Proceedings of
ASME TURBO EXPO 2002
June 3 – 6, 2002 Amsterdam, The Netherlands

GT-2002-30248

APPLICATION OF METHODOLOGIES TO EVALUATE THE HEALTH STATE OF GAS TURBINES IN A COGENERATIVE COMBINED CYCLE POWER PLANT

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ABSTRACT

In the paper, a comprehensive methodology for gas turbine health state determination is applied to a single-shaft Fiat Avio TG 20 gas turbine working in the cogenerative combined cycle power plant of Fiat – Mirafiori (Italy).

In order to determine operating state variations from new and clean condition, the following procedures were applied to historical field measurements:

- normalization procedure to determine the variations between measured and expected values;
- inverse cycle technique to calculate the values of the characteristic parameters that are indices of the machine health state.

The application of these techniques to long period operating data allowed measurement validation and the determination of the machine health state. The results showed the good capability of the developed techniques for the determination and the analysis of performance drop due to compressor fouling and to turbine malfunction.

NOMENCLATURE

k	ratio of specific heats at constant pressure and volume
f	function obtained through linear regression
F	correction factor
M	mass flow rate
N	rotational speed
p	pressure, period
P	power
Q	measurement used for the diagnostic assessment
R	gas constant
R^2	coefficient of determination
R_a^2	adjusted coefficient of determination
T	temperature
η	efficiency
μ	$= \frac{M\sqrt{kRT}}{p}$ mass flow function

Subscripts and Superscripts

amb	ambient
c	compressor
CC	combustion chamber
GTCC	gas turbine combined cycle
cond	condenser
CP	normalized by means of cycle program
HP	high pressure
HR	heat rate
f	fuel
i	inlet section
LP	low pressure
o	outlet section
t	turbine
GT	gas turbine
LR	normalized by means of linear regression functions
'	expected value
*	normalized value

INTRODUCTION

Combined cycle power plants can achieve very good economic performance depending on several factors such as high efficiency, low maintenance costs and good availability. In order to achieve efficient management, knowledge of the plant actual operating state and, in particular, of the gas turbine health state is required (Zwebek and Pilidis, 2001). In fact, gas turbine degradation reflects on the complete combined cycle plant, which can lead to relevant power losses or, in the worst cases, to downtime for the whole plant. In particular, this latter case may occur when no supplementary firing is present in the heat recovery steam generator and both gas and steam turbines drive the same alternator, as in the combined cycle plant under investigation.

The analysis of the gas turbine operating state can be performed either by means of techniques based on the analysis of historical measurement trends (Trend Analysis) or especially by using methodologies that allow the determination of some characteristic parameters that are representative of the machine actual health state (Gas Path Analysis).

Trend Analysis can be used to analyze measurement variations from their expected values so that the probable causes of such deviation can be identified (Pinelli and Venturini, 2001a,b). To obtain readable information from historical measurement trends, data have to be homogenized through a process called normalization: each measurement taken on the gas turbine is divided by its expected value calculated in the same boundary conditions and actual working point so that the variations of the normalized measurements are only due to a change in the machine operating state or to a fault in the measurement system. The expected value can be obtained by means of a cycle program or through a linear regression algorithm.

The use of the Trend Analysis technique alone, though it provides immediate and easy-to-read information, can not lead to the determination of the causes of the machine malfunction. For this reason, Gas Path Analysis techniques have been developed in recent years (Bettocchi and Spina, 1999)so that more detailed information about the actual health state can be obtained by means of the determination of characteristic parameters that are indices of the actual operating state. Such techniques have shown good capability as diagnosis tools. The technique adopted in the paper determines the gas turbine operating state by means of characteristic parameters.

In the paper, the two above-mentioned methodologies for the diagnosis of gas turbine health state are applied to a single-shaft Fiat Avio TG 20 gas turbine working in the cogenerative combined cycle power plant of Fiat – Mirafiori (Italy).

Gas turbine health state is determined by evaluating the variations of the parameters with respect to the expected values in the new and clean condition. In order to do this, the following procedures are applied:

- a normalization procedure to determine the variations between measured and expected values;
- the inverse cycle technique to calculate the values of the characteristic parameters that are indices of the gas turbine health state.

The normalization technique was performed by calculating the expected value by means of a cycle program calibrated on the machine under investigation used in direct mode. A comparison between the results obtained by using the cycle program and the linear regression algorithm is also presented. Then, it was possible to determine the gas turbine health indices by means of the cycle program inverse solution.

The application of these techniques allowed measurement validation and the determination of the machine health state. The most convincing results deriving from the analysis of historical operating data over a six-month period are presented and discussed, showing the good capability of the developed techniques. In particular, performance drop due to compressor fouling was established and studied in detail.

TECHNIQUES FOR OPERATING STATE ANALYSIS

Trend Analysis - Normalization technique. Trend analysis can be performed by means of normalization techniques which allow measurements taken in different working points to be comparable with each other. In the paper, Q measurements used for the operating state determination are normalized with respect to the expected value calculated by means of a cycle program. The cycle program, calibrated on the particular gas turbine, calculates the expected value of the Q measurements as a function of the measurements defining the gas turbine working point.

The expected values can also be calculated through relations obtained by means of a linear regression procedure (Pinelli and Venturini, 2001a,b).

The normalization technique allows:

- measurement validation, through the definition of measurement acceptability bands;
- qualitative information about measurement trend and, as a consequence, about gas turbine operating state variation to be obtained.

Gas Path Analysis - Inverse cycle calculation technique. The Gas Path Analysis technique adopted in the paper calculates the values of the gas turbine characteristic parameters of each component (efficiency, flow function, pressure drop) by means of a cycle program solved in inverse mode (Bettocchi and Spina, 1999). Starting from the measurements taken on the machine, the cycle program adapts the values of the characteristic parameters until the measurements are reproduced.

The analysis of the variations of the characteristic parameters (indices of the gas turbine health state) from their expected values in the "new and clean" condition allows the determination of the machine actual operating state.

The use of both normalization and inverse cycle calculation techniques permits an improvement in measurement reliability and in the accuracy of operating state determination since the operating state analysis can be supported by information about the time evolution of all the quantities. In Fig. 1, a logical scheme of the process is reported.

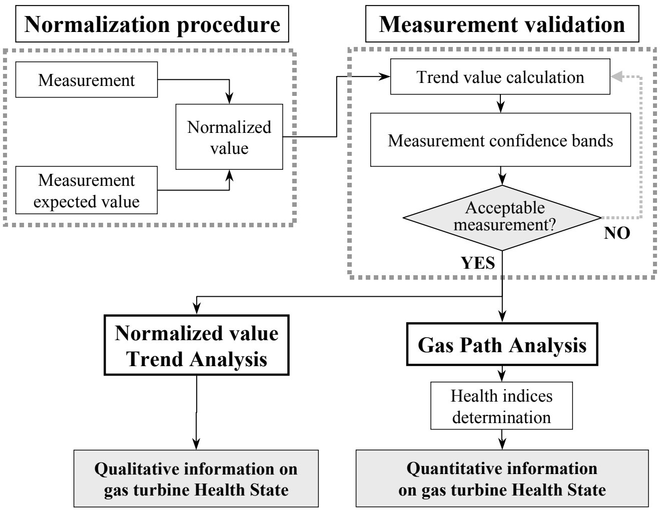


Figure 1 – Comprehensive methodology for gas turbine health state determination

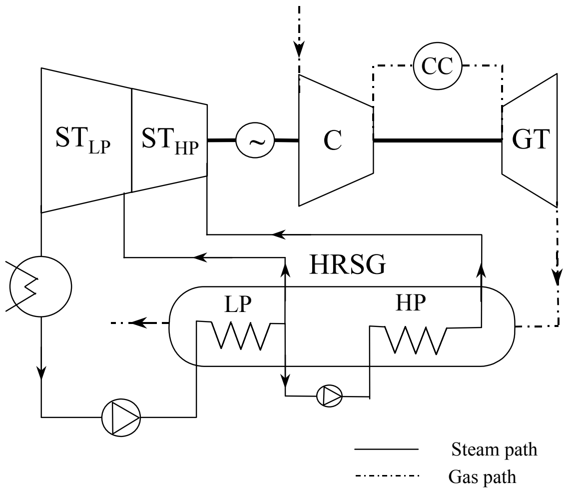


Figure 2 – Combined cycle power plant simplified lay out

Table 1 - GTCC power plant available measurements

Gas turbine	Steam cycle
T_{ic}: inlet compressor temperature	p_{HP}: HP steam inlet pressure
p_{amb}: ambient pressure	T_{HP}: HP steam inlet temperature
N: rotational speed	M_{HP}: HP steam mass flow rate
P_{GTCC}: combined cycle power output	P_{LP}: LP steam inlet pressure
p_{oc}: outlet compressor pressure	T_{LP}: LP steam inlet temperature
T_{oc}: outlet compressor temperature	M_{LP}: LP steam mass flow rate
T_{ot}: exhaust gas temperature	T_{cond}: condenser temperature
M_f: mass flow rate	

GENERALIZED CYCLE PROGRAM SET UP

Available data. The machine under investigation is a single shaft 38 MW FiatAvio TG20 gas turbine working in the cogenerative combined cycle power plant of Fiat – Mirafiori (Italy), whose simplified lay out is reported in Fig. 2. The available measurements are reported in Table 1.

The available data cover a seven months period (208 days) from April to October. The measurements were taken during normal running with a frequency of five/six times per day. Regarding the available measurements it is to notice that: (i) the relative humidity was not recorded (following the ISO standard day, a constant value of 60% has been adopted throughout the calculations); (ii) the ambient pressure was recorded only once a day.

The measured quantity P_{GTCC} is the net power output of the whole combined cycle that is equal to the sum of the steam and gas turbine power outputs. Since the gas turbine power output was not measured directly, P_{GT} was estimated by calculating the steam turbine power output through the available steam path measurements and by subtracting this quantity from the total power output P_{GTCC}. To perform the calculation, an alternator efficiency equal to 0.97 (nominal value) was assumed and both high and low pressure steam turbine isentropic efficiencies were considered in accordance with operating curves supplied by the user. Steam turbine aging was not taken into consideration.

For the period under examination, maintenance reports were not available. Nevertheless, the analyses developed below allowed the identification of the probable maintenance actions performed and their consequences on engine health state, showing the capability of the presented methodologies.

Cycle program set up. The first step for the application of both techniques is the set up of a generalized cycle program on the machine under investigation. The set up phase consists in adapting compressor and turbine generalized non-dimensional performance maps until the behavior of the machine type under investigation is represented as accurately as possible (Bettocchi et al., 2001). The set up was performed by using the design data that are representative of the average characteristics of the machine type under investigation. In Fig. 3, the results of the set up process are reported. In the Fig., the curves supplied by the manufacturer are compared to those calculated by means of the cycle program. Such curves report the correction factors for the heat rate (Fig. 3a) and for the power output (Fig. 3b) versus ambient temperature.

The two curves are reported for ambient temperature values in the range 5÷30 °C. In fact, temperatures above 30 °C were never encountered along the period under investigation and temperatures below 5 °C were never reached owing to the presence of the anti-icing system. As can be seen, the agreement between the manufacturer curves and the calculated ones is very good for the heat rate curve which presents an uncertainty which is nearly negligible. The power output curve is underestimated by the program in the entire ambient temperature range considered, with a maximum disagreement of ≈ 2 % for T_{amb} = 5 °C. Nevertheless, the accordance between the two curves has been judged satisfactory.

APPLICATION OF THE NORMALIZATION TECHNIQUE

Measurement normalization is performed by dividing each measured value by its expected value calculated in the same ambient and load conditions. The expected value can be determined by using either the previously set up cycle program (CP technique) or a linear regression based procedure (LR technique). Both techniques were applied, but only the results derived by CP technique are presented in detail, since they were considered more reliable. A comparison between the results obtained by using the two techniques is presented at the end of this paragraph to assess both procedure capabilities.

All the available measurements, p_{oc}, T_{oc}, T_{ot} and M_f were normalized and used for gas turbine health state determination, while the other measurement were used by the cycle program to determine the engine working point.

The subsequent step for the application of the normalization technique is the determination of measurement acceptability bands. These bands define whether a measurement has to be considered reliable or not, according to both measurement uncertainty and maximum variations of measurements due to malfunction (Pinelli and Venturini, 2001a,b). In this way, unrealistic measurements are recognized and can be discarded. On the other hand, a normalized measurement value which lies outside measurement uncertainty limit but within acceptability band can be due to a sensor fault or to an incipient component fault. A subsequent analysis through either the inverse cycle technique or a sensor fault diagnosis procedure (not performed in the paper; see Spina, 2000, for sensor Fault Diagnosis and Identification techniques commonly used in gas turbine applications) can detect the cause of the deviation from the trend.

The variations of each measurement due to gas turbine malfunction, reported in the first column of Table 2, were obtained by using the previously characterized cycle program. The cycle program was run imposing percentage variations of the characteristic parameters (efficiency and/or mass flow function for each component) representative of some of the most common faults that can occur on a gas turbine. In this way, the corresponding variations of all the measurements were obtained.

The faults that were considered for the calculation are those classified as sudden faults, since measurement variations due to aging or deterioration are taken into account by means of the normalization process.

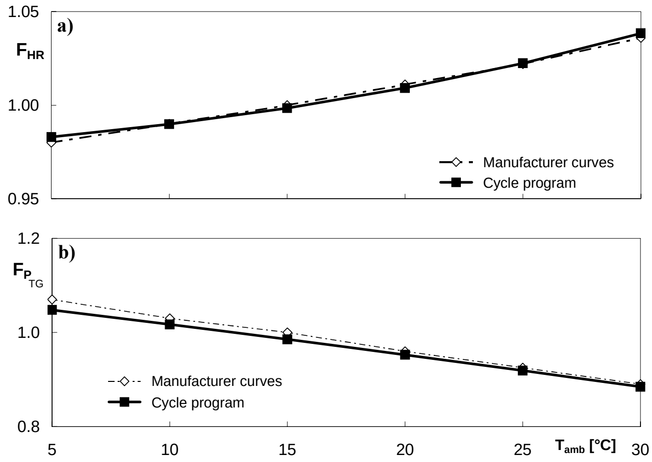


Figure 3 – Heat rate (a) and power output (b) correction factor curves

Table 2 - Measurement maximum variations due to malfunction and to sensor uncertainty: acceptability band calculation

	Variation due to malfunction [%]	Measurement uncertainty [%]	Acceptability band [%]
T_{oc}	[-0.5; +3.1]	±0.8	[-1.3 ; +3.9]
p_{oc}	[-5.0; +1.7]	±1.0	[-6.0; +2.7]
T_{ot}	[+0.6; +5.7]	±1.0	[-1.0; +6.7]
M_f	[+0.7; +6.8]	±2.0	[-2.0; +8.8]

Since measurements were taken using standard machine instrumentation during normal operation, typical values of industrial sensor accuracy, reported in the second column of Table 2, were adopted.

The p_{oc} and T_{oc} acceptability band amplitude, reported in the third column in Table 2, was then calculated as the sum of the values reported in the first two columns. Regarding T_{ot} and M_f, since their variations due to malfunction are always positive, the lowest value of the acceptability band was considered equal to measurement uncertainty. The acceptability band was then centered around the trend value.

A measurement is considered acceptable when its normalized value lies within the acceptability bands. If this is not verified the measurement should not be processed by the diagnostic tool because of its unreliability.

In Figs. 4a through 4d, the raw and normalized values of the available measurements (p_{oc}, T_{oc}, T_{ot} and M_f) over the period under consideration are shown. Raw measurements are divided by a constant value to be plotted together with normalized values. As can be noticed, raw data analysis does not provide useful information about gas turbine health state because of the marked scatter. On the other hand, the analysis of the normalized measurements makes it easier to identify three significant periods: period p_1 (days 1÷51), period p_2 (days 60÷114) and period p_3 (days 161÷209). After each period, the normalized measurements show a performance recovery that can be attributed to an off-line wash. For all the quantities investigated, fluctuations around the trend line can be observed (in particular for period p_1). This behavior can be attributed to the lack of the relative humidity measurement (Mathioudakis and Tsalavoutas, 2001) and, in a lesser degree, to daily variations of the ambient pressure.

- *Outlet compressor pressure p_{oc}*. The analysis of p^*_{oc} trend (Fig. 4a) allows the identification of the periods when off-line washes were performed. As can be observed in the Figures, off-line washes are characterized by a quite complete recovery.
- *Outlet compressor temperature T_{oc}*. The almost constant trend of T^*_{oc} along the periods (Fig. 4b), together with the decrease in p^*_{oc}, is a clear indication of the compressor fouling.
- *Fuel mass flow rate M_f*. In Fig. 4c, the beneficial effect of normalization is particularly put into evidence. Mass fuel flow rate raw measurements are characterized by a marked scatter and by a trend which is decreasing (period p_1 e p_2) or almost constant (period p_3). At the contrary, M^*_f normalized values remain almost constant across periods p_1, while they slightly increase across periods p_2 and p_3 as expected when the machine is subjected to progressive performance deterioration. However, it is also to be noticed that, in period p_2, also normalized values present a significant scatter.
- *Exhaust gas temperature T_{ot}*. In the plant under consideration, the exhaust gas temperature T_{ot} is kept almost constant. In fact T_{ot} higher value is controlled by the gas turbine control system (for the case considered, the threshold value is equal to 520 °C), while its lower value is limited by the steam cycle. Raw T_{ot} measurements present a strong decrease followed by a progressive increase across two weeks during period p_1. In fact, in that period, power output was lowered to 80 % of its nominal value. In any case, such consistent load variation did not influence the normalization nor the inverse cycle technique results. In fact, In Fig. 4d, the T^*_{ot} trend increases across the whole period considered, according to the fact that T_{ot} is the most sensitive measurement on health condition.

The application of acceptability bands to normalized measurement values puts into evidence that p^*_{oc} and T^*_{oc} normalized measurement values can all be considered reliable. Regarding T^*_{ot} and M^*_f, as can be seen in Figs. 4c and 4d, some measurements are not acceptable (black triangles) and, thus, the corresponding measurement sets were not processed by the inverse cycle technique.

LR and CP based normalization technique comparison. The expected value of each measurement for the application of the normalization technique can also be calculated through relationships obtained by means of a LR technique (Pinelli and Venturini, 2001a,b). The obtained relations relate Q

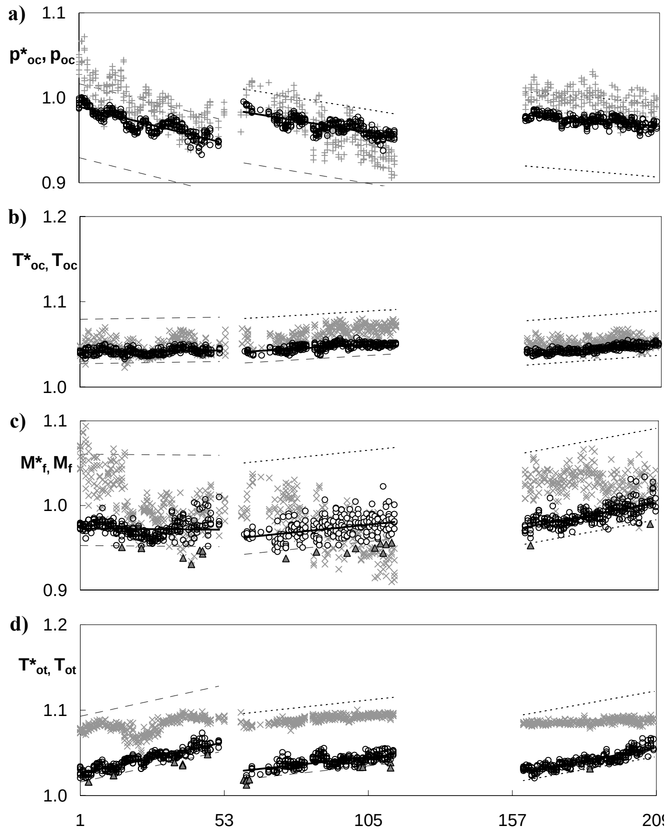


Figure 4 – Measurement values: (x) raw measured values; (○) normalized values; (---) acceptability bands; (—) trend lines, (▲) unacceptable measurements

measurements to the measurements defining the gas turbine working point. To determine such relations, a reference condition (baseline period) in which measurements taken on the machine can be regarded as representative of the gas turbine behavior has to be identified. The period chosen as baseline to obtain the relations covered eight operating days between the end of May and the beginning of June. A total amount of 44 sets of measurements were taken during the days considered. This period was chosen since in that period the gas turbine was run at part load and, thus, measurements at various working point were available. The following relations were then established:

$$p'_{oc}, T'_{oc}, M'_f, T'_{oc} = f_i(T_{ic}, N, P_{GT}), \quad i=1,\dots,4 \quad (1)$$

In Table 3, the values of the coefficient of determination R^2, which expresses how strongly the dependent variable depends on the independent variables (Neter et al., 1996), and of the adjusted coefficient of determination R_a^2 are reported. The R^2 values are close to 1, which represents the best fit. In Table 3, it is also possible to notice that R_a^2 values are all close to the corresponding R^2 values: this means that the considered independent variables are all significant.

Table 3 - R^2 and R_a^2 values for p'_{oc}, T'_{oc}, T'_{ot} and M'_f

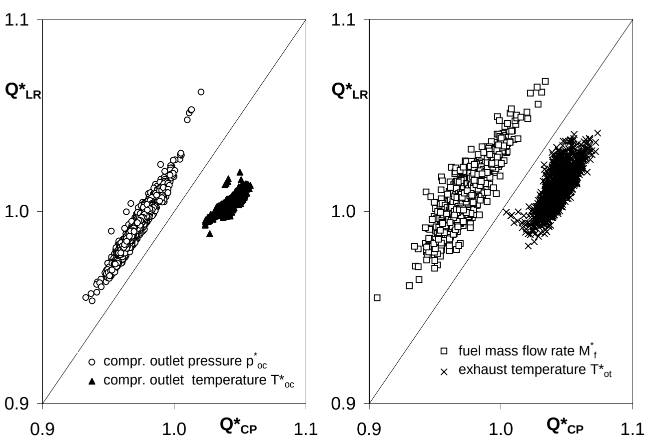
	R^2	R_a^2
p'_{oc}	0.9564	0.9531
T'_{oc}	0.9570	0.9538
T'_{ot}	0.9801	0.9787
M'_f	0.9945	0.9941

In Figs. 5a and 5b, a comparison between the normalized measurement values obtained by using the cycle program and by using the linear regression procedure is shown. A bias error due to a scaling factor can be observed for all the measurements. This is due to the fact that Eqs. (1) were calculated starting from measurements taken during a period different from the one used to calibrate the cycle program. Apart from this, a good agreement can be observed for p^*_{oc} and T^*_{oc}, while M^*_f and T^*_{ot} distributions are more scattered. In any case, the results obtained by using the two techniques are comparable each other.

The main advantage of the LR technique is that normalization can always be performed, since its application only requires measurements taken on the engine, while the CP technique needs the availability of a cycle program. The information provided by the LR technique is more qualitative, but easy-to-read and immediate.

APPLICATION OF THE INVERSE CYCLE CALCULATION TECHNIQUE

Starting from the four available Q measurements (outlet compressor pressure p_{oc}, outlet compressor temperature T_{oc}, exhaust gas temperature T_{ot} and mass flow rate M_f), the cycle program solved in inverse mode allows the calculation of four health indices. The other available measurements (inlet compressor temperature T_{ic}, rotational speed N and gas turbine power output P_{GT}) are used to determine the machine working point.



(a) (b)

Figure 5 – Comparison between LR and CP measurements normalization

The health indices were chosen to be efficiency and mass flow function of the compressor and turbine (η_C, μ_C, η_T and μ_T respectively), since they are the most significant for the analysis of engine operating state and the ones which minimize calculation inaccuracy (Pinelli and Spina, 2000; Pinelli and Venturini, 2001a).

In Figs. 6a and 6b, the values of compressor efficiency and mass flow function are reported. As it can be noticed, both compressor efficiency and mass flow function trends are decreasing, while a performance recovery can be observed at the end of periods p_1 and p_2.

As previously derived from the analysis of the results of the normalization technique, such periods highlight the moments in which off-line washes were performed. The quantitative analysis of the results confirms that such behavior can be attributed to compressor fouling. The fluctuating trend of the mass flow function and of the compressor efficiency within each period can be explained through the same considerations made for the fluctuations of the normalized measurements.

Considering the turbine, a slightly increasing trend of both turbine efficiency η_t and mass flow function μ_t can be observed from Figs. 7a and 7b. A noticeable scatter of the η_t and μ_t health indices at the end of periods p_1 and p_2 was also observed.

In Fig. 8, the heat rate trends due to compressor and turbine malfunctions are reported separately. Such values were calculated by means of the cycle program: power output was equal to the P_{TG} value, calculated from the measured value P_{GTCC}, and the actual health index values were imposed separately for the compressor and the turbine. Then, the heat rate values that were obtained were divided by the overall gas turbine heat rate calculated in "new and clean" conditions (i.e. all health indices equal to 1). As can be seen, the trend of the heat rate due to the turbine malfunction alone is decreasing, according to turbine efficiency η_t and mass flow function μ_t trends reported in Figs. 7a and 7b. Such behavior, though not expected from a physical point of view, can be found when a combination of gas turbine malfunctions and T_{ot} estimation error occurs, as will be shown below.

Finally, the gas turbine overall heat rate was also reported in Fig. 9, since this quantity can always be calculated, starting from the measurements that are usually available.

RESULTS AND DISCUSSION

The numerical results deriving from the CP normalization procedure and from the inverse cycle technique are summarized in Table 4. Percentage variation of each quantity was obtained from values which the interpolating line assumes at the beginning and end of each period. In the Table, a positive variation means an increase across the considered period, while the negative sign means a decrease.

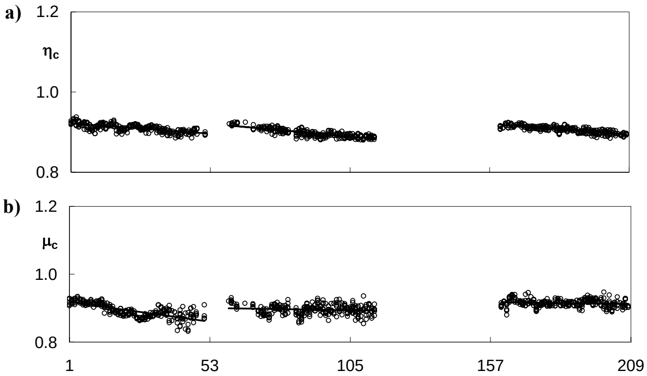


Figure 6 – Compressor efficiency η_c (a) and mass flow function μ_c (b)

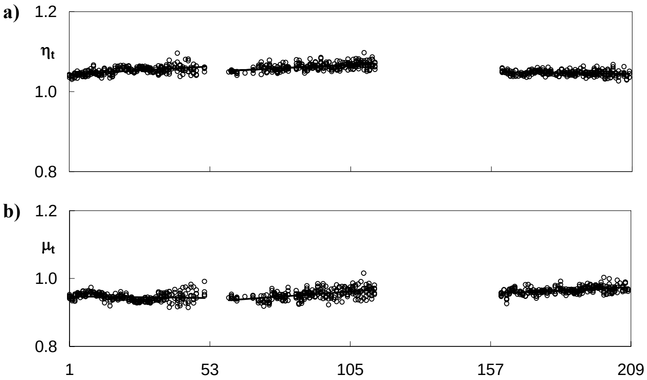


Figure 7 – Turbine efficiency η_t (a) and mass flow function μ_t (b)

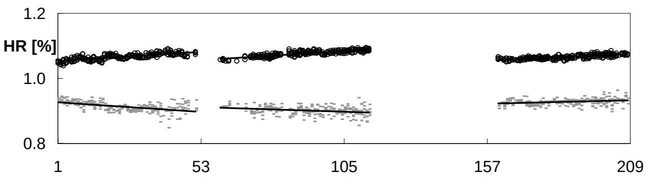


Figure 8 – Heat rate trend due to compressor (○) and turbine (-) malfunction

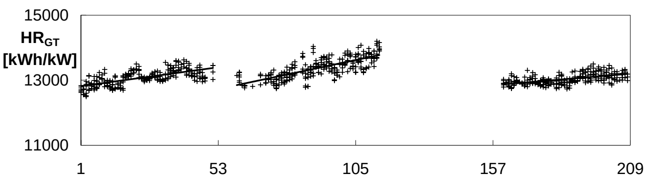


Figure 9 – Gas turbine overall heat rate

Since maintenance reports were not available, the following considerations have to be considered an interpretation of the numerical results obtained.

- *Compressor performance.* Across period p_1, the mass flow function μ_c decreases more than the efficiency η_c, with a ratio slightly higher than 2: such condition is considered by many authors (Lakshminarasimha and Saravanamuttoo, 1985; Diakunchak, 1992; Zhu and Saravanamuttoo, 1992; Lakshminarasimha et al., 1994; Pinelli and Venturini, 2001b; Zwebek and Pilidis, 2001) as a reliable index of compressor fouling. In particular, Zwebek and Pilidis (2001) assess that fouling can be represented by μ_c and η_c ratio equal to 2. Moreover, across period p_1, compressor deterioration due to fouling seems to be rather rapid since p^*_{oc} decreases by about 2% per month instead of 0.6 % per month, as reported by Pinelli and Venturini (2001b). However, the significant drop in p^*_{oc} (-4.1 %) can be attributed only in small part to compressor fouling and implies that another malfunction may have occurred, i.e. stator turbine erosion, as shown below. During periods p_2 and p_3, compressor fouling seems not to be as severe as it was previously observed for period p_1. In fact, a decrease in only compressor efficiency η_c was found, while the mass flow function μ_c remains almost constant. This combination of characteristic parameter variations is attributed by Zhu and Saravanamuttoo (1992) to compressor mechanical damage (compressor efficiency decrease alone equal to 5 %). Thus, in the case under investigation, the damage is not as significant as that reported by these two authors, since the actual compressor efficiency decrease is about 3.3 %.
- *Turbine performance.* Calculations made across periods p_1 and p_2 highlighted an increase in the turbine efficiency η_t. This result seems to be contradictory for a machine which is deteriorating because of aging. Mac Leod et al. (1992), who investigated experimentally the effects of first stage turbine erosion on the performances of a single shaft engine, found out that this deterioration caused an increase of the turbine efficiency, in conjunction with other effects (increase of fuel mass flow rate and overall heat rate). The calculations presented in this paper seem to agree with the results presented by Mac Leod et al. (1992), and, thus, an erosion of

Table 4 - Normalized measurement and health index drops and performance recovery [%]

Period	p_1	*recovery*	p_2	*recovery*	p_3
Meas.	261		289		258
Days	50		55		48
$\mathbf{p^*_{oc}}$	-4.1	*3.5*	-2.9	*2.6*	-1.3
$\mathbf{T^*_{oc}}$	0.3	*-0.2*	1.1	*-1.3*	1.1
$\mathbf{M^*_f}$	3.5	*-3.2*	1.9	*-2.1*	2.8
$\mathbf{T^*_{ot}}$	3.4	*-3.0*	1.8	*-2.0*	1.6
$\boldsymbol{\eta_c}$	-2.5	*2.0*	-3.3	*3.6*	-2.5
$\boldsymbol{\mu_c}$	-5.6	*3.7*	-0.6	*2.5*	-0.5
$\boldsymbol{\eta_t}$	1.8	*-1.0*	1.7	*-2.2*	-0.3
$\boldsymbol{\mu_t}$	-0.5	*-0.7*	3.0	*-0.9*	1.7
$\mathbf{HR_c}$	2.6	-1.9	2.7	-3.0	1.7
$\mathbf{HR_t}$	-3.1	1.3	-1.6	3.1	1.0
$\mathbf{HR_{GT}}$	4.3	-3.9	7.2	-6.5	2.5

the first stages of the turbine under investigation has probably occurred.

In particular, the erosion seems to become more severe during period p_2, since, in addition to turbine efficiency, the turbine mass flow function increases significantly throughout the period. During the summer stop, which occurred after period p_2, significant maintenance actions, involving the hot parts of the gas turbine, were probably performed. In fact, during period p_3, turbine efficiency variation was almost negligible and turbine mass flow function increase is less significant with respect to that calculated for period p_1.

Table 4 also reports the performance recovery due to maintenance. It can be noticed that p^*_{oc} recovery values are in good agreement with previously observed results for a different type of engine (Pinelli and Venturini, 2001b). Furthermore, the η_c and μ_c recovery with respect to corresponding drops across periods p_1 and p_2 is almost complete after the summer stop.

The variations of the gas turbine characteristic parameters reported in Table 4, are sometimes considerable and seem to be representative of a particularly damaged operating state. However, it should be considered that these values might be overestimated. In fact, when the turbine is subjected to deterioration, an erroneous estimate of exhaust gas temperature T_{ot}, due to an apparent measurement uncertainty (Benvenuti et al., 1994; Doel, 1994), can be observed. The consequences in health index determination of a 1 % underestimation of the exhaust gas temperature T_{ot} are reported in Fig. 10 for the gas turbine typology under consideration.

Such estimation error can lead to two effects:

1. since inlet turbine temperature values are estimated through the T_{ot} measurement, also T_{it} is underestimated. So, the gas turbine could have been running at a T_{it} value higher than its design value, causing an increasing first stage nozzle erosion (Kurz and Brun, 2001);
2. an error in health index calculation (Stamatis et al., 1992; Pinelli and Spina 2002).

Such an estimation error causes the parameters μ_c, μ_t and η_t reported in Table 4 to be overestimated by about 1.75, 1.25 and 0.3 respectively.

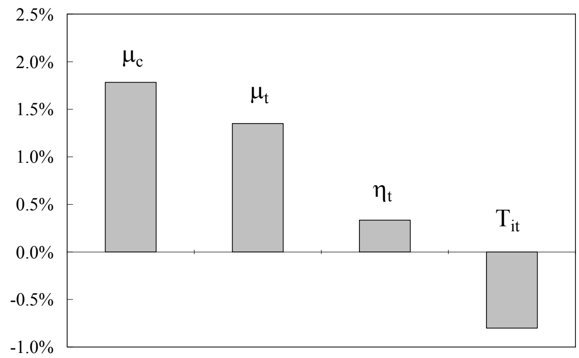


Figure 10 – Health index and inlet turbine temperature variations due to a 1% underestimation of exhaust gas temperature T_{ot}

CONCLUSIONS

In the paper, a comprehensive methodology for the diagnosis of gas turbine health state determination was presented and applied to a single-shaft gas turbine working in a combined cogenerative power plant.

The two techniques permitted the analysis of long period field operating data and the quantification of engine performance drop in terms of variations of normalized measurements, health indices and overall heat rate. The analysis highlighted the presence of compressor fouling and slight turbine stator erosion which were studied in detail. The results showed the good capability of the presented techniques since malfunctions could be identified in spite of the lack of any information about maintenance schedules.

The combined use of both sources of information, i.e. normalized measurements and health indices, is more effective for the analysis of gas turbine operating state. In fact, while normalization proved to be more sensitive to measurement variations, the inverse cycle calculation technique allowed more detailed information to be obtained about actual machine health state. Furthermore, since the information that can be found in literature about gas turbine malfunctions is not usually complete and comprehensive, the combined use can provide readable information to feed neuro/fuzzy expert systems, which will be developed in future works.

ACKNOWLEDGMENTS

The work was carried out with the support of the M.U.R.S.T. (Italian Ministry of University and Scientific & Technological Research).

The authors gratefully acknowledge Prof. Roberto Bettocchi and Prof. Pier Ruggero Spina for the suggestions provided during the work.

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