THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
345 E. 47 St., New York, N.Y. 10017

89-GT-205

Adaptive Simulation of Gas Turbine Performance

STAMATIS, A., Assistant
MATHIOUDAKIS, K., Assistant
PAPAILIOU, K. D., Professor
National Technical University
Lab. of Thermal Turbomachines
P.O. Box 64069, 15710 Athens, Greece

ABSTRACT

A method is presented allowing the simulation of Gas Turbine performance with the possibility of adapting to engine particularities. Measurements along the gas path are used, in order to adapt a given performance model by appropriate modification of the component maps. The proposed method can provide accurate simulation for engines of the same type, differing due to manufacturing or assembly tolerances. It doesn't require accurate component maps, as they are derived during the adaptation process. It can also be used for health monitoring purposes, introducing thus a novel approach for component condition assessment. The effectiveness of the proposed method is demonstrated by application to an industrial Gas Turbine.

NOMENCLATURE

BPD	Burner pressure drop coef.
f	Fuel/air ratio
h	Specific Enthalpy
H_f	Fuel calorific value
M	Mach Number
N	Rotational Speed
p	Pressure
P	Power
PF	Power Function
PR	Pressure ratio
Q	Mass flow parameter $m\sqrt{T}/p$
R	Gas Constant
T	Temperature
W	Mass flow rate
W_{ext}	Engine external load
W_F	Fuel flow rate
γ	Isentropic exponent
δ	p/p_{ref}
η_{is}	Isentropic efficiency
η_p	Polytropic efficiency
θ	T/T_{ref}

SUBSCRIPTS

1,...,12	Axial stations (Fig.3)
ct	compressor turbine
b	burner
c	compressor
f	fuel property
pt	power turbine
s	Static property

1. INTRODUCTION

Condition Monitoring of Gas Turbines has received much attention in recent years. A significant number of the techniques employed in this area deals with the assessment of the aerothermodynamic performance of components. The main task consists in estimating the condition (intact or degraded) of the gas path components as well as in diagnosing of faults occuring in them.

The possibility of estimating performance parameters and cycle details for any operating conditions encountered in field operation, is of fundamental importance to any technique of performance monitoring. Engine performance computer models are used for this purpose. Such models are based on a conceptual division of the engine into its components, according to the kind of thermodynamic process occuring in each one of them (the major ones being the compressor, the combustor, the turbine). Determination of performance parameters and cycle details is achieved by solving a system of equations, expressing the state changes of the working substance and the compatibility conditions between the components.

A common feature of all available component-based computer simulation techniques is the requirement of component maps. The reliability of the predictions is highly dependent on the accuracy of these maps. Such maps are not easily obtained by the users, as they are proprietory to the manufacturers. A number of techniques have been proposed by various authors for overcoming this problem. They are mainly based on similarity considerations (1,2,3). Recently, methods of producing the maps by using generalized stage data for compressors or turbines have been proposed (4).

Presented at the Gas Turbine and Aeroengine Congress and Exposition—June 4-8, 1989—Toronto, Ontario, Canada
This paper has been accepted for publication in the Transactions of the ASME
Discussion of it will be accepted at ASME Headquarters until September 30, 1989

There is one aspect, however, which cannot be covered by these methods. It is a well known 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. Engine models as they have appeared up to now, are calibrated in order to reproduce the performance of a typical engine of the series and cannot track such small deviations. A second fact known by experience and recently documented in (5), is that disassembly and rebuilt of an engine can cause small shifts in its performance. Nor can such shifts be tracked by existing performance models.

This problem is tackled by the method proposed in the present paper. The novel feature of the technique, which will be described, 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:

a) it can ensure the follows up of every individual engine, giving the possibility of a very accurate simulation of its performance

b) 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.

The structure of the method makes it especially suitable for introducing it into "Expert Systems" monitoring the performance of Gas Turbines. The engine model can be adapted to particular engines during the "learning phase" of setting the system up, and be exploited afterwards, during engine supervision. Finally, the method allows, besides accurate prediction of performance, direct component condition assessment and fault detection.

We shall start describing the method, by reviewing the basic principles used for computer simulation of Gas Turbine performance. The outline of these principles provides the background for explaining the contribution brought in by our method.

2. BASIC PRINCIPLES OF PERFORMANCE SIMULATION

In order to build a performance model, a Gas Turbine is viewed as an assembly of different components (modules). Each component is identified according to the kind of thermodynamic process it accomplishes, as is known from engine operation theory. The engine cycle at any operating point is defined by the values of the thermodynamic properties of the working fluid at stations at the inlet and exit of the components. Every station is characterized by a number of thermodynamic parameters of the fluid, namely: Total and static pressures and temperatures, mass flow rate W, Mach number M, fuel/air ratio f, specific enthalpy h. A performance model must be able to provide all these quantities at any station in the engine.

For engine performance predictions, it is sufficient to assume flow uniformity radially and circumferentially at any station along the engine (one-dimensional model). The working fluid is assumed to be a perfect gas, with properties depending on temperature. The above parameters are interrelated through the well known compressible flow relations, which show that only three of them are independent. Determination of the independent ones is sufficient for calculating the rest.

If $\underline{Y}_{IN}$ is the vector of independent variables at inlet and $\underline{Y}_{OUT}$ the corresponding vector at the exit, for each module there exists a relation of the form:

$$f(\underline{Y}_{IN},\underline{Y}_{OUT})= 0 \qquad (1)$$

$\underline{Y}_{IN}$, $\underline{Y}_{OUT}$ do not necessarily include the same variables. This relation is usually derived through conservation laws (mass, energy, momentum), as well as from existing experience in component operation. It can be an analytic relation, possibly including empirical constants (e.g. duct pressure loss), or a set of curves (e.g. compressor map).

Compatibility of component functioning imposes "matching" conditions, as for example power balance between turbines and compressors. A set of simultaneous equations which have to be satisfied by the fluid parameters is thus formed. Solution of this system, for one operating point gives the full cycle details. We shall not give any details for such a procedure, as they can be found in a number of publications (see, for example, refs (1,2,3,4)). We shall refer, however, to two aspects, which are related to the present work. The solution to the system of equations is done numerically, since they are highly non-linear. The approach usually followed is the following: First the values of some suitably chosen variables v_1 are guessed, and the equations are explicitly solved, giving the full set of parameters. Error terms are then formed, from the differences of quantities calculated from different equations:

$$e_1= |Pi_1-Pi_2| \qquad (2)$$

where Pi_1, Pi_2 are the values of a parameter Pi calculated by two different equations. (Take as an example the turbine power. One value can be calculated from balance with the compressor power and an other one from turbine flow, pressure ratio, efficiency). These values should be the same for steady operation. The guesses are then repeated, until the error terms are zeroed. For the purpose of the present method, it is most suitable to formulate this procedure as a minimization problem, following a least squares logic. The advantage of such a procedure will be understood later in the paper.

A model built in this way needs as an input the component data, usually provided in the form of performance maps. When these are specified, selection of a suitable set of independent parameters will define one steady state operating point. All cycle details and performance parameters are then uniquely defined. This means that, once the component data are specified, for each operating point we have a unique set of calculated parameters. Whether these are the same with the actual ones for a particular engine, is a question discussed in the following section. For the subsequent discussion, an Engine Model operating according to the above described logic will be termed a straight model, in contrast to the adaptive model, introduced in the present paper.

3. REQUIREMENTS FROM PERFORMANCE MODELS AND COMPONENT DATA

An Engine model supporting a Condition Monitoring system has to meet the following requirements:

a) Increased prediction accuracy, even for individual engines b) Quick calculation time, in view of potential on-line applications c) Possibility of incorporating extra measurement data, when such data are available.

The effectiveness of a thermodynamic model in this respect, is linked with three elements used in building it: The input data, the modeling equations and the numerical method of solution.

The data which are given as input to a model can be divided into two categories: (i) Data related to the particular operating condition (for example ambient conditions, fuel calorific value, speed, load), which define the engine operating point.(ii) Data related to the performance of the engine components, corresponding to equation (1), as for example, the compressor and turbine performance maps. If these maps do not represent exactly the compressor and turbine operation of a particular engine, then the predictions will differ from actual measured values. Data from this second category are usually not available to the user. But even when the engine manufacturer is concerned, the available data usually represent an average engine or come from a specific prototype tested. Therefore, they do not correspond exactly to each specific engine produced.

A way to achieve accurate predictions by a computer model, is to provide it with the possibility of modifying the inaccurate maps, so that they correspond to a particular engine of interest. This is exactly achieved by the adaptive model introduced here. Before explaining the methodology employed, it is useful to understand why an available set of maps, may not lead to accurate predictions for a particular engine. The maps may differ from the ones of a specific engine depending on their origin:

a. Maps measured on isolated components. Such maps may differ from actual "on engine" maps, due to interactions with other components or different operating environment (e.g. heat transfer effects).
b. Maps predicted by computer programs. Such maps may differ from actual ones due to insufficient modelling capabilities or lack of the necessary physical data.
c. Maps measured on a different engine. They can be different because of engine-to-engine dissimilarities. Such maps are sometimes difficult to measure, due to practical difficulties, as for example high temperatures of the hot components.

Finally, it should be noted that installation effects may also cause some performance variations introducing, for instance, non-uniform pressure and temperature at the inlet, constrain that a ter exit diffuser performance, etc.

We present now the method used for modification of the component maps and building up the adaptive model.

4. MODEL ADAPTATION

The performance maps of each engine component are expressed by functional relations between performance parameters characteristic of each component, of the form of equation (1). These relations can be in an analytic form or in the form of a chart. If a particular parameter has a value X_{ref} on the reference map and a value X_{act} on the actual "on engine" map, then the correspondence between the two can be expressed by means of a modification factor MF defined as follows:

$$MF = \frac{X_{act}}{X_{ref}} \qquad (3)$$

Knowledge of the reference performance map and the values of MF gives the possibility of reproducing the actual maps. Care must be taken however in the way these factors are introduced they must be consistent with existing representation of the maps and the set of equations used. For example, in the case of the compressor we can employ the following definitions: For given values of rotational speed and pressure ratio, we define:

$$MF_1 = \frac{Q}{Q_{ref}} \qquad MF_2 = \frac{\eta_{pc}}{(\eta_{pc})_{ref}} \qquad (4)$$

These coefficients are defined for each point of a speed line of the map, as shown in Fig.1.

The value given to any component parameter used by the model is thus introduced as a product:

$$P_{act} = MF\ P_{ref} \qquad (5)$$

We see that a value of a component parameter is now defined by means of two numbers: its reference value and the value of the corresponding modification factor. When the reference values are available, let's see how the values of the modification factors can be determined.

Having chosen a set of modification factors values MF_i, it is possible to define an optimization problem, which allows the determination of their values, needed for adapting the maps.

In a straight engine model the solution of the equations for a particular operating point, discussed in Section 2, proceeds by guessing values for some variables v_i and calculating error terms e_i, equation 2. Besides the parameters necessary to form the error terms, values of all cycle details are calculated. They include the values of the quantities measured along the gas path during experiments. For any measured quantity Q_m there is a corresponding calculated Q_c. We, then, form a cost function FC as follows:

$$FC = \sum_{i=1}^{M} a_i e_i^2 + \sum_{i=1}^{N} b_i (Q_{c_i} - Q_{m_i})^2 \qquad (6)$$

where M is the number of error terms of the model, N is the total number of measurements and a_i and b_i are weight coefficients depending on both measurement and desired model accuracy. If modified maps are introduced into the model, by means of a particular set of values for MF_i's, the value of FC obtained, will be a function of the original guess for v_i's and MF_i's:

$$FC = FC(v_1, v_2, \ldots, v_M\ ;\ MF_1, MF_2, \ldots, MF_N) \qquad (7)$$

The set of independent variables which minimizes the value of this function to zero, satisfies the matching conditions for the engine, while it ensures that the measured and predicted quantities are the same. A set of values for the modification factors is produced for the particular operating point. We get thus a set leading to an optimal reproduction of measured quantities, through the simulation model. The flow chart of the procedure is depicted in Figure 2. Covering the entire operating range of the engine, will give the full set of MF_i's needed. The computational technique employed for solving the nonlinear minimization problem is the Nonlinear Generalized Minimum Residual Method, proposed in (10). This is a very fast method, while it has a satisfactory behaviour with respect to convergence history.

The method described above has the advantage that it can incorporate a variable number of measured quantities. The number of modification factors which can be determined changes accordingly. The way described above can be characterized as "internal" to the model. The adaptation can also be done "externally", by requiring the minimization of the two sums of equation 5 separately. In this case the minimization of the first sum is actually achieved by the straight model. Such a procedure has the disadvantage of requiring larger calculation time. It has the advantage, however, that since it is external to the straight model, it can be coupled very easily to straight models, which the user already possesses.

5. APPLICATION TO AN INDUSTRIAL GAS TURBINE

The method has been applied to the case of the single shaft version of the TORNADO Gas Turbine, manufactured by Ruston Gas Turbines (6,7,8). This application is interesting in that it demonstrates that the adaptive model can actually track deviations from the "average" engine, by using test bed data. A straight engine model had already been developed for this engine (9).

Test data was taken from one of the prototype Tornado engines, which, after 13,000 hours operation and use for some years as a development test core, has large tip clearances that are well outside manufacturing tolerances and significantly larger than the normal values observed on engines in service. This results in a significantly lower standard of performance than the "average" Tornado.

The elements used are the following:

a) Component data. Maps have been provided by RGT. A compressor map typical to the TORNADO has been used. It is known that such a map differs slightly from the actual compressor "on the engine" map. For the compressor turbine a map calculated by RGT using the Ainlay-Mathieson correlation has been used. For the power turbine, finally, since no component map was provided, a map similar to the one of the compressor turbine was used, scaled to the design point data.

b) Test Data. They are acquired from operating conditions covering a wide range of compressor operating conditions, by means of an engine data logging system (8).

5.1 Formulation of the Problem

The division of the engine into components and the stations considered is shown in Fig.3. It must be noticed that in this particular application the turbine is divided in two parts: the core turbine and the power turbine. The two are separate in the actual engine, since this engine can be converted into a twin shaft version by simply decoupling the core from the power turbine. Each operating condition of the engine is set by defining the rotational speed and a particular output demand (load). For each equilibrium operating point we have chosen the following modification factors for the different components

Compressor

$$MF_1 = \frac{\dfrac{W_2\sqrt{T_2}}{P_2}}{\left(\dfrac{W_2\sqrt{T_2}}{P_2}\right)_{ref}} \qquad MF_2 = \frac{\eta_{p_c}}{(\eta_{p_c})_{ref}} \tag{8}$$

Combustion Chamber

$$\eta_b H_f = MF_3 \cdot (\eta_b H_f)_{ref} \tag{9}$$

Core Turbine

$$\frac{W_6\sqrt{T_6}}{P_6} \cdot \frac{N}{\sqrt{T_6}} = MF_4 \left(\frac{W_6\sqrt{T_6}}{P_6} \quad \frac{N}{\sqrt{T_6}}\right)_{ref} \tag{10}$$

$$\eta_{is_{ct}} = MF_5 (\eta_{is_{ct}})_{ref}$$

Power Turbine

$$\frac{W_9\sqrt{T_9}}{P_9} \cdot \frac{N}{\sqrt{T_9}} = MF_6 \left(\frac{W_9\sqrt{T_9}}{P_9} \quad \frac{N}{\sqrt{T_9}}\right)_{ref} \tag{11}$$

$$\eta_{is_{pt}} = MF_7 (\eta_{is_{pt}})_{ref}$$

The measurements incorporated in the adaptive model, namely the quantities Q_i of equation 5, are: W_f, W_a, T_4, P_{s4}, T_9, P_{s9}, T_{12}.

5.2 Results

First we demonstrate that predictions using a straight engine model (9) and the component maps described above (approximate maps), differ from actually measured values, for different operating points. In Figures 4,5,6,7 comparisons between measured and predicted quantities for two rotational speeds and different loads, are shown. It should be remembered that the operating points are defined in the same way in both the test bed and the computer model: by specifying rotational speed and external load. We observe in these Figures that predicted values deviate from measured ones in various degrees, depending on speed and load. These Figures demonstrate that the straight performance model, cannot guarantee accurate predictions.

Introducing now the measured values into the adaptive model, we produced a set of modification factors, for adapting the component maps. A sample result of these calculations is shown in Fig.8,9,10. The modification factors calculated for the range of operating points we tested, are shown in these Figures. It must be noticed that the mass flow corrections resulting from this figure are of the order of 3% to 5%. This agrees with RGT's experience, about differences in flow capacity of different TORNADO's. The clusters of points at the ends of the curves are calculated for samples taken at one operating point, during a long time interval. Their degree of dispersion ashows the scatter one should expect for the modification factor at one operating point.

Comparison between measurements of the total pressure and temperature and corresponding predictions coming from both the straight and the adaptive model, are shown in Figures 11,12. The evolution of differences between measured and predicted total pressure and temperature along the engine, are shown in this Figure. It is observed that significant deviations exist between measurement and prediction for the straight model. On the other hand the temperature is very well predicted with the adapted model. The prediction of the pressure is not as accurate but one may note that prediction error has been reduced from 8% for the straight model to 1.6% for the adaptive model.

6. APPLICATION TO FAULT DETECTION

The determination of the Modification Factors can also be used for detecting faults either in the engine components or in the sensors. If for example the efficiency of a component drops, this will show up in a change of the value of the corresponding modification factor and can, thus, be detected. If on the other hand a sensor fails, its reading will influence the calculated values of MF's. Such a case has been simulated on the data of the test case presented above.

The reading of T_4 has been modified by 5%, simulating thus a fault on that sensor. The rest of the measurements has been kept the same. Recalculation of the modification factors has been performed and the new values obtained, in comparison to the ones of operation without fault, are shown in Figure 13. It is clearly seen that the cluster of values has undergone a discrete move. This fact hints that predictions of the model can be used for detecting faults of this kind. In fact, the model may be linked to a pattern-recognition method,such as that of ref.(11). The modification factors can be treated as "features" and an automatic diagnosis can be performed from the clusters formed in a feature space, according to the method of ref.(11).

In order to distinguish whether a fault is due to a sensor failure or comes from an actual engine problem, the observation of shifts in the calculated MF values has to be combined with runs in the direct mode, using the obtained values. The details of such a procedure are currently under elaboration.

Finally, besides jumps in calculated values indicating the presence of a fault, continuous monitoring can also be performed using the present procedure. In this mode, the values of MF's must be calculated at regular intervals during engine operation, their trending indicating how each component's deterioration is occuring.

7. CONCLUSIONS

A procedure for developing computer performance models capable of adapting to specific engines has been presented. This is achieved by using an optimization procedure and measurements provided during engine operation.

A demonstration of the procedure has been given, applying it to a single shaft industrial Gas Turbine. The obtained results have shown that:

- average component maps are not sufficient for accurate prediction of all engine parameters
- the adaptive engine performance model can predict rather accurately aerothermodynamic parameters along the gas path.

A particular feature of this 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.

Besides adapting to particular engines, the procedure seems to present an alternative for detecting faults in engine components and/or sensors, as well as indicating the condition of each component when continuous measurements are available for engine monitoring.

ACKNOWLEDGEMENTS

The experimental data included in this paper have been obtained during testing for the research contract BRITE Nr. RI-1B-0159F(CD).The authors express their thanks to the Hellenic General Secretariat for Research and Technology and the European Communities, for their financial support. Thanks are expressed to RUSTON GAS TURBINES for allowing the inclusion of the experimental data in the paper. Special thanks are due to Mr. M.K. Smith of RUSTON GAS TURBINES for valuable discussions and suggestions.

REFERENCES

1 SELLERS J., DANIELE,C.,"DYNGEN-A Program for calculating steady-state and transient performance of turbojet and turbofan engines", NASA TN D-7901, April 1975.

2 SARAVANAMUTTOO,H.I.H., McISAAC,B,D.,"Thermodynamic Models for Pipeline Gas Turbine Diagnostics", Paper ASME 83-GT-235, Trans. of the ASME, Vol.105 Series A, pp 875-84, 1983.

3 PALMER,J.R., YAN CHENG-ZHANG., "TURBOTRANS-A programming Language for the Performance Simulation of Arbitrary Gas Turbine Engines", Paper ASME No 82-GT-200.

4 MUIR,D.E., SARAVANAMUTTOO,H,I,H., MARSHAL,D.J., "Health Monitoring of Variable Geometry Gas Turbines for the Canadian Navy" Paper ASME 88-GT-77.

5 McLEOD,J.C., LAFLAMME,J.C.G.,"The effect of a Compressor Rebuilt on Gas Turbine Engine Performance", Paper 26, AGARD CP-448, June 1988.

6 WOOD,G.R.,"The RUSTON TORNADO. A 6MW Gas Turbine for Industrial Application", Paper ASME No 81-GT-171

7 CARCHEDI,F., WOOD,G.R.,"Design and Development of a 12:1 Pressure Ratio Compressor for the RUSTON 6MW Gas Turbine", Paper ASME No 82-GT-20.

8 TIMPERLEY,S., SMITH,M.K.,"A Data-Logging and Performance Analysis System for Application to Industrial Gas Turbines", Paper ASME No 83-GT-104.

9 MATHIOUDAKIS,K.,LOUKIS,E.,STAMATIS,A.,PAPAILIOU, K.D.,"Noise/Vibration Imaging Techniques for Gas Turbines Investigations", The Contribution of NTUA. Project Report No 2, BRITE Project No 1368, Dec.1987.

10 "Techniques for Solving Large Sparce Nonlinear Systems of Equations", Research Report SCA-105, Scientific Computing Associates Inc., New Haven, CT06510, June 1986.

11 BARSCHDORFF,D., KORTHHAUER,R.,"Aspects of Failure Diagnosis on Rotating Parts of Turbomachines Using Computer Simulation and Pattern Recognition Methods" Presented at the International Conference on Condition Monitoring, Brighton, England, May 21-23, 1986.

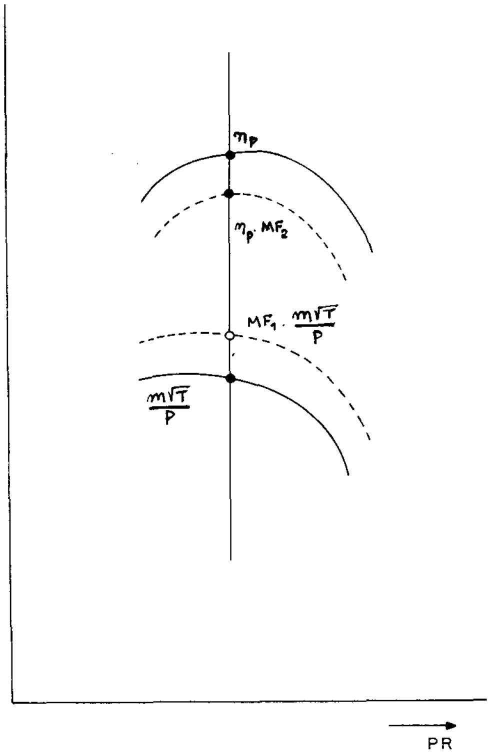

Fig.1 Principle of map modification by means of modification factors.

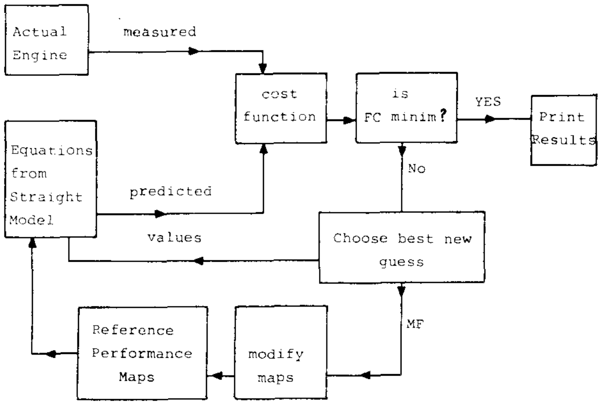

Fig.2 Flow chart of adaptive model.

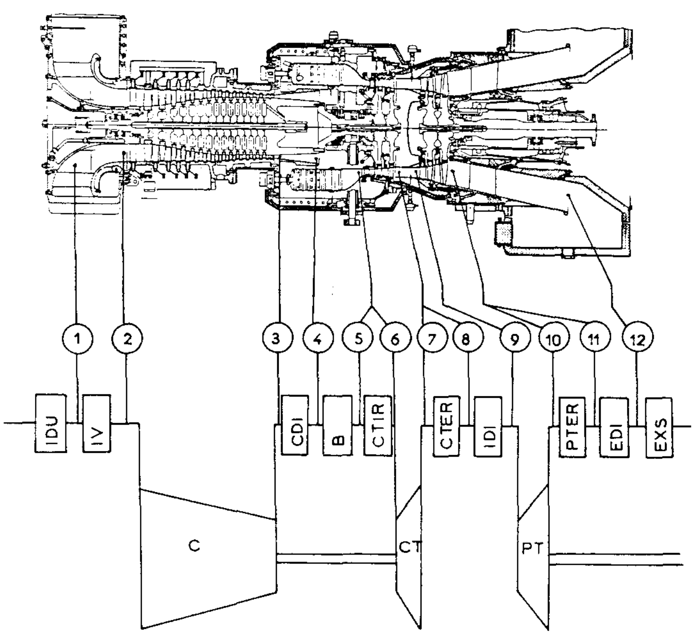

Fig.3 Engine layout and components; B burner; C compressor; CDI compressor diffuser; CTIR compressor turbine inlet remix; CT compressor turbine; CTER compressor turbine exit remix; EDI exhaust diffuser; EXS exhaust stack; IDI interduct diffuser; PT power turbine; IDU inlet duct.

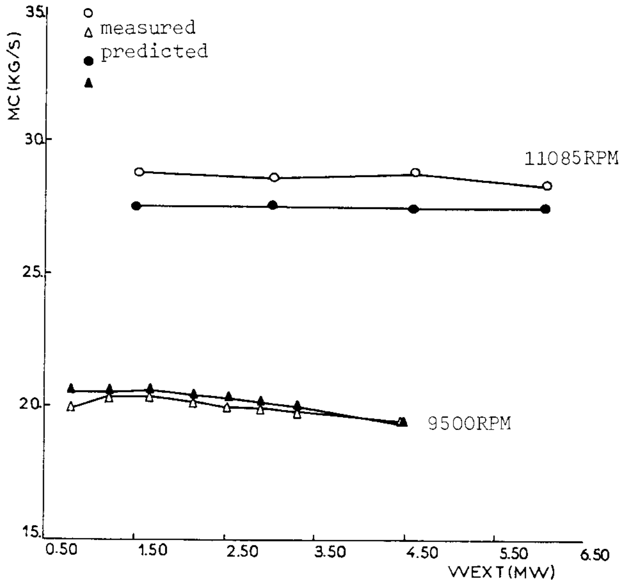

Fig.4 Comparison of measured values to predictions of the straight model. Mass flow rate.

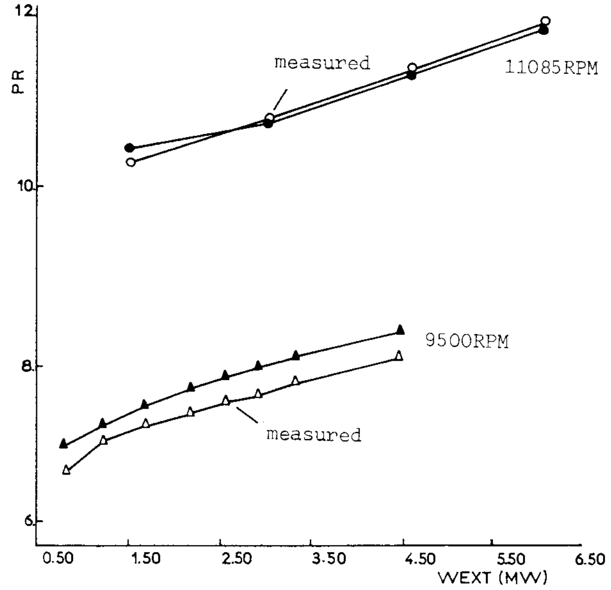

Fig.5 Comparison of measured values to predictions of the straight model. Compressor pressure ratio.

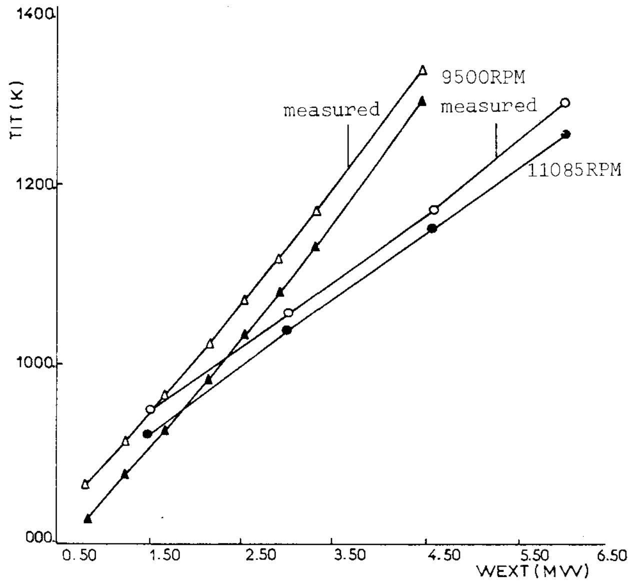

Fig.6 Comparison of measured values to predictions of the straight model. Turbine inlet temperature.

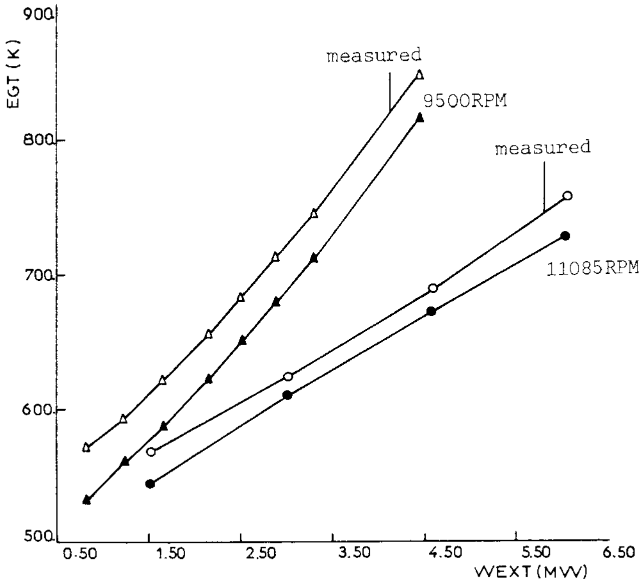

Fig.7 Comparison of measured values to predictions of the straight model. Exhaust Gas Temperature.

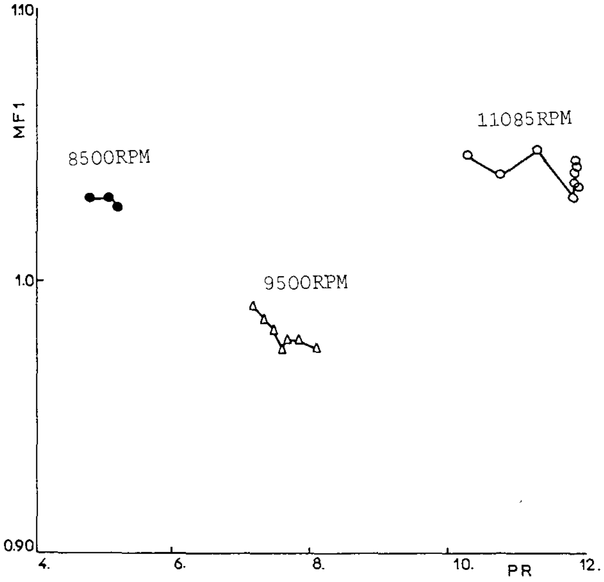

Fig.8 Modification factor MF1 versus compressor pressure ratio.

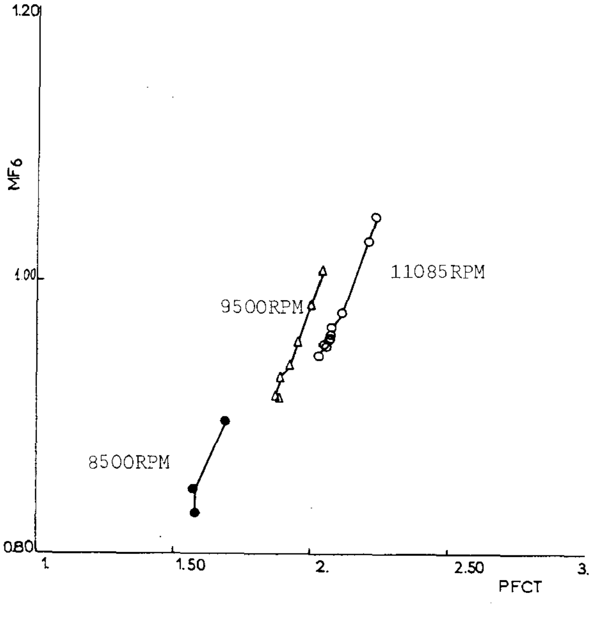

Fig.10 Modification factor MF6 versus power function of compressor turbine.

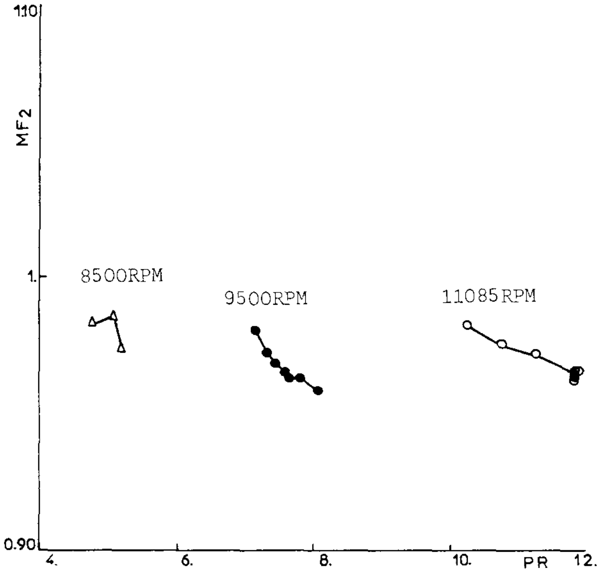

Fig.9 Modification factor MF2 versus compressor pressure ratio.

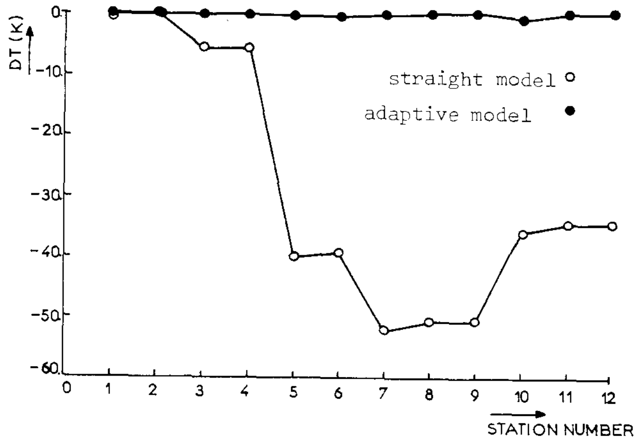

Fig.11 Difference of predicted and measured temperature along the engine, for the straight and the adaptive model.

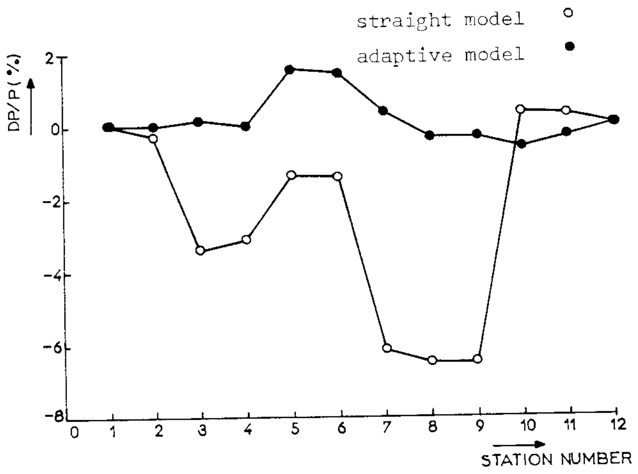

Fig.12 Difference of predicted and measured total pressure along the engine, for the straight and the adaptive model.

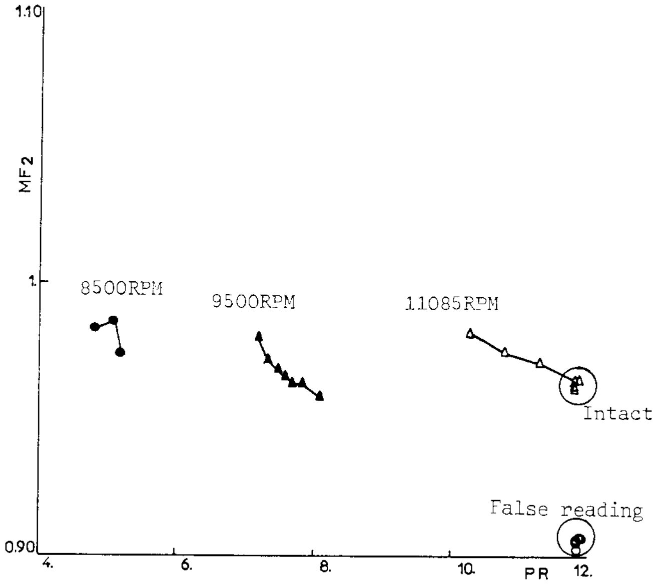

Fig.13 Influence of sensor fault on calculated values of MF. 5% error on T_4 reading.