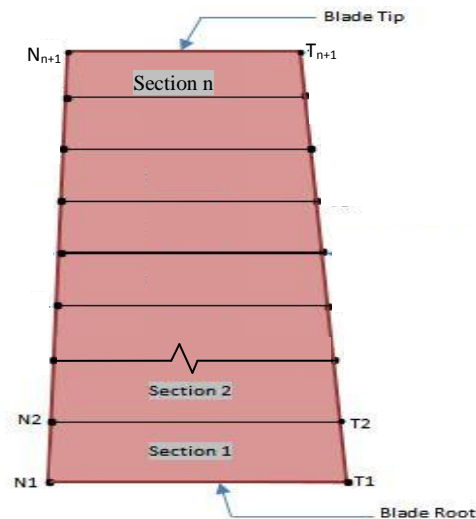


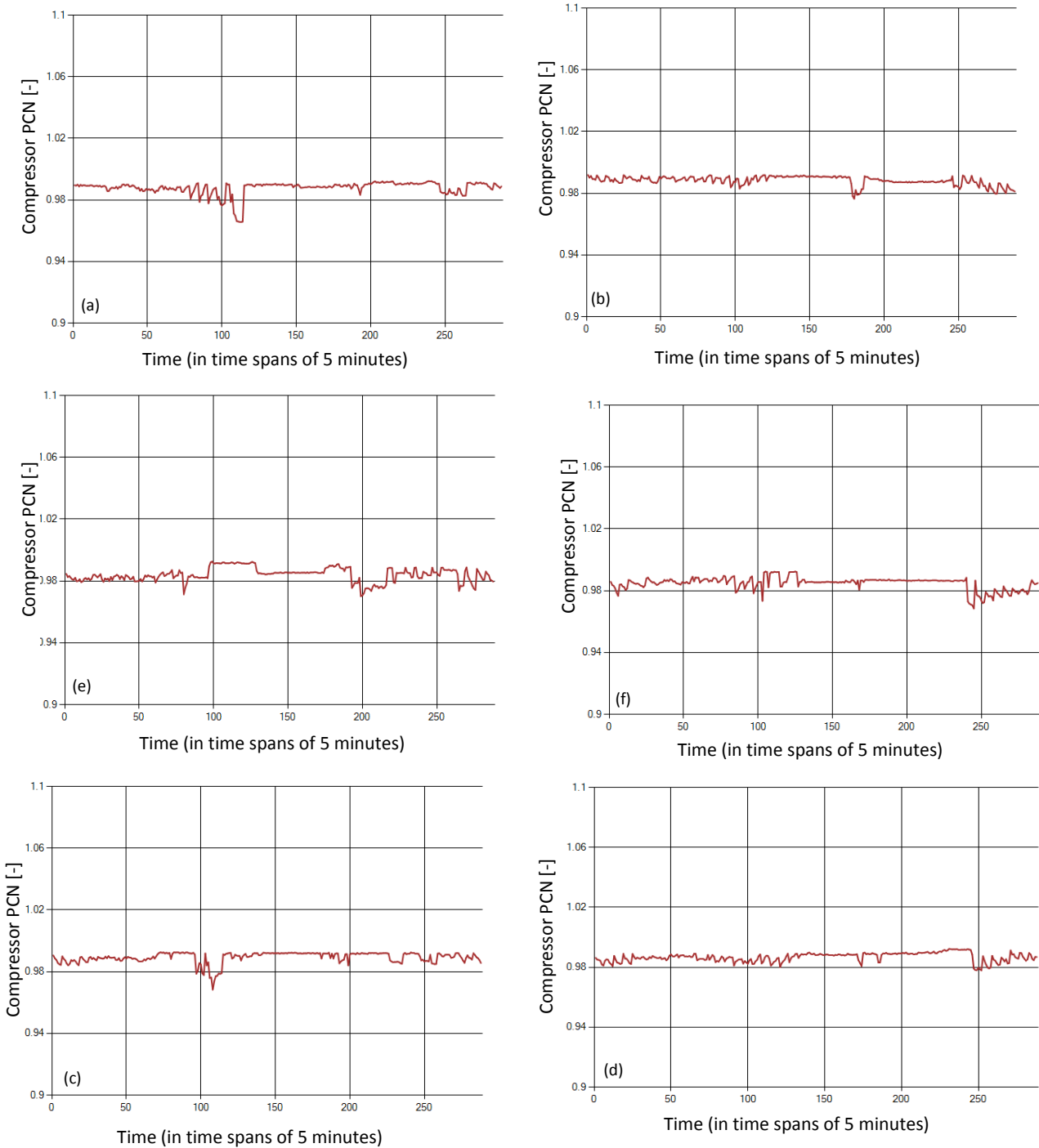
Figure 2: Blade Sections and Nodes for Stress Cycles Estimation

MODEL APPLICATION AND RESULTS

The fatigue cycles counting model developed in this research is applied to ten different days of engine operation. The equivalent fatigue cycles are evaluated at the blade mean section using the variation of total stresses. Figure 3 shows the compressor relative rotational speed values with time of the day for the ten different days of engine operation. The equivalent

number of fatigue cycles depends on the transition of shaft speed from one point to the other. Three different k values are used, $k = 0.9, k = 0.95$ and $k = 1$. The equivalent fatigue cycles obtained for the different days of engine operation using the different values of k are presented in Table 1. Also, the mean value obtained from the three values of k used in

each day of engine operation is also given in Table 1. The equivalent fatigue cycles from the US Air Force aircraft model are also presented in the table for the purpose of comparison. The equivalent fatigue cycles from the aircraft model comes from the type 3 speed transitions



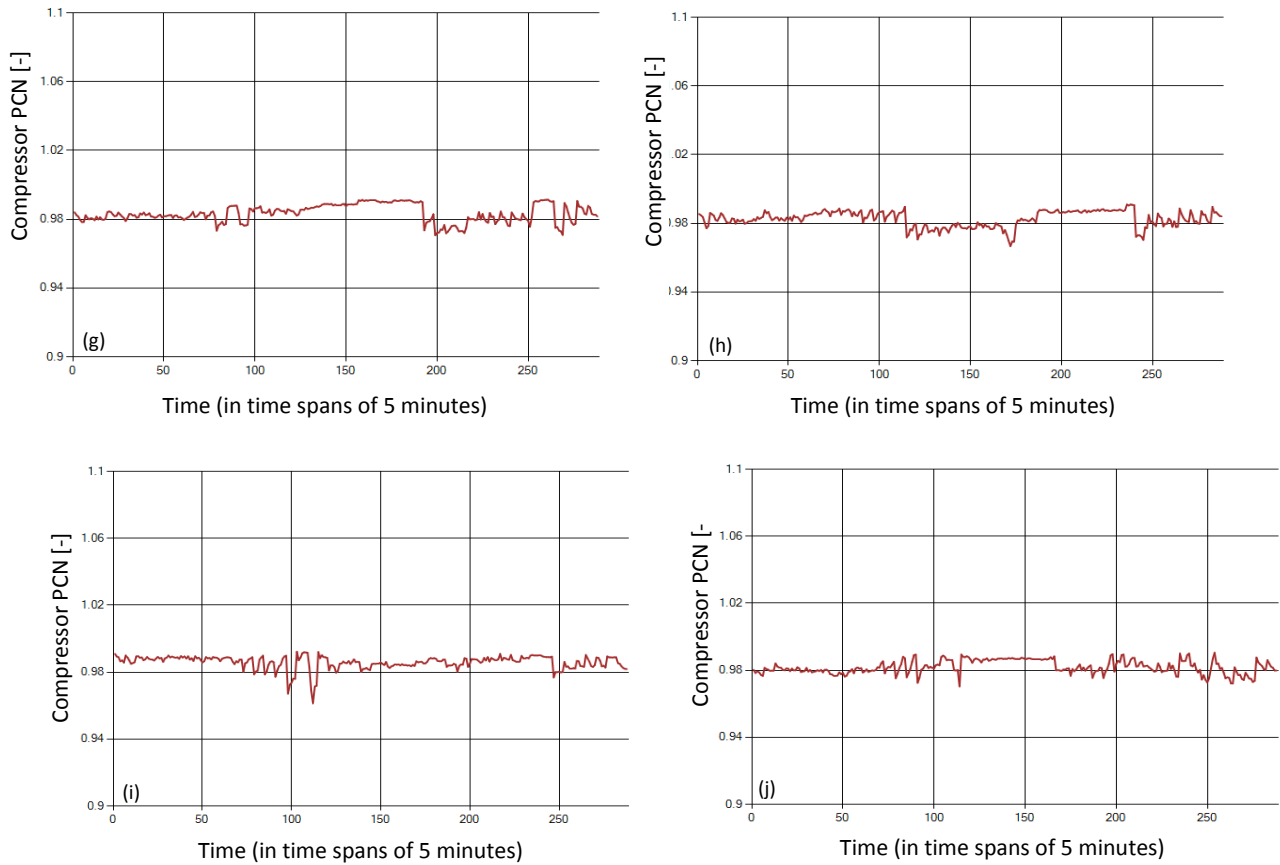


Figure 3: Compressor PCN Variation with Time for different Days of Engine Operation

Table1: Fatigue Cycles Accumulated from different Days of Engine Operation

S/NO.	Equivalent Fatigue Cycles			Mean Value	Aircraft Model
	Proposed Model				
	$k = 0.9$	$k = 0.95$	$k = 1$		
1	4.3991	3.6628	3.0641	3.7087	2.925
2	4.5854	3.7683	3.1050	3.8196	3.175
3	4.8109	4.0006	3.3383	4.0499	2.925
4	5.1626	4.2558	3.5173	4.3119	3.150
5	5.4910	4.5900	3.8494	4.6435	3.025
6	5.5841	4.6976	3.9671	4.7496	3.025
7	5.8680	4.9163	4.1332	4.9725	3.075
8	6.7374	5.6491	4.7487	5.7117	3.100
9	6.9482	5.8620	4.9617	5.9240	3.125
10	7.3672	6.2095	5.2480	6.2749	3.075

Figure 3 (a) to (j) are arranged in order of magnitude in terms of the number of fatigue cycles obtained using the proposed model starting from the figure that gives the smallest fatigue cycles to the one that gives the highest fatigue cycles. The equivalent fatigue cycles decreases with increase in k , thus the smallest fatigue cycles are obtained for $k = 1$. For further usage of the results, it is recommended here that the mean value is used to avoid using results that may lead to too conservative fatigue life analysis or non-conservative fatigue life analysis. Duelling on the fatigue cycles with $k = 1$, higher fatigue cycles are obtained with greater variation of shaft speed. Comparing Figure 3(a) and (j), it is very clear that the shaft speed variations with different periods of engine operation for the day depicted by Figure 3(a) are less

compared to that of Figure 3(j). This is a very obvious case. Comparing the shaft speed variations between some days visually may be difficult, e.g. in Figure 3(g) and (h). But by applying the developed formula to the raw data of engine operation, the fatigue cycles are obtained, and that the data presented in Figure 3(g) undergo less transitions or variations of engine shaft speed compared to that of Figure 3(h).

The equivalent fatigue cycles obtained from the aircraft model are less than those obtained from the proposed model for $k = 1$ (the value at which the two models are comparable) for all the days of engine operation considered. This is because the proposed model takes into account all variations of engine shaft speed but the aircraft model only considers type 3 speed transitions. Intermediate speed transitions are

neglected in the later. Considering Figure 3(j), the engine shaft speed undergoes several speed variations most of which are variations between two intermediate speed levels. This will lead to fatigue failure in less time and hence higher equivalent fatigue cycles compared to other days as depicted by the proposed model. The aircraft model neglects the intermediate speed transitions thus the equivalent fatigue cycles obtained for that day operation of the engine is not the highest. Going by the aircraft model, day two operation of the engine (Figure 3(b)) with highest number of type 3 speed transitions leads to the highest equivalent fatigue cycles. In actual sense, in day 2 engine operation, although there are more type 3 speed transitions, the speed variations between successive points of engine operation are low and will not lead to faster fatigue failure as depicted by the aircraft model. Generally, the results from the two models are a bit comparable in all the days of engine operation considered in this research, but the proposed model gives results that portray the actual manner of engine operation.

CONCLUSIONS

Low cycle fatigue cycles accumulation model suitable for industrial gas turbine operations is developed and applied to different days of engine operation using GE LM2500+ type engine in this work. The hot section high pressure turbine blades are targeted. The developed model considers the variation of total stress imposed on the blades from successive time spans of engine operation. Each blade is divided into a number of sections and the accumulation of fatigue cycles is carried out at the blade mean section. The model is developed from an aircraft model widely used by the UA Air Force for aircraft engines. In applying the model to real engine operation data, it was observed that the days with greater variation of engine shaft speed lead to greater equivalent fatigue cycles. Comparing the results to the aircraft model reveals that the results are although close to that of the aircraft model but are larger than those of the aircraft model for all the days of engine operation considered. This is because the developed model takes into account all transitions of engine shaft speed; the aircraft model application to the raw data accounts for only type 3 speed transitions. Also, results from the developed model clearly shows that more fatigue cycles are associated with greater speed transitions, but this is not the case with the aircraft model. The aircraft model with three different speed transitions contributing to fatigue cycles should thus be limited to aircraft applications. The developed model is easy to apply and the results produced depict the nature of transitions the engine shaft speed undergoes for a given period of engine operation. With the usage of this model, counting one fatigue cycle for each day operation of an industrial turbine will be avoided. The developed model is suitable in accumulating the fatigue cycle in industrial gas turbine operations. This

study contributes to the existing body of knowledge by providing a fatigue cycles counting model that is suitable for industrial gas turbines operations.

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