

## Condition Monitoring of Industrial Gas Turbine Critical Operating Parameters Using Statistical Process Control Charts

Harindharan Jeyabalan<sup>1, a\*</sup>, Lim Meng Hee<sup>2, b</sup> Mohd Salman Leong<sup>3, c</sup>

<sup>1</sup> Razak School of Engineering and Advanced Technology, University Technology Malaysia

<sup>2</sup> Institute of Noise and Vibration, University Technology Malaysia

<sup>3</sup> Institute of Noise and Vibration, University Technology Malaysia

<sup>a</sup>harindharan@gmail.com, <sup>b</sup>mhlhim@ic.utm.my, <sup>c</sup>salman.kl@utm.my

**Keywords:** gas turbine; condition monitoring; package operating parameter; statistical process control

**Abstract.** This paper presents condition monitoring of industrial gas turbine by monitoring its critical operating parameters using statistical process control. This will consequently enables the detection of any degradation of gas turbine operating parameters and thus to be prepare for any forward actions required. Basically performance of gas turbine and its critical operating parameters degrades over time. These parameters however degrades and eventually reach the OEM recommended limits without even triggering any earlier alerts. Therefore, corrective maintenance actions are required to bring the parameters back to an acceptable operating condition which causing downtime in operation and accounts for large maintenance together with operating costs. Hence by identifying any degradation and deviation in gas turbine parameters in advance before it reaches its OEM limit will help to improve maintenance scheduling and practices and thus enhanced the reliability of the machine. It also able to identify false alarms and shutdowns which can cause unnecessary maintenance and non profitable stops. SPC method is also found to be able to estimate the progression of component/ performance degradation and thereby generating a continuously updated prediction of the remaining useful life of machine components. SPC based machine condition monitoring uses statistical process control charts such as individual and moving range methods to create the operating threshold of the machine. These thresholds were showed to be capable to determine and identify performance degradation in advance or earlier before it reaches the OEM limits for each individual parameters.

### Introduction

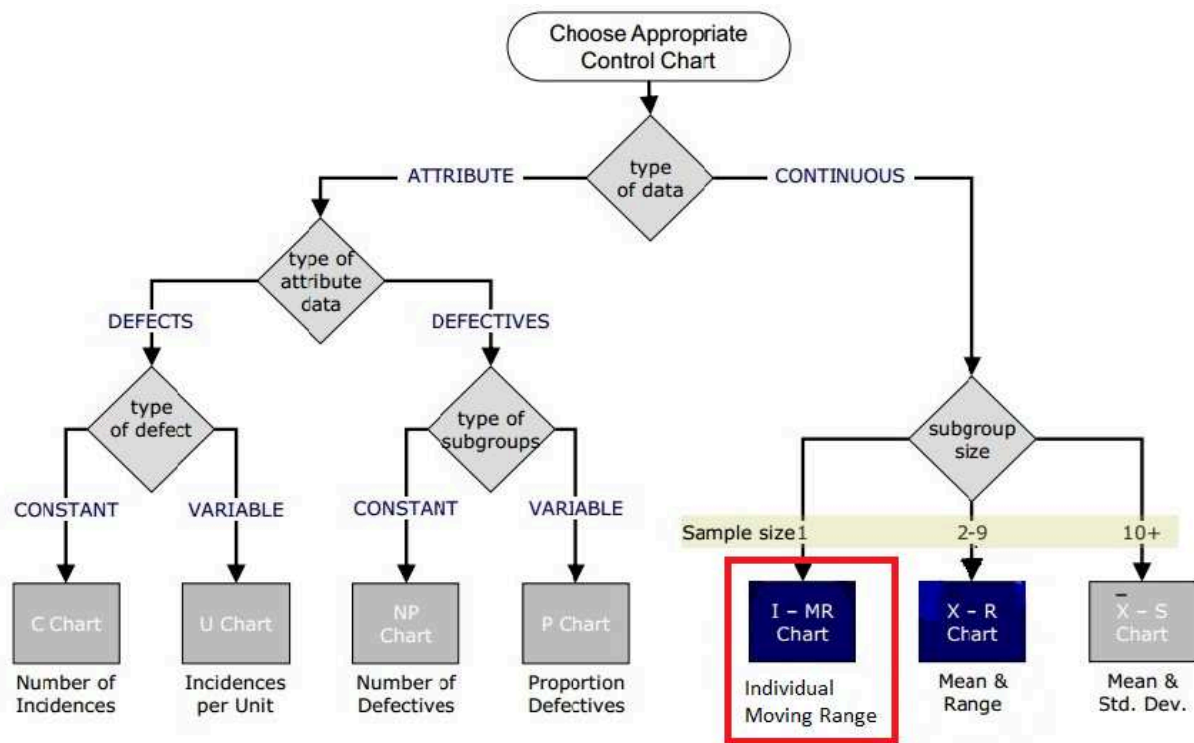
Gas turbine packages which are statistically showing a higher downtime shall be due to the operational concerns. All the package operating parameters can be expected to change at slow, constant rate over time. However in certain circumstances the process of the changes can be faster due to the environmental impacts such as exposed to sea breeze, rain water, hazardous gases, oil, grease, cryogenic liquids and also operational demand such as increase from normal operating limits in speed, load, temperature and pressure. Whether the changes are slower or faster it is imperative to reduce the impact of it by monitoring the performance of the gas turbine package parameters before it is reaching shutdown limits. This is crucial to maintain the unit availability for continuous operation. This task made possible by the technology advancement of the condition monitoring by monitoring the performance of gas turbine package parameters. This can be achieved by creating operating envelopes for each package parameters by applying statistical process control using individual and moving average chart.

## Literature Review

To date most of the research and control techniques were focused on driver (i.e gas turbine) only as compared to complete package equipments ( power turbine, gear ,compressor & pumps).Several studies were carried out to create limits & controls to optimize gas turbine operation. J.L Agüero[1], senior member of IEEE developed modification in turbine control limits speed deviations to the governor. This modification limits the power delivered to control the frequency and to avoid large and sudden power unloading takes place when the grid frequency recovers from a big dip. Chenxing sheng [2], explained the recent progress made in mechanical condition monitoring and fault diagnosis. They classified the fault diagnostics into three methods, which are control mode, pattern recognition and artificial intelligence. Among them , the fault diagnosis based on control mode needs to establish model through theoretical or experimental methods. Pattern recognition techniques perform cluster description for a series of process or events and recognizes the fault based on the extraction of fault characteristics. Fault diagnosis applies artificial intelligence by creating rules & facts based on operating history, maintenance practices and engineering constraints. Carl s. Byington & mathew J. Watson[3] introduced a combination of model-based and data-driven approaches to gas turbine engine fluid system health management. Experimental data were collected on a test setup representative of aircraft fuel and lubrication systems and these data were used to train a developed model of the system as well as data driven routines. These methods provides reliable health assessments of hydraulic pump and valves, which are the essential components of these systems and significant early steps towards addressing the issue of on-board diagnostics and prognostics for gas turbine accessory components. Y.G.Li[4] developed a novel adaptive gas path analysis (adaptive GPA) to estimate the actual engine performance and gas path component health status by using gas path measurements such as gas path pressures, temperatures, shaft rotational speeds, fuel flow rate, etc. This method was reported to be able to determine the thermal performance and gas path component health status such as compressor , combustor and turbine.Jerome Peilhes[5] enhance available knowledge in the literature of cooling systems of gas turbine vanes by the internal cooling system of the vanes. Efficiency of cooling system is very reduce aerodynamic losses and costs of maintenance of the engine as component life decreases. The studies and researches were carried out separately for condition monitoring of gas turbine or their accessories to improve the operating performances. Our current research attempt to perform condition monitoring & fault detection for gas turbine package by taking inputs from existing instrument measurement's.

## Analytical work

Process data usually having a larger fluctuation in its values due to the variation of the machine operating condition. It is a common practice to assume the data is in normal before the statistical process control chart can be used to create operating thresholds for distribution. The individual and moving range (I-MR) chart is the most suitable control chart for continuous data with sample/subgroup size lower than 2[6] . Figure 1 explains SPC selection process chart.



**Figure 1** SPC selection process [7]

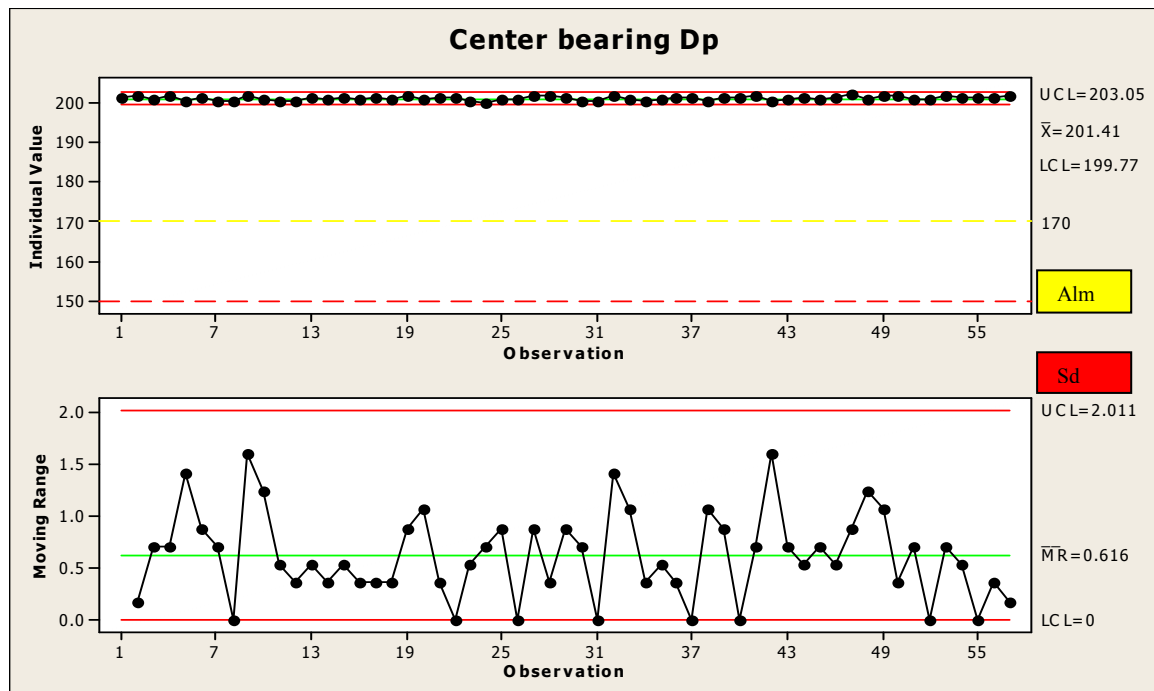
I-MR chart comprises of individual and moving range charts. Individual chart used to detect trends and shifts in data, plots each measurement as individual data point and each data points stands on its own. Moving Range Chart explains each data points plots the same difference (range) consecutive data points as they come from the process in sequential order and there will be one less data point in the moving range chart than the individual chart. From the chart below upper control limit ( UCL) and lower control limit ( LCL) were determined for one of the critical gas turbine parameter by applying individual moving range (I-MR) chart. Table 1 & 2 shows the formula to calculate the control limits of the parameter. For an I-MR chart, sample/subgroup size used is n of 2. The control limits is a function of average (R bar). This is the reason why MR chart needs to be in control before the control limits at individual chart can be determined. If the data range is relatively large and unstable, the control limits can be inflated of proportion and which could be a cause for errant analysis[7]. Figure 2 shows I-MR chart's for one of the critical operating gas turbine package parameter.

**Table 1 :** Control limit calculation [6,]

|          | LCL                               | UCL                               |
|----------|-----------------------------------|-----------------------------------|
| I Chart  | $\bar{X} - 3 \cdot \bar{R} / d_2$ | $\bar{X} + 3 \cdot \bar{R} / d_2$ |
| MR Chart | 0                                 | $D_4 \bar{R}$                     |

**Table 2:** Constants for Calculating Control Limits

| n (Sample/subgroup size) | D2    | D3 | D4    |
|--------------------------|-------|----|-------|
| 2                        | 1.128 | -  | 3.268 |
| 3                        | 1.693 | -  | 2.574 |



**Figure 2** I-MR charts for centre bearing differential pressure

If an operator observed that the operating point is well below or higher than the UCL and LCL limits, remedial action to identify the root cause of the problem shall be taken [8].

**Table 3:** Condition monitoring limits for centre bearing differential pressure.

| Tag Description   | ALM     | SD      | UCL        | LCL        |
|-------------------|---------|---------|------------|------------|
| Centre bearing dp | 170kpad | 150kpad | 203.05kpad | 199.77kpad |

## Discussion

A gas turbine supported by 3 roller element bearings at three locations respectively at front, centre and rear of the machine. The centre bearing is designed to take a much bigger load in delivering the required power. With that in consideration, the oil supply to the centre bearing has a higher flow rate together with built-in safety protection measure to monitor its performances. Oil supply to the centre bearing is essential to create the thin oil film between rotor shaft and bearing surfaces during operation. Failure to provide required oil supply can cause catastrophic failure at bearing and rotor shaft. More over oil leaking outside the bearing, during operation can cause internal or external fire which is of a safety concern. Figures 3a, 3b, 3c, 3d are the screenshots taken from one of the gas turbine package's HMI screen. The chart showed the centre bearing differential pressure value is decreasing over time due to various reasons. However the operators are unaware of the concern as no alert or alarm triggered. With the aid of statistical process control and the resulted operating envelopes, the operators are able to notice the alert and to start taking the necessary measures to overcome the problem. By generating the operating envelopes deviation in the operating condition could be detected earlier when the centre bearing differential pressure measurement was 190.3kpa. It is showed that with the existing method the operator could only detect the deviation when the value reached critical measurement of 164.2kpad (figure d) below the alarm value. These figures was generated from actual field measurement from one of the offshore operator.

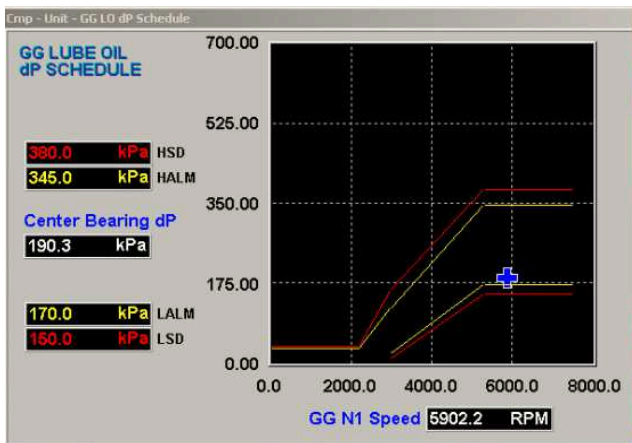


Figure 3a GG lube oil schedule

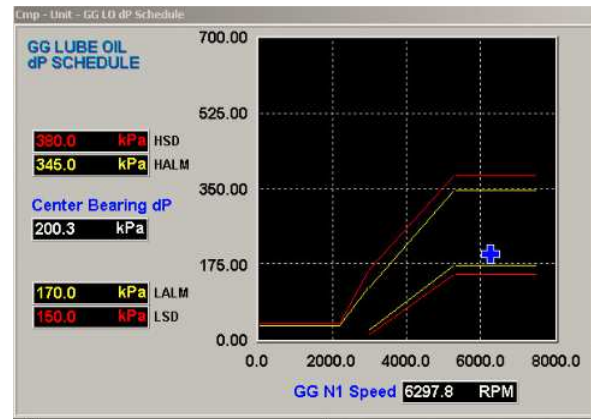


Figure 3b GG lube oil schedule

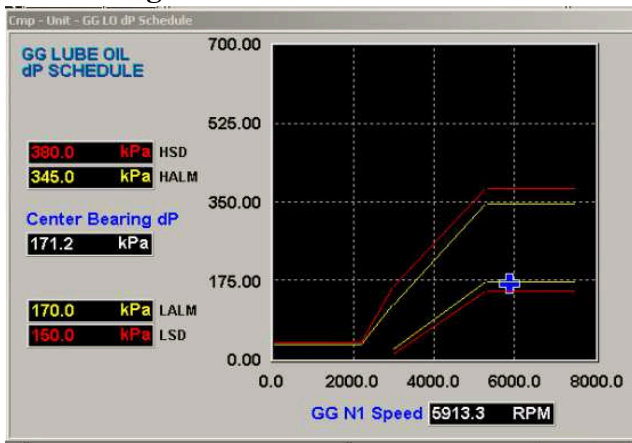


Figure 3c GG lube oil schedule



Figure 3d GG lube oil schedule

## Conclusion

This paper described a case study of condition monitoring of a gas turbine package using statistical process control. The two interrelated methods discussed are individual and moving range charts. This method can also be applied to any gas turbine packages in energy and marine industries. For aerospace (civil & military) this technique is less applicable as the existing methods applying human aid to do continuous condition monitoring at the trending of the operating parameters. This is because aerospace industry were given high priority in safety which required continuous monitoring together with immediate solutions. This method is however capable to analyse individual parameter and therefore can be applied to a subsystem of the entire package.

## Acknowledgements

The author would like to thank the Advance Gas Turbine Solutions and its personnel for their collaboration by allowing to use their data and case study to be published. This paper is also supported by the institute of noise and vibration, UTM and UTM Flagship Grant (Q.K130000.2409.01G44) and Research University Grant of UTM (Q.K130000.2540.06H51 and Q.J130000.2524.05H01) financed by the Ministry of Education, Malaysia.

---

**References**

- [1] J.L. aguero, Availability and limitation of spinning reserve & limitation of non-desired unloading. Paper published by IEEE senior member.
- [2] Chenxing sheng, Zhixiong Li, Recent progress on mechanical condition monitoring and fault diagnoses. Reliability engineering institute, Wuhan University of technology, 2011.
- [3] Carl S byington, Mathew J Watson, Automated health management for gas turbine engine accessory system components. IEEEAC paper #1313.2007.
- [4] Y.G. Li Gas turbine performance and health status estimation using adaptive gas path analysis. Journal for engineering for gas turbine and power. Vol.132, Apr 2010.
- [5] Jerome Peilhes ‘Turbine blade cooling system optimization’. Journal of turbo machinery by ASME. Vol.135, November 2013.
- [6] Douglas C. Montgomery, Introduction to Statistical Quality Control. Reference handbook, 6<sup>th</sup> edition by Wiley & Sons, 2009.
- [7] <http://www.sixsigmatraining.org/downloads/imr-and-xbar-charts.pdf>. Online resource by sixsigma.minitab.com/blog/understanding-statistics/how-create-and-read-an-i-mr-control-chart. Online resource by six sigma.