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Adaptive Modeling of Jet Engine Performance with Application to Condition Monitoring

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A method of simulation of the performance of jet engines, with the possibility of adapting to engine particularities, is presented. It employs an adaptation procedure coupled to a performance model solving the component matching problem. The proposed method can provide accurate simulation for engines of the same type, with differences that are due to manufacturing or assembly tolerances. It does not require accurate component maps, because they are derived during the adaptation procedure. It can also be used for health monitoring purposes, for component fault identification, and condition assessment. The effectiveness of the proposed method is demonstrated by application to two commercial jet engines.

Nomenclature

A = cross section area at a station along the engine
DT = $(T_{\mathrm{predict}} - T_{\mathrm{given}})/T_{\mathrm{given}}$, Fig. 4
EGT = exhaust gas temperature
EPR = engine pressure ratio
F = objective function
F_G = gross thrust
F_N = net thrust
K_{cc} = combustion chamber pressure loss coefficient
N = turbojet shaft rotational speed
$N1$ = turbofan low-pressure shaft speed
$N2$ = turbofan high-pressure shaft speed
P = pressure
$\boldsymbol{P}$ = performance and gas path variables vector
$\boldsymbol{u}$ = operating conditions vector
WA = air mass flow rate
WF = fuel mass flow rate
$\boldsymbol{X}$ = component parameter vector
Δ = difference operator
η = component efficiency

Subscripts
F = fan
IPC = intermediate pressure compressor
N = nozzle
2 = fan inlet
3 = intermediate compressor exit
4 = high-pressure compressor exit
5 = combustion chamber exit
6 = high-pressure turbine exit
7 = low-pressure turbine exit
25 = fan exit

I. Introduction

JET engine performance computer models constitute a very important tool, useful for different aspects of engine study. During the early stages of engine conception, they are used to evaluate the influence of different design choices on overall performance. During the service life of an engine, they offer the possibility of estimating performance parameters and cycle details for the conditions encountered during operation. This possibility is of fundamental importance to any technique of engine performance monitoring.

The building of performance models is based on dividing the engine into components (e.g., compressor, combustor, turbine, nozzle), according to the kind of thermodynamic process occurring in each one of them. The determination of performance parameters and cycle details is achieved by solving a system of equations and expressing the state changes of the working gas and the compatibility conditions between the components. A key element of component-based computer simulation techniques is the requirement of component maps. The reliability of the predictions is highly dependent on the accuracy by which these maps are known. However, the maps are not easily obtainable by the users, because they are usually available only to the engine manufacturer.

A number of techniques have been proposed by various authors for overcoming this problem. They are mainly based on similarity considerations,[1-3] while recently, methods of producing the maps by using generalized stage data for compressors or turbines have been proposed.[4] There is one aspect, however, which cannot be covered by these methods. It is the fact that, due to assembly or manufacturing tolerances, different engines of one particular series exhibit small differences in their performance. Such differences can be of importance during the condition monitoring procedure, since deviations from baseline constitute the fundamental point of the procedure. A second fact known by experience and recently documented,[5] is that the disassembly and rebuilding of an engine can cause small shifts in its performance. Such shifts cannot be tracked by such performance models.

A solution to this problem is offered by the method proposed in this article. The principles of the technique of adaptive simulation of gas turbine performance, introduced by the research group of authors,[6] are employed for this purpose. The technique is further extended as to the way it is interacting with the basic engine model, which basically performs the solution of the component matching problem. The original implementation of the technique was of the "internal" type: the procedure was embedded in the performance model itself, and the adaptation is performed simultaneously with the solution of the engine matching problem. Although the procedure in this form offers an effective method from a computational point of view, it requires that the model is built for the particular engine studied, making it suitable only for this engine (an industrial gas turbine[6]). The extension pre-

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sented here is of the "external" type, an existing engine code is employed as it stands, and the adaptation procedure is performed by interaction with the code without intervening in it, but only in its input and output data. This allows for the development of adaptive models on the basis of available generalized jet engine performance simulation codes,[2,3] and gives the possibility of producing adaptive models for a large variety of aeroengine configurations.

The main feature of the technique is the possibility it offers for adaptation of a computer model to a particular engine. Advantages over previously existing techniques with respect to applications are as follows:

1) It gives the possibility of a very accurate simulation of every individual engine performance.

2) If the component maps of the engine are only approximately known, the exact ones can be reconstituted by employing only engine gas path parameter measurements.

3) The method allows (besides accurate prediction of performance), direct component condition assessment and fault detection, as will be discussed in this article.

We shall start by describing the principle of the method, followed by the description of the procedure itself, and application examples.

II. Principle of the Method

A generalized engine performance model, similar to the ones proposed in Ref. 1, is used as the basis to the method and will be called "core model" hereafter. Such a model produces a set of values for all engine performance variables, once it is fed with the appropriate design point data, component maps, and the variables that define the operating point. The component maps in this model are given in a generalized form and are scaled to the design point, giving the possibility of covering similar engines. If the maps of a particular engine are even slightly different from this model's map then the calculated performance variables will not coincide with the actual ones. Thus, the reliability of performance predictions by means of such models is highly dependent on how accurately the design point data and the maps of the components are known. Such data, however, are either not available to the engine user, as mentioned above, or even if they are, they can be inaccurate. Component maps produced by component testing or prediction codes are not necessarily accurate when a particular engine is modeled. The reasons for this have been discussed in more detail in Ref. 6.

The adaptive modeling technique has the possibility to produce this information by taking advantage of the fact that, instead of component data, global performance or flow path variable values are known to the user (e.g., through the engine specification or from test cell data). This is achieved by solving an optimization problem: unknown component data are handled as independent unknowns and their values are determined by requiring a prediction of global variables as close as possible to the available values. Starting from an initial guess, component maps are transformed in successive steps until the optimum agreement condition is fulfilled. Thus, if some approximate maps are initially available, application of the procedure will provide a final set of maps that ensure an optimum prediction capability to the engine performance model.

How the procedure is formulated mathematically will now be discussed.

III. Adaptation Procedure

As mentioned above, the core model for an engine performs the solution of a system of equations, which express relations between the following quantities: 1) component parameters, describing its performance through the component maps. We consider that they are contained in a vector X; 2) global performance and/or flow path variables that can be contained in a vector P; and 3) input and control variables (e.g., ambient conditions, settings) which can be contained in a vector u.

All these parameters are linked though equations that express the thermodynamic changes occurring in the components as well as the compatibility of the component operation (e.g., mass flow conservation through the engine, compressor-turbine power balance). Thus, from a mathematical point of view, the core model can be represented in an implicit form by a system of equations:

$$f(X, P, u) = 0 \tag{1}$$

The solution of this system for a given set of X and u leads to the calculation of any global performance or flow variable P_i. We can therefore consider that each performance variable P_i is a function of the independent variables X and u:

$$P_i = P_i(X, u) \tag{2}$$

Considering that we dispose a set of N given values (from measurements or specifications manuals) P_{Gi}, $i = 1, \ldots, N$ for a particular u, we can form an error function F as follows:

$$F = \sum_{i=1}^{N} a_i(P_i - P_{ui})^2 \tag{3}$$

where a_i stands as weighing factors depending on either the accuracy of the corresponding measurement or the certainty of the quantity is known from the engine specification manuals. Using Eq. (2), the relation (3) shows that F is a function of only X and u:

$$F = F(X, u) \tag{4}$$

This function gets only positive values, which are smaller the closer the predicted values are to the given ones. The particular X which makes F minimum contains the component parameter values that produce the prediction nearest to the available data. When the predicted variables coincide with the measured ones, F will get a zero value.

The problem is therefore to obtain the X that will satisfy this condition. This can be expressed by the requirement of determining corrections ΔX to the original component data X such that, for a given u

$$F(X + \Delta X) = \text{minimum} \tag{5}$$

The application of a multivariable optimization procedure will give the values of corrections ΔX, which produce the best estimated for P.

Determining ΔX consists of determining the map modifications necessary to satisfy the optimization condition. Starting with an approximate map of a component, e.g., the compressor, this map can be modified by a point transformation. For example, in the compressor map, each point of a speedline will be transformed to a new one by means of a mass flow correction Δm and a pressure ratio correction ΔPR, as shown in Fig. 1. Application of the procedure for the whole operating envelope of an engine will give a set of ΔX, which in turn provides the modified maps leading to the best reproduction of engine performance.

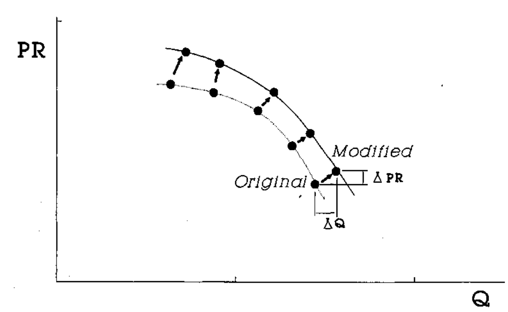

Fig. 1 Point-by-point transformation of a compressor map.

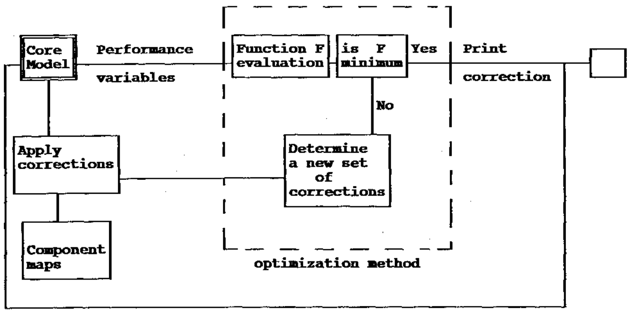

Fig. 2 Flow chart of adaptation technique coupled to an engine core model.

The flow diagram of the procedure coupled to the core model of the engine is shown in Fig. 2. This procedure has been incorporated in a single computer program. The numerical method chosen for the optimization part is that of the polytope algorithm[7,8] (the downhill simplex method is due to Nelder and Mead[7]). This algorithm possesses two important features. The first is that the method itself requires only function evaluation, not derivatives (which may be singular in some characteristic map operating regions). The second feature is that requiring only function evaluations allows for the extension of the objective function in order to include nonsmooth penalty terms, ensuring the physical meaning of the calculated quantities (e.g., efficiencies greater than 1 are not allowed).

IV. Setting up an Adaptive Model

When a particular engine is considered, a core model must already be available. The problem that is then faced is the selection of appropriate $\boldsymbol{P}$ and $\boldsymbol{X}$ vectors in order to set up the adaptive model ($\boldsymbol{u}$ is already defined by the particular engine configuration). This selection is performed by taking into account the behavior of F [Eq. (4)]. In order to ensure that the optimization algorithm will produce a unique solution and that it will exhibit an effective computational behavior, a sensitivity analysis must be performed.

We start by an initial selection of $\boldsymbol{P}$ and $\boldsymbol{X}$. All the available measurements or performance data are selected as components of $\boldsymbol{P}$, and all unknown component parameters as components of $\boldsymbol{X}$. The variation of each individual term in F [Eq. (4)], is then studied by applying deviations in the values of each individual component of $\boldsymbol{X}$. The components of $\boldsymbol{P}$ that exhibit significant alterations of the value of the corresponding term are preserved in $\boldsymbol{P}$, otherwise they are neglected. Having formulated a final selection for $\boldsymbol{P}$, a similar procedure is applied for components of $\boldsymbol{X}$. Components that produce alterations in the value of F are preserved, otherwise they are neglected. The procedure will become more clear through an example presented in the applications section. This analysis produces a final optimum choice for the vectors $\boldsymbol{P}$, $\boldsymbol{X}$.

Summarizing, application of the procedure consists of the following stages: 1) setup of the core model for the particular engine of interest; 2) choice of the vectors $\boldsymbol{P}$, $\boldsymbol{X}$ components. A sensitivity analysis is performed for this purpose on the basis of the available performance data; 3) initial implementation of the model for adapting to the particular engine, on the basis of available data; and 4) exploitation of the model established in the previous steps during engine operation.

The procedure can be incorporated in a single computer program. Because this model allows adaptation to a particular engine performance, we already adopted[6] the term "adaptive engine model."

V. Application to Engine Test Cases

In order to demonstrate its effectiveness, the method has been applied to the case of two commercial engines: 1) the JT8D turbofan and 2) the J85 turbojet. For both engines the given data were taken from engine specification.

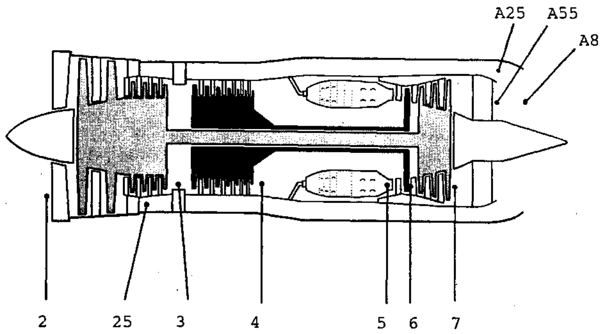

Fig. 3 Schematic of the JT8D turbofan.

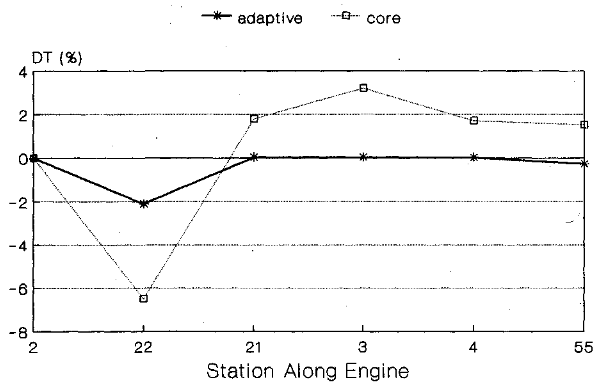

Fig. 4 Deviation of the predictions from manufacturer's data along the engine.

A schematic of the JT8D turbofan is shown in Fig. 3. A large number of performance variables were available at the design point, whereas the variation of $N1$, $N2$, EGT, WF, and F_N with EPR was available at off-design points. The adaptation was performed in two stages, first at the design point and then at off design conditions. An example of results of the prediction at the design point is shown in Fig. 4. The difference of total temperature predicted by the core and the adaptive model are shown. A significant improvement is observed when the adaptive model is employed.

An example of results of the sensitivity analysis performed for setting up the adaptation at off-design points is shown in Fig. 5. We observe that the thrust is relatively insensitive to fan efficiency alterations, whereas the other three parameters are sensitive. A similar behavior is observed for the other component parameters, leading to a selection of $\boldsymbol{P} = (N1, N2, EGT, WF)$. The variation of F with respect to the high-pressure compressor efficiency and combustion chamber loss coefficient deviations are shown in Fig. 6. While F is sensitive to changes of the former, it remains almost unaltered for changes of the later. Combustor losses can therefore be eliminated from $\boldsymbol{X}$. After studying all parameters it was decided to include in $\boldsymbol{X}$ only the parameters of the three compressor sections, giving a total of nine components in $\boldsymbol{X}$.

The comparison of predictions to manufacturer's data is shown in Fig. 7. It can be seen that while the core model gives a significant deviation from the manufacturer's data, the adaptive model predicts them with high accuracy. An example of the modification that resulted from the adaptation is shown in Fig. 8, where the intermediate compressor map before and after the adaptation are shown. It should be mentioned that although entire speed lines are shown for the adapted map, the adaptation has been performed only on the point of the speed line that lies on the operating line of the engine. The entire speed line is shifted on the map according to the corrections for this point without a change in its shape. In this sense, the adaptation is actually accurate for a region of the compressor map around the operating line. Although the rest of the map is not actually adapted, this does not reduce the

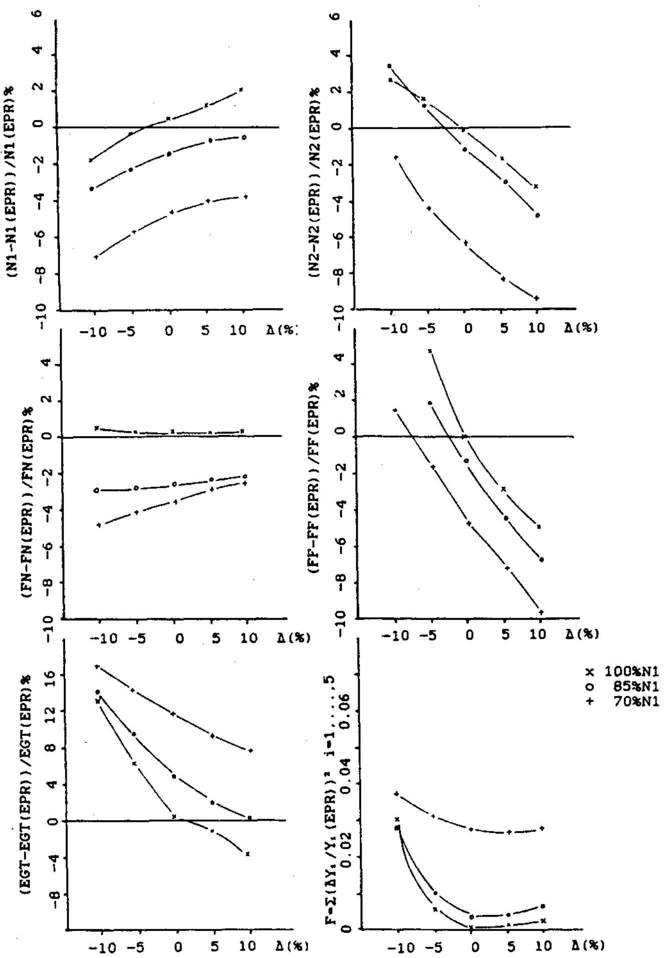

Fig. 5 Variation of performance variables in the function of deviation in fan efficiency η_F for a given EPR.

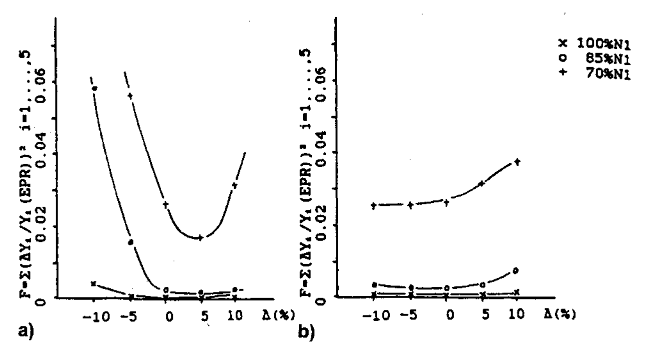

Fig. 6 Variation of the error function F in the function of deviations in a) intermediate compressor efficiency η_{IPC} and b) combustion chamber pressure loss coefficient K_{cc}.

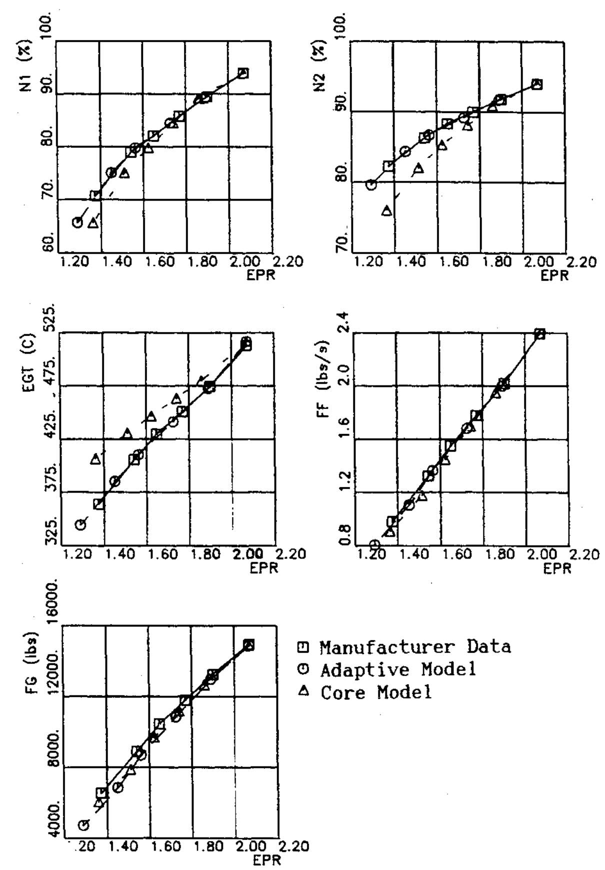

Fig. 7 Comparison of manufacturer's data to predictions by a core engine model and an adapted model; JT8D turbofan.

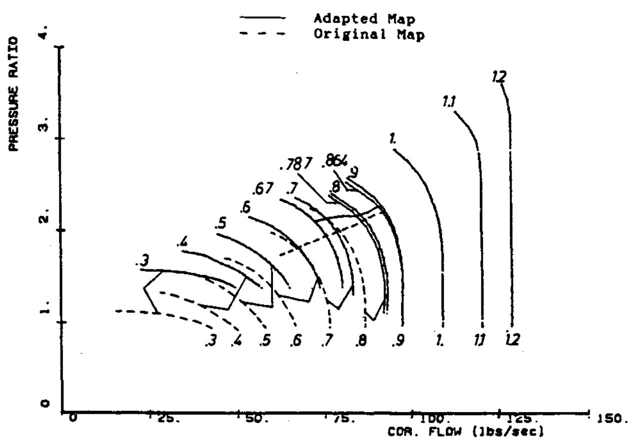

Fig. 8 Example of map modification produced by the adaptive model (intermediate compressor).

practical usefulness of the adaptation, since engine operation corresponds to the operation of the compressor in the adapted region.

Results from the application to the J85 single shaft turbojet are shown in Figs. 9 and 10. The vector $\boldsymbol{P}$ in this case consisted of manufacturer's data in the form of curves FG, $P5$, WA, EGT vs N, shown in Fig. 9. The improvement on the predictions not only on these quantities but also on fuel flow WF (not included in $\boldsymbol{P}$) is noticed. On the other hand, application to other operating conditions, after the adaptation is performed, is demonstrated in Fig. 10. This figure shows that once the adaptation is performed over a range of conditions, engine operation over a wider range of conditions can successfully be predicted.

VI. Engine Condition Assessment Through Adaptive Modeling

The structure of the adaptive model allows the direct application to engine condition monitoring (ECM). Application can be done in two different ways: 1) fault simulation and 2) fault detection.

Simulation of faults is achieved by introducing deviations in component parameters (as they would be caused by the presence of a fault), and producing the resulting deviations in measured quantities (fault signatures). Of course, such a possibility exists already with the core model, but the improved reliability of the adaptive one gives more accurate results, as demonstrated in Fig. 11. This figure shows that predicted signatures by the adaptive model are much closer to the manufacturer ones than the ones predicted by the core model.

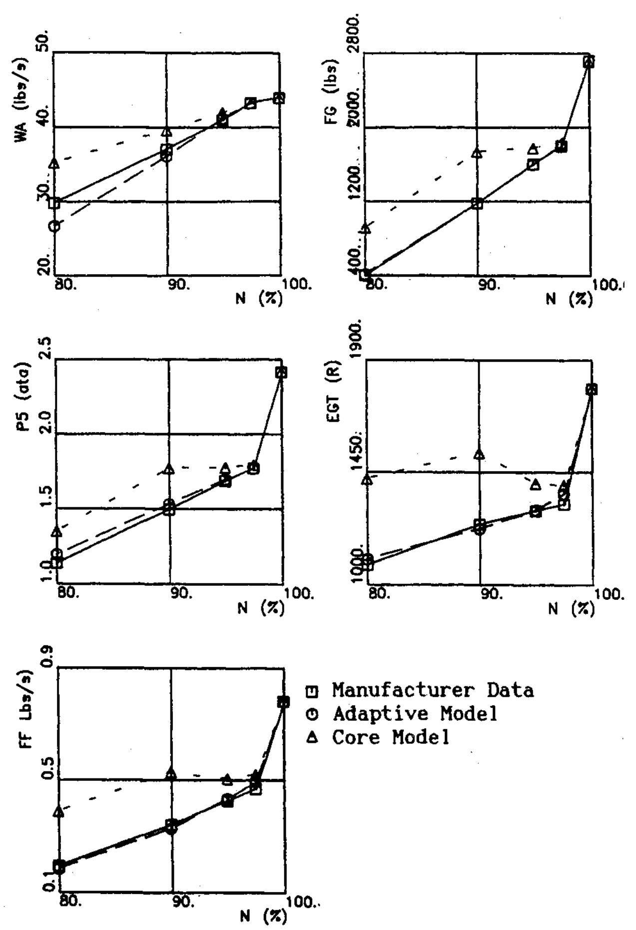

Fig. 9 Comparison of manufacturer's data to predictions; J85 turbojet. Mach = 0, altitude = 0.

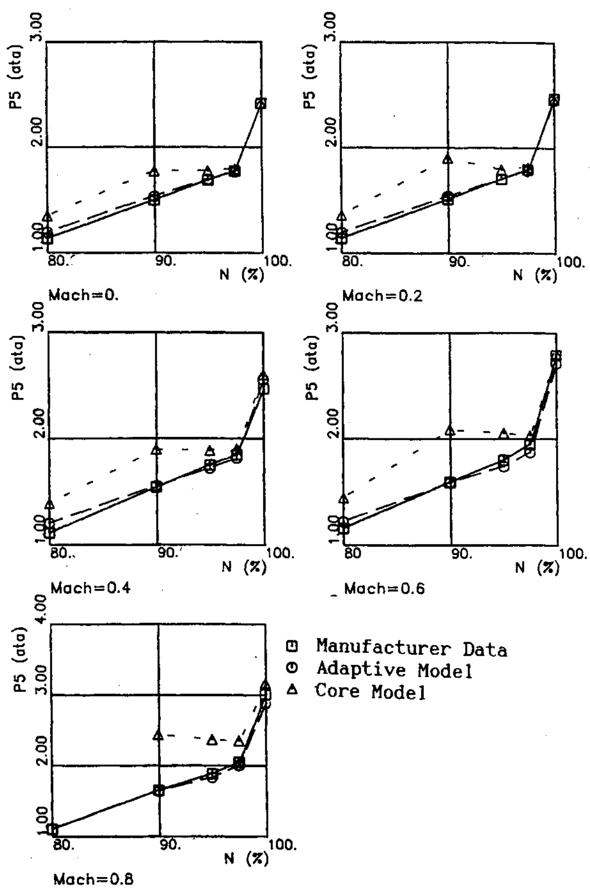

Fig. 10 Comparison of manufacturer's data to predictions. J85 turbojet for different flight Mach numbers.

Fault detection consists of deriving deviations in the component parameters, when the signature (deviations) on the measurements are known. When data from a faulty engine are introduced into the model previously calibrated on the healthy engine, the estimated deviations of components parameters correspond to alteration in the engine components. The details of applying this technique have already been established.[9] In this article a different methodology is introduced. This methodology is an alternative to the linearized gas path analysis techniques.[10] The basic idea is based on the model's ability to estimate components' characteristics when specific performances are known. By extending this method, keeping the main procedure untouched, the adaptive model can estimate changes in component situations when certain deviations on engine performances are measured. In Fig. 12, a fault signature given by the manufacturer and one obtained by the adaptive model is compared. It must be mentioned here that an accurate diagnosis is achieved when the number of possible faults is equal or less than the number of the deviations measured.

The applicability of this second procedure shows that the adaptive modeling provides one additional capability: if the deviations do not correspond to a fault, but to small engine-to-engine differences, the corresponding component deviations are defined and the model is suitable for normal operation prediction of the particular engine considered. Therefore, the procedure is able to produce not only a model customized to a particular engine type, but also track differences of different engines of one particular series.

The sensitivity analysis used during the establishment of the model can also produce information useful for ECM. There are two different aspects of application and corresponding approaches. The first approach can be characterized as a manufacturing one, because it is oriented to the selection of

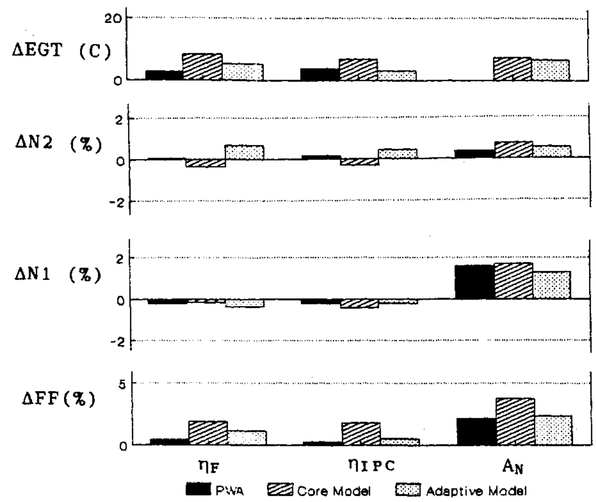

Fig. 11 Measurement deviations when a 2% reduction of the corresponding component parameters is imposed.

the most appropriate measurements set, in order to ensure good capability of in-service monitoring. Having decided which are the more suitable component parameters to monitoring, we form various objective functions, including different sets of global performance parameters and flow variables (measurement candidate sets). The final choice is the set that gives the most sensitive objective function.

The second approach can be characterized as a user-oriented approach. The user is faced with the problem of choosing the best possible set of component parameters to be estimated when a given measurement possibility exists. In that case the objective function has a standard form and its vari-

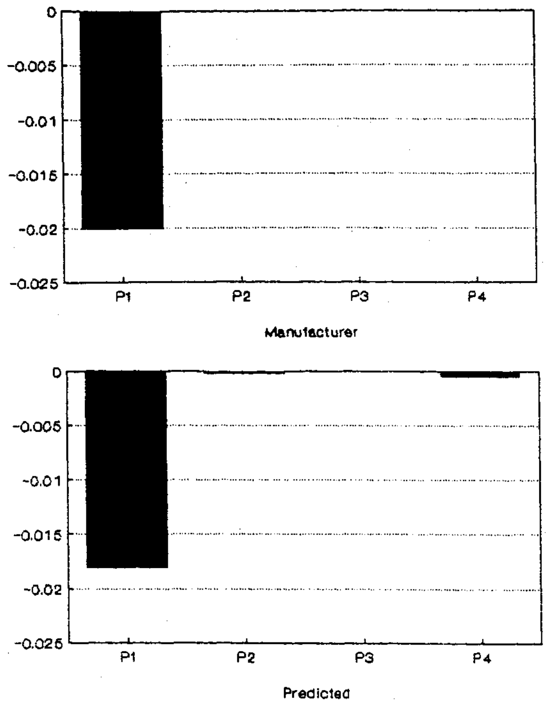

Fig. 12 Comparison of manufacturer's fault signature-to-signature obtained by the present method.

ation, the result of different component parameter deviations, is examined. The parameters giving the maximum sensitivity are the ones that should be sought when fault detection is considered.

VII. Discussion

Some features of the implementation of the method will now be discussed. Since the method employs a multivariable optimization technique, two questions relevant to the implementation of such techniques arise:

1) Is the solution obtained unique? In the present case this reads: is the engine condition uniquely specified or is there another condition with the same symptoms?

2) Is the solution sensitive to the initial guess? For the user of the method this translates to: how would an initial guess be performed in order to ensure correct functioning of the method?

The answer to these questions is given by the following arguments. It is known from a mathematical point of view that when the number of parameters to be estimated is greater than the number of known variables that are used to form the cost function, the solution is not unique and depends on the first guess for the values of the parameters. It is also valid that we get a unique solution for X (containing component parameters) when the number of its components is less than or equal to the number of components of P (available performance and flow path variables). However, in the general case, the number of components parameters fully describing the engine operation is large, although the available performance and flow path variables are the specific ones measured on an engine installed in a test cell or on aircraft. Consequently, their number is fixed for a particular engine (bearing in mind that in the test cell one can usually measure more variables than on the wing). Therefore, during application it is essential to restrict the parameters of interest to a smaller number, according to the particular situation with an engine in hand. It is at this point that the engineering judgement of the model user will play an important implementing role (e.g., existing experience on most frequently occurring faults can lead to a reduction of the function of possible fault scenarios one is looking for). In the past the present authors have proposed a method to circumvent this problem.[11]

On the other hand, an alternative approach in order to circumvent the problem of uniqueness of the solution can be based on physical considerations. There are certain limits within some parameters that are allowed to take values, e.g., temperatures should not exceed a threshold, and efficiencies cannot exhibit very large deviations from the corresponding design values. These constraints can be taken into account in the optimization procedure by means of penalty terms incorporated to the cost functions. In the authors' experience the combined use of the above two approaches is the most effective way to achieve a unique and physically meaningful solution. As for the initial guess, the one of zero deviation from the data corresponding to most recent condition of the engine has always been proven to be suitable. It may be useful to the reader to refer to a work of similar nature where such problems have been discussed.[12]

A final point of interest is the requirements in computer power for implementation of the model. Memory and speed requirements for an efficient practical implementation of the model can be effectively covered by today's personal computers. Although general estimation of running time cannot be given since it depends on the particular application (e.g., direct simulation or adaptation with a particular number of dependent and independent variables), it can be stated that running times for a typical turbofan range from a few seconds for a direct simulation to a few minutes for a "heavy" adaptation run.

VIII. Conclusions

A method of building engine performance models customized to particular engines has been developed. The method employs an optimization procedure coupled to an existing engine model, and performance data coming from measurements or specifications. A particular feature of the procedure is that it does not require accurate component performance maps. The necessary accuracy of the maps may be acquired in the course of its application.

The method possesses two features in view of applications by a user: 1) it can accommodate even small engine-to-engine differences for engines of one particular model, and 2) it allows the estimation of component conditions. This feature makes it directly usable for ECM.

A demonstration of its effectiveness has been given by presenting applications to two commercial jet engines. The obtained results have shown that the adaptive engine performance model can very accurately predict aerothermodynamic parameters along the gas path, as well as overall engine performance over a wide range of operating conditions. It has been also demonstrated that the same method can be successfully used for the detection of faults in engine components.

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