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ENGINE TEST SIMULATION AND DIAGNOSTIC OF A SMALL AUXILIARY POWER UNIT (APU) GAS TURBINE ENGINE.

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Abstract

A well scheduled maintenance plan will result in optimum availability and reliability as well as minimize engine downtime and cost of maintenance. The reason for carrying out maintenance in a gas turbine engine is not only to prevent breakdown, but also to recover performance at the barest minimal cost. In this research, a maintenance scheduling tool known as the Gas Path Analysis (GPA) was used to perform some diagnostics on a small Auxiliary Power Unit (APU) GTCP30-92 model. An engine test was carried out experimentally on the APU, collated data used to do performance and diagnose analyses on the engine with the use of PYTHIA software. The APU engine was built experimentally by inputting the calculated results to simulate and update the model through non-linear adaptation., since the initial values will normally not give the expected result gotten from the calculations. The engine performance was further checked under constant total entry temperature (TET) and varying operational conditions in a clean and degraded engine configuration. The test was carried out at the Cranfield University Test Centre, and analysis and comparison of the clean and deteriorated engine of the point measured were explained. The fault was predicted, implanted and calculated, manually, by the linear GPA, and later by the linear and non-linear GPA PYTHIA software diagnostic prediction using the same measurement set. Comparison on the two were carried out considering the speed, and accuracy, and complexity of the system. The results show that the PYTHIA software is a useful tool in carrying out analysis based on gas turbine diagnosis. A further diagnosis on implanted fault was also carried out in the turbine capacity and efficiency of the engine model, and it was clearly seen that factors influencing the degradation of component parts of a gas turbine could be predicted with the aid of PYTHIA software's non-linear GPA. This research shows that, with the use of PYTHIA, it is possible to simulate and diagnose the performance model of a small APU GTCP30-92 engine. PYTHIA will therefore be a very handy tool for design and maintenance engineers of the gas turbine field.

Keywords: Diagnostics, fault coefficient matrix, Gas turbine engine, Gas path analysis, influence coefficient matrix, linear GPA and non-linear GPA, PYTHIA, simulation

1.0 Introduction

When a gas turbine (GT) is purchased, it is a necessary practice that with time in the period of use in operation, these engines will reduce in its efficiency. These engines require periodic inspection without which could lead to break down due to deterioration in component parts [1]. The overhauls are not only to prevent breakdown, but also to bring the engine performance back to its required state so as to reduce cost of maintenance to the barest possible minimal [2]. Condition health monitoring play a vital role here because it appears to be the most efficient means for predicting the health status of the component parts of an engine. Some of the various factors that contribute to the engine health degradation include; environment, corrosion, erosion, fuel contamination, load profile, foreign object damage at the intake, domestic object damage, i.e. component parts degradation, hot gas path, fouling and seal damage [3]. These factors individually or collectively contribute to the deterioration of the health of the engine, which in turn lead to reduced performance of the engine [4]. Example: efficiency and flow capacity could be affected negatively by foreign objects inhaled into the engine during suction, stator vanes and rotor blades can be affected when attacked by erosion which could result in reduction in efficiency of the component parts, and the nozzle guide vane and rotor can be destroyed by the hot gas [5], etc. With these in mind, it becomes necessary to implement methods of detecting and correcting the deterioration of the GT engine by the manufacturers and end users as well. These could be achieved if the present health condition of the engine is known; the future health could be predicted for necessary maintenance procedure to be taken to renew the engine's health.

Techniques developed to help the user predict and monitor the engine degradation include; artificial neural network, expert systems, Gas Path Analysis (GPA) and fuzzy logic. GPA seems to be preferable because it is a sophisticated tool used in monitoring the health condition of a GT engine, and it has the ability to detect multiple degradations. In the year 1967, L.A.Urban [6] introduced a method known as the linear model based GPA for the first time in order to take into record the non-linearity of engine behaviour, a model based method known combined with conventional improvement was also first introduced by [2]. Even with the fact that it could detect more than one fault at a time and how fast it is to bring out result, GPA has its disadvantages, some of which include; sensor fault, non-linearity and noise measurement [7]. These give rise to the invention of non-linear GPA to enable non-linear performance in the engine. Above all, it still stands out as the most preferred to be used here for this report. The primary aim of carrying out this experiment is to acquire the laboratory knowledge of gas turbine engine test through the performance and diagnostics analyses, and writing a technical report [8]. The objectives of this diagnosis and simulation include: To obtain practical knowledge on how to carry out test in GT, have knowledge on how to record data from engine test performance, have clear analytical approach to GT diagnosis, have knowledge on engine performance deterioration, use linear and non-linear GPA to diagnose the engine, develop/improve in technical skills. This research work will make a clear distinction between linear and non-linear GPA, and further show the effectiveness of applying Pythia for a small APU diagnostic.

2.0 Literature review

Improving gas turbine (GT) performance requires the bringing together and optimisation of the disciplines and skills needed to acquire an operationally competition GT engine [1, 9]. Surely, the design and performance of the individual components of such engine like the compressor, combustor, and the turbine could separately present an engineer with a worthwhile career, which all begins with a micro turbine such as the APU presented in this research.

The efficiency of an engine reduces with time due to the degradation in some components parts, and could be as a result of some factors that could cause these components to degrade. An example of such fault could be fouling which is a major cause of engine parts deterioration; this occurs as a result of foreign object or contaminants entering the engine especially during suction at the intake, these deposits could be accumulated at the surface of the blade [10]. Engines such as gas turbines are very prone to fouling due to the debris in air they ingest during suction. Such fault could also be found in turbines, but it is very common with compressor. Factors such as salt, pollen, dirt, etc. pass through the filter deposit on the turbine blade, even when the filtration system is good and these fouling results in reduction in flow capacity of the engine by some percentage and also reduction by some percentage of the efficiency which depends on the severity. These factors could further be classified as foreign and domestic object damage [11]. The foreign objects are those objects from outside the engine while the domestic objects are as a result of fault occurred in the components part of the engine. In either ways, the engine capacity and efficiency is reduced according to the gravity of the fault damage [12]. Lost blade could result in increase in flow capacity and if the capacity is decreased, the foreign particles could block the gas paths. Erosion, corrosion and other factors are responsible for components damage and reduce the engine's performance which in turn affects reliability and efficiency of the engine [13].

3.0 Methodology

The method of approach in other to achieve the aforementioned objective include: Carry out a test on a small APU GTCP30-92 engine at the engine test area of Cranfield University, and the readings taken accordingly; carry out data analysis on the measured data, do calculation on the engine overall performance, input calculated results to model the engine via PYTHIA software; create a small APU GTCP30-92 engine model performance with the help of PYTHIA- simulation software and match it with the real engine test data; an updated model of the engine that matched the design point performance re-modelled and adapted for the rest of the exercise. A -2% fault in efficiency drop and -4% flow capacity drop was implanted in turbine as a degraded fault implant, the performance of deteriorated and clean engine condition was calculated and compared; Linear GPA was used to predict the engine degradation by calculation; the capability of the linear and non-linear GPA was used to predict the same component fault with the same measurement, and the results of the linear and non-linear GPA diagnosis were analysed and compared.

3.1 Description of the engine APU GTCP30-92

It is an Auxiliary Power Unit APU gas turbine engine that provides electrical and pneumatic power start. It is installed in an unpressurized area of the rear pressure bulkhead, beneath engine 2 and the horizontal stabilizer in an air craft. It can also serve as a supply of cooling air to aircraft secondary systems during hot climate period and also used to start the aircraft on ground, used also for emergency in case of flame out during a mission. The GTCP30-92 model has a single stage centrifugal compressor and also consists of gear box assembly, turbine rotating assembly, fuel system, combustion chamber component, an electrical system (ac/dc generator), gas path component, etc. as could be seen in figure 1.

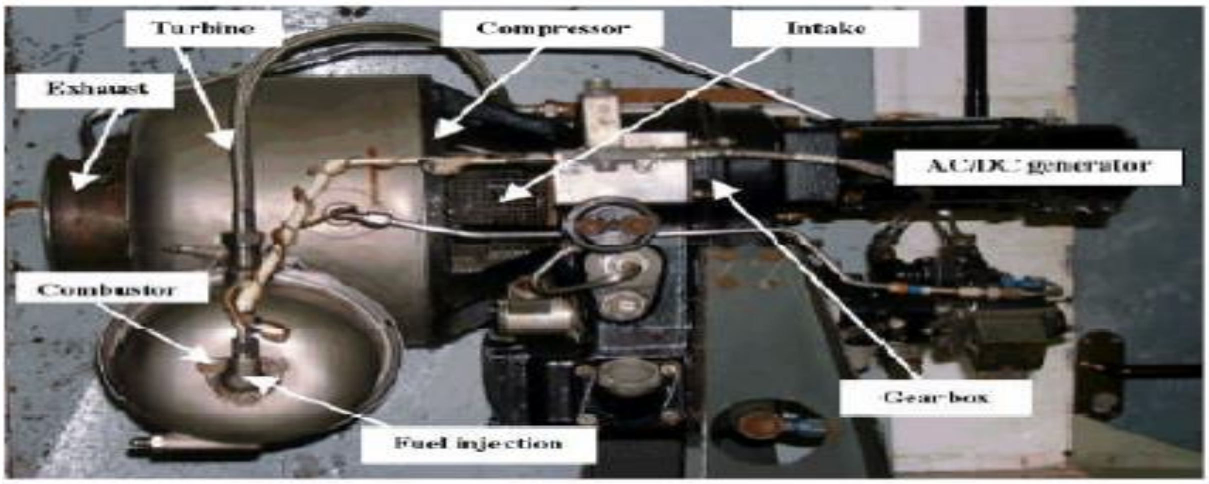

Figure 1: Main components of APU GTCP30-92 [8]

3.2 Engine test procedure set up and instrumentation.

This test was performed according to the standard workshop rules and regulations at the test centre of Cranfield University in the presence of a group of students, a lecturer and a technician that specializes on the operation of the engine and the test was carried out in accordance with the procedure stated in the instruction manual. The main power was switch on, allowed to stabilize after a few seconds before the readings where collated. The readings were taken from the instruments that correspond to their respective sensors. Three values for temperature and pressure were taken respectively and their mean value was obtained, and other values such as the rotational speed, fuel flow, ambient pressure, etc. where also taken. The following precautions were observed; we ensured that ear protector was worn due to the high level of noise generated by the engine, ensured that the students did not go too close to the engine after stoppage because of the hotness of the compressor, turbine and exhaust pipe. Also avoided error due to parallax when taking the readings.

3.3 Instruments used for test set up measurement

Figure 2 below is a schematic view of the **APU GTCP30-92** engine with its various component parts and station numberings and the instruments used in carrying out the measurements.

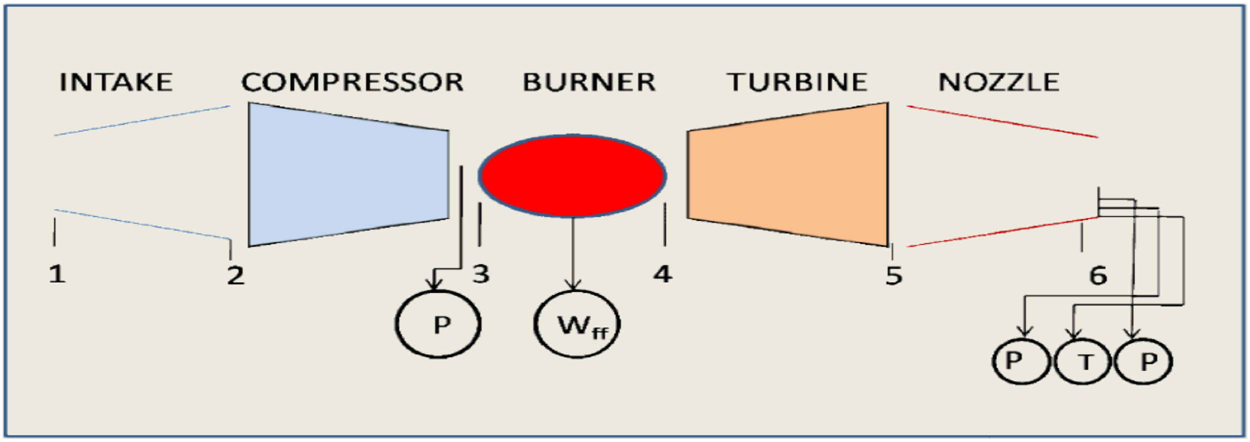

Figure 2: Engine model with station numbers for APU GTCP30-92 source [8] assignment manual.

The equations below are used to effect the calculations for the engine. In equation (1), p is the pressure. M is the Mach number. In equation (2), CW= compressor work, W=mass flow rate, Cp= coefficienct of performance, while T is the temperature of the engine. In equation (3), we have air, gas and fuel flow respective, and in equation (4) TW=turbine work, W=mass flow rate , and T4 and T5 are temperature difference. In equation (5), FAR is the fuel air ratio, LHV is the low heat value, and then we have the compressor efficiency, while in equation (6)T4 and T3 are the temperature difference, FAR and LHV remains the same as in equation (5).

$$\frac{P_6}{p_6} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}}$$

$$\Rightarrow M = \sqrt{\frac{2}{\gamma - 1}\left[\left(\frac{P_6}{p_6}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \qquad (1)$$

$$CW = W_{air} Cp_{air} (T_3 - T)$$

(2)

$$W_{air} = W_{gas} - W_{fuel}$$

(3)

$$TW = W_{gas} C_{pgas} (T_4 - T_5)$$

(4)

$$T_4 = \left[\frac{FARxLHVx\eta_{comb.}}{C_p}\right] + T_3$$

(5)

$$\eta_{comb} = \frac{C_p (T_4 - T_3)}{FARxLHV}$$

(6)

- **Temperature measurement**

  Three thermocouple temperature sensors made of the k-type chrome (chromium-nickel alloy) –alumel (aluminium-nickel alloy) where used to measure the temperatures and a measurable range of -200/1370^{0}C with an accuracy of +/-2.2^{0}C or 0.75% of the measure which is greater. Due to the reason that alloys are poor conductors, heat conduction along the wire was minimal and could not be transferred.

- **Pressure measurement**
  Measurement for the three static pressure where taken, and the average was derived and the total exhaust pressure was obtained by connecting a nut to the pneumatic line at the exit of the compressor. A digital meter indicator known as DP1101 were connected with these five tubes to give pressure indication in four different scales at an accuracy of 0.04% and a full scale deflection of 20kpa. The values of pressures gotten were used as absolute pressure in the calculation.
- **Fuel flow meter**
  This is an instrument which has graduation like that of a ball. It is used to measure the fuel flow by installing it in the engine fuel line, it is calibrated for a particular fuel density and values where obtained from the calibration and used to obtain the fuel flow on the fuel flow meter on the corresponding chart between the graduations. The graduation on the X-axis read 12.4 which correspond to 4.476g/s.
- **Measurement points**
  In other to achieve accurate results, the measurement of the parameters such as temperature, and pressure were obtained from different points at the exhaust tube radius to get an accurate value for the mass flow and this was achieved by calculating the mean value of total pressure and temperature measured in the intersection between the circumference and radius of the instruments.

3.4 Design point calculation

The experimental test on the APU GTCP30-92 was performed at the Cranfield University test centre with all necessary safety procedures observed. Some readings where obtained directly from the sensor indicator while others were taken from the sensor in the inner engine cell test room. At the point of experiment, three different temperatures and pressures were taken which averages were taken as t_6 and p_6 respectively, the compressor exit pressure was 1.2bar at a temperature of 16^0C along the highest and lowest measured values. A further calculation was carried out to obtain T_6 and P_6, although the results obtained were high. As stated above, the obtained static temperature and pressure were relative and were added to the ambient to obtain absolute values as shown in equation (7) below.

$$P_{abs}=P_{rel}+P_{am} \qquad (7)$$

There is a high percentage difference between the test results and the simulated results when compared especially at the nozzle area and specific fuel consumption, and on this note the PYTHIA software was used to match the real data of the engine through the help of the PYTHIA adaptation modelled engine. Some considerations were taken before selecting parameters for the adaptation, which includes the fact that these selections should have function in relating it with the targeted parameters to enable the convergence and reasonable adaptation result and to provide dimensions in adaptation results to adapt parameters and the targeted parameters to be equal in order to provide freedom in the adaptation and for easier converge. The following parameters were therefore considered; compressor pressure ratio, compressor isentropic efficiency, turbine isentropic efficiency, combustion exit temperature and intake mass flow, and the targeted parameters are net thrust and fuel flow rate.

The target performance parameters with the linear and non-linear adaptation and the target deviation bar for the design point adaptation setting, and the non-linear result shows more accurate results, and it was used to upgrade the first result via PYTHIA to achieve a new set of results. These new set of result were more accurate than the initial values and were hence used as the design point clean engine results which were applied to the rest of the analysis. In the simulated result, the nozzle exit area and specific fuel consumption deviations as compared to the normal results is extremely high. The simulated results were not reliable, so an adaptation was carried out and the percentage deviation was satisfactory, and hence used for the rest of the work. The design point performance of the clean engine was simulated at 0% efficiency and flow capacity respectively, without implanting any fault, and the result obtained was the same as that of the clean engine.

- **Deteriorated engine performance**

The following precautions were ensured when carrying out the deteriorated performance; it was ensured that the sensor noise is not considered, the measurement is sensor fault free, and the deterioration of the turbine efficiency and the flow capacity degradation is within the range of -2% and -4%

- **Fault implantation**

The turbine was degraded by simulating the degraded engine performance. The PYTHIA software was used to implant fault in the turbine [5, 14]. A turbine flow capacity drop of -4% and efficiency drop of -2%, followed by a -1% drop in flow capacity when the efficiency is 0%, but the turbine pressure ratio deterioration remains the same with that of the deterioration of the flow capacity. That is, while a -4% and -2% of the turbine pressure drop was implanted in both cases one and two, when flow capacity remains unchanged, a -1% turbine efficiency drop was also implanted keeping flow capacity constant at 0% to simulate the deteriorated engine. When an engine is deteriorated, it results in high specific fuel consumption and reduction in power output. The engine deteriorates in performance due to the fault implanted in the turbine and the deviation occurs in the engine performance. This approach is done in various cases.

- **Case 1: (-2% turbine efficiency drop and -4% flow capacity drop)**

Using -2% and -4% efficiency and flow capacity drop respectively, increases the temperature T_5 from 556.12k to 556.95k, giving a percentage deviation of 0.149% and the pressure P_4 also decreases from 2.080001kpa to 1.93053 kpa, giving a percentage deviation of -7.186% which in turn decreases the turbine work from 57438N to 48660N. In this case, the turbine will be unable to perform its usual required work, it also amounts to increased specific fuel consumption from 202.046mg/Ns to 214.7mg/Ns, giving a percentage deviation of 6.26%. These causes the reduction in thrust and the nozzle exit velocity.

- **Case 2: (-1% flow capacity drop and 0% Turbine efficiency drop)**

Comparing with other effects shows that -1% flow capacity drop is minimal. The deviations were small, apart from the PR and turbine work which are 0.951 and 0.851 respectively, other values fall below 0.5% in deviation, and for example T_5 and P_4 are 0.678 and -2.3 respectively, and so on.

- **Case 3: (0% flow capacity drop and -1% turbine efficiency drop)**

This reduces the turbine work from 57438N to 53860N, the exit velocity reduces from 41.3m/s to 40.6m/s, thrust from 22.15KN to 21.17KN, the SFC increases from 202.046mg/Ns to 202.11mg/Ns, mass flow from 0.545kg/s to 0.547kg/s, P_4 reduces from 2.080001atm to 2.06221atm. These reductions stated here shows that the turbine has been deteriorated.

4.0 Results and discussions

The degradation of the efficiency and flow capacity as a result of contaminants inhaled during suction at the engine intake system is termed fouling. This compound the effect of engine performance negatively to reduce the efficiency and flow capacity of the engine gas path component. There is a 1% drop in the flow capacity and later a 1% drop in efficiency; this is to enable the determination of fouling index on the engine performance. The linear relationships were assumed and 2% drop in the fouling index represent 2% drop in the efficiency and flow capacity respectively.

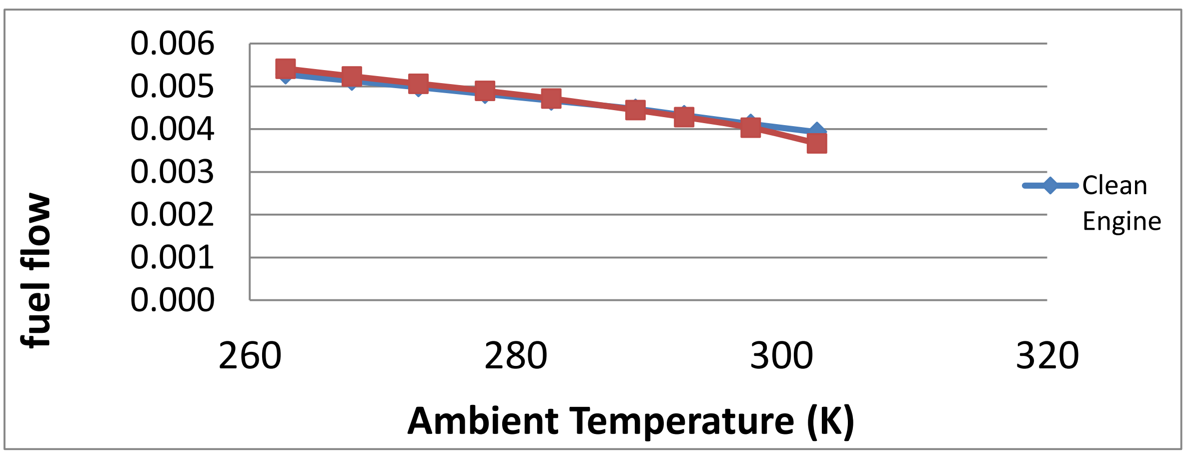

Figure 3: Effect of Ambient Temperature on fuel flow

it can be seen in figure 3 how increased in ambient temperature affects the fuel flow for the clean and deteriorated engine. With fault implantation as stated above, the fuel flow experience a drop of about 0.001. Similarly, in figure 4, the increase in ambient temperature from 260^0C to 310^0C, with the fault implantation experiences a drop in pressure ration from2.5 to about 2.8.

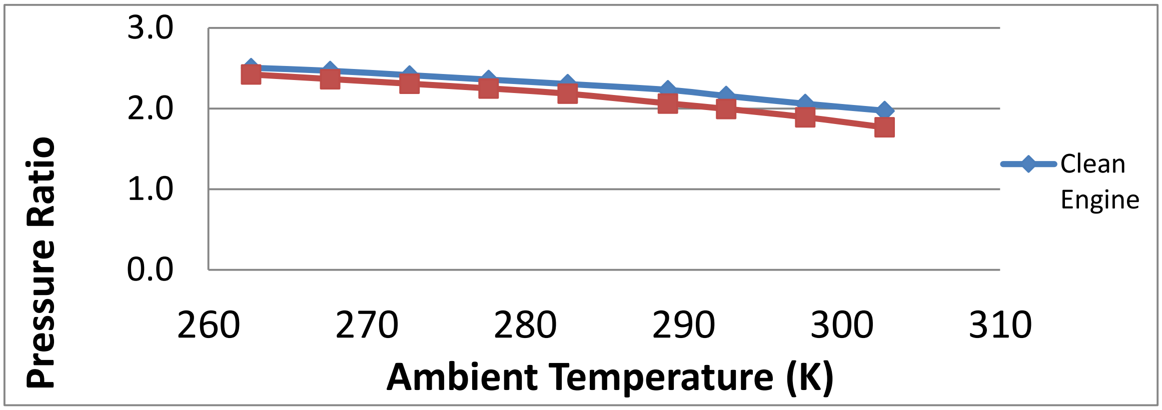

Figure 4: Effect of Ambient Temperature on Pressure Ratio

Figure 5 shows a drop of compressor work due to fault implantation deviated from the clean with about 8%, similarly, in figure 6, the ambient temperature affected the PCN 0.02.

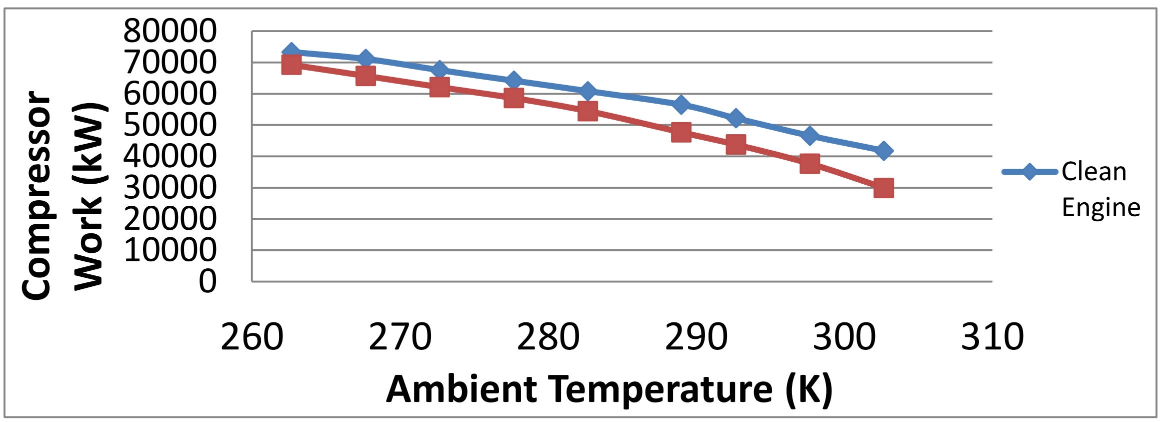

Figure 5: Effect of Ambient Temperature on Compressor Work

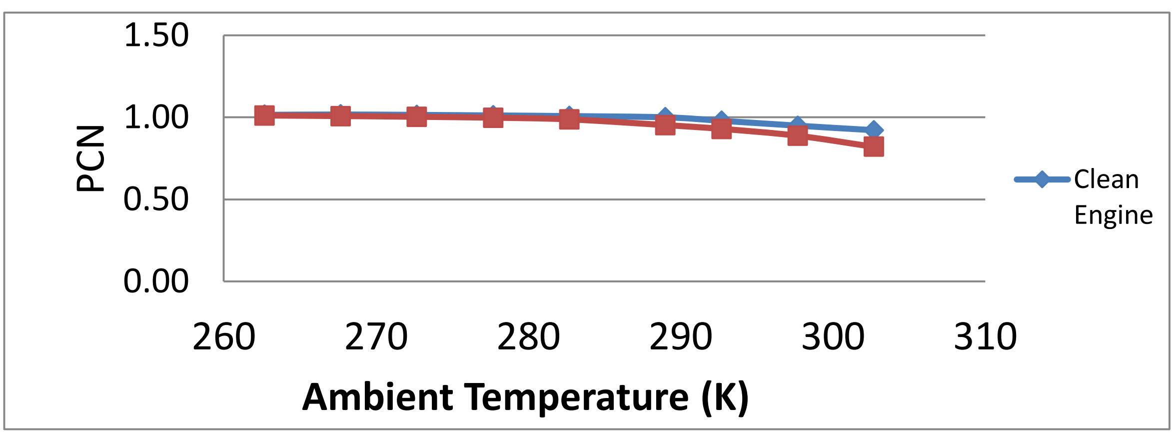

Figure 6: Effect of Ambient Temperature on PCN

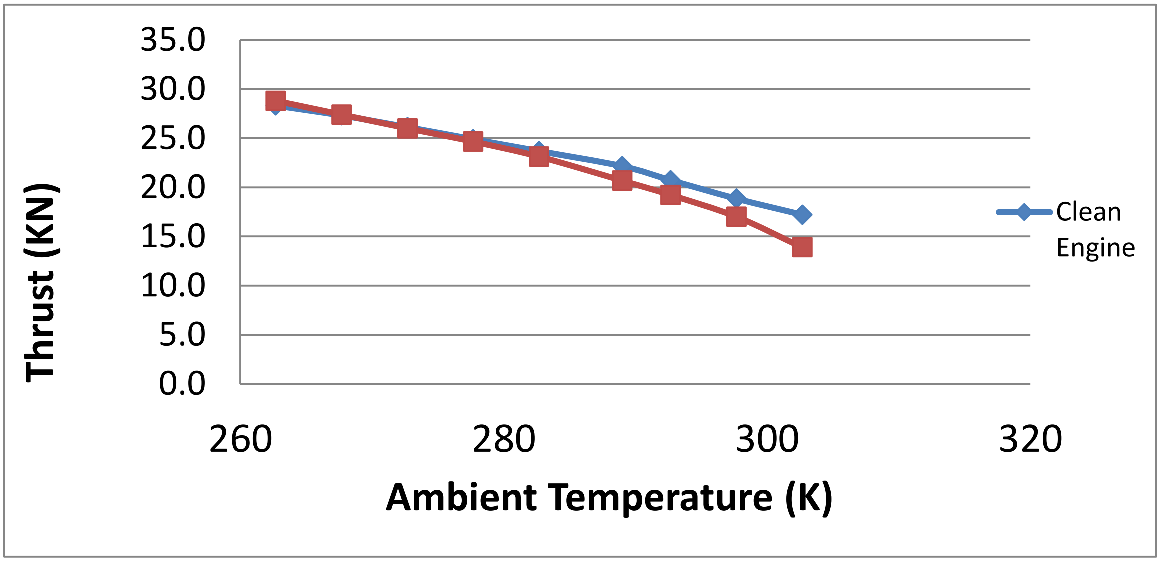

Figure 7: Effect of Ambient Temperature on Thrust

The fault implantation alongside the ambient temperature affected the thrust performance of the engine with about 0.5% as can be seen in figure 7.

- **Selection of proper redundant measurable parameters**

The factors to be considered in the measurement parameters selection for the gas path measurement include; visibility, sensitivity and correlation of it to degradation. The sensitivity analysis was carried out on these measurements. This is to enable the distinguishing of best redundant parameters that could be measured. Various combinations were made with these parameters that could result in minimum RMS, because RMS determines the level of accuracy of these parameters. The combinations made include P4, SFC and T5/ fuel flow, P5 andT5/ PCN, SFC and T5/ P5, T5 and SFC/ fuel flow, T5 and P4. These combinations were simulated via PYTHIA for both the clean and degraded engine and it was selected based on the fact that it has common relationship with the component to be degraded. Various sensitivity tests were carried out on the -2% and -4% drop in efficiency and flow capacity respectively.

The various combinations show a very low RMS values. They indicate that the level of accuracy is very high. The best combination is the P4, T5 and SFC with RMS of 0.007059971 which is the least in all the combinations carried out so far, and as such, becomes the best value. The GPA fitness (0.9901012) which is close to unity shows a high level of accuracy as well. Hence, to achieve a reasonable result in the RMS calculation, the combination P4, T5 and SFC was used, and with the fact that they are sensitive to the degradation of the turbine.

- **Selection of measurements**

The measurement selection criteria are based on the fact that these parameters could help determine the faults to high level of accuracy as indicated by the RMS. Over-instrumentation does not have much gain in terms of accuracy in any of the combinations, and these indicates that it will rather just cause a high installation and maintenance cost. In other to determine the engine degradation, that is, deviation of component health parameters using manual calculations, P_4, T_5 and Specific Fuel Consumption(SFC) are determined, because they have a close relationship with the component(Turbine). Calculations on other parameters combined, showed that the most preferred is the T_5, P_4 and SFC because it gives the most reasonable RMS value and thus preferred results. It is also shown in the fault signature that P_4 and SFC are more deviated compared to other combination. Hence, P_4, T_5 and SFC were the selected parameters used in the prediction of the engine degradation via linear GPA in the PYTHIA software, for reasons that: the combination significantly deviates and shows that they are sensitive to the component (turbine) degradation. The 3x3 matrix was used for the manual calculations to find the determinant of Influence Coefficient Matrix that will be used to calculate Fault Coefficient Matrix and inverse, and the determinant and inverse of a matrix can be gotten easily by the use of square matrix.

- **Linear and non-linear GPA diagnostics prediction with pythia**

PYTHIA is so important in the sense that it has the ability to analyse linear and non-linear GPA diagnostics in an engine. The non-linear appears to be more advantageous as compared to the linear GPA, because the non-linear GPA can be used to diagnose the engine when it behaves non-linearly. The three measureable parameters are P_4, T_5 and Specific Fuel Consumption (SFC). The components parameters degraded are the turbine flow capacity and the turbine efficiency and the measurements were simulated via PYTHIA software. It is obvious that linear GPA predicted the fault implanted in the turbine for the (-2% and -4%) degradation as -2.45858% for the turbine efficiency and -4.58248 for the flow capacity, while in the non-linear GPA, the fault was predicted to be -1.938242% for the turbine efficiency and 4.056973% for the flow capacity. It can be deduced here that the non-linear GPA is more accurate than the linear GPA and the Root Mean Square (RMS) shows that non-linear GPA is more accurate than the linear GPA, though the linear GPA has some advantage over the non-linear GPA in the sense that it is fast in computational speed and very simple.

- **In terms of accuracy**

From the table above, it is obvious that the non-linear GPA is more reliable in terms of accuracy when compared with the linear GPA and the calculation as well. It is that way because, through some iterations the Newton-Ralphson method is used to reduce the errors , just as we have seen above that the -2% turbine efficiency and the -4% capacity flow implanted in the engine, the non-linear GPA predicted a fault of -1.938242% and -4.056973% for the efficiency and flow capacity respectively, and the linear GPA predicted a fault of -2.45858% and -4.58248% for the efficiency and flow capacity respectively , and the calculation is -7.1861 and 0.149248 for efficiency and flow capacity respectively.

This indicates that non-linear GPA is more accurate. The RMS is used in determining accuracy and in this case it proves that non-linear GPA is the most accurate of all means compared above with its value as low as 7.059971×10^{-3}, but the linear GPA shows .5495787 which indicates a reasonable difference in linear GPA error, and the RMS calculation value is 0.051588. Figure 8 below shows that the implanted fault bar and that of the non-linear GPA are almost the same height for both the efficiency and flow capacity, while linear GPA is longer for both the efficiency and flow capacity.

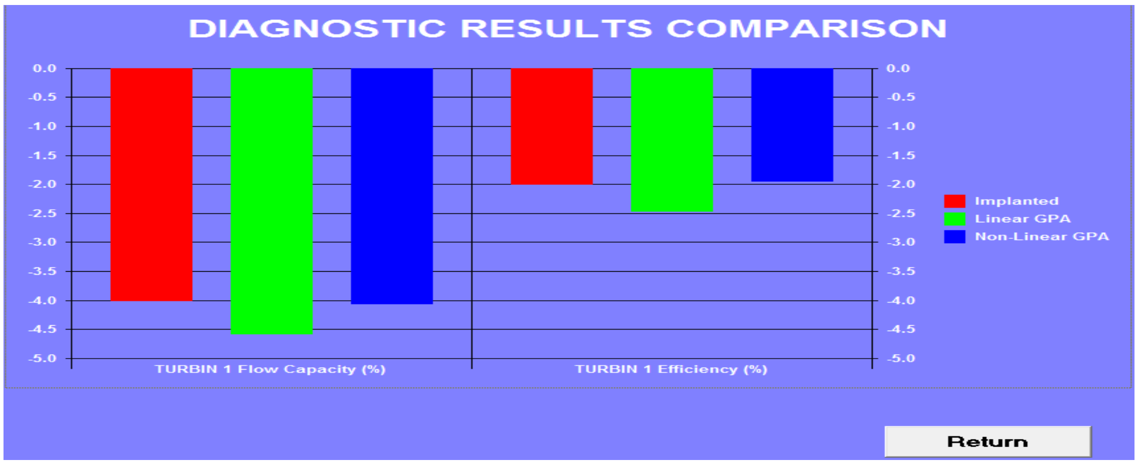

Figure 8: Diagnostic result comparison for linear and non-linear GPA.

GPA fitness or index is an alternate means of comparing between linear and non-linear GPA. and it is given by the formula below:

GPA Index=1/1+e (8)

where e is the measure of the difference between measured and predicted deviation. The GPA fitness for linear GPA was 0.5980696 and that of the non-linear GPA was 0.9901012. It proves here again that non-linear GPA is more accurate, because according to [2], when GPA index approaches unity, it shows how accurate the degradation is being predicted.

- **In terms of computational speed and time**

Though non-linear GPA is preferred over the linear GPA from the simulated result shown earlier, linear GPA also has an advantage over the non-linear in terms of computational speed and time. The time for the linear GPA seems to be very short and the computational speed is fast. The results appear faster compared to that of the non-linear GPA because here the time is longer and the speed is not as high as that of the former.

5.0 Conclusions

The content of this work is a result gotten from the small APU-GTC30-92 engine used to compare, analyze and also to predict the life of a gas turbine engine and maintenance intervals using PYTHIA software. The negligible difference between the experimental result and that of the simulation shows that this software (PYTHIA) is reliable for determining the deterioration life of a gas turbine engine. The simulated turbine shows a deterioration only -2% efficiency and -4% flow capacity drop. This deficiency was implanted into the PYTHIA software which was used to carry out diagnostics analysis by the linear and non-linear GPA method. The parameters used were for found to be suitable and as seen in the result, indicates that it is optimum and preferable compared to over instrumentation which would have increased maintenance cost and instrumentation. The results also showed that the non-linear GPA potentials used to detect accurate components degradation is higher than the linear GPA, because of the non-linear nature of the engine using Newton-Ralpson method through iterative means. The linear GPA is faster in computational speed and simple, but could not handle the non-linearity of the engine. The result of the calculation was also reasonable enough to detect the implanted fault in the component. With all these in place, we can infer that the PYTHIA diagnostic method using the non-linear GPA is a preferred means of predicting and detecting implanted fault in the gas turbine engine. This goes to show that the software is important and a useful tool in the maintenance of gas turbines.

6.0 Recommendations

In order to prevent excess installation and maintenance cost, prevention of over instrumentation in measurement should be ensured. The PYTHIA software should be made more user-friendly by notifying the user on the exact data causing any particular setback at any point in time. There should be an improvement in the linear and non-linear GPA ability accuracy of the engine and for the inevitable noise, it should also be included for more accuracy in diagnostic results. Though the non-linear GPA appears accurate, the speed, computational efficiency and the reliability could still be improved upon. Other forms like the neural network, genetic algorithm fuzzy logic and sort of GPA setback should be put in use to improve the proficiency of gas turbine diagnostic systems.

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