Gas Turbine Field Performance Determination: Sources of Uncertainties

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This paper presents an analysis of the uncertainties in the determination of gas turbine health, which arise by using a method of gas path analysis. This method uses field measurements to estimate, through a mathematical model of the gas turbine thermodynamic cycle, the characteristic geometric and performance parameters, which are indices of gas turbine health. The investigated sources of uncertainties are the influence of measurement accuracy and the a priori selection of the characteristic parameters that have to be considered constant during the calculation. This fact implies that variations occurring on these parameters in the actual gas turbine cause an estimation error on the characteristic parameters used as problem variables. The analysis leads to the selection of the appropriate measurements to be used in the gas turbine health determination and to the identification of both the most critical measurements and parameters.
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Introduction

Gas turbines often have a critical task in industrial applications. Therefore, any unscheduled maintenance or outages can induce great additional costs and lost revenues. These costs are not only caused by maintenance or repairs but also by the standstill of industrial production. For this reason, in many critical applications, standby gas turbines are installed but used only during emergency; thus, a more considerable investment is needed.

The maximization of machine availability, optimizing its management and maintenance, can substantially reduce money loss due to gas turbine stops.

To achieve an increase of gas turbine availability, up-to-date knowledge of the gas turbine operating state is required to diagnose the causes of performance degradation ([1]). So, it is possible to plan in advance maintenance stops and, in some cases, to change the gas turbine control logic to adapt it to the actual machine operating state.

Among the various techniques that can be used for the determination of the gas turbine operating state, the gas path analysis often permits the achievement of good results. This method uses field measurements to estimate, through a mathematical model of the gas turbine thermodynamic cycle, the characteristic geometric and performance parameters (i.e., characteristic flow passage areas and efficiencies of the compressor and turbine, combustor efficiency, pressure drops in the gas path, etc). The calculation of the characteristic parameters is performed by solving in inverse mode linear or nonlinear models of the gas turbine thermodynamic cycle ([2–8]).

Bettocchi and Spina [8] developed a method based on gas path analysis that make use of the program for gas turbine cycle calculation and of the measurements taken from the standard machine instrumentation. The gas turbine operating condition analysis is performed adapting the characteristic geometric and performance parameters, used as inputs by the cycle program, until the real measurements are reproduced. The method can use, for the gas turbine cycle calculation, either an in-house program or a cycle deck developed by the manufacturer.

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The determination of the operating state with this method could be uncertain because of some factors, such as

- measurement accuracy
- a priori selection of the geometric and performance characteristic parameters that have to be investigated.

This a priori selection is necessary because the particular method used permits the evaluation of a number of characteristic parameters equal to the number of available gas path measurements. So, some characteristic parameters have to be considered constant during the calculation. The second source of uncertainty becomes now evident if it is considered that the characteristic parameters kept constant may be changing in the actual machine due to deterioration or faults.

It has been shown ([2,7,9]) that when using techniques for the determination of gas turbine operating state, the uncertainties listed above play a significant role. In fact, these uncertainties may alter the estimated parameter as much as the alteration due to an actual loss in gas turbine performance.

In this paper, an analysis of the influence of measurement accuracy and a priori fixed parameter variations on the estimated parameters for gas turbine health determination is presented. This analysis can lead to (i) the selection of the appropriate measurements to be used in the operating state determination, and (ii) the identification of both the most critical measurements and parameters.

Evaluation of the Influence of Uncertainties

The gas turbine health determination requires the evaluation of the actual values of characteristic geometric and performance parameters, which are indices of the machine operating state. The comparison between the actual parameter values and the ones in the "new and clean" conditions allows the evaluation of the shifts between the actual gas turbine operating state and the expected one.

The evaluation of the characteristic parameters is performed utilizing the method developed by Bettocchi and Spina [8], which uses the program for gas turbine cycle calculation and the measurements taken by means of the standard machine instrumentation. The gas turbine operating condition analysis is performed "adapting" the characteristic geometric and performance parameters used as inputs by the cycle program, until the computed estimates of the measurable parameters agree with the values measured on the gas turbine. The analysis of the variations between computed and expected values of the characteristic parameters allows the localization of inefficient operations due to deterioration and faults.

The measurable parameters $\mathbf{Q}_m$ computed by the cycle program are a function of the nondimensional machine characteristic parameters $(\mathbf{X})$ and of the parameters that unequivocally determine the actual point at which the gas turbine is operating $(\mathbf{Q}_{WP})$:

$$\mathbf{Q}_m = \mathbf{f}(\mathbf{X}, \mathbf{Q}_{WP}) \tag{1}$$

where $\mathbf{f}$ is a nonlinear function that represents the mathematical model of the system. Inverting Eq. (1), it is possible to calculate the characteristic parameters starting from the measurements, that is

$$\mathbf{X} = \mathbf{f}^{-1}(\mathbf{Q}_m, \mathbf{Q}_{WP}). \tag{2}$$

This calculation is performed by solving the system of equations obtained by equating to zero the residual between the values measured on the machine and computed by the cycle program. The solution algorithm repeatedly calls the cycle program and modifies the characteristic parameters $\mathbf{X}$ until the system of equations is satisfied ([8]).

It is possible to notice that the measurement accuracy affects the solution of Eq. (2), resulting in an uncertain determination of parameters $\mathbf{X}$. Moreover, there could be another source of uncertainty. It has been seen in a previous paper ([8]) that the number and type of gas turbine characteristic parameters which can be determined, depend on the number and type of the available measurements. In particular, the number of characteristic parameters which can be determined is generally equal to the number of available measurements, without considering the $\mathbf{Q}_{WP}$ measurements, which are used for defining the machine working point. Excluding the latter, the standard instrumentation of a gas turbine permits few gas path measurements (maximum six to eight). So, if the number of the characteristic parameters to be estimated is greater than the available measurements, some of them have to be kept constant. If we split the vector $\mathbf{X}$ representing the parameters into two parts, a constant one $(\mathbf{X}_f)$ and a variable one $(\mathbf{X}_v)$, Eq. (2) can be written

$$\mathbf{X}_v = \mathbf{f}^{-1}(\mathbf{Q}_m, \mathbf{Q}_{WP}, \mathbf{X}_f). \tag{3}$$

As can be seen from Eq. (3), a variation due to aging or deterioration that occurs on a characteristic parameter which was considered as a fixed parameter, causes an estimation error on the characteristic parameters that have to be estimated.

Finally, two sources of uncertainty are recognized: the first deriving from measurement uncertainty due to the bias and precision errors of the sensors and the second caused by the reduced number of available measurements that force some parameters, which otherwise may vary, to be kept constant.

The calculation procedures of the influence of the two sources of uncertainty on the estimated parameters are dealt with separately.

Measurement Accuracy. The procedure for determining the influence of the ith measurement accuracy on the jth parameter is presented.

Let X_j be the parameter for which we want to calculate the influence of a given measurement Q_{mi}. If this measurement is altered by a small percentage amount ε

$$Q_{mi}^* = Q_{mi} + \varepsilon \tag{4}$$

it is possible to evaluate the variation δQ_{mi} of the ith measurement as

$$\delta Q_{mi} = Q_{mi}^* - Q_{mi}. \tag{5}$$

Applying Eq. (3) for the parameter considered, the following is obtained:

$$X_j^* = f_j^{-1}(Q_{ml}, \ldots, Q_{mi}^*, \ldots, Q_{mn}, \mathbf{Q}_{WP}, \mathbf{X}_f). \tag{6}$$

Finally, the sensitivity of the jth parameter to the ith measurement can be obtained:

$$\delta X_j = X_j^* - X_j. \tag{7}$$

In the case in which the measurement accuracy does not coincide with ε, the sensitivity can be obtained multiplying the real accuracy, ΔQ_{mi}, by the ratio $\delta X_j / \delta Q_{mi}$ that represents the numerical partial derivative of the jth parameter on the ith measurement:

$$\Delta X_{ji} = \Delta Q_{mi} \left(\frac{\delta X_j}{\delta Q_{mi}} \right). \tag{8}$$

This is possible under the hypothesis that the partial derivative can be considered constant in the range defined by ΔQ_{mi} (i.e., the mathematical model of the system can be linearized in the range defined by ΔQ_{mi}).

It could be useful to define also a quantity that can represent the weighting factor of the ith measurement on the jth parameter:

$$W_{Qji} = \frac{\delta X_j}{(\delta Q_{mi}/Q_{mi})}. \tag{9}$$

This quantity can give qualitatively and quantitatively information on the relationship between the jth parameter and the ith measurement and also give the possibility of evaluating which measurements exert the strong influence on each parameter, independent of sensor accuracy.

Applying this procedure it is also possible to evaluate the influence of the accuracy of measurements defining the working point.

The total error on the variable parameters deriving from the uncertainties on all the measurements are estimated using the root-sum-square formula (RSS), that can be written

$$\Delta X_j = \sqrt{\sum_{i=1}^{n} \left(\Delta Q_{mi} \frac{\delta X_j}{\delta Q_{mi}} \right)^2 + \sum_{i=1}^{t} \left(\Delta Q_{WPi} \frac{\delta X_j}{\delta Q_{WPi}} \right)^2}, \quad j = 1, \ldots, s. \tag{10}$$

Error Due to Fixed Parameters. In this case the procedure is slightly different from the previous. In fact, having split the $\mathbf{X}$ vector into two parts, from Eq. (1) results

$$\mathbf{Q}_m = \mathbf{f}(\mathbf{X}_v, \mathbf{X}_f, \mathbf{Q}_{WP}). \tag{11}$$

Now, altering of a small amount one of the fixed parameter $\mathbf{X}_f$, a set of calculated measurements corresponding to the variation of the considered parameter is obtained from Eq. (11). Then, using Eq. (3), it is possible to evaluate how the algorithm interprets the change of the fixed parameter in terms of the estimated ones. Also in this case it is possible to define the weighting factor of the ith fixed parameter on the jth variable parameter through the relation

$$W_{Xji} = \frac{(\delta X_v)_j}{(\delta X_f / X_f)_i}. \tag{12}$$

The variation of the jth parameter is then

$$\Delta X_{ji} = W_{Xji} \left(\frac{\Delta X_f}{X_f} \right)_i. \tag{13}$$

Application of the Method

The analysis of error propagation due to the uncertainties described above was applied to a model of a 10 MW two shaft heavy-duty industrial gas turbine with variable power turbine nozzle.

For this machine configuration, three independent operating parameters, in addition to the boundary conditions p_a, T_a and RH, are needed to unequivocally determine the actual point at which

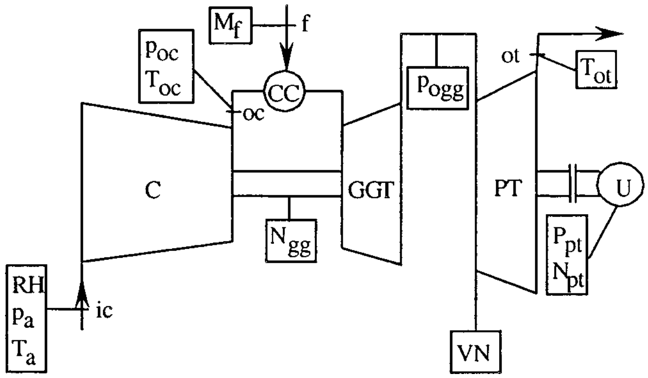

Fig. 1 Layout of the gas turbine with the measurements considered

the gas turbine is operating: in the analysis performed below, the measured values of the gas generator (N_{gg}) and power turbine (N_{pt}) rotational speeds and of the shaft power (P_{pt}) were used. All these measurements ($\mathbf{Q}_{WP}$) define the working point of the machine.

The standard instrumentation of a gas turbine generally allows five or six measurements, in addition to the ones already used for defining the working point. These measurements ($\mathbf{Q}_m$) are used to calculate the characteristic parameters which define the operating state of the gas turbine. The measurements which were considered to be available for calculating the characteristic parameters are: the pressure and temperature at the compressor outlet (p_{oc}, T_{oc}), the fuel mass flow rate (M_f), the turbine outlet temperature (T_{ot}), the variable turbine nozzle angular position (VN), and the pressure (p_{ogg}) at the gas generator outlet. Figure 1 shows the layout of the gas turbine with the measurements considered.

The characteristic parameters, which were considered as indices of gas turbine health, are the compressor and turbines mass flow functions and efficiencies, the combustor efficiency and pressure drop and the leaking and cooling mass flow rates.

Two sets of calculations were performed:

1 First, the case in which six measurements are available for the determination of gas turbine operating state was considered. The influence on the estimated parameters of the accuracy of all measurements was calculated. The assumed values of measurement errors are listed in Table 1. These values were chosen with respect to the ISO 2314 International Standard [10] and considering that the measurements were taken on the field with the standard instrumentation of the machine during normal operation and not when conducting an acceptance test ([11]). For this reason some errors were considered higher than that reported in the ISO 2314. As estimated parameters, the six most important indices for the gas turbine health determination were chosen; they are the efficiency and the mass flow function of the compressor (η_c, μ_c), the efficiency and the mass flow function of the gas generator turbine (η_{ggt}, μ_{ggt}) and the efficiency and the mass flow function of the power turbine (η_{pt}, μ_{pt}) ([8,9]). The influence on the estimated parameters of a one percent variation of the remaining parameters η_{cc}, Δp_{cc} and of the cooling mass flow rate having the highest influence on the thermodynamic cycle (M_{cool}) was then evaluated.

2 Secondly, the case in which the pressure at the gas generator outlet (p_{ogg}) is not available was considered. This measurement is not usually present in a practical situation. In this case, one more parameter must be fixed. Two different situations were then considered, in which the additional fixed parameter was alternatively the efficiency (η_{pt}) and the mass flow function of the power turbine (μ_{pt}). So, in addition to the same calculation performed for the first case, the influence on the estimated parameters of a one percent variation of these two parameters was considered.

Table 1 Typical measurement errors in percent of the reference value and reference values

Measured Quantities	Measurement Errors (percent of reference value)	Reference Values
p_a	0.10	101.3 (kPa)
T_a [1]	0.35	288 (K)
RH	3.00	60 %
p_{oc}	0.40	1439.9 (kPa)
T_{oc} [1]	0.50	669.1 (K)
p_{ogg}	0.40	306.0 (kPa)
T_{ot} [1]	0.60	712.6 (K)
M_f	2.00	0.645 (kg/s)
VN	1.00	1.127 area ratio
P_{ot}	0.50	10000 (kW)
N_{gg}	0.25	10800 (rpm)
N_{pt}	0.25	7900 (rpm)

[1]Percent values of temperature measurements correspond to an error of ±1K, ±3K, and ±4K on T_a, T_{oc}, and T_{ot}, respectively.

Results and Discussion

The results of the calculations related to different sets of measurements are described below.

Case 1—Six Measurements. The influence of measurement accuracy was first considered. In addition to the measurements necessary to define the working point ($N_{gg}, N_{pt}, P_{pt}, p_a, T_a, RH$), the whole set of $\mathbf{Q}_m$ measurements ($p_{oc}, T_{oc}, p_{ogg}, T_{ot}, VN, M_f$) reported above was considered to be available. As a consequence, six of the nine characteristic parameters were considered as problem variables ($\eta_c, \eta_{ggt}, \eta_{pt}, \mu_c, \mu_{ggt}, \mu_{pt}$) and the other three as fixed ($\eta_{cc}, \Delta p_{cc}, M_{\mathrm{cool}}$).

In Fig. 2, the error on the estimated parameters due to the error on the 12 measurements ($\mathbf{Q}_m$ and $\mathbf{Q}_{WP}$) is presented. As can be seen, the flow functions are the parameters most sensitive to measurement accuracy. The maximum error calculated with the RSS formula is of about three percent. It can be noticed also that, while the flow functions exhibit a comparable amount of error among them, the power turbine efficiency error is much higher than the errors on the compressor and gas generator turbine efficiencies.

The reason for this can be deduced from the analysis of Figs. 3 and 4, where the absolute values of the weights of $\mathbf{Q}_m$ and $\mathbf{Q}_{WP}$ measurements on the six estimated parameters are reported. Here it is possible to see how each measurement affects the estimation of each parameter. Analyzing these figures and observing Table 1, it is possible to notice that

- the outlet compressor temperature affects remarkably the estimation of the compressor and the gas generator efficiency, while the ambient temperature affects all the estimated parameters and

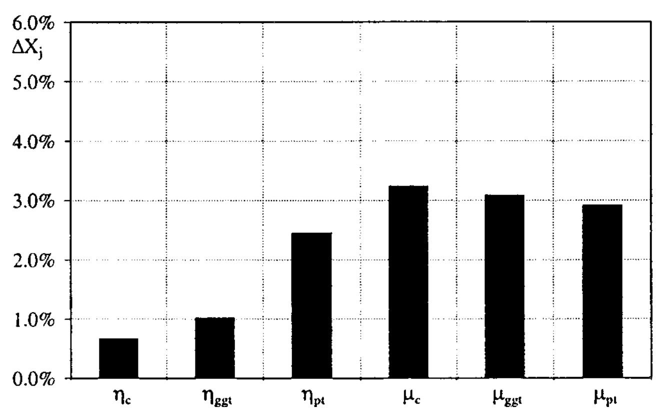

Fig. 2 Error on the estimated parameters due to the error on the measurements Q_m and Q_{WP} (Case 1a)

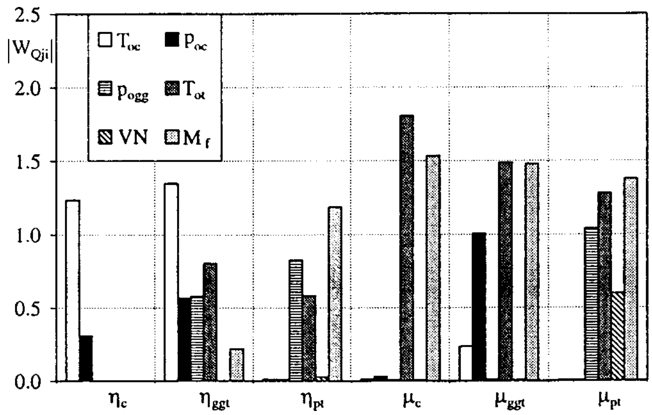

Fig. 3 Absolute value of the weighting factors of the Q_m measurements on the estimated parameters (Case 1)

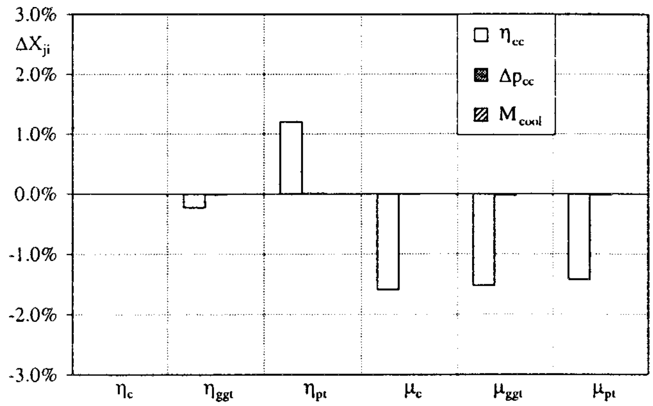

Fig. 5 Contribution ΔX_{ji} due to a one percent variation on the fixed parameters η_{cc}, Δp_{cc}, and M_{cool} (Case 1)

particularly the compressor flow function. These two measurements, however, present a good accuracy: Their contribution to the error evaluated with the RSS formula is only of limited relevance.

• the exhaust gas temperature and the fuel mass flow rate influence the estimation of all the parameters, excluding the compressor efficiency. But, while the first contributes only a little to the parameter total errors thanks to the good accuracy ΔQ_m of its measuring sensor (see Table 1), the second affects remarkably the total errors, since the accuracy of its measuring sensor is very low. In particular, focusing on gas generator and power turbine efficiencies, it can be noticed from Fig 3 that η_{ggt} is less influenced than η_{pt} by the fuel flow measurement. This can be regarded as the main reason of the remarkable difference between the estimation errors on these two parameters (Fig. 2).

The influence on the estimated variable parameters of a variation that may occur on one of the three fixed parameters η_{cc}, Δp_{cc}, and M_{cool} was considered. Figure 5 shows the influence ΔX_{ji} on the six variable parameters due to a one percent variation. As can be seen, the combustor efficiency is the only fixed parameter that has a relevant influence on the estimation of the variable parameters. On the contrary, the influence on the estimated variable parameters of one percent variation on Δp_{cc} and M_{cool} is negligible. In particular, the cooling mass flow rate begins to influence the estimated parameters for variations higher than ten percent.

Case 2a—Five Measurements (η_{pt}=const). In this case, a reduced set of Q_m measurements was considered. In particular, it was taken into account the case in which the measurement of the pressure at the gas generator turbine outlet (p_{ogg}) was not available. As a consequence, only five of the nine characteristic parameters can be used as problem variables. The choice of the additional parameter to be fixed is determined by

1 the necessity of having univocally determinate the system of equations that relate the variable parameters to the available measurements; this defines the set of parameters that can be additionally fixed;

2 the field experience, that determines the parameters having less probability to be subjected to variation due to aging or deterioration. In this way, fixing a parameter that does not vary frequently, it is possible to considerably reduce the probable error due to variations on fixed parameters.

For the two-shaft industrial gas turbine considered, among the parameters determined by the first condition ($\eta_{ggt}, \eta_{pt}, \mu_{pt}$), the efficiency and the mass flow function of the power turbine are the parameters that are less susceptible to variations.

In this first case, the power turbine efficiency was considered as the additional fixed parameter.

Figure 6 shows the error on the estimated parameters due to the error on the 11 measurements ($\mathbf{Q}_m$ and $\mathbf{Q}_{WP}$). Comparing with the results shown in Fig. 2 (case of six $\mathbf{Q}_m$ measurements), it can be noticed that the lack of p_{ogg} measurement determines a remarkable increment of the error on the power turbine mass flow function, while the other parameters remains almost the same as in Fig. 2. This is mainly due to an increment of the weight of the fuel flow measurement only on the power turbine mass flow function.

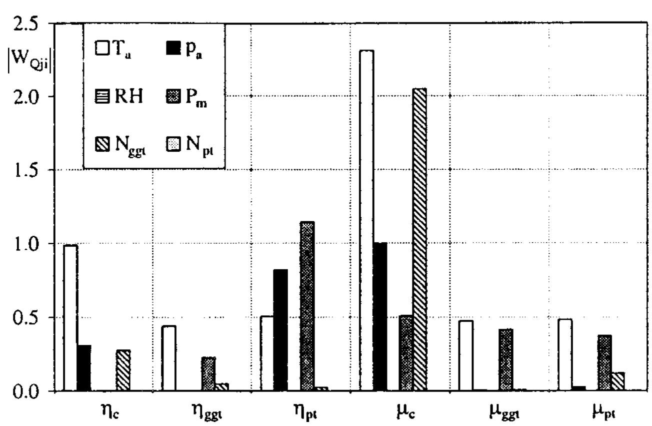

Fig. 4 Absolute value of the weighting factors of the Q_{WP} measurements on the estimated parameters (Case 1)

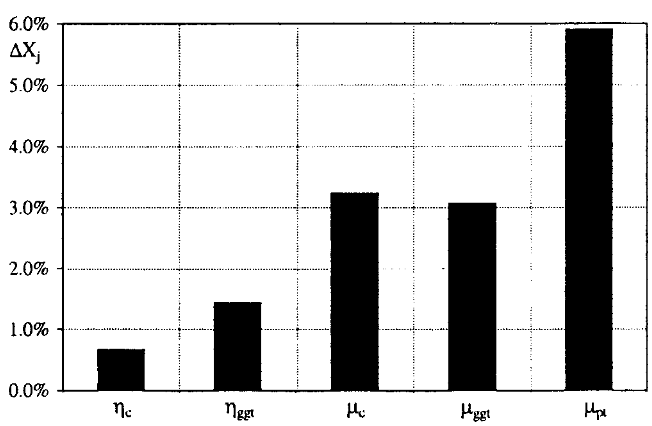

Fig. 6 Error on the estimated parameters due to the error on the measurements Q_m and Q_{WP} (Case 2a)

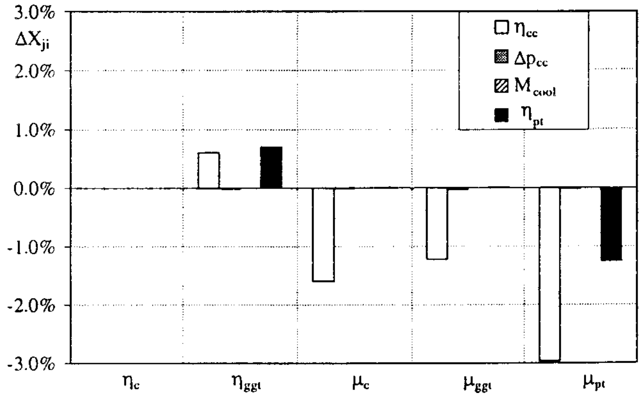

Fig. 7 Contribution ΔX_{ji} due to a one percent variation on the fixed parameters η_{cc}, Δp_{cc}, M_{cool}, and η_{pt} (Case 2a)

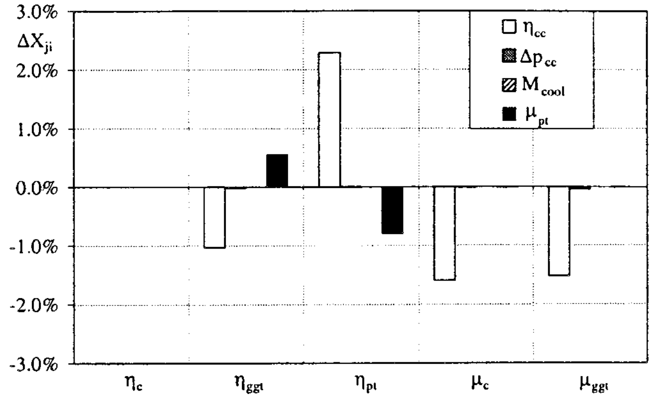

Fig. 9 Contribution ΔX_{ji} due to a one percent variation on the fixed parameters η_{cc}, Δp_{cc}, M_{cool}, and μ_{pt} (Case 2b)

Figure 7 shows the influence on the estimated variable parameters of a one percent variation on the three fixed parameters considered above (η_{cc},Δp_{cc},M_{cool}) and on the additional fixed parameter η_{pt}.

In this case, in addition to the combustor efficiency, also the power turbine efficiency presents a relevant influence on the estimation of the variable parameters.

Case 2b—Five Measurements (μ_{pt}=const). This case is similar to the previous one but the power turbine mass flow function μ_{pt} was considered as additional fixed parameter.

Figure 8 shows the error on the estimated parameters due to the error on the 11 measurements ($\mathbf{Q}_m$ and $\mathbf{Q}_{WP}$). Comparing these results with the case of six measurements available (Case 1), it can be noticed that an increment on the total error is recognizable both on the power turbine and gas generator turbine efficiencies.

Figure 9 shows the influence on the estimated variable parameters of a one percent variation on the three fixed parameters η_{cc}, Δp_{cc}, M_{cool} and on the additional fixed parameter μ_{pt}. Also in this case, in addition to the combustor efficiency, the additional fixed parameter μ_{pt} is the one which exerts a more relevant influence on the estimation of the variable parameters.

Comparing the calculations in Cases 2a and 2b, it can be seen that

- the maximum total error concerns a characteristic parameter of the power turbine, the mass flow function μ_{pt} in the first case, and the efficiency η_{pt} in the second;
- the error on μ_{pt} in Case 2a is higher than error on η_{pt} in 2b;
- the influence of the fixed parameter η_{cc} on the estimated parameters is in Case 2a higher than in Case 2b.

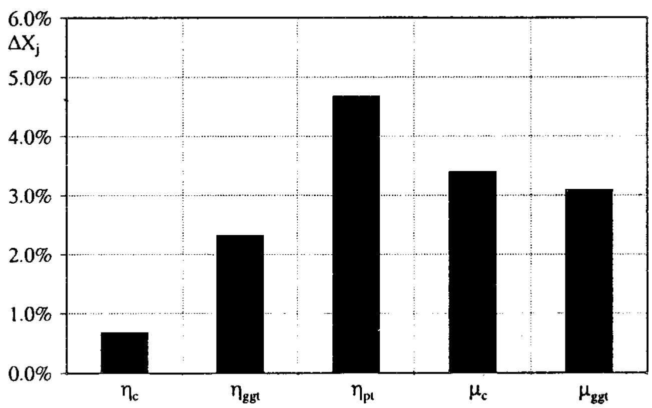

Fig. 8 Error on the estimated parameters due to the error on the measurements Q_m and Q_{WP} (Case 2b)

Conclusions

The analysis performed in this paper permitted the evaluation of the influence of measurement accuracy and a priori fixed parameter variations on the estimated characteristic parameters. The measurement accuracy was considered in the range of a typical industrial instrumentation.

This analysis shows that the error on the estimated parameters due to these uncertainties can hide a real variation of the characteristic parameter due to actual component deterioration or faults. When six measurements are available for the determination of the gas turbine operating state, the maximum total errors on the estimated parameters due to $\mathbf{Q}_m$ and $\mathbf{Q}_{WP}$ measurement accuracy (evaluated with the RSS formula) are close to three percent. Further, the combustor efficiency is the only fixed parameter that has a relevant influence on the variable parameter estimation. Then, the effect on the estimation error of a reduced set of available measurements was analyzed.

The calculations performed put into light that the lack of p_{ogg} measurement results in an increase of the estimation error on the gas generator efficiency and on one between the power turbine efficiency and the power turbine mass flow function, depending on the additional fixed parameter. Moreover, there is a significant influence of the additional fixed parameter on the variable parameter estimation. Finally, in the case of five measurements available, with respect to the total errors, it seems more convenient to fix the mass flow function instead of the efficiency of the power turbine.

The present analysis shows the criticality of two measurements: the exhaust gas temperature and the fuel mass flow rate. But, while the former does not affect remarkably the total error due to the good accuracy of the sensor, the latter has the highest influence on all the parameter estimations. The reason for this can be seen in the high uncertainty of its determination.

A remarkable improvement in the diagnostic reliability can be reached increasing the accuracy of a critical measurement such as the fuel mass flow rate and augmenting the number of available measurements. Further, improvements in the obtained results may be reached considering that gas path analysis method for gas turbine health determination is based on the evaluation of the shifts between computed and reference values of characteristic parameters. Therefore, the evaluation of the reference values on each particular gas turbine unit (custom baseline) allows the reduction, or the elimination, of the bias error. In this manner, only the precision error, remains to influence the estimation of desired parameters.

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Nomenclature

c_p = specific heat at constant pressure
c_v = specific heat at constant volume
k = c_p/c_v
M = mass flow rate
N = rotational speed
n = number of gas path measurements
P = power
p = pressure
$\mathbf{Q}_m$ = vector of measured parameters
$\mathbf{Q}_{WP}$ = vector of measurements necessary to define the working point
R = gas constant
RH = relative humidity
s = number of characteristic parameters
t = number of working point measurements
T = temperature
VN = variable nozzle angular position
W_{Qji} = weight of the ith measure on the jth parameter
W_{Xji} = weight of the ith fixed parameter on the jth variable parameter
$\mathbf{X}$ = vector of nondimensional characteristic parameters
ε = small measurement perturbation
η = efficiency
μ = $M\sqrt{kRT}/p$ mass flow function

Subscripts and Superscripts

$*$ = altered measurement/parameter
a = ambient
c = compressor
cc = combustor
cool = cooling
f = fuel, fixed parameter
gg = gas generator
i = inlet section
o = outlet section
ot = power turbine outlet section
pt = power turbine
t = turbine
v = variable parameter

Acronyms

C = compressor
CC = combustor
GGT = gas generator turbine
PT = power turbine
U = user

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