OPERATING STATE HISTORICAL DATA ANALYSIS TO SUPPORT GAS TURBINE MALFUNCTION DETECTION

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ABSTRACT

The paper describes a methodology to determine gas turbine operating state based on the analysis of normalized field data. This methodology consists in normalizing measured value with respect to that expected, calculated in the actual boundary conditions and working point. The normalization procedure, if applied on line, provides useful information to support the machine Health State determination.

In this paper, the methodology has been applied to field measurements taken on a 5 MW gas turbine running in a natural gas compression plant. The first results of field measurements analysis along a two year period are presented. Relations between compressor performance drops and the probable causes of malfunctioning have been identified. Some significant results are then presented.

NOMENCLATURE

F	function vector derived from linear regression technique
k	number of dependent variables
M	mass flow rate
n	number of independent variables
N	rotational speed
VN	variable nozzle angular position
p	pressure
P	power
$\mathbf{Q}_m$	vector of measurable quantities along the gas path
$\mathbf{Q}_{wp}$	vector of quantities identifying engine working point
R^2	coefficient of determination
R_a^2	adjusted coefficient of determination
RH	relative humidity
T	temperature
X	vector of independent variables
Y	vector of dependent variables
α	regression curve coefficients of proportionality
η	efficiency
μ	$= \frac{M\sqrt{kRT}}{p}$ mass flow function

Subscripts and Superscripts

amb	ambient
c	gas turbine compressor
f	fuel
m	measurable
o	outlet
p	politropic
wp	working point
’	expected value
¯	average value
*	normalized value

Acronyms

C	compressor
CC	combustion chamber
GGT	gas generator turbine
PT	power turbine
REG	regenerator
CF	centrifugal compressor

INTRODUCTION

In natural gas compression plants, production losses caused by engine stops for maintenance heavily influence management costs.

An accurate maintenance management can be achieved by using techniques that lead to knowledge of actual Engine Health State, since this allows:

- advance planning of engine stops in order to perform them only if necessary;
- a reduction of emergency stops and thus an increase in engine availability;
- adaptation of the gas turbine control logic to its actual Health State so that the loss of performance can be partially recovered.

Engine Operating State can be determined by means of Gas Path Analysis (GPA) techniques, which, starting from measurements taken on the machine, allow the calculation of characteristic parameters (efficiencies, characteristic flow passage areas and pressure drops along the gas path) that are indices of the machine health state (Urban, 1972; Stamatis et al., 1990; Benvenuti et al., 1993, 1994; Bettocchi and Spina, 1999; Bettocchi et al., 2001).

Such techniques have shown the ability to give information on gas turbine operating state, but it has been shown (Urban, 1972; Stamatis et al., 1992; Pinelli and Spina, 2000) that they are affected by some sources of uncertainties that can reduce their reliability. So, it is advisable to support these techniques with other methodologies, such as Trend Analysis. In fact, the analysis of field historical data can lead to a more complete knowledge of engine actual Health State and can support the interpretation of the results obtained with GPA.

A Trend Analysis requires measurements taken in different conditions to be comparable with each other, avoiding actual ambient and load-condition dependence. In this manner, apart from sensor uncertainties, measurement variations over a given period can only be due to gas turbine operating state variation.

In order to perform this analysis, a normalization methodology has been developed. This methodology consists in normalizing the measured value with respect to the expected value calculated in the same boundary conditions and actual working point.

With normalized measurement analysis methodology, measurement variations from the expected value can be related to their probable causes and can allow identification of sensor drifts. Given its simplicity, the methodology can easily be used by plant personnel.

MEASUREMENT NORMALIZATION METHODOLOGY

To obtain readable information from historical data trends, measurements have to be comparable. This can be made by normalizing the measured value with respect to that expected calculated in the same boundary conditions and actual working point. Such expected value can be calculated in two ways:

1. by means of a cycle program. In this case, different situations can occur:
   - the Cycle Deck developed by the manufacturer is available. This cycle program reproduces the characteristic data values of a gas turbine-type, which presents average characteristics among gas turbine units of the same model;
   - a generalized cycle program is available. In this case, the program has to be set up to reproduce the machine type under investigation, for instance by using the performance curves supplied by the manufacturer to the user (Bettocchi et al., 2001).

   Before being used, both Cycle Deck and the generalized cycle program have to be calibrated in order to represent the particular machine under examination.
2. by means of functional relations, obtained, for instance, by using a linear regression procedure. In this case, a baseline condition across gas turbine life has to be identified (for example, the condition after overhaul maintenance). In this condition, it is necessary to have available some measurement sets taken at different loads and ambient conditions. Starting from these sets of measurements, making use of a linear regression technique, it is possible to find relations in the form $\mathbf{Q}_m=F(\mathbf{Q}_{wp})$, through. The relations obtained relate the most significant thermodynamic measurements $\mathbf{Q}_m$ (such as pressure and temperature at the compressor outlet) to ambient and load conditions $\mathbf{Q}_{wp}$ (ambient pressure and temperature, relative humidity, rotational speeds, output power) over the entire gas turbine working point range. The regression procedure has to be performed once for each $\mathbf{Q}_m$ measurement and has to be updated when the chosen baseline condition can be considered no longer representative for the engine. The obtained relations are then used to normalize each measurement.

The methodology described in the first point needs a cycle program, that is rarely available to gas turbine users, while the one described in the second point only requires measurements taken along the gas path and thus can always be applied by the user. In this paper, the second scenario has been considered.

In Fig. 1 the logical scheme for the application of the normalization procedure is shown. Three steps can be recognized:

- acquisition and storage of the raw measurements on the PC of the gas turbine control system. To increase the reliability of the entire methodology, it is necessary to process the data by a FDI system to detect and isolate sensor faults so that unreliable measurement sets are not considered (Spina, 2000; Pinelli and Venturini, 2001);
- calculation of the value for the normalization procedure in the same ambient and load condition. Working point measurements $\mathbf{Q}_{wp}$ are used as inputs in the relations obtained through the linear regression procedure or in the cycle program.

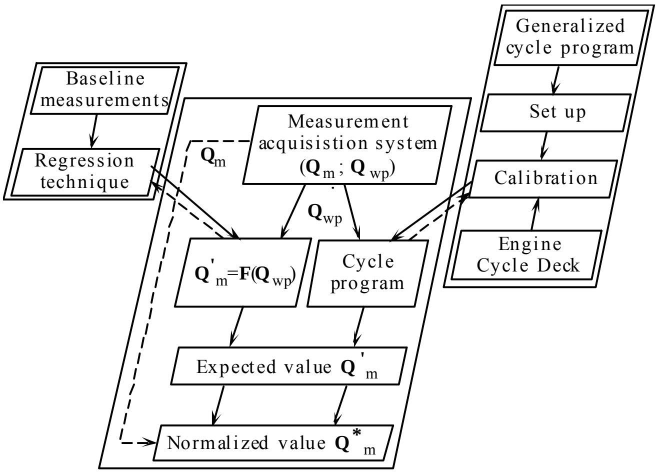

Figure 1 - Normalization procedure

So it is possible to calculate the expected value $\mathbf{Q}'_m$ for each measurement along the gas path;

- calculation of the normalized value $\mathbf{Q}^*_m$ as $\mathbf{Q}_m/\mathbf{Q}'_m$.

The methodology developed can be applied to each measurement set both on line and to historical data. In this latter case, it is necessary to build a database, in order to relate measurement trends to maintenance actions executed during normal engine running. Normalized measurement trend analysis, together with maintenance report availability, allows the identification of relations between performance variations and the causes of malfunctioning.

LINEAR REGRESSION PROCEDURE

The calculation of the expected values $\mathbf{Q}'_m$ can be performed applying linear regression techniques. In a linear regression model (Neter et al., 1996), the response variable Y_j depends on the X_i independent variables in a linear form. In this particular case, the Y_j variables are the quantities Q_{mj} measured along the gas path, while the X_i variables are the working point measurements $\mathbf{Q}_{wp}$. For the *j*th variable Q_m, the implicit relationship $\mathbf{Q}_m = F(\mathbf{Q}_{wp})$ can be expressed as

$$Q_{mj} = \alpha_{0j} + \sum_{i=1}^{n} \alpha_{ij} Q_{wp_i} \qquad j=1,\ldots,k \qquad (1)$$

where α_{ij} are constants of proportionality.

To choose the best set (number and type) of independent variables, the coefficient of determination R^2 and the adjusted coefficient of determination R_a^2 can be used. The quantity R^2 measures how strongly the dependent variable depends on the independent variables. When $R^2 = 1$ there is perfect dependence with no scatter, while $R^2 = 0$ implies no dependence. The adjusted coefficient of determination R_a^2 takes into account the number of dependent variables through the degrees of freedom: the closer the value R_a^2 is to the value of R^2, the less it is useful to add other independent variables to the model.

This mathematical procedure was applied to field measurements taken on a gas turbine.

Considering the measurements taken during a performance test performed after overhaul maintenance as baseline, it was possible to obtain the relations used for the normalization procedure. Different functional dependencies from independent variables were tested and the following relations were finally established

$$p'_{oc} = f_1\,(N_{GGT},\, T_{amb}) \qquad (2)$$

$$T'_{oc} = f_2\,(N_{GGT},\, T_{amb}) \qquad (3)$$

In relations (2) and (3), according to physical dependencies of p_{oc} and T_{oc}, the considered variables do not depend on P_{PT} and N_{PT}, while it was not possible to relate p'_{oc} e T'_{oc} to the ambient pressure and relative humidity, since these latter measurements were almost constant for all measurement sets. In Table 1, the values for R^2 and R_a^2 are reported. The values of R^2 are very close to one and indicate very strong dependence, while the values of R_a^2 suggest that the independent variables considered are all significant. The comparison between baseline measurements and their values calculated by means of the linear regression model are shown in Figure 2 for p_{oc} and T_{oc} respectively. In both Figures, the good accordance between calculated and baseline values can be noticed.

Exhaust gas temperature expected value T'_{ot} could not be calculated by means of regression techniques as a function of ambient and load conditions, since the measured values for T_{ot} remained constant for all baseline measurement sets.

Table 1 – R^2 and R_a^2 values for p'_{oc} and T'_{oc}

	R^2	R_a^2
$\mathbf{p'_{oc}}$	0.9944	0.9941
$\mathbf{T'_{oc}}$	0.9989	0.9988

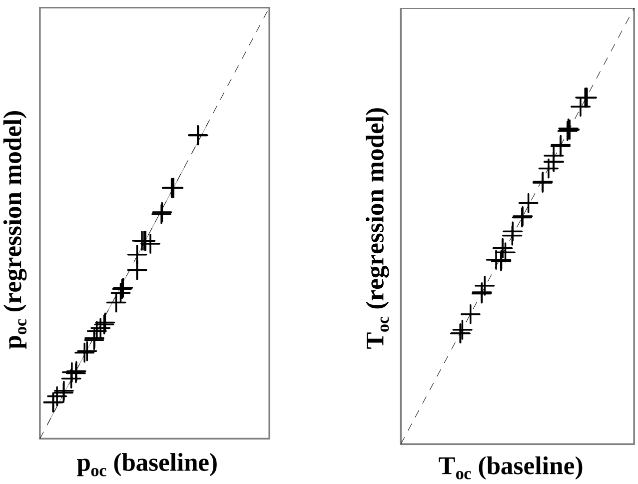

Figure 2 - Comparison between baseline measurements and calculated values for p_{oc} and T_{oc} (“------“: perfect match between regression and baseline values)

APPLICATION OF NORMALIZATION METHODOLOGY

The methodology was applied to field measurements taken on a 5 MW regenerative gas turbines with power turbine variable nozzles. The gas turbine is used as mechanical drive in a natural gas compression station.

Table 2 shows the measurements available on the machine. Only historical trends for outlet compressor pressure and temperature (p_{oc} and T_{oc}) have been used to apply the methodology and so only the behavior of the axial compressor could be investigated in detail.

Normalized historical data analysis was carried out over a period of two and a half years. By means of maintenance reports, it was possible to relate performance drop and maintenance actions to the corresponding measurement variations.

During the period considered, overhaul maintenance was performed and the gas turbine compressor was powered by adding an additional stage. Such condition was considered as reference for the engine, i.e. the measurements taken during a performance test performed after overhaul maintenance were chosen as baseline for the linear regression procedure.

Results and discussions

In Figures 3a and 3b, field measurements of outlet compressor pressure p_{oc} and temperature T_{oc} and the normalized trends of politropic efficiency η^*_{pc}, outlet compressor pressure p^*_{oc} and temperature T^*_{oc} for the period 6/16/1997 - 1/16/2000 are reported respectively.

As can be seen, from the analysis of raw data distributions (Fig. 3a) it is not possible to obtain any significant information either on measurement reliability or about compressor operating state. For instance, in the last part of the period considered, compressor performance seems to improve, since p_{oc} increases, while T_{oc} decreases. Such unexpected behavior is correctly interpreted by means of the analysis of normalized data. In fact, in Fig. 3b, the application of the normalization procedure makes it possible to easily identify the days in which maintenance took place. Thus, it is possible to quantify the drop in performance in terms of p^*_{oc} and η^*_{pc} and the recovery after maintenance.

Table 2 – Measurements stored on engine control panel

Q_m measurements	Q_{wp} measurements
p_{oc}: outlet compressor pressure	T_{amb}: ambient temperature
T_{oc}: outlet compressor temperature	p_{amb}: ambient pressure
T_{ot}: exhaust gas temperature	RH: relative humidity
Δp_{filter}: pressure drop at compressor intake	N_{GGT}: gas generator turbine rotational speed
NGV: variable nozzle angular position	N_{PT}: power turbine rotational speed
T_3: temperature at the recuperator outlet (air side) T_7: temperature at the recuperator outlet (gas side)	P_{PT}: power output (calculated)

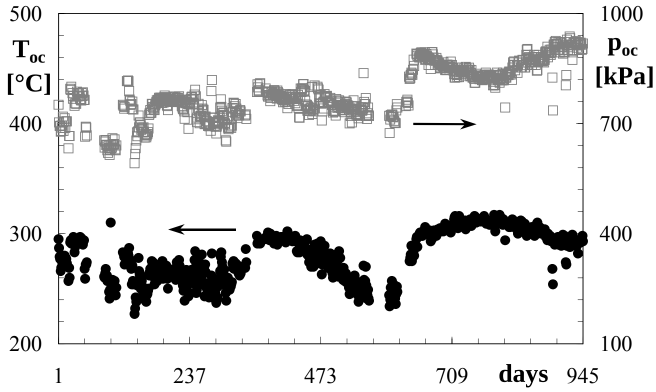

Figure 3a - Field measurements of outlet compressor pressure p_{oc} ("□") and temperature T_{oc} ("●")

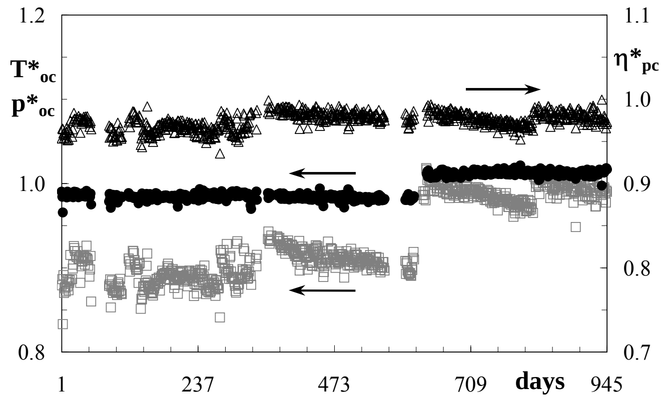

Figure 3b - Normalized values of politropic efficiency η^*_{pc} ("Δ"), outlet compressor pressure p^*_{oc} ("□") and temperature T^*_{oc} ("●")

The analysis was focused on the axial compressor, aiming at establishing relations among performance drops, performance recovery after maintenance and normalized measurement trends.

In Fig. 4 and 5, the normalized value trends of the compressor outlet pressure (p_{oc}), temperature (T_{oc}) and politropic efficiency (η_{pc}) are reported for the period 6/1/1999-12/30/1999 (Period 1) and 8/1/1998-12/27/1998 (Period 2) respectively. In the former, a compressor wash was performed, while, in the latter, a 8000 h maintenance occurred.

Furthermore, in the Figures measurement reliability bands were reported. A measurement lying within the bands is to be considered acceptable, outside, it is unacceptable. In the latter case, measurements must be excluded from the gas turbine diagnosis process to avoid incorrect evaluations of the machine operating state.

The upper and lower bands were fixed at +3% and –4% around the trend value of the compressor outlet pressure, and at +5.5% and –1% around the trend value of the compressor outlet temperature. These values were chosen according to (Pinelli and Venturini, 2001): (i) measurement uncertainty, considering typical values for sensor inaccuracy in industrial applications; (ii) measurement variations due to faults, calculated by simulating, through the machine thermodynamic cycle program, the most common faults that can occur on a gas turbine.

In Fig. 4 an appreciable increase in the normalized values of the compressor outlet pressure and politropic efficiency can be noticed, while compressor outlet temperature remains almost constant. This highlights the fact that the off-line wash seems to have a positive influence on the compressor performance recovery. In the same Figure, it is possible to notice that the outlet compressor pressure measurement in day 891 (black symbol) lies out of the reliability bands and thus has to be considered not acceptable for diagnostic tool processing.

In Fig. 5, the case of 8000 h maintenance performed across days 463-465 is reported. In these days, a compressor wash was performed during a scheduled stop. The measurement trend analysis underlines that the compressor wash was probably not necessary, since it did not cause a significant improvement of the compressor performance. Thus, in this case, the scheduled maintenance could have been useful to prevent other possible faults (mechanical damage, lubrication system faults, etc.), but the off-line wash seems to be redundant.

Compressor wash effectiveness was tested for the two gas turbines over the period under examination. In the plant considered washes are performed every six months or whenever a scheduled maintenance requires an engine stop.

In Fig. 6, the average values of compressor outlet pressure and politropic efficiency drops between two off-line washes and the subsequent performance recovery are shown. The values reported were calculated as average values on all the washes performed during the period under investigation. It was found that the average decrease for outlet compressor pressure is about 3.6%, while for politropic efficiency the value is near to 1.5%. As can also be seen, since performance recovery was almost complete, washes were effective and, so, the significant drop in p^*_{oc} and slight decrease in η^*_{pc} can be attributed to compressor fouling.

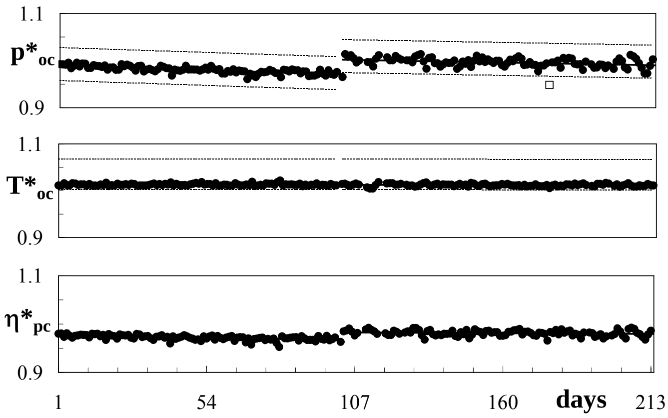

Figure 4 – Period 1: Acceptable ("●") and not acceptable ("□") normalized values of compressor outlet pressure p^*_{oc}, and temperature T^*_{oc} and politropic efficiency η^*_{pc}.

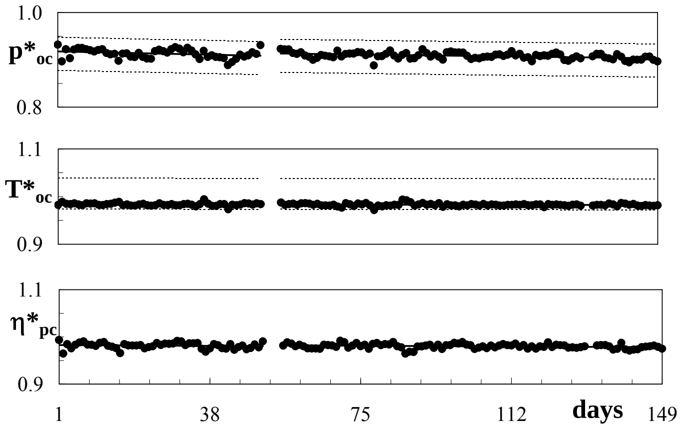

Figure 5 – Period 2: Acceptable ("●") normalized values of compressor outlet pressure p^*_{oc} and temperature T^*_{oc}, and politropic efficiency η^*_{pc}.

The results were tested through an inverse solution of a cycle program calibrated on the engine.

The program can determine, starting from measurements, the machine actual operating state by adapting the gas turbine characteristic parameters (Bettocchi et al., 2001).

As inputs of the cycle program, outlet compressor pressure p_{oc} was varied by 3.58% with respect to its nominal value, while the outlet compressor temperature T_{oc} was kept equal to its nominal value. After the calculation, percentage variations between computed and reference values for compressor efficiency η_c and mass flow function μ_c were found to be 0.98 and 0.95 respectively, values that are considered, by some authors, representative of compressor fouling (Diakunchak, 1992, Zhu and Saravanamuttoo, 1992).

The calculated output power was found to decrease by about 7.5% because of fouling, while it was almost equal to its nominal value after washes.

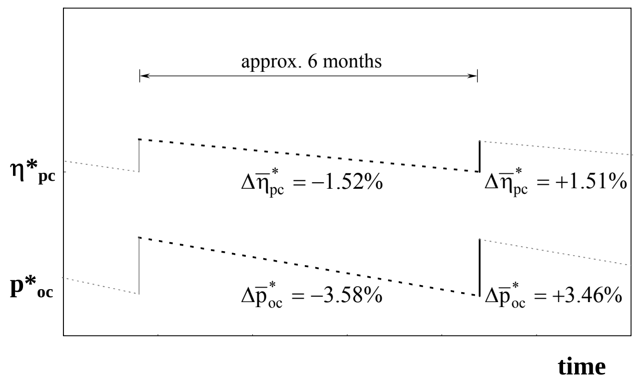

Figure 6 – Average compressor outlet pressure and politropic efficiency drops between two off-line washes (-----) and due to wash recovery (——)

CONCLUSIONS

In this paper a methodology for gas turbine operating state determination based on normalized measurement trend analysis has been presented.

The main features of the methodology are:

- capability to support Gas Path Analysis techniques, since, taking into account previous engine history, it allows better knowledge of machine operating state and a more comprehensive interpretation of the results;
- application both on line and to field historical measurements;
- ease of implementation on PC and of use by plant personnel;
- supply of immediate and easy-to-read information.

Some results of the application of the methodology for the operating state determination of a 5 MW gas turbine working in a natural gas compression plant have been presented. The analysis of the normalized measurement trends permitted the identification of relations between performance drops and the probable causes of malfunctioning.

In particular, for the gas turbine under consideration, it was possible to quantify the performance drop caused by compressor fouling and the recovery due to compressor wash. The results, expressed in terms of normalized outlet pressure and temperature and politropic efficiency, highlighted the capability of the methodology developed.

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