ABSTRACT

The paper discusses how the principles employed for monitoring the performance of gas turbines in industrial duty can be explained by using suitable Gas Turbine performance models. A particular performance model that can be used for educational purposes is presented. The model allows the presentation of basic rules of gas turbine engine behavior and helps understanding different aspects of its operation. It is equipped with a graphics interface, so it can present engine operating point data in a number of different ways: operating line, operating points of the components, variation of particular quantities with operating conditions etc. Its novel feature, compared to existing simulation programs, is that it can be used for studying cases of faulty engine operation. Faults can be implanted into different engine components and their impact on engine performance studied. The notion of fault signatures on measured quantities is clearly demonstrated. On the other hand, the model has a diagnostic capability, allowing the introduction of measurement data from faulty engines and providing a diagnosis, namely a picture of how the performance of engine components has deviated from nominal condition, and how this information gives the possibility for fault identification.

INTRODUCTION

Present day computer capabilities and software development provide great possibilities for education. Advantages are clearer for complex engineering systems. The gas turbine is such a system. A particular aspect of gas turbine operation is the field of performance monitoring and fault diagnosis. It is a field that has to be addressed in gas turbine related courses for engineering students, while education and training in this field is beneficial for almost all levels of personnel involved with gas turbine operation.

The usefulness of simulation programs for engineering education purposes is well recognized today. Various aspects of integrating the computer in the engineering educational process have been studied by different authors, as reviewed and discussed by Wankat and Oreovicz (1993).

Another aspect of educational use is the possibility of having a more effective educational process. The Mechanical Engineering educator is faced with the challenge of following the ever-increasing demands resulting from implementation of advanced new technologies. Increased specialized knowledge is required by young engineers from a highly competitive environment. The educator must provide them with the supplies which will allow them to respond to these demands and contribute to the progress and growth of the society they are members.

When the situation of one particular field is examined, it must be remembered that other fields in a curriculum also pose similar requirements. Time and means for education in that particular area are thus limited and therefore they must be used in an optimized manner. Computer assisted teaching comes to provide tools to increase teaching efficiency and fulfill such requirements.

The importance of using the possibilities of modern technologies and computers for achieving a better education in matters related to gas turbines and their components, in particular, has become apparent. Several authors have dealt with various aspects of this matter, the works of Ramsden, (1999a,b) Miller et al, (1999), Perez-Blanco and Hinojosa, (1999) being some recent examples of presenting educational activities in this area. Interactive computer packages have been developed for teaching engineering students in the field of turbomachinery, as for example, Leotard et al (1998).

The present paper discusses the educational aspect of gas turbine condition monitoring and fault diagnosis, a subject discussed for the first time in the open literature, to the knowledge of the authors. Although hints of educational use of engine models can be found in previous papers, the subject has not been discussed in any detail. A software package materializing a model, with a structure studied to suit educational purposes is presented and used as a vehicle for discussing the relevant educational matters. The particular structure of this
model has a definite advantage over other available gas turbine performance simulation programs. Models offering excellent capabilities for presenting overall engine design and performance studies exist (e.g., Kurzke, 1995) but do not provide the diagnostic capabilities of the present model.

**COMPUTER MODELS AND GAS TURBINE PERFORMANCE EDUCATION**

Employing computer models for education gives possibilities that could only be offered by observing an actual gas turbine in operation. A computer model produces very easily a lot of information that would be difficult, expensive and some times even impossible to obtain on an actual engine. Engine behavior can be studied at all possible permissible operating conditions, while even physically non-permissible conditions can be examined, if sufficiently deep modeling is involved. Virtually any physical quantity can be observed, without the need of expensive instrumentation, which must be used on an actual engine. Even quantities that would be impossible to obtain due to geometrical or operating restrictions can be obtained (for example, turbine entry temperature, interstage pressure for a multistage compressor or turbine etc).

A model provides also advantages over observing an engine operating in the field. Operating restrictions usually impose a very narrow envelope of conditions, so a long time may be needed before the operator gets the hands-on experience. The possibilities for understanding the principles of gas turbines operation, offered by a computer model, have been discussed in more detail by Mathioudakis et al (1999).

These advantages become even more pronounced when operation under abnormal conditions, namely deteriorated engines or engines with faults, are considered. If experience is to be gained by observing actual engines this will have to happen either by (a) studying cases where faults have occurred on an operating gas turbine or (b) by setting up tests in which faults have been artificially introduced. Case (a) is a situation that may or may not happen and any operator would try to avoid anyway. Case (b) can result to very costly tests while many faults would not be implemented for fear of more generalized damage, anyway. For these reasons, both approaches cannot be considered as very useful for educational purposes.

**THE PRINCIPLES OF GAS TURBINE ENGINE CONDITION ASSESSMENT AND FAULT DIAGNOSIS**

Techniques for Gas turbine condition assessment or fault diagnosis are based on the fact that if the condition of an engine changes, then under the same operating conditions values for various measured quantities are different from the corresponding ones of a “healthy” engine. The task of a condition assessment method is to (a) detect the presence of an abnormal condition, and (b) to identify this condition, namely to specify the symptoms but also to identify the kind, location and severity of the fault. An important task of a diagnostic method is the derivation of a conclusion as to which component has suffered a change, the kind and magnitude of this change. The derivation of such a conclusion is a diagnosis.

In order to achieve a diagnosis, the possibility of correlating the values of measured quantities to engine component condition must exist. This can be based on empirical information or on knowledge of the structure of the gas turbine system and the laws governing its operation. This later knowledge is usually incorporated in a model of the engine. The model can be used to represent the actual engine and therefore to interrelate the values of measured quantities to the values of engine component parameters. These last parameters reflect the condition of the corresponding components. A typical example of a component parameter is its efficiency: a change in the condition of the blades of a compressor or turbine reflects on its efficiency in most cases.

For diagnostic purposes, the gas turbine can be considered as an input-output system, as shown in Fig.1. Ambient conditions and the values of the variables used for controlling the engine (e.g. fuel flow rate, variable geometry vane position) are the inputs. All quantities measured are considered to be the outputs, as for example output power, rotational speed, exhaust gas temperature etc.

![Figure 1: Schematic representation of the gas turbine process](Image)

A further step is taken by considering the Gas Turbine Process as a system consisting of discrete components. The gas turbine process represents all the interactions imposed onto its components by the fact that they are linked to form the gas turbine engine. For example, the compressor is on the same shaft as the turbine and must thus operate at the same rotational speed, while the turbine produces the power absorbed by the compressor. The operation of the gas turbine is determined by the characteristics of its components. For example, for a given gas turbine, changes in the performance characteristics of its compressor lead to changes in its overall performance characteristics. The gas turbine can thus be represented as shown in Fig.2. The variables designated as inputs in fig. 1 are named "operational inputs" in fig.2. Component performance maps and all relevant parameters are designated as "component parameters input".

The representation of Fig.2 gives the conceptual basis for gas turbine diagnostics. Faults and deterioration of components cause changes of the component parameters. Therefore, for the same operating conditions, expressed by certain values of the operating
inputs, different outputs are generated by the gas turbine. A diagnostic method uses the values of the operating inputs and the corresponding outputs to determine the values of component parameters. These are then compared to the values of "healthy" components and if they differ, a faulty condition is diagnosed. The task of the diagnosis for the gas turbine represented as in figures 1,2 is schematically shown in figure 3.

A key factor for the effectiveness of software used for educational purposes is the form of the visual interface. The visual interface is designed to perform the following functions:

- Contain the variables associated with gas turbine performance grouped in the three different kinds identified in figure 2, namely operational input, component parameter input, output.

- Contain a visual impression (picture) of the actual engine. An axial engine cutout is considered to be a good choice. It may be preferable to flow-chart type of representation, since it is a closer link to the picture of the actual engine, at least for those familiar with Mechanical Engineering Drawing.

- Contain some space available for graphic representation of what can be considered as the most important performance and condition related information.

DEFINING THE VISUAL INTERFACE OF A DIAGNOSTIC MODEL

A software package built for educational purposes in the field of gas turbine performance and diagnostics has been constituted by the group of the authors. The package is named TEACHES (Turbine Engine Advanced Calculation and Health assessment Educational Software).

In addition to this basic information that is chosen to constitute the basic display functions of the system, a number of other functions are also useful. For those to be easily usable and the program to become more user friendly it is useful to adopt a structure widely used by many commercial packages: different groups of functions are given in the form of menus.

Choice of operating system: In order to have a tool that can have a widespread use, an operating system has to be chosen that is widely used and known to many users. Systems thought to fulfill this requirement are the operating systems of the WINDOWS family.

The basic layout of the visual interface of the TEACHES software is shown in figure 5. The particular application shown and used for the subsequent discussion in this paper refers to the configuration of a twin shaft industrial gas turbine.

The interface software is supported by a gas turbine performance model, which can be used: (a) for direct simulation of engine operation at any possible operating point in its operating envelope, (b) for diagnosis of the condition of the engine components, once a set of measurement data is available. The functions of this software and their educational implementation are discussed in the following sections.
BASICS OF GAS TURBINE ENGINE OPERATION

At an introductory level, some basic notions about the performance of a gas turbine can be demonstrated. For this purpose the "simulation" mode of the software is used. Data can be introduced for all the variables named “operational inputs” in the representation of figure 2. A detail of the corresponding part of the interface is shown in figure 6. Apart from ambient conditions, a choice of independent setting parameters is offered, by providing a number of different possible choices. This possibility is useful for both demonstrating operational principles but also diagnostics. Concerning operation, it is possible to show to what extent various performance parameters are influenced by changes in ambient conditions.

Figure 5: The layout of the basic screen of the gas-turbine engine performance simulation and diagnostics software TEACHES.

Figure 6: The operational parameters input section of the visual interface.

After a calculation of one operating condition is completed, the main quantities of interest are displayed on an engine cutout, as shown in figure 7. This type of display has an advantage over the block diagram type displays: It shows local quantities, such as temperatures, in relation to their actual mechanical location on the engine. Further, detailed data for the values of pressure, temperature and performance parameters of the engine can be seen by selecting the "Results" menu. This kind of information gives a feeling of what changes take place in the engine in order to achieve the performances at the specific operating points. Basically all the cycle information is provided.

Figure 7: Display of main performance parameters on an engine cutout.

A number of graphs can then be displayed, according to the choice of the user. Overall performances or variation of specific quantities for various operating conditions can be examined. Presentation of such quantities gives a first feeling of how the engine behaves. Choice of appropriate sets of operating points may provide dependence of performance on different factors. For example the dependence of power on ambient temperature, for operation with constant exhaust gas temperature (an option frequently chosen for combined cycle applications) can be immediately seen. A graph displayed for such an application is seen in figure 8.

Figure 8: Output power versus ambient temperature for constant exhaust gas temperature (EGT).

More such graphs can be displayed, which may be of interest to the user. Another example is shown in figure 9, where compressor delivery pressure is shown as function of the load.

A typical example of educational use is the presentation of the impact of ambient conditions on engine performance. For a
given turbine inlet temperature, it can be shown how much power output will be reduced during a hot day, in comparison to a cold day. The temperature-limited operation employed by engine control systems is thus demonstrated. Similarly, for a given load demand the increase in turbine inlet temperature for hotter ambient conditions can be shown, by choosing now output power as the setting parameter. The required change in TIT is thus evaluated and can be used to discuss life reduction matters, for example.

At this point different aspects of off-design analysis can be easily demonstrated. Movement of operating point along the compressor map while turbine operating points moves only a little for a wide range of operating conditions can be demonstrated. The operating points along the compressor and gas generator turbine maps are shown in figure 10. Aspects related to engine control can also be demonstrated. For example, lines of constant turbine entry temperature can be directly estimated and graphically presented.

UNDERSTANDING THE EFFECTS OF MALFUNCTIONS

The first possibility is through the simulation of component faults. Such faults are simulated by modification of the performance characteristics of the components. The modified characteristics are then introduced into the model and the deviations of cycle or performance parameters are observed. In this way one can for example demonstrate very easily the performance drop due to compressor fouling or Exhaust Gas Temperature variations due to turbine nozzle erosion.

Map modifications are effected by using scalars, multiplying the component performance parameters. Such scalars have been for example, introduced by the group of the authors in the past under the term “modification factors” MF defined as MF=X/Xref, where X is the current value of a parameter and Xref its value for a component in intact condition (Stamatis et al, 1990a). For example, setting the corresponding modification factor to a value of 0.98 represents a reduction in pumping capacity of a compressor by 2%. The present model uses these factors first for simulation and further for diagnosis. Using the adaptive modeling technique ensures that the model can be adapted to a particular gas turbine and model very precisely its behavior. The model represents thus accurately an engine and the information provided to the person using it is not only qualitatively sound but also quantitatively accurate.

To simulate the existence of a malfunction, modification factors with values different from unity are introduced. The visual interface allowing the introduction of these values is shown in figure 11. For ease of interpretation the actual value fed to the model is the quantity (MF-1)*100, namely the percentage deviation of each component parameter.

In the example display of figure 11, a case is shown, in which the compressor has suffered a 2% reduction in mass flow capacity and 0.5% reduction in efficiency. The modification to the compressor performance map, for this reduction in flow capacity is shown in figure 12.
Introduction of malfunctions gives several possibilities for demonstrating their effect on engine parameters. First of all, by performing simulations for healthy and faulty engines the impact of faults can be directly assessed. For example, for given ambient conditions and limit of turbine temperature, it can be directly evaluated how much less power a gas turbine will produce, when the compressor is fouled.

The important notion of “fault signature” can be very easily introduced, when the above-mentioned possibility exists. Values of measured quantities can be calculated for both healthy and faulty operation and their differences are calculated to provide the signatures. The present model is equipped with the capability of directly evaluating such a signature, whenever a fault is simulated. A picture of a fault signature in the form of measurement deviations from reference values provided by the model, is shown in figure 13. The fact that different signatures are produced by different faults can be very easily demonstrated. Also, the fact that the same fault can give different signatures depending onto which parameter can be kept constant, can also be directly shown.

**COMPONENT CONDITION DIAGNOSIS**

The purpose of adaptive modeling itself is to derive values of MF’s for the different components, so that a given set of measurement data is matched. This mode of operation of the model is called "adaptive" mode.

Adaptive operation of the model gives a possibility of direct fault diagnosis, from a given set of measurements. If the model has been calibrated on an engine in its "healthy" condition then MF’s get the value of 1, for whatever set of measurements is fed to the model. If a fault occurs, leading to alteration of the performance of a component, measured quantities will have values different from those in healthy operation. If these values are fed to the model, MF’s will change in order to produce the alterations to the maps, leading to the measurements in hand. Observation of changes in MF values gives therefore a direct indication of occurrence of a fault. The pattern of change of MFs can then be used for identifying the fault itself. A display of the model output for diagnostic application is shown in figure 14. The results of this figure come from an engine with a gas generator turbine suffering a deterioration, which led to a 3% reduction in swallowing capacity and 1% efficiency reduction.

A particular problem when examining a diagnostic problem is the fact that the number of unknown component parameters (which have to be determined for diagnosis) must be less or equal to the number of available measured variables, in order to have a unique diagnostic answer. This aspect is also included in the model presented here, through an interface allowing the selection of the measured variables and the parameters whose values are to be evaluated. The form of this interface is shown in figure 15. This possibility can be of practical use to the diagnostic engineer but also to the engineering student, showing how certain choices...
are more sensitive than others, while there are combinations, which cannot actually provide a solution.

Figure 14: Chart of component modification factors, characterizing engine condition.

Figure 15: Choice of combinations of available measurements and "health" parameters to be evaluated

FURTHER EDUCATIONAL ASPECTS

Several other aspects that make this model useful for educational use have been considered. The basic rule followed in constructing the software is that it should be operational in a way similar to what students are accustomed today, by commercial software. The purpose is to make the software friendly to the user, so that all its features can be exploited. In this way the interactive character is enhanced, a feature very useful for educational purposes, (as for example discussed by Wankat and Oreovicz, 1993). Along this approach, an on-line help possibility is provided. On the other hand, data can be exported for further processing if desired and apart from interactive use, data sets can be batch processed. The ability to export calculation data or process existing data sets makes this software more useful to the student, as it can interact with other tools he or she uses for their studies.

An aspect of the software and the process discussed in the present paper is that it can be addressed to different levels of personnel. The main intended implementation area is university education, in conjunction to courses dealing with gas turbine performance. This software has actually been used in classroom for demonstration purposes, while students have been asked to use it in order to be able to answer specific questions on the expected behaviour of a gas turbine under different operating scenarios. Possibilities of looking into component performance, parameter interrelations, importing series of data and exporting data for post processing, make the software suitable for executing various such exercises.

The software can also be used for further education of process engineers, dealing with gas turbine operation or for educating technicians supervising gas turbines, as it can reproduce all basic trends and behavior of a gas turbine engine. Finally, it can be a useful tool for assisting the diagnosis of specific faults or it can be used for performing actual Diagnoses, provided that a particular gas turbine has been modeled.

SUMMARY - CONCLUDING REMARKS

The use of a computer model for education in the field of gas turbine condition monitoring and diagnostics has been discussed.

Particular aspects of engineering education, which can benefit from the use of computer models, have been discussed. A particular software package designed for educational purposes has been presented. The various aspects of implementation of this software into the educational process were discussed. Specific examples were employed to demonstrate the possibilities offered by such a computerized way of instructing the principles of Gas Turbine performance monitoring and diagnostics.

REFERENCES


