INVESTIGATION OF LOW-PRESSURE TURBINE AND AIRCRAFT PERFORMANCE PARAMETERS THROUGH MULTIPLE REGRESSION ANALYSIS

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ABSTRACT
Faults in aircraft performance can be identified by the experts via analysis of the recorded flight information in today’s aircraft technology. The parameters used in identification of the faults include exhaust gas temperature, fuel flow, engine fan speed, vibration, oil pressure and oil temperature. In this study, a model that predicts the vibration parameters of the low pressure turbine using real time data of a Boeing 737-500 is developed. Using the developed model, it is aimed to determine a possible deterioration in performance by predicting vibration parameters of low pressure turbine and allowed vibration limits. Multiple regression analysis technique was used in the developed model. In our study, very highly significant relationships between vibration parameters of the low-pressure turbine and air speed, thrust lever angle right, N2 speed left and exhaust gas temperature were explored.

Keywords: Low Pressure Turbine Vibration, Data Mining, Engine Health Monitoring.

1. INTRODUCTION

Gas turbine engines operate in high temperature and high pressure environments. Thus, the performance of the engine parts deteriorate in time. A minor damage in an engine part may not be a big problem for a gas turbine engine but, it could eventually ruin the whole system if not fixed early. Big damages in the gas turbine engines may result in high maintenance costs and worse still, it may cause an air crash. In order to diminish the above-mentioned risks, the gas turbine engines are examined through Engine Health Monitoring and structural condition monitoring, which is called Engine Health Management (EHM).
Monitoring (EHM) techniques in maintenance hangars. Parameters such as exhaust gas temperature (EGT), fuel flow (FF), engine fan speeds (N1 and N2), vibration, oil pressure (OIP) and oil temperature (OIT) are used in predicting the actual condition and performance in gas turbine engines [1].

There are several reasons that could cause damages in gas turbine engines. These reasons could include accumulation of dirt, corrosion, oxidation, damaged bearings, high blade clearance, damaged or burned turbine blade and vanes, damaged combustors, damaged fuel nozzles, broken rotor discs and blades. Dirt accumulation on the compressor blades spoil the air foil structure resulting an inconvenient air flow. Thus, dirt accumulation has great importance among the factors that eventually damage gas turbine engines. Additionally, foreign object damage, bird strike and domestic object damage could cause sudden and big damages in aircraft engines [2] which is not a desired situation in the aviation industry Lack of authorized technical staff, spare parts and long maintenance times could result an additional cost to airlines companies. In order to prevent this, aircrafts are periodically overhauled as an obligation. In addition to this mandatory maintenance, predictive maintenance programs are also applied to modern aircrafts.

Predictive maintenance is a method that can monitor a system in use and make a care plan [3]. The aim of the predictive maintenance is to predict a possible damage and prevent it to evaluate in the engines so that more productive use of gas turbine engines could be possible. It is possible to have more efficient aircrafts by EHM, that uses model based methods (prediction of parameters, equality equations, gas path analysis, nonlinear least square, and Kalman filter) and soft computing methods (genetic algorithms, expert systems, neural networks-NNs, fuzzy logic, rough sets and decision tree.). Possible damages could be predicted by the above-mentioned techniques. Thus, researches on diagnostics and monitoring technology are intensively conducted these days. Vibration analysis among these predictive methods has provided promising results in determination of possible damages in advance in aircraft engines [4].

2. RELATED WORKS

EHM and damage prediction have great importance in maintenance and performance analysis in aircrafts. There are some studies analyzing the effect of vibration in predicting damage in literature. A damage prediction was made using Training Support Vector Machines (SVM) and fuzzy logic by Xu et.al. [4]. Narayanan et.al. predicted vibrations by using old parameters of a jet engine in an artificial neural networks (ANN) method [5]. Hu et.al. monitored a jet engine health by using real test flight data in an ANN study [6]. A damage prediction study was conducted by Wegerich [7] through real H-60 gearbox vibration data in a similarity-based modelling (SBM) technique. Yildirim and Kurt used multiple regression analysis method to analyze the relationship between aircraft data and EGT parameter [8].

3. PREDICTIVE MAINTENANCE AND MAINTENANCE METHODS

A. Maintenance Approaches

In general, there are 4 main maintenance approaches varying based on working conditions in order to keep the systems in operation [3];

I. Fixing maintenance: In this approach, maintenance is undertaken only after a fault or fail occurs to make the machines operational again. This method is the most inefficient one among the maintenance approaches.

II. Periodic and protective maintenance: This approach includes applying maintenance programs to machines in pre-defined timelines and take action against possible failible machine parts.

III. Predictive maintenance: In this approach, machines are monitored by various analysis techniques to predict possible failures in advance. After monitoring, a convenient maintenance program is defined and applied.

IV. Pro-Active maintenance: In this approach, it is aimed to prevent a possible failure by learning the underlying reason and taking away those reasons.

B. Predictive Maintenance Methods

There are several methods that could be used in predictive maintenance. These methods include vibration analysis, infrared tomography (thermal camera), oil analysis, ultrasonic monitoring, monitoring engine current and steam trap monitoring. Usage rates of these methods as predictive maintenance tools are shown in Figure 1.

In vibration analysis technique, it is possible to collect data while the machine is in operation and possible problems could be quickly detected. Thus, this technique is used by 45%, which is highest rate among the other methods. Vibration analysis method could provide more information about a system compared to other tools.
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**Usage rates of predictive maintenance methods** [3]

**C. Vibration Analysis**

Possible failures in systems containing rotor such as electric engines, fans, pumps, compressors, diesel engine-generators, gas turbine engines etc. could be predicted in advance [9]. These machines provide alert signals in case of a failure. The best alert signal is vibration, which is defined as a reaction of mechanical systems to inner or outer forces [10].

Vibration analysis is the most applied and fastest one in the predictive maintenance methods. In this method, vibration data of a part is collected as electric signals via a detector and the signals is transferred to a working device. A computer software collects this information and uses in monitoring the condition of the monitored system. This method could be applied to any system having a rotor part. The method works collecting vibration data at regular intervals and analysing them to monitor the mechanical condition of a system [3].

**4. STRUCTURE AND PROPERTIES OF A TURBOFAN ENGINE**

Turbofan engines are high speed, high power and efficient systems, which make them attractive for commercial aircrafts. These engines have several parts operating at high temperature and pressure. A possible damage in these parts could result in vibration. Figure 2 shows the structure of a turbofan gas turbine engine.

**Figure 2.** Structure of a twin spool turbofan gas turbine engine [11]

**5. MODEL DEVELOPMENT AND METHOD**

In this study, multiple regression analysis was used to investigate the relationships between low-pressure turbine (LPT) vibration data and the factors affecting those data. Multiple regression analysis is a statistical method used in understanding cause and effect relations in cases that depend on several factors. The general i’th form of the model is given as equation (1) for a main mass, where k is an independent variable for a total observation of N [12].

\[
y_i = b_0 + b_1 x_{i1} + b_2 x_{i2} + \ldots + b_k x_{ik} + u_i \quad (1)
\]

This functional relationship could be shown in a matrix form as in the following equation (2);

\[
Y = X\hat{b} + u \quad (2)
\]

For a sample model of n, the formula gets in the form of equation (3);

\[
y_i = \hat{b}_0 + \hat{b}_1 x_{i1} + \hat{b}_2 x_{i2} + \ldots + \hat{b}_k x_{ik} + u_i \quad (3)
\]

Equation (3) could be expressed in a matrix form as in equation (4);

\[
Y = X\hat{b} + e \quad (4)
\]

In equations (2) and (4), Y is N*1 order dependent variable vector, X is N*(k+1) order independent variable matrix, u is N*1 order error vector, e is n*1 order residual vector and \(\hat{b}\) is predicted coefficient vector.

**5.1 PURPOSE OF THE STUDY**

The purpose of this study is to investigate the relations between LPT vibration parameters and Air speed, TAT, thrust lever angle left, thrust lever angle right, N1 speed right, N2 speed left, EGT for health monitoring of an aircraft engine. Schematics of the model is shown in Figure 3.

**Figure 3.** The purpose of the study and hypothesis

**A. Hypothesis**
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**H0:** There is no significant effect of Air speed, TAT (Total Air Temperature), thrust lever angle left, thrust lever angle right, N1 speed right, N2 speed left and EGT on the LPT vibration parameters.

\[ H_0: \hat{y}_0 + \hat{b}_1 x_{11} + \hat{b}_2 x_{21} + \cdots + \hat{b}_n x_{n1} + u_i = 0 \] (5)

**H1:** There is a significant effect of Air speed, TAT (Total Air Temperature), thrust lever angle left, thrust lever angle right, N1 speed right, N2 speed left and EGT on the LPT vibration parameters.

**B. Collecting and Analysis of Data**

In maintenance procedures Flight Data Recorder (FDR) data are collected regularly for the purpose of maintenance and investigation of failure. In this study Boeing 737-500 airplane flight data were collected from FDR. The real Air speed, TAT, thrust lever angle left, thrust lever angle right, N1 speed right, N2 speed left, EGT and LPT vibration data were collected from a Boeing 737-500 airplane and the relationships between these 43 collected data and 62 vibration parameters were analysed with SPSS 22 software. Before analysis all data were normalised with Equation (6) so all parameters had new values between 0 to 1.

\[ x' = \frac{x - x_{\text{min}}}{x_{\text{max}} - x_{\text{min}}} \] (6)

The multiple regression technique was used in the analysis. Descriptive statistics about used data are shown in Figure 4.

**C. Result**

T test was used in order to investigate if the coefficients of the regression model are meaningful. The assumption is accepted when the significance value (Sig.) of T statistic is less than 0.05, and thus the coefficients found in the model are considered as meaningful. Sig. value indicates the presence of statistical significance and it is a value used with the purpose of determining the level of the existing difference. The level of significance is usually taken as 0.05 and 0.01. A level of 5% significance means a confidence interval of 95% and a level of significance of 1% means a confidence interval of 99%. The general approach to interpretation of the Sig value is given in Table 1. Multiple regression analysis was performed to determine the effect of independent variables on the LPT vibration parameter. Result of the multiple regression analysis is shown in Figure 5.

**Table 1. The interpretation of the Sig. value [14].**

<table>
<thead>
<tr>
<th>Sig. Value</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01 &lt; Sig. ≤ 0.05</td>
<td>The results are significant.</td>
</tr>
<tr>
<td>0.001 ≤ Sig. &lt; 0.01</td>
<td>The results are highly significant.</td>
</tr>
<tr>
<td>Sig. &lt; 0.001</td>
<td>The results are very highly significant.</td>
</tr>
<tr>
<td>0.05 ≤ Sig. &lt; 0.10</td>
<td>The results are considered not statistically significant</td>
</tr>
<tr>
<td>Sig. &gt; 0.10</td>
<td>A trend toward statistical significance is sometimes noted.</td>
</tr>
</tbody>
</table>

When the significance value (Sig.) of the T statistic in multiple regression models is greater than 0.05, the analysis is repeated by removing the nonsense variable from the model. As it is seen from Figure 5., the significance values of T statistic of Altitude, Total Air Temperature, Thrust Lever Angle Left and Engine N1 left parameters were found to be larger than 0.05 and therefore these variables were removed from the model. Then analysis was repeated and the results are given in Figure 6. When the results are examined, it is seen that Engine N1 Right is greater than 0.05 and this parameter is removed from the model. The results in Figure 7 were obtained when the reanalysis was performed. In the developed model, Airspeed, Thrust Lever Angle Right, Engine N2 Left and Engine EGT Left appear to be very highly significant for the LPT vibration parameter according to Table 1. Results of the multiple regression analysis technique applied to investigate the parameters effecting the LPT vibration parameter in the developed model are given in Figure 7 and Figure 8. In Figure 8, which shows the results between the dependent variable and the independent variable, the "Adjusted R Square" value indicates the...
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estimated power of the generated equation. The estimation power of this model is 93.6%.

![Figure 6. Screen shot of the SPSS analysis software](image)

**Figure 6.** Screen shot of the SPSS analysis software

<table>
<thead>
<tr>
<th>Coefficients*</th>
<th>Unstandardized</th>
<th>Standardized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>Coefficients</td>
<td>Beta</td>
</tr>
<tr>
<td>(Constant)</td>
<td>3.44</td>
<td>0.76</td>
</tr>
<tr>
<td>Airspeed</td>
<td>0.33</td>
<td>0.64</td>
</tr>
<tr>
<td>Thrust Lever Angle Right</td>
<td>1.275</td>
<td>0.569</td>
</tr>
<tr>
<td>Engine N2 Left</td>
<td>-0.60</td>
<td>0.277</td>
</tr>
<tr>
<td>Engine EGT Left</td>
<td>0.45</td>
<td>0.18</td>
</tr>
</tbody>
</table>

* a. Dependent Variable: LPT Vibration

**Figure 7.** Screen shot of the SPSS analysis software

<table>
<thead>
<tr>
<th>Coefficients*</th>
<th>Unstandardized</th>
<th>Standardized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>Coefficients</td>
<td>Beta</td>
</tr>
<tr>
<td>(Constant)</td>
<td>0.496</td>
<td>0.769</td>
</tr>
<tr>
<td>Airspeed</td>
<td>0.267</td>
<td>0.64</td>
</tr>
<tr>
<td>Thrust Lever Angle Right</td>
<td>1.275</td>
<td>0.569</td>
</tr>
<tr>
<td>Engine N2 Left</td>
<td>-0.60</td>
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</tr>
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<td>0.45</td>
<td>0.18</td>
</tr>
</tbody>
</table>

* a. Dependent Variable: LPT Vibration

**Figure 8.** Screen shot of the SPSS analysis software

It is seen that the developed model is a very highly significant because the table "Sig." Value in Figure 9, is 0.000 <0.001. In Figure 7, Figure 8, and Figure 9., LPT vibration is dependent variable and Airspeed, Thrust Lever Angle Right, Engine N2 Left, and Engine EGT Left are independent variables. In the same figures, "R", "Beta", "Sig", "R" and "R^2" denote the non-standardized regression coefficient, the standardized regression coefficient, the significance level, the correlation coefficient, and the determination coefficient, respectively. In the Figure 8, Airspeed, Thrust Lever Angle Right, Engine N2 Left and Engine EGT variables have very highly significant relationship with LPT vibration parameter (R=0.97). The total variance (Adjusted R^2) of the independent variables on the dependent variable is 93.6%. Relative importance order of independent variables onto LPT vibration parameter according to Beta coefficient is Thrust Lever Angle Right, Engine EGT Left, Airspeed and Engine N2 Left. When the T-test results on the significance of the regression coefficients are examined, it is seen that the Thrust Lever Angle Right parameter is the most important independent variable onto LPT vibration. According to the results of the regression analysis, the mathematical model expressing multiple regression equations for LPT vibration prediction is shown in Equation 7.

\[
\text{LPT vibration} = 0.548 + 0.262 \times \text{Air speed} + 0.734 \\
\times \text{Thrust lever angle right} - 1.739 \times \text{Engine N2 left} + 1.205 \times \text{Engine EGT Left}
\]

Figure 10. shows a comparison between the obtained values through regression model and real LPT vibration parameters.

![Figure 10.](image)

**Figure 10.** The comparison between the obtained values through regression model and real LPT vibration parameters

There are several methods evaluating the performance of the results obtained through developed regression analysis models in literature [13]. These methods include Mean Square Error-MSE, Root Mean Squared Error-RMSE and Mean Absolute Error-MAE. Mean Square Error-MSE method is the mean of the square law distance between real values and predicted values. Mean Square Error-MSE method is shown in Equation 8.

\[
\text{MSE} = \frac{1}{N} \sum_{i=1}^{N} (y_i - \hat{y}_i)^2
\]

where \(y_i\) is real output value, \(\hat{y}_i\) is value predicted output and \(N\) is number of samples. Root Mean Squared Error-RMSE is the square root of MSE and is shown in Equation 9.

\[
\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (y_i - \hat{y}_i)^2}
\]

Mean Absolute Error-MAE method is the mean of the absolute distance between real values and predicted values. Its mathematical expression is shown in Equation 10.

\[
\text{MAE} = \frac{1}{N} \sum_{i=1}^{N} |y_i - \hat{y}_i|
\]

where \(y_i\) is real output value, \(\hat{y}_i\) is value predicted output and \(N\) is number of samples. The results of the
developed model using MSE, RMSE, MAE is shown in Table 2 and Figure 10.

**Table 2.** The performance results of the developed model

<table>
<thead>
<tr>
<th>Generated model</th>
<th>MSE</th>
<th>RMSE</th>
<th>MAE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.0062</td>
<td>0.0787</td>
<td>0.0477</td>
</tr>
</tbody>
</table>

6. CONCLUSION

It is found that the parameters Air Speed, Total Air Temperature, Thrust Lever Angle Left, Thrust Lever Angle Right, N1 Speed Right, N2 Speed Left and Exhaust Gas Temperature have a significant effect on the LPT Vibration Parameters of a Boeing 737-500 airplane. Table 1 also shows that the parameters Airspeed, Thrust Lever Angle Right, Engine N2 left and Engine EGT Left are very highly significant for the LPT vibration parameter. It is clear that there are similar tendencies between the vibration values obtained through both the developed regression model and sensors on the aircraft (Fig 10.). The performance results of the developed model are shown in Table 2. Estimation of the LPT vibration parameter is difficult because the aircraft engines are exposed to various disturbing effects on the ground and at the airplane. In this study, LPT vibration parameter is successfully predicted with the developed model.

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7. REFERENCES


VITAE

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