Computer Modeling and Data Processing Methods. An Essential Part of Jet Engine Condition Monitoring and Fault Diagnosis

Summary

Methods of processing measurement data in order to derive information about the health of an engine are presented. Both aerothermodynamic performance and fast response measurement data are covered. The principles and representative results of an advanced Gas Path Analysis method are given. The method of Adaptive Performance Modeling and its application to fault diagnosis is described. Identification of faults on rotating blades by using unsteady pressure measurements is discussed. Extraction of diagnostic information from casing acceleration as well as acoustic measurements is also discussed.

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1. Introduction

Knowledge of the physical and operational condition of any part of an Engine, whenever desired, is the basis of Engine Condition Monitoring. In order to get this knowledge, the following steps must be undertaken:

a. Measurement of physical quantities related to the condition of the different Engine parts.

b. Reduction of the measured values to a meaningful parameter set.

c. Interpretation of the meaning of the obtained parameter values, on the basis of previous experience or knowledge of the physical processes taking place within the Engine.

Successful accomplishment of the tasks included in each one of these steps is necessary in order to reach a correct conclusion about the state of the Engine and take appropriate action.

The accomplishment of step-a can be ensured by careful selection of measuring locations and instruments suitable for the quantities and ranges of their values. The outcome of this step is a set of values for the measured physical quantities, with a certain level of uncertainty sufficient for the purpose of the monitoring process. It must be noticed here that the achievement of this purpose depends on two factors:

i. The correct choice of measurement location and instrument

ii. Present day technology development level, offering the corresponding instrumentation.

While the expected outcome of step-a is as well defined as above, the same is not true for steps b,c. It can be easily understood that the task of interpretation is easier when the reduced parameters are closely related to physics of the problem under consideration. In order to make more clear this statement, let's consider the following example: Assume that the condition of the blading of a compressor stage is monitored. For this purpose the pressure and temperature at its inlet and outlet are measured.

Let's consider that there are three alternative methods of reducing the data :

1. Derivation of corrected performance parameters, temperature, mass flow and pressure at inlet and outlet.

2. Derivation of results of method-1 plus cascade performance parameters for rotating and stationary blade rows.
3. Derivation of the actual blade geometry, which has produced the measured quantities (by solving for example the corresponding fluid flow inverse problem).
If information of method-1 is available, one needs to have experience on the particular compressor examined or similar machines in order to reach a conclusion. Information from method-2 does not require knowledge of the particular machine performance , but only more general knowledge of cascade performance principles. Finally, if information of method-3 is available, the geometry of the blading is directly available and no interpretation of the measurement results is needed at all.

This example shows that the task of interpretation of reduced parameters as to their physical meaning, is greatly dependent on the level of reduction. This level can vary from a slight correction of the measured quantities (method-1 above), to determination of the actual physical parameter under observation (method-3 above), the later one being the ultimate target of the procedure. Usually the situation which the Monitoring Engineer is facing is somewhere between the two extremes, in most cases closer to the least favorable.

It is easily understood that the possibility of reducing measured data as far as possible is greatly desirable. Not only it is desirable, however, but is absolutely essential in cases in which:
- fast decision must be taken about desired action
- the decision must be taken automatically by a computer.

On the other hand, we must keep in mind that the task of data reduction is undertaken, almost exclusively in the present day, by digital computers. Methods employed for reducing measured data to parameters which can be much easier interpreted by human experts or even by appropriately instructed computer will be presented in the following sections. The methods will be classified according to the kind of measurement to be processed and the method of reduction employed. While the work of various investigators will be quoted along through the paper, the results presented come mainly from work carried out at the Laboratory of Thermal Turbomachines, National Technical University of Athens.

2. Kinds of Data and Processing Techniques

Before discussing kinds of measurements performed, it is useful to remember what the purpose of Jet Engine Condition Monitoring is. The engine user wishes to ensure that:

a. The engine operates at the desired operating conditions, delivering power as specified, with reasonable efficiency.

b. The structural integrity as well as the continuity of operation is guaranteed, for the scheduled operation intervals. In the opposite case it is wishful to forecast the remaining time of " healthy " operation.

Measurements performed on an engine for this purpose can be classified according to the way of data collection:

a. Steady state measurements

b. Unsteady measurements of fast varying quantities

Steady state measurements usually include fluid flow parameter along the engine flow path as well as global performance parameter at a specific operating point. They are mainly useful for identifying the condition of the Gas Path components of the Engine. Unsteady measurements include unsteady pressure and vibration measurements, which can be used for identifying mechanical condition of rotating engine parts, not only related to the Gas Path but to the engine mechanical integrity as well (e.g. bearings). In the second category of data one can include transient performance measurements, which cover the thermodynamic measurements performed at steady state, when a rapid change of engine operating condition is imposed.

Different methods of data processing are employed for different kinds of measurements. For the steady state measurements thermodynamic principles are employed and the related methods are known under the name of " Gas Path Analysis ". For unsteady measurements signal processing methods are applied and their results are usually further processed in order to deduce diagnostic information.

At this point it is useful to make comment on the usefulness of modeling in the data reduction procedure. Modelling is useful in two ways:

i. It can guide the data reduction procedure, which can be done a way such that physical compatibility is guaranteed. The reduced parameters have a physical meaning.

ii. Accurate models can substitute for the actual physical process in providing information on the values of measured quantities.

In this way modeling can provide information which would otherwise be accessible only through experience of operation of actual engines. It can therefore substitute for both experiment and collected information from user experience, reducing thus the volume of data bases needed for the interpretation of processed data. This reduction can lead to considerable savings of cost and time for the application of Condition Monitoring Techniques. In view of these benefits, it seems that modeling should play an important part in the implementation of data processing techniques.

We proceed now in discussing groups of techniques as subdivided above, starting with techniques related to aerothermodynamic performance.

3. Techniques for Aerothermodynamic Data

The common feature of these techniques is that they are based on measurements of aerothermodynamic quantities, namely pressure and temperature along the Gas Path, as well as performance parameter such as thrust or fluid flow. They are based on the fact that any problem on the engine components in contact with the gas path results in a change of the values of the measured quantities.

According to the level of processing techniques of this kind could be subdivided into the following groups:

a. Direct observation of trends of corrected measured quantities

b. Parameter deviation estimation from measured quantities deviations

c. Estimation of component characteristic parameters

We are not going to comment on group-a techniques since they involve minimal processing and are exclusively dependent on user experience. We will give description of group-b, c methods, by giving particular attention to methods developed by the research team of the authors.

3.1. Parameter Deviation Estimation

The idea on which such methods are based, is the fact that any change in the performance of the components which are in contact with the gas path, will result in a change of the aerothermodynamic cycle parameters. If this second change is traced, the original cause can, in principle, be detected.

Problems on the engine components result in change of their performance parameters (e.g. efficiency, swallowing capacity), which in turn result in deviations of the measured quantities from their values with undisturbed operation (baseline values). When the deviations of the measured quantities are observed, it is not generally possible to know which engine component has been submitted to change, unless previous experience on the particular engine exists. If the changes of the parameters of the components are known, however, it is much easier to identify where the fault is as well as its kind. Since such component parameters are not directly measurable, it is necessary to deduce their deviations from the available measurements, as shown schematically in figure 1. This is the objective of methods of this category. Methods of this kind have been developed by different authors [1,2,3].

In an effort to develop an effective diagnostic system based on GPA, practical limitations are encountered. These limitations appear when, in order to increase reliability on performance estimation as well as to isolate malfunctioning components of the engine, one has to increase the volume of information concerning its state. The usual approach to meet this requirement is the increase of the number of measured quantities, by installing additional sensors. In the case of engines under development, the main restriction is the cost of the additional instrumentation. In already existing engines, one additional restriction is faced, which concerns the integrity of the powerplant: Installation of new sensors cannot be undertaken by the user, unless this is allowed by the engine manufacturer.

A method of overcoming these practical limitations has been introduced in [3] under the name of Discrete Operating Conditions Gas Path Analysis, DOCGPA. This method utilizes the ignored amount of independent information coming out of measurements realized by the already existing sensors, at different operating points. The mathematical background of this method has been described in - [3,4]. Here we will only present representative results in order to demonstrate the effectiveness of the method.

A comparison of values estimated by the method to the ones proposed by the manufacturer of a commercial turbofan are shown in figure 2. It must be pointed out that the method has used only four measured quantities at three operating points in order to estimate the six parameter deviations. Conventional methods require as many measured quantities as the estimated parameters are, namely in this case, six measurements would be necessary. On the other hand, if a certain number of parameters is estimated by using additional measurements, the uncertainty of the estimation is reduced as the number of operating points increases as shown in figure 3.

It should be mentioned here that the implementation of the method requires the availability of performance models with sufficient capacity of predicting engine behaviour. Such models provide the Influence Coefficients necessary for implementation of the method. An example of such coefficients calculated for the above-mentioned turbofan is shown in figure 4. The nonlinear dependance on operating conditions exhibited by these coefficients is a necessary condition for applying DOCGPA. The reliability of the performance models employed is tested by checking their predictions against manufacture's data, as for example shown in figure 5.

3.2 Estimation of Component Characteristic Parameters

An alternative way of estimating the condition of engine components stems from the Technique of Adaptive Performance Modelling, developed at NTUA [5]. This technique employs the values of measured quantities in order to determine parameters characteristic to the performance of each component, which can be used to asses its health. In order to make things more clear we proceed to a brief description of the principle of the method. More details are given in [5].

The performance maps of each engine component are expressed by functional relations between performance parameters characteristic of each component. 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:

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

where

MF: modification factor

X act: The actual (usually measured or calculated from other measured quantities) value of the parameter X.

X ref: The reference (initial) value of X (usually assumed or known with uncertainty).

Knowledge of the reference performance map and the values of MF gives the possibility of reproducing the actual maps. Care must be taken 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 figure 6.

When the performance maps are introduced in a model by means of reference maps and a set of modification factors, it is possible to formulate the model in such a way that by introducing the values of a number of variables in the data, the same number of modification factors can be estimated. The block diagram of such a procedure is shown in figure 7. This means that by feeding the model with extra measurements, modification factors are calculated. From the definition of the modification factors we see that their values characterize the state of a component with respect to a reference condition. If this reference condition is chosen as the healthy state of the same engine, then the values of the modification factors can be used directly for fault diagnosis.

The procedure described above is implemented directly into the engine model. There are cases, however, in which the engine model should not be modified or cannot be modified (e.g. code available only in executable form). The technique can still be applied in a slightly different way, as shown by the block diagram of figure 8. The difference in this case lies in the method of solution. While the engine matching problem is solved simultaneously with the adaptation problem in the previous case ("internal" adaptation), in this case the two problems are solved separately ("external" adaptation). On the other hand the modification factors can be introduced not only as ratios of corresponding quantities, but also as deviations from the reference values.

The advantage of the technique of Adaptive Modelling is that the engine model itself is providing the diagnostic information (in contrast to deviation estimation methods, which stand independent and need input from such a model). On the other hand, the method provides the possibility of very precise modeling, even though the component characteristics are not known with a great accuracy, overcoming thus the shortcomings of existing modeling techniques [6,7,8]. By having a set of approximate maps, an initial run of the model can be performed in order to establish maps with which the model can reproduce reliably engine performance. Subsequent rans for collected data sets can then be used for monitoring of the Engine.

The technique has been applied to different engines, in order to test its efficiency and examine its capabilities. The improved possibility of modelling can be seen in figure 9, where the predictions from an adaptive model are compared to predictions of a non-adapted one as well as to manufacturers specifications [9]. The engine under consideration is a commercial turbofan. Component maps have been initially estimated by employing generalized maps and scaling at the design point [9]. The adaptation was then performed by using data of overall performance, provided by the manufacturer in the documentation accompanying the engine. For the same engine, component parameter deviations were estimated from measurement data deviations. The technique applied in this case was of the "external" type, mentioned above.

Another test case examined, was that of an industrial Gas Turbine, on which experiments were performed for both healthy and unhealthy operation. The model was of the "internal" type in this case. The prediction improved by the adapted model in this case is demonstrated in figure 10. It must be mentioned that the original reference maps were provided by the manufacturer in this case. Nevertheless, the possibility of prediction using these maps is rather poor for the particular engine, since they represent an average engine and not every individual engine of the series.

The impact of a sensor fault (simulated) on modification factors can be seen of figure 11, while the impact of an actual engine fault is shown in figure 12. These two figure demonstrate that any kind of fault reflects directly onto the values of the modification factors, which can thus be used for fault diagnosis.

4. Techniques for Fast Response Measurement Data

Fast response measurements data are usually available as time signals of some quantity related to engine operation as for example pressure or vibration acceleration. It would be possible to give a generalized statement about the principle on which these techniques are based.

The rotation of the engine shaft is a source of periodic variation of various quantities, as for example air pressure and velocity or force transmitted to bearings. The periodic variation of any quantity related to engine rotation has some features related to the particular structural and operational condition of the engine. If a change in this condition occurs, these features will be altered. It is in general possible to reveal the changes which have produced these alterations and then decide if they constitute a harm to the engine or not. The purpose of the techniques discussed in this section is to perform exactly this task, namely to reveal what is happening inside the engine by analyzing unsteady measurement data.

Information about engine parts can be gathered from signals of various physical quantities. A broad range of engine parts and kinds of failures can covered by measurements of:

a. internal aerodynamic pressure field
b. casing vibration
c. shaft displacement at bearing location
d. emitted sound

Processing and analysis of data of group-c has received particular attention [10,11,12] and there are various commercial systems utilizing related techniques. We are not going therefore to mention them here. Techniques related to group-b type of data are also widely used in various types of machinery. We are going to mention techniques of this kind in the extent they are related to gas turbines.

4.1 Techniques Based on Internal Pressure Field Measurement

The rotating blades of a turbomachinery component of an engine produce fluctuating pressure field at any fixed position inside the casing. The pattern of the blade-to-blade pressure field around a rotor circumference depends on the geometrical shape of the blades, which reflects their mechanical condition. - Namely, it changes when blade faults occur,as blade bending or loss, as well as when the blade shape changes due to erosion or fouling for example. It is therefore expected that measurement of this pressure field will give the possibility to determine the condition of rotating blades.

A simple analysis can show that when a fault has produced a change of the form of one or more rotating blades, the resulting disturbance of the pressure field will show-up as an increase in the harmonic content at multiples of the rotational frequency. This principle has been demonstrated by numerical experiments [13,14], which showed that faults on the rotating blades can be identified from the harmonic envelope they produce on the power spectrum of an internal pressure signal. An example of such a result is shown in figure 13. The distinctly different patterns for different blade defects can be seen from this figure. Experiments performed on an industrial Gas Turbine ~~by~~ the authors' group [15] have verified this conclusion.

The signals from pressure transducers prove thus to provide an excellent indication of the kind of faults appearing on individual blades. It must be pointed out that these faults influence insignificantly the overall engine performance and cannot thus be detected by thermodynamic data analysis methods. On the other hand, the results presented above have shown that modeling can be used to provide signatures of the different kinds of faults. In such a case, the signatures of faults do not need to be established experimentally and be stored in a data base, since they can be produced by the simulation procedure.

4.2 Techniques Based on Casing Acceleration

Vibration monitoring provides important information about the "health" of mechanical parts and provide an early indication of incipient mechanical failures.

The aspects of malfunction covered in most of the recent publications refer mainly to problems showing up in shaft related vibrations . Such problems are, for example, bearing failures, misalignment, shaft cracks, structural resonances, unbalance, shaft bow, fluid film and bearing instability, rubs. Most of the published data and fault signatures discussed in the open literature refer to such cases. Identification of the condition of the blading itself has received less attention, although blading problems have been reported [13] to rank among the most frequent faults.

The authors' group has developed techniques aiming to the identification of blading faults, from casing acceleration measurements. The basic idea employed is that casing acceleration contain information about the unsteady pressure field of the blades, which can give easily interpretable diagnostic information, as discussed previously. It is expected that alterations of the internal aerodynamic field will reflect on accelerometer readings. This has been demonstrated in [16], where a number of conclusions about the features of casing acceleration measurements have been derived: Each accelerometer signal carries information not only from the stage in its immediate vicinity, but also from other stages along the compressor.The vibrations of the compressor casing surface are not symmetrically distributed around the circumference, a fact of diagnostic value, since accelerometers placed at the same axial location can provide information about stages at other axial locations. An example of the findings reported in [16] is given in figure 5, where the RMS of accelerometer signals for the different operating points of our experiments is shown. This figure shows the following: (1) The overall level of the RMS is significantly changing from one speed to another, in comparison to smaller changes on each speedline. (2) At one operating speed the RMS is changing with the pressure ratio.

In order to derive information about what is happening in the engine interior a systems approach has been established. The transmission characteristics of the compressor casing can be mathematically expressed as a set of vector transfer functions, if the compressor casing is modelled as a linear system. The inputs of the linear system are all the excitations of the casing. They are continuously distributed over the internal surface of the casing and its connections to adjacent engine components. A schematic view of the system and the excitations, is shown in fig.15a. It is a distributed parameter, distributed input system. In order to study its characteristics, we lump the most important excitations and form an equivalent system with lumped inputs. The vibration of any point of the compressor casing can be considered as output of the linear system. The resulting simplified system is shown in figure 15b.

The calculation of any of the vector transfer functions from time domain signals is based on a well established method known from systems theory, see for example [17]. 4 unsteady pressure transducers P2-P5 have been regarded as outputs and accelerometers as inputs. Using this procedure the power spectra for the pressure transducers at the operating point F were reconstructed. A comparison with the corresponding directly calculated spectrum, fig.16, shows a very good agreement, particularly in frequencies corresponding to the periodic components of the signals.

The general conclusion drawn is that for any operating point the unsteady pressure transducers spectral densities can be reconstructed from accelerometers signals, using a complex average vector transfer function for the speedline of the operating point. The averaging over the different operating points does not influence the possibility of reconstructing features of the internal pressure signals.

4.3 Techniques Based on Acoustic Data

Noise emitted by an engine is produced by many sources with various origins intensities and frequencies. These sources can be divided into two main categories: i)Aerodynamic origin sources. ii)Mechanical origin sources. Since sound is influenced by both factors, it is expected that its measurement will give the possibility to reveal problems of both kinds of components. The methods of analysis are in general similar to the ones applied to vibration data. Additional information can be provided by considering the spacial distribution of acoustic characteristics [15]. Although such methods have found applications in other kinds of machinery, no significant applications on gas turbine engines have been reported in the open literature.

The author group has performed acoustic measurements on an industrial gas turbine with implanted blade faults [15]. It has been found that ceratin blade faults produce a distinct acoustic signature, as for example is shown on figure 17. On the other hand, acoustic imaging techniques, have proven to give the possibility of identifying the existence and location of stator faults.

5. Summary, Conclusions

The methods presented in this paper cover a wide range of possible faults, which are related to both parts in contact with the gas path and other mechanical parts of an engine.

Two methods related to aerothermodynamic data have been presented:(a) A method for estimating parameter deviations from measurement deviations. This method has the advantage of determining more parameter deviations than available measurements, giving thus the possibility of extracting more diagnostic information from existing sensors, than usual GPA methods. (b) The method of adaptive modeling. This method gives the possibility of accurate predictions even in the case of lack of precise component data. This same method gives the possibility of direct diagnosis of faults in the gas path components.

The possibility of performing blade fault diagnosis by using unsteady pressure measurements has been demonstrated and the way of doing it presented. The diagnostic value of casing acceleration measurements and methods for reducing information about internal pressure signal features have been discussed. Finally the use of acoustic data for diagnosis has been demonstrated.

Discussion about the features of all these methods made obvious the importance of modeling as a guide to meaningful data reduction and a means of reducing the necessary empirical information about signatures of the different faults.

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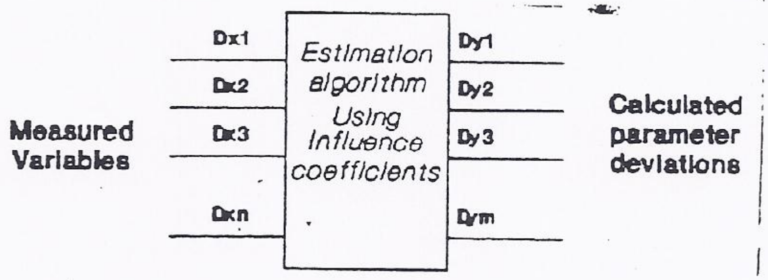


FIGURE 1 : The principle of parameter deviation estimation by means of Gas Path Analysis.

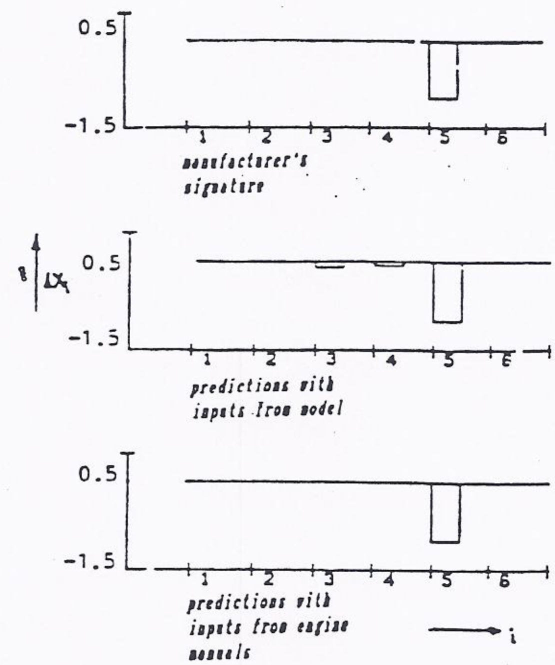


FIGURE 2 : Comparison of predictions of parameter deviation estimation to manufacturer's data. Four measurements at three operating points.

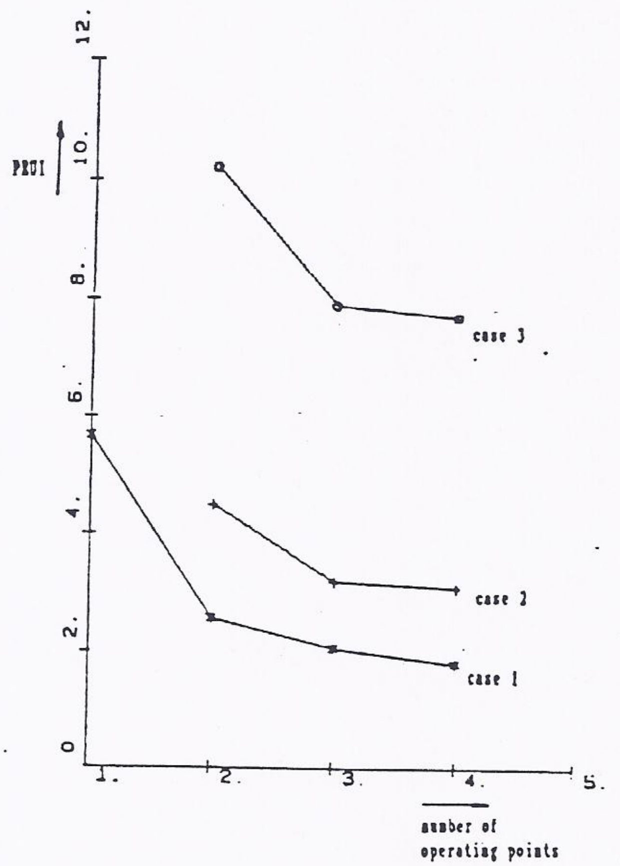


FIGURE 3 : Reduction of uncertainty in parameter deviation estimation, when the number of operating points increases.

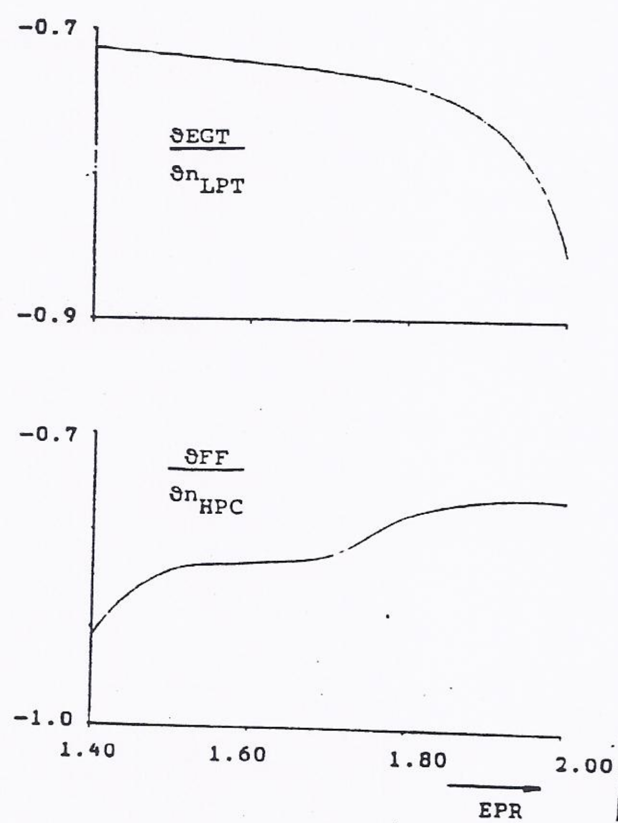


FIGURE 4 : Nonlinear variation of influence coefficients with Engine Pressure ratio.

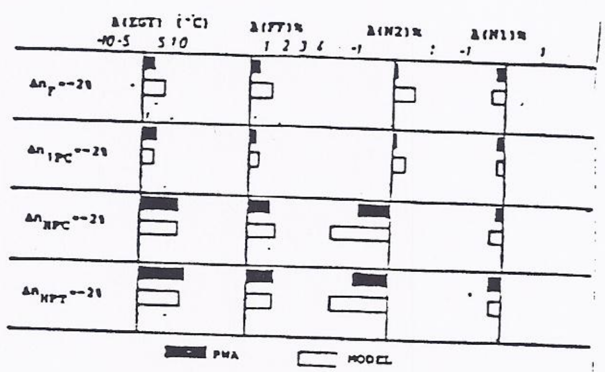
	EGT	FF	N2	N1
Fan efficiency drop	▲	▲	▲	▼
Intermediate compressor efficiency drop	▲	▲	▲	▼
High pressure compressor efficiency drop	▲	▲	▼	▼
High pressure turbine efficiency drop	▲	▲	▼	▼

PWA

▲ Increase ○ Model Validation

▼ Decrease

Qualitative



Quantitative

FIGURE 5 : Comparison between deviations predicted by the performance model and corresponding values provided by the manufacturer.

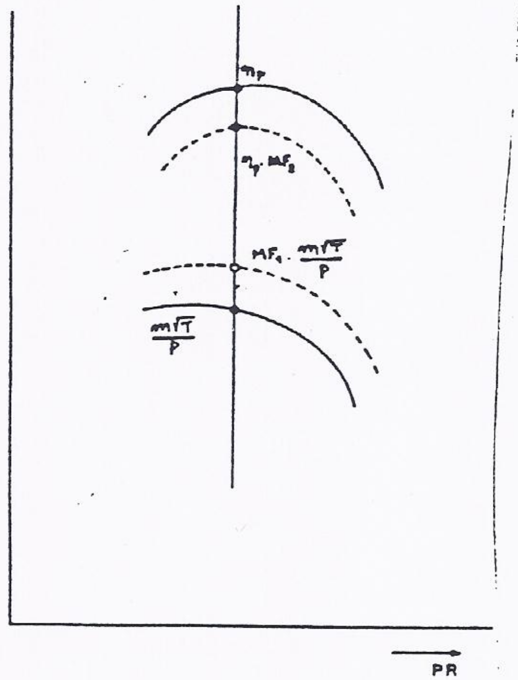


FIGURE 6 : Principle of map modification by means of modification factors.

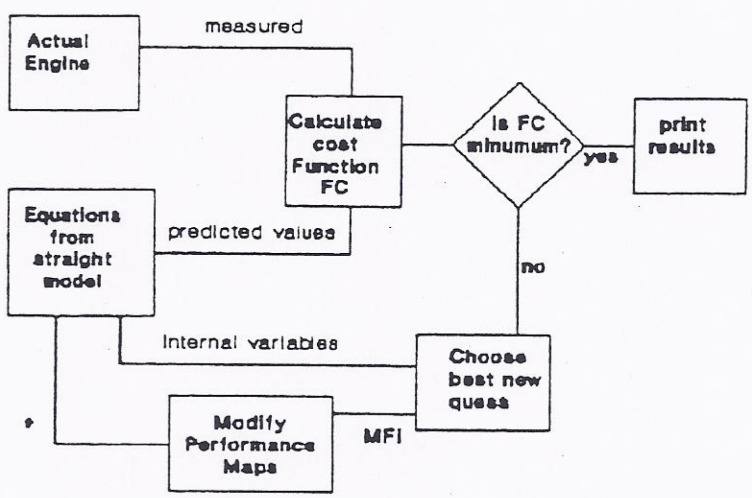


FIGURE 7 : Flow chart of adaptive model. "Internal".

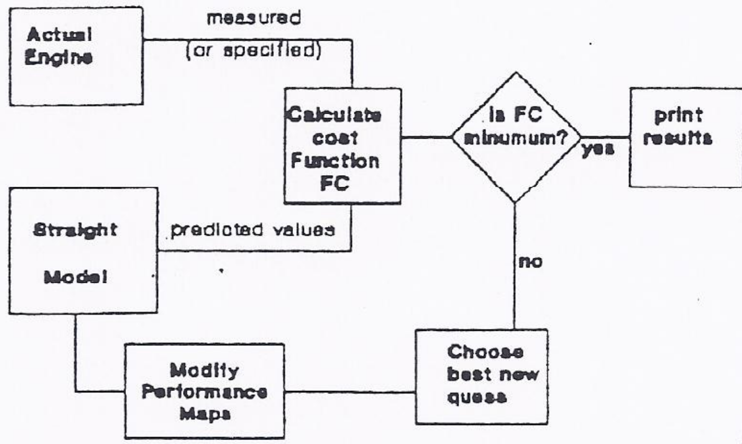


FIGURE 8 : Flow chart of adaptive model. "External".

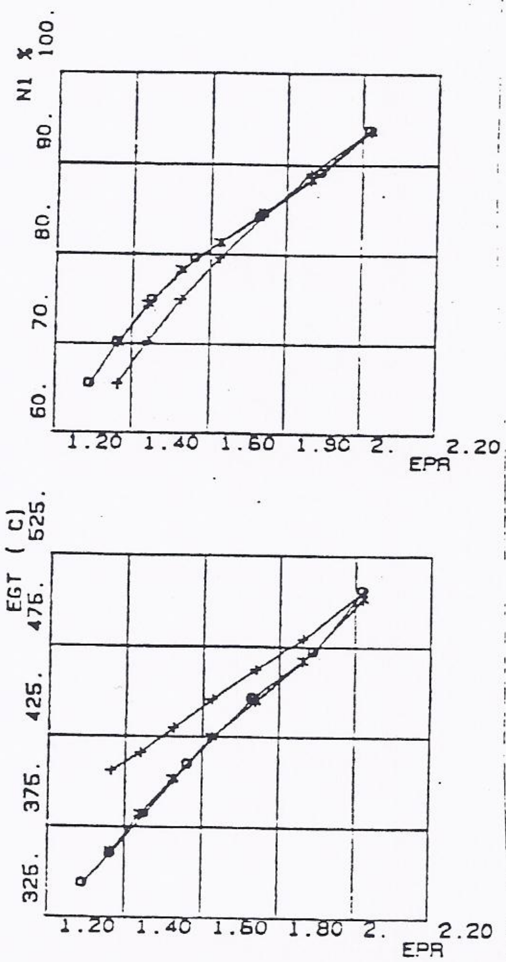


FIGURE 9 : Comparison of predicted to specified performance of a commercial turbofan. * Manufacturer's data, + straight model, o adaptive model.

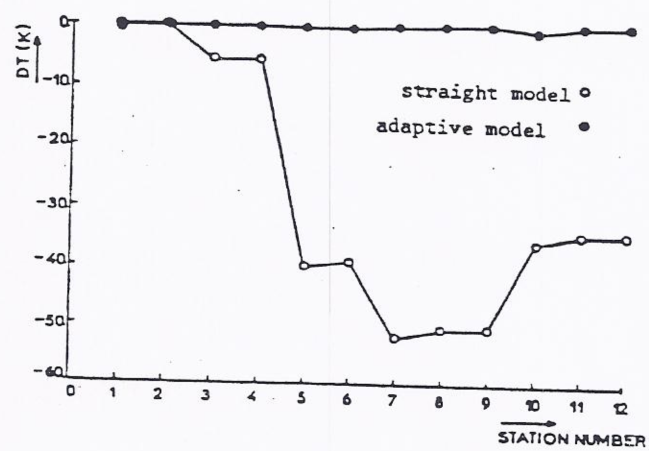


FIGURE 10 : Difference of predicted and measured temperature along a Gas Turbine, for straight and adaptive model.

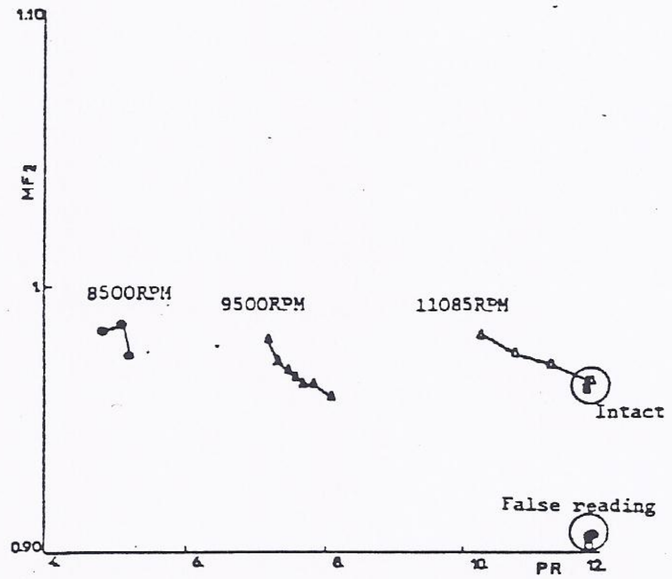


FIGURE 11 : Influence of sensor fault on calculated values of MF. 5% error on EGT.

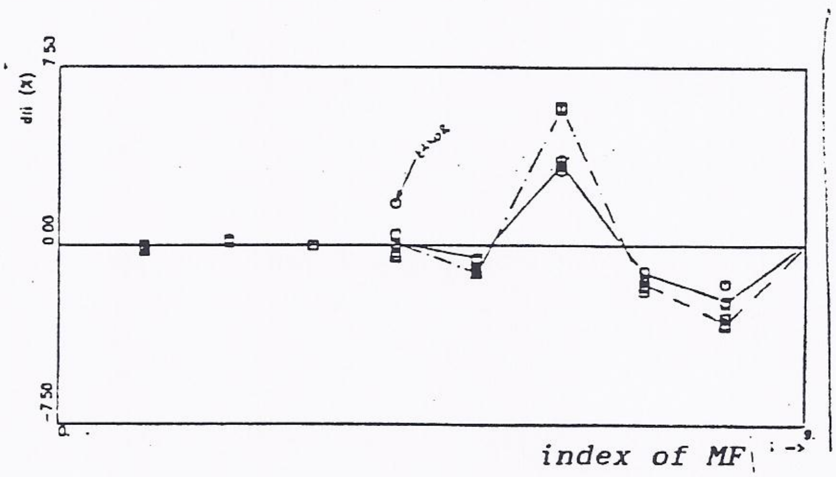


FIGURE 12 : Signature of a burner fault.

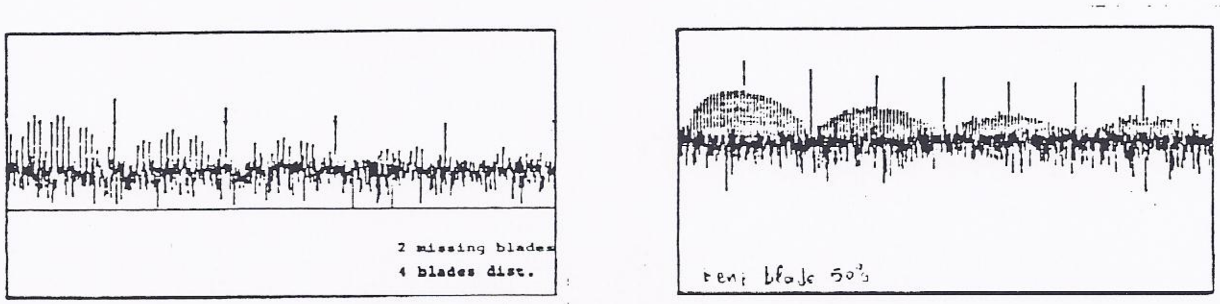


FIGURE 13 : Signatures from power spectra of internal pressure, derived by numerical simulation

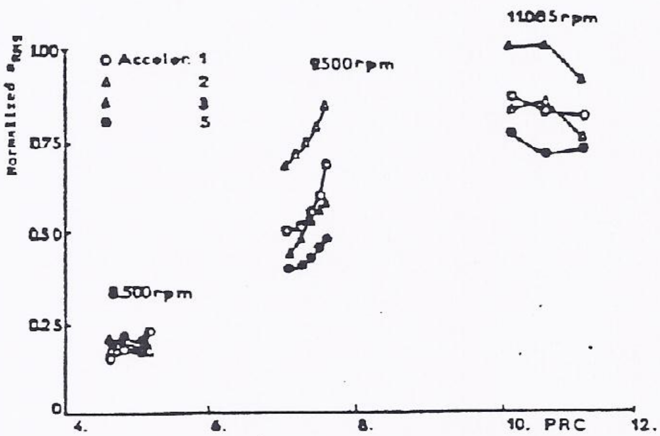


FIGURE 14 : RMS of accelerometer measurements in function of compressor pressure ratio.

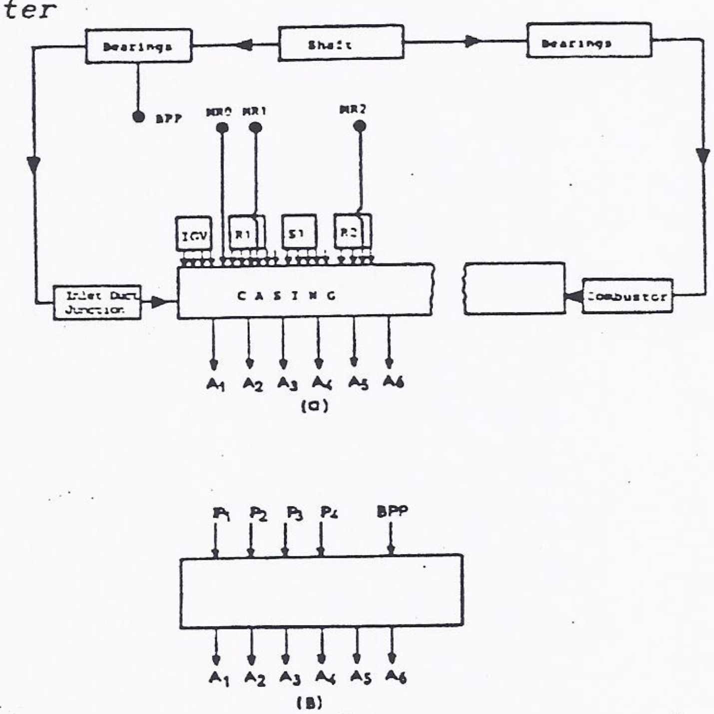


FIGURE 15 : The compressor casing as a linear system. (a) The full distributed parameter system (b) the lumped input-output system.

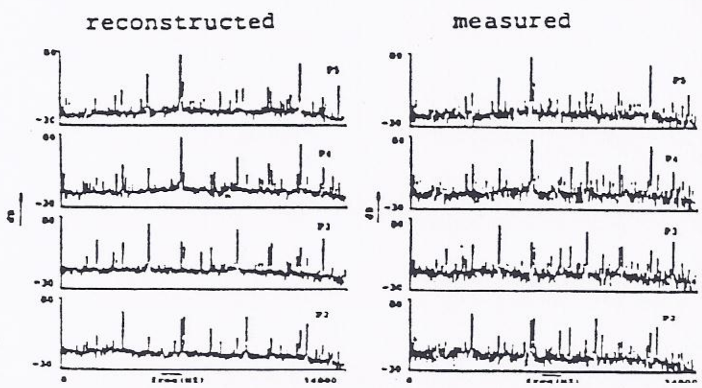


FIGURE 16 : Comparison between measured and reconstructed power spectra of unsteady pressure signals.

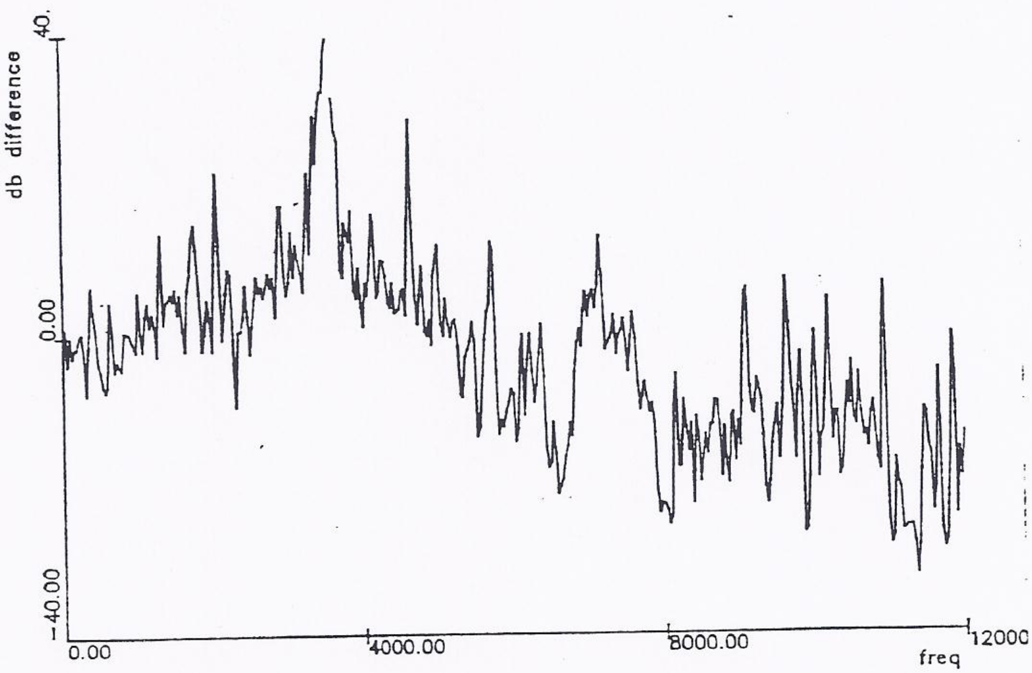


FIGURE 17 : Difference in spectra of acoustic pressure for an engine with one mistuned stator blade.