Aero Engine Vibration Measurement, Analysis and Trend Monitoring

Wilbur George Fernandes, Vinay C. A and Priyadarshini.L

Abstract

An engine is the most important functional entity in the aircraft. Vibration data is often an indicator of sudden changes in the state of an aircraft engine. Any faults developed in the engine, change its standard vibration signature thus making it one of the important parameters to judge its present condition, diagnose the problem and plan repairs and overhauls to optimize its availability. This paper describes the details of development of a system to measure vibration, acquire data, process it and monitor the vibration signal trend in order to analyze and ascertain if the vibration signals generated are within the acceptable limits. In the process, a transducer mounting bracket is designed using CATIA V5 and dynamic vibration analysis was carried out using commercial software ANSYS 13.0 and the results have indicated that the natural frequency of the mounting bracket is above the engine exciting frequency. Tests are conducted on the aircraft engine for different power settings to record the vibration at various locations. The signal processing of the raw vibration data to obtain the peak amplitude and corresponding frequency of interest is done using a custom code, developed using commercial software MATLAB and the code was validated using a 1g vibration calibrator. The in-house MATLAB code developed has been able to give satisfactory results in comparison with PROSIG DATS-lite analysis software which is industry standard software for vibration data analysis. A vibration trend curve has been plotted using the features extracted from the signal processing. Vibration levels measured are found to be within the limits specified by the Original Equipment Manufacturer (OEM) and a few exceptional cases of high vibration observed in the trend plot are also detailed with root cause analysis and appropriate corrective maintenance actions.

Keywords: Engine, Vibration, Data acquisition, Signal processing, Trend analysis

1 Introduction

Vibration is a common phenomenon observed in all rotating machines. These vibrations sometimes have harmful effects on the life of the equipment and also on its operational stability. Hence, knowledge of vibration is useful in design, construction, operation and maintenance of any structure or machine regardless of its area of application. Vibration signal trend monitoring and analysis can give early indications of developing faults in a component, thus alarming the user to take timely action and avoid production downtime, maintenance cost, catastrophic failure and also unsafe working environment[1,2,3].

For production acceptance testing, for rapid identification of faulty components and also in the interest of future design efforts, a deep understanding of vibration measurements is desirable. This study has been carried out on a Light Transport Aircraft (LTA) installed with a turboprop engine. It is a lightweight turbine engine which drives a propeller to generate thrust as shown in Fig. (1). the two major sections of the engine are the compressor and compressor turbine and the power turbine and power turbine shaft. These two rotors can rotate at different speeds and in opposite direction and this configuration is called free turbine engine.

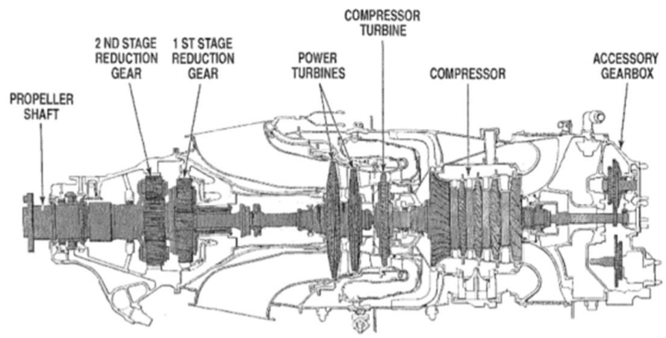

Figure 1: LTA turboprop engine ï components and construction.

2 Vibration measurement system

The architecture of the vibration Data Acquisition (DAQ) system employed is shown in the following block diagram Fig. (2).

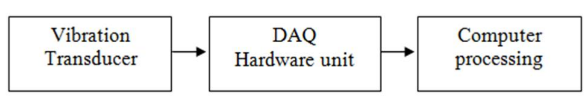

Figure 2: Structure of vibration measurement system.

2.1 Vibration transducer

Vibration transducer used is an Endevco Isotron Model 751 with Integrated Circuit Piezoelectric (ICP) type with built in amplifier to suit the transducer output to the input characteristics of the Analogue to Digital Converter (ADC), is the single axis accelerometer selected with the characteristics [4] such as range ±10g, frequency bandwidth 0-50kHz, sensitivity 2.011mV/g 4 and output range ±10V. The

ADC provides a constant source current excitation per channel of 3.6mA to the accelerometer. A user programmable anti-aliasing filter (low pass filter) is incorporated in the ADC card.

2.2 Mounting technique

Accuracy of the data acquisition mainly depends upon the transducer mounting technique and the mounting location. Stud mounting, magnetic mounting, adhesive mounting etc are a few techniques employed for installing the transducers. In the present work, stud mounting technique with the help of a mounting bracket is employed to have reliable and repeatable measurements even at high frequencies. Four accelerometers (A, B, C &D) are used as shown in Fig. (3). Accelerometer A is mounted at the frame on the casing near the power turbines, accelerometers B & C are mounted adjacent to the reduction gearbox at 3 oĉclock and 6 oĉclock positions respectively and accelerometer D is mounted besides the accessory gearbox. Though the sensor mounting locations have been recommended by the OEM, effort has been made to understand the importance of arriving at the optimum locations [6, 7].

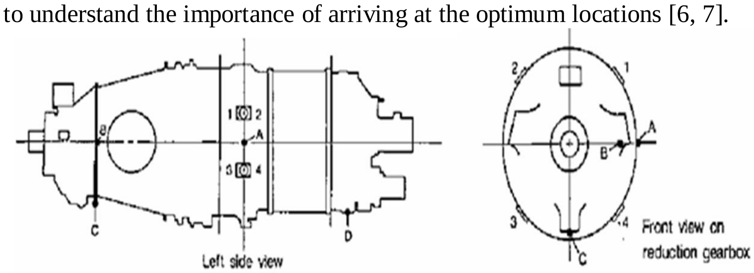

Figure 3: Accelerometer mounting locations [5].

2.3 Mounting bracket

The accelerometer is mounted on the engine using a mounting bracket as shown in Fig. (4). the bracket interfaces are designed so as to fit the mounting location at the engine. Also good surface contact is ensured for proper duplication of the vibration signals generated at the engine. The material of the bracket is AMS 5659. The mounting bracket serves as a connector between the engine and the accelerometer and is prone to very high vibration. Hence, dynamic analysis of the bracket was carried out to arrive at a safe design.

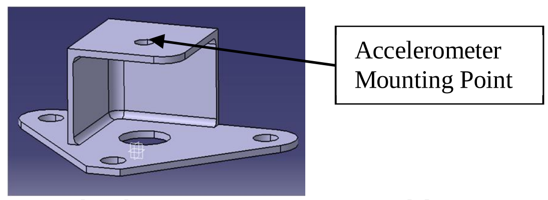

Figure 4: Accelerometer mounting bracket ï CATIA geometric model.

2.4 Dynamic analysis of bracket

A normal modal analysis was carried out on the accelerometer mounting bracket to determine its vibration characteristics. The finite element modelling using 3D Solid 185 element was generated in Altair Hypermesh 11.0 Fig. (5). All Degrees of Freedom (DOF) was arrested at the three holes in the bracket to simulate tight clamping to the engine casing. Another case of simply supported (SS) boundary condition was also analysed in order to simulate any loosening of clamping bolts. Dynamic Analysis of the mounting bracket was done using Ansys 13.0 commercial Finite Element Analysis (FEA) software which was used to solve and carry out post processing. The analysis results shown in Table 1 clearly indicate that the first natural frequency in fixed condition (3961.4 Hz) and that in simply supported condition (2234.3 Hz) is well above the engine exciting frequency (1000 Hz). Hence this design is safe. The mode shapes observed for the first four modes is shown in Fig. (6).

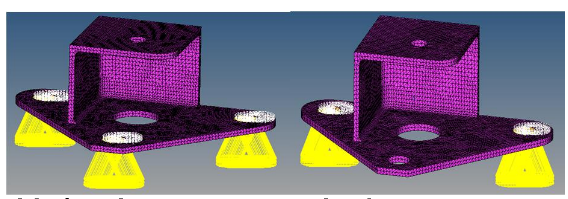

Figure 5: FE Model of accelerometer mounting bracket.

Table 1: Modal frequencies in hertz

Mode	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Natural frequency (Fixed)	*3961.4*	*4864.3*	*7070.5*	*9696*	*10540.0*	*16477*	*20358*	*24302*	*26241*	*27970*
Natural frequency (SS)	*2234.3*	*4283.9*	*5838.7*	*6957*	*9083.2*	*10142*	*14424*	*16716*	*21862*	*23049*

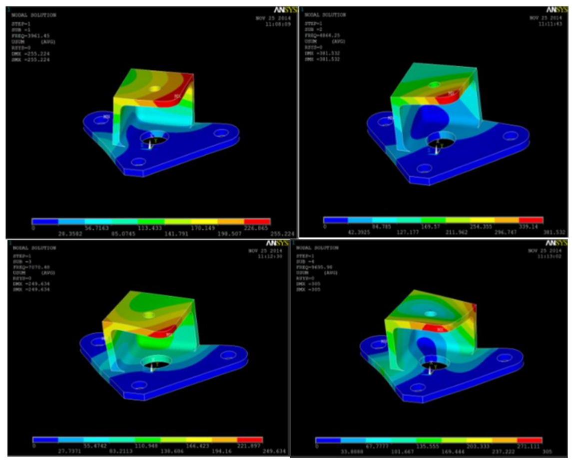

Figure 6: First four mode shapes of the accelerometer mounting bracket.

2.5 Data acquisition

Independent data logger type DAQ hardware unit, ACRA Control KAM-500 from Curtiss-Wright Corporation was used in this case. One of its major advantages is that it is highly configurable system and enables fully customized systems to be built. The analogue output of the transducer is sampled at discrete intervals of time. For appropriate digital representation of the analogue signals the sampling rate should be at least twice the largest frequency as per Nyquist theorem. The sampling frequency used here is 2048Hz. ADC116 from ACRA Control KAM-500 is used for analogue to digital conversion and the encoded data is stored in ASCII format.

2.6 Signal Processing

The raw vibration signals from the engine ground runs were processed and analysed using MATLAB code which was written for specific need to carry out the data processing. The algorithm was able to do the process of ópeak pickingô to find out the maximum amplitude of acceleration and its corresponding frequency. The first part of the program corresponds to importing the raw vibration data in ASCII format from the module data recorder. The real signal is then multiplied by the real constants to set the resolution of the ADC and also to take into account the sensitivity factor of each sensor. The plot command is then used to plot the time domain waveform of vibration signal as seen in Fig. (7). Spectral density or the power spectrum as in Fig. (8) was calculated using the Pwelch function in MATLAB.

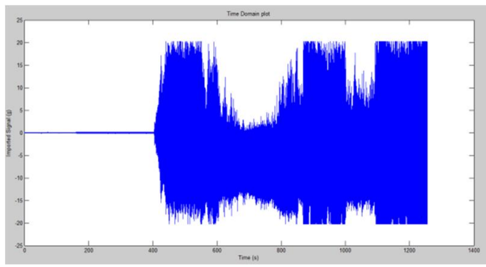

Figure 7: Time domain waveform imported to MATLAB.

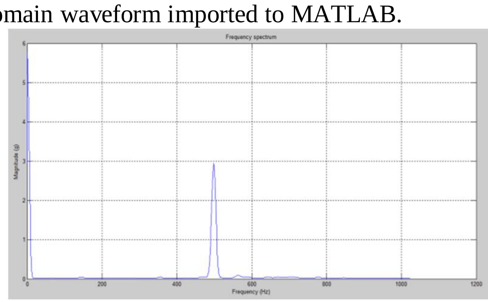

Figure 8: Frequency domain plot.

2.7 Calibration and validation

Bruel and Kjaer Type 4294 1g calibrator was used to validate the MATLAB program which is having an excitation frequency of 159.2 Hz and acceleration 10 m/s^2 RMS. A known excitation was generated and compared the results with MATLAB program and also with a commercial vibration analysis software Prosig DATS-lite Analysis. The Fig. (9). shows the calibration set-up used. The sensor used was Endevco Isotron with sensitivity 478.46 mV/g. The test data was recorded using ADC 116 from ACRA Control KAM 500 and stored for post processing.

Figure 9: Accelerometer calibration set-up.

2.7.1 Calibration results

The post processing of the calibration data was carried out using the commercial Prosig DATS-lite Analysis software and also using the custom code developed in-house using MATLAB platform. The results obtained are tabulated in Table 2 and the time domain waveform and frequency spectrum obtained in each case are shown in Fig. (10-11). The results of the post processing show that the MATLAB code has been able to give satisfactory results with an error of less than 2% and is also convincingly close to that obtained with industry standard software Prosig DATS-lite analysis and can replace it with further testing and validation with huge potential to cost savings.

Table 2: Comparison of calibration results

Approach	*Frequency*	*Amplitude*
Prosig DATS-Analysis	*159.09*	*0.988*
In house MATLAB	*159.00*	*0.986*

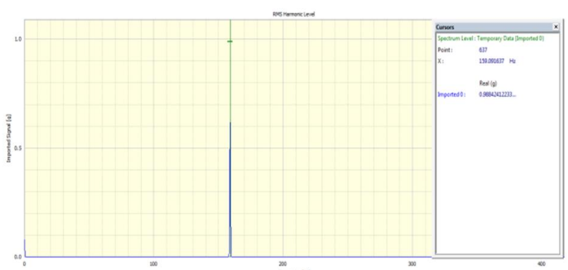

Figure 10: Frequency domain waveform of calibration data ï Prosig.

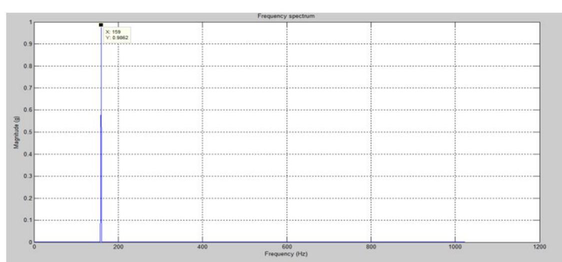

Figure 11: Frequency domain waveform of calibration data ï MATLAB.

3 Vibration trend analysis and results

Vibration trend monitoring technique is most widely used for the assessment of engine health monitoring. Any changes in the trend will alert the analyst regarding the developing problem. Here, the peak acceleration level is determined and plotted against each ground run performed on the engine. But, to conduct a detailed diagnostic analysis further processing of the signal and extraction of more characteristic features is essential.

3.1 Description of test condition

3.1.1 Test condition

Tests are performed on the aircraft in static condition and it is termed as Engine Ground Run (EGR). The test conditions for each event of every EGR are predefined. Engine Start up to Cruise Power setting (i.e. 40% Torque); where vibration levels are dominant are taken into consideration for analysis.

3.1.2 Vibration limits

The vibrations measured at the locations A, B, C and D should not exceed the limits specified by the engine manufacturer. Also care should be taken so that the equipment used for verification must not be subject to natural frequency resonance within the range specified. The vibration limits are shown in Fig. (12) and the allowable steady state vibration limit is 2.5 Pk-g.

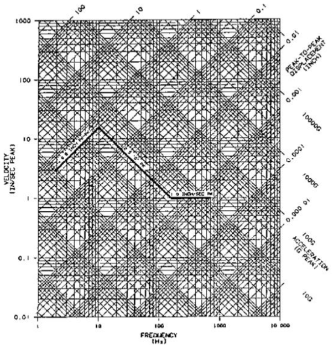

Figure 12: OEM recommended vibration limits [5].

3.2 Vibration trend plot

The peak acceleration (Pk-g) values from all the sensors are plotted for each EGR and the trend curve is obtained. The signal processing of the raw vibration data yields maximum RMS acceleration value and its corresponding frequency. But, since the vibration limits given by the engine manufacturer are in terms of peak acceleration, conversion is done using the following formula:

$$\text{Peak acceleration} = \text{max. RMS acceleration} * 1.414 \quad (1)$$

The Pk-g accelerometer values are calculated and tabulated in Table 3.

Table 3: EGR Summary

Accelerometer Position on engines	*ABO*		*AGB*		*RGB3*		*RGB6*	
	LH	*RH*	*LH*	*RH*	*LH*	*RH*	*LH*	*RH*
Max-RMS-g	*0.51*	*1.09*	*0.17*	*0.205*	*1.26*	*0.69*	*1.16*	*0.8*
Pk-g	*0.73*	*1.54*	*0.24*	*0.29*	*1.79*	*0.98*	*1.64*	*1.13*

Similarly, the vibration testing is carried out for 45 EGRs and the data acquired is processed to determine the Pk-g acceleration level. Further, the Pk-g acceleration is plotted against corresponding EGR to yield the vibration trend plot shown in Fig. (13).

3.3 Analysis and inference

The vibration trend plot for both the engine gives the vibration level at locations where the accelerometers are mounted. Vibration levels are lowest at the location D besides the accessory gearbox (AGB) for both the engines. The sensors at the reduction gearbox (RGB) location (B and C) show high levels of vibration in both engines as the RGB is close to the one of the main vibration source i.e. propeller. In few grounds run some cases of high vibrations above the safe limits were observed refer Fig. (13). to determine the root cause of this upward trend seen, a detailed study has been carried out which has revealed many useful maintenance actions. To isolate the engine damage due to vibration limit exceedance, engine main parameters such as compressor rpm, turbine temperature, torque limits, engine oil temperature etc. were assessed for that particular test condition and engine performance was found to be normal and satisfactory. Further, up on inspection of the particular accelerometers it was found that accelerometer mating connector was improper in one case and accelerometer mounting bracket fasteners were unthreaded due defective thread profile in the other case.

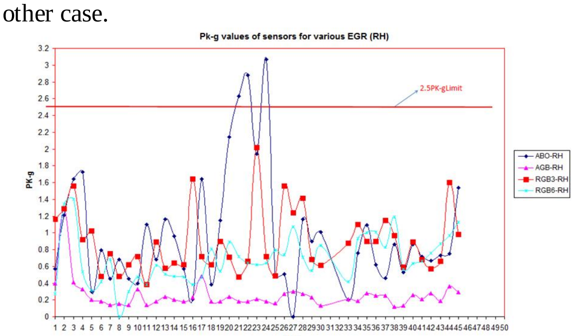

Figure 13: Vibration trend plot ï RH engine.

These studies have helped the engine maintenance team to take pro-active maintenance actions before it leads to actual failures.

4 Conclusion

The objective of measuring the vibration signals generated by a light transport aircraft engine after its installation to the airframe was verified with reference to the acceptable limits by the OEM. The study is also set out to design a suitable transducer mounting bracket and analyse it for its dynamic performance. The architecture of the data acquisition system is studied and the trend curve is plotted from the vibration signal data gathered during the EGR which was processed using in-house MATLAB code. It has been found that the vibration measurement system described is able to successfully indicate any abnormal operating conditions with an upward trend and alert the analyst to give input to the engine maintenance team for further corrective action.

Acknowledgement

The authors wish to thank all partners and associated partners for their contribution to the program and for their permission to publish this paper.

References

[1] Maurice L Adams, *Rotating Machinery Vibration*, Marcel Dekker Inc, chapter 7, 2001.
[2] B. K. N Rao, *Handbook of Condition Monitoring*, Elsevier Advanced Technology, pp 83-84, 1996
[3] R. A Collacott, *Mechanical Fault Diagnosis and condition monitoring*, A Halstead Press Book, John Wiley & Sons, New York, 1977.
[4] Endevco Corporation, Model 751 Isotron Accelerometer, *Product specification sheet.*
[5] Vinay C.A, P Radhakrishnan and S Jayagopal, *Ground test schedule for LTA powerplant system*, CSIR-National Aerospace Laboratories, Bangalore, India, 2013.
[6] Keming Wang, Dongzhe Yang, Kourosh Danai and David G Lewicki, ñModel-Based Selection of Accelerometer Locations for Helicopter Gearbox Monitoringò, Journal of The American Helicopter Society, Vol.44, No. 4, pp 269-274, 1999.
[7] H Alkhadafe, A. Al-Habaibeh, S Daihzong and A Lotfi, ñOptimising Sensor Location for an Enhanced Gearbox Condition Monitoring Systemò, IOP Publishing, (25th International Congress on Condition Monitoring and Diagnostic Engineering), 2012.