Trend Analysis for Maintaining Correlation of Gas Turbine Engine Test Cells

RATIONALE

The FAA has issued Advisory Circular, AC43-207, on December 26, 2002 that recommends a 7 year re-correlation, trending or periodic checks. The FAA, AC43-207 bases their recommendation on the SAE Aerospace Recommended Practice (ARP) 741 rev. B (or latest revision).

This document describes a recommended practice and procedure for the trending of parameters to maintain the test cell correlation status. Trending is performed to monitor test cells for changes that can affect engine performance or the data acquired from engine tests. Over time the quality of the acceptance test data for an engine can be affected by the test cell environment. This could lead to unanticipated and expensive results of either accepting a poor performing engine or rejecting a good performing engine. The use of trending the data for engine acceptance can avoid such costly errors.

TABLE OF CONTENTS

1. SCOPE

1.1 General

This document describes a recommended practice and procedure for the trending of parameters to maintain the test cell correlation status. Trending is performed to monitor test cells for changes that can affect engine performance or the data acquired from engine tests.

1.2 Benefits

This recommended practice will benefit the original equipment manufacturer (OEM), commercial users, repair stations, and military depots as well as intermediate level maintenance activities. Specific cases in which the information contained herein will be beneficial are:

a. As a recommended and less expensive method to maintain test cell correlation status.

b. As a method for maintaining correlation of test cell data between engine, airframe and third party overhaul centers supporting:

   1. Commercial requirements

   2. Military requirements

   3. As an early indicator for changes in performance such as:

      (a). Performance changes driven by the test cell

      (b). Performance changes driven by the engine

      (c). Performance changes driven by the measurement system

By trending engine and test cell parameters it can be determined whether changes have occurred to the test stand, instrumentation, or engine that will affect the performance data collected in that specific test stand. The trended data allows the test cell owner to be confident that the data taken from tests in the test cell is valid and accurate. If a change to the test cell, instrumentation, or the engine has occurred, trending allows the change to be identified early.

If the test cell is subjected to abnormal test conditions (i.e. stalls, surges, blade-outs, engine failure) either intentional or otherwise which can damage instrumentation or the test facility hardware, then data trending will show a shift in the trend indicating a resulting effect. Trending will also capture instrumentation drift.

After a test facility is correlated and the correlation factor has been determined, trending is an effective way to maintain confidence in the correlation. The trending of the data needs to commence immediately following the correlation test. Therefore the test cell does not need to be re-correlated as often. Indeed, referring to the reference documents, trending is a recommended alternative to a physical re-correlation of the test cell. If trending is performed on a consistent basis then re-correlation need only be performed when deemed necessary based on the trended data, engineering judgment, or if modifications have been made to the test cell.

The trend data can be taken a step further and the operator can compare the trend data not only to the correlation factors, but they can also use the trend data to monitor the shop performance, engine build standards and overall fleet health for that engine model.

1.3 Limitations

This recommended practice is meant as a general guide to trending; therefore specific practices and details may be instituted by the OEM or government agencies. Although this document describes the practice of trending gas turbine engine parameters, these trending practices can be used for trending any type of measurement.

2. APPLICABLE DOCUMENTS

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of the other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1 SAE International Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

ARP5435 APU Gas Turbine Engine Test Cell Correlation

ARP741 Turbofan and Turbojet Gas Turbine Engine Test Cell Correlation

ARP4755 Turboprop/Turboshaft Gas Turbine Engine Test Cell Correlation

2.2 Other References

Downing Ph.D., Douglas, and Jeff Clark, Ph.D. “Statistics The Easy Way.” Barron’s Educational Series, Inc., 1989.

Wheeler, Donald J.; and Chambers, David S. “Understanding Statistical Process Control”; SPC Press, Inc.; Second Edition, 1992.

Rolls Royce PLC Publication Reference: PPR 1474; Issue No.1; March 2007.

Federal Aviation Authority (FAA) Advisory Circular, AC43-207 issued on December 26, 2002.

3. DEFINITIONS

a. CALIBRATION: The comparison of a particular instrument or system with a standard of known accuracy

b. CORRELATION: The comparison of engine performance parameters measured on a common engine tested in two test facilities, where one facility is the reference

c. CORRELATION FACTOR: A multiplier used where appropriate to adjust for the difference in performance between the customer facility and a reference facility, also known as a “correction factor” or a “facility modifier”.

d. ENGINE DRESS KIT: Typically consists of aerodynamic hardware, accessories, and test instrumentation required to permit operation of the engine in the test cell.

e. INDOOR TEST CELL: A facility for the testing of gas turbine engines in an enclosed environment.

f. OUTDOOR TEST STAND: An open air facility, without any enclosure, for testing gas turbine engines

g. TEST FACILITY (TEST CELL): An area in which a gas turbine engine is operated to determine its performance and other information as required by a given test.

h. TRENDING: The statistical practice of recording and plotting parameters over time.

i. Outlier: Data sample that is outside of predetermined tolerance band.

4. TEST CELL TRENDING

4.1 General

When Gas Turbine engines are tested in a test cell, the characteristics of the test cell have a significant effect on the engine performance data. Engine performance data, within the same engine family, follow normal variations (natural process variation) within statistically acceptable limits. Such variations are caused by engine-to-engine differences, and variations in other factors (e.g. humidity, fuel, ambient conditions, etc.) which are analytically corrected for, but carry a certain amount of uncertainty within the correction. Changes in the test cell characteristics can be detected by a trend-analysis of the engine performance data for pass-off parameters, and detecting points that fall outside the statistical limits of normal variation, or outliers. It may be noted that an outlier may also be caused by a change in the engine production, or in the post-overhaul assembly process, or the inadvertent installation of defective parts. Hence, the observation of an outlier in the data plots may not necessarily indicate a change in the test cell characteristics.

It is recommended that a list of parameters be prepared for trending before starting the process. The OEM, or other correlation agency, and the production/overhaul shop should have a formal agreement on the list. Typically the parameters are the ones used for production or post overhaul pass-off testing.

Trending is the statistical process of recording and plotting a parameter against time. As the parameter is trended the average is determined and the upper and lower control limits are established, indicating the acceptable band within the natural process variation. The control limits can be determined by a combination of several methods.

- Standard Deviation Techniques
- Statistical Process Control (SPC)
- OEM defined tolerance bands

Engineering judgment must be applied when using any of these methods. Trending must be started immediately following the correlation test. Once a fair amount of data is collected (at least 10 data points for a parameter) trending analysis can be started. However, to be statistically significant and more meaningful, at least 30 points are needed. For a sample size smaller than 10, and in facilities where engines are tested infrequently, an appropriate statistical process control methodology (like Individual Moving Range, Ixmr) may be used.

It is recommended that a running frequency histogram be plotted for each parameter. As an example, the following table is a list of the measured/corrected value of a parameter from testing the same engine-type at the same facility on different dates.

TABLE 1 - DATA OBTAINED FOR A PARAMETER FROM TESTING

0.951	0.898	0.951	0.902	0.919	0.898	0.901	0.908	0.904	0.912	0.908	0.920	0.951	0.899
0.921	0.951	0.925	0.908	0.907	0.908	0.909	0.903	0.916	0.900	0.925	0.918	0.907	0.914
0.908	0.898	0.902	0.909	0.951	0.920	0.899	0.909						

Please note that for the purpose of this analysis, the unit of the parameter is irrelevant. There are 36 data points in the above sample. The minimum (min) value of the parameter from the test data in Table 1 is 0.898, while the maximum (max) value is 0.951. The range, R of the entire sample, which is the difference between the max and the min, is 0.055. By definition, R is the smallest value in the set of data subtracted from the largest value. It would be sufficient, in this case, to create between 10 and 15 intervals, each 0.005 units wide, for plotting the frequency histogram. There is no set procedure to determine the number of intervals. One method is to take the square root of the total number of data points rounded to the nearest whole number (in this case, this method will yield 6 intervals). A second method is to use judgment and experience with a general guide line of approximately 10 intervals for 30 to 100 data points in the sample. The histogram prepared from the above data is given in Figure 1 below.

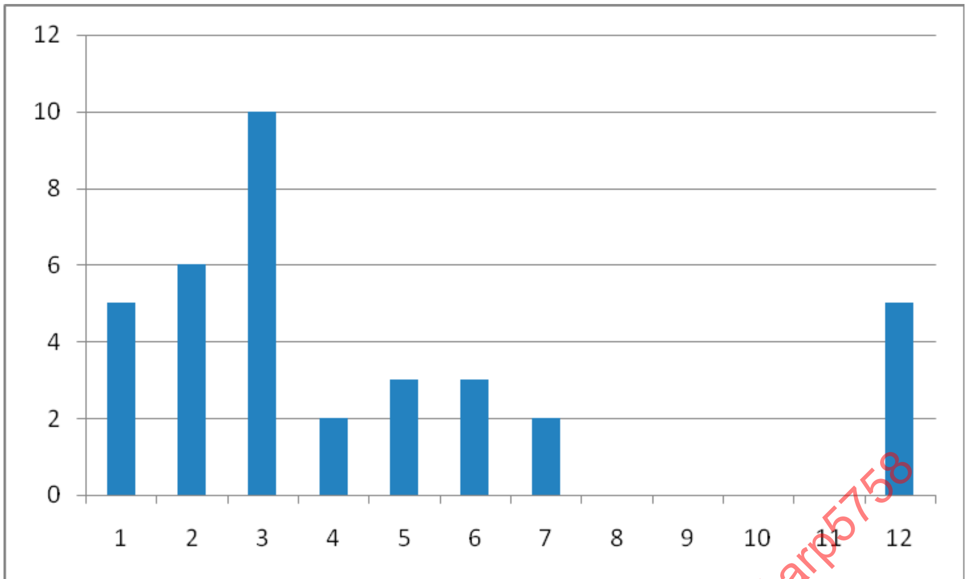

FIGURE 1 - FREQUENCY HISTOGRAM OF THE DATA FROM TABLE 1.

Note that the X-axis is the Interval No. and the Y-axis is the number of data points captured in the range of the specific interval (for example, Interval No. 6 has 3 data points). There are 12 intervals in the above histogram and it reveals a peak at the 12th interval which is centered over the interval 0.950-0.954. This interesting aspect of the data is difficult to be brought out without the aid of the histogram plot. Even without doing any further analysis (like plotting the control charts, etc.), an investigation should be conducted to find the reason for the unexpected peak.

The following is an explanation of the use of standard deviation.

The average, $\bar{x}$ of a set of data for a parameter, x is given by

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}, \quad (1)$$

where n is the number of data points in the sample.

To find the upper and lower control limits the standard deviation (σ) must be determined. Standard deviation, σ can be found by using,

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}} \quad (2)$$

Once the standard deviation is found it can be used to determine the upper and lower control limits. The control limits are defined by a multiple of the standard deviation from the average. For example, a 2σ spread would mean that the distance between the upper and lower control limits is twice the standard deviation. Therefore, the upper control limit would be one standard deviation above and the lower control limit would be one standard deviation below the average value. This establishes the band around the average for a 2σ spread. In statistical process control, the natural process variation is considered to be the 6σ spread, or ±3σ band from the average. For the data to be acceptable, the pre-set process band (±1σ, 2σ, or 3σ) must be within the acceptable band given by the OEM. It may be noted that in some cases, the acceptable band may be cropped, or truncated due to red-line considerations. Experience has shown that FADEC controlled engines demonstrate less variation of performance parameters during testing.

There are instances when the sample size is small (<10), or the engine tests are widely spaced in time (one, or two engines a month). In such cases, each data set needs to be used to evaluate the statistical limits of the process. This is done by an Individual Moving Range (Ixmr) analysis. Following is an example of the analysis of the test data for a parameter x from a small sample size. Let us analyze a subset of the data from Table 1, as reproduced in Table 2 below.

TABLE 2 - PARAMETER VALUES FROM INFREQUENT ENGINE TESTING

Test No.	1	2	3	4	5	6	7
Value, x	0.898	0.902	0.919	0.898	0.901	0.908	0.904
mR		0.004	0.017	0.021	0.003	0.007	0.004

In this case, the average of x is given by,

$$\bar{x} = 0.90429 \text{ ,} \tag{3}$$

and the standard deviation is given by,

$$\sigma = 0.88652\overline{mR} = 0.008374, \tag{4}$$

where $\overline{mR}$ is the average of the moving range *mR*, and the multiplier 0.88652 is for converting the Range-average to σ for I_{xmr} analysis. The moving range is the modulus of the difference between each set of two consecutive data points. The natural limits of the process will be given by the control band (a multiple of σ, ±1σ, 2σ, or 3σ) around the average value of x, as given by Equation (3) above. In such cases of small samples, it is also important to look at the control chart for the moving range *mR*, with its average $\overline{mR}$, and its upper control limit (UCL_R) of 3.268$\overline{mR}$ (no lower control limit exists for a sample size of 2 for the moving range *mR*). In the above example,

$$\overline{mR} = 0.0093333\text{, and} \tag{5}$$

$$UCL_R = 0.030501 \tag{6}$$

If a range value exceeds UCL_R, or if a test data for the parameter x falls outside the control band defined by a multiple of σ (±1σ, 2σ, or 3σ), it usually indicates an assignable cause of variation (as different from a natural cause of variation) and a thorough investigation must be done before proceeding with further engine testing.

4.2 Factors Affecting Performance Measurement of Gas Turbine Engines

The following items are known to have an influence:

a. Configuration of the test cell airflow path, particularly the inlet, test section (work platforms, thrust stand), augmenter tube, and exhaust stack configurations

b. Ambient conditions

c. Instrumentation: calibration, location, measurement accuracy, and quantity

d. Test cell power measurement system

e. Testing procedure

f. Data acquisition system

g. Fuel properties

h. Engine dress kit

i. Heat Generating Devices: Dynamometers, load banks, bleeds, heaters

j. Modifications to the engines

k. Modifications to the build process

4.3 Parameters to Trend

The parameters that should be trended and monitored for data shift should include all parameters used for the correlation and final engine pass-off. Also engine performance and test facility diagnostic parameters can be used. Some examples follow, but are not limited to:

a. Test facility parameters

1. Test cell pressure drop (measured between positions up and downstream of the engine in the test cell air flow)

2. Ambient pressure, temperature, and humidity

3. Test cell total air flow and stand bypass airflow (airflow that does not go through any part of the engine)

4. Fuel flow and properties

5. Wind speed and direction

The ambient conditions do not need to be trended over time as long as an instrumentation recalibration schedule is created and followed. However, it is advisable to monitor and record the weather data during test. This will be used as a diagnostic aid in the event that an outlier is evident in the data.

b. Engine corrected parameters, includes pass-off and diagnostic:

1. Engine Pressure Ratio (EPR)

2. Exhaust Gas Temperature (EGT)

3. Specific Fuel Consumption (SFC)

4. Power output (thrust or torque)

5. Engine Speeds (N1, N2, and N3 if applicable)

6. Major Engine Temperatures and Pressures

Other parameters may be specified for individual engine models. As part of the configuration control for the engine it is advised that you maintain logs of the trimmed and untrimmed data for the engine at test, such that you can trend either or both data sets.

4.4 Parameter Trend Requirements

For trending to be effective the parameters trended need to be from successive and similar tests, also knowledge of modifications to the test facility or engine is required.

The trended data is typically taken at a minimum of three power points in each engine test. (i.e. flight idle, cruise power and maximum power)

Many operators have a variety of engine models that run through the test facility. It is also possible that a given overhaul center will test engines of the same model that have had very different levels of overhaul workscope applied. In these cases it is recommended that the data is trended in their respective families. (i.e., new engines, repaired engines, full overhaul engines)