TRANSIENT PERFORMANCE OF GAS TURBINES

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Abstract. *In the design and analysis of gas turbines it is essential the knowledge in advance of its performance at several working conditions, notably at critical ones. The simulation of those regimes of operation can be achieved with the aid of specially developed softwares. The simulation also contributes to diminish the time and the costs of design and production. As part of an effort to develop softwares to perform numerical simulation of gas turbines, a module of transient simulation was developed, both for shaft and volume, and incorporated to GTAnalysis. This computational software is capable of numerically simulate high performance gas turbines that equips modern aircraft and aero-derivative engines used in the thermal power plants. It was carried out a study and performance analysis of the engine important parameters during transient operation. Turbojets, turboshafts and turbofans, single or multishaft configurations, were studied. This work reports such studies and presents some of the results achieved so far.*

Keywords: *Gas Turbine, Performance, Transient, Shaft Transient, Volume Transient*

1. Introduction

At design point the gas turbines operate efficiently and safely because all their components are well matched and the flow aligned with the blades passages. Unfortunately, gas turbines are required to operate at off-design over a wide range of operation conditions, which depend on the engine applications whether at land, sea or air, both civil and military. Engine parameters that can suddenly be changed in any application and may cause surge or exceed maximum cycle limits are: rotational speed, altitude, angle of attack and yaw. In all these possible operation conditions it is required that the gas turbine operate safely and efficiently.

To assure safe operation in all possible operating points it is necessary to know beforehand, in the early stages of development, the performance of main components (compressor, combustion chamber and turbine), which are described by performance maps. These maps can be generated from bench tests or calculated by specially developed computer programs. The former is more complex and expensive than the latter. Engine simulation is less expensive and er if compared to the rig tests of a prototype.

GTAnalysis is a computer program specially developed for gas turbine simulation (Bringhenti 1999, Barbosa and Bringhenti, 1999; 2000), that is able to simulate, at steady state, almost all possible gas turbine configurations, with or without variable geometry (Bringhenti 2003, Bringhenti et al., 2001, Bringhenti and Barbosa, 2001; 2002a; 2002c; 2003; 2004). Gas turbines actually operate at transient off-design condition for a considerable time. Whilst at steady state the rotating shaft inertia, the thermodynamic parameters variations in volumes, the heat transfer at the engine metallic parts to the fluid, as well as the variations of engine dimensions were not taken into account, during transients they have to be analyzed because they influence significantly the engine behavior. This work deals with the shaft and volume transients only, now incorporated to GTAnalysis. A simple turbojet engine, a three-shaft turbofan and a twin-shaft turboshaft with free power turbine were chosen for this study, although other possible configurations would equally be simulated. Details of the GTAnalysis computer program have already been published (Bringhenti and Barbosa, 2002b).

2. Gas turbine performance simulation

Following the same GTAnalysis development philosophy, the calculation of gas turbine transient performance is carried out based on the characteristics of its isolated components. For the transient analysis, new blocks were developed in addition to the blocks already used by GTAnalysis. These new blocks perform the transient calculations, as well as the management strategy to handle the required transient performance calculations.

Transients occur at every time when there are changes in altitude, flight speed, engine speed, and thrust, set by the pilot or the load. Some transients are too quick, other last for some seconds but they are equally important because they may give rise to undesirable engine behavior that could lead to failure.

2.1 Transient phenomena

The phenomena related to transient performance must be considered besides the ones related to steady state performance. The transient of gas turbine is composed of several physical phenomena caused by the variation of momentum, energy and mass flow inside the engine components. Their rate of change will fix the transient times of each engine. As mentioned earlier, shaft, thermal and volume transients are the most important transients. Shaft and volume are the focus of this work.

2.1.1 Shaft transient

The basic physics behind shaft transient is the relation between the resultant torque on rotating shaft and torque variation. Therefore, gas turbines shaft transients are strongly dependent on their rotating parts inertia.

The resulting torque may occur due to power unbalance between compressor and turbine; this resulting torque causes an angular momentum variation and consequently an increase or decrease in shaft rotation. The power unbalance is caused every time that a new engine operational condition is required, such as, changes in power, thrust, altitude, inlet conditions, geometry, etc.

2.1.2 Thermal transient

Changes in power or thrust required by an engine are made by fuel control schedule. In a typical acceleration, when more thrust or power is required, more fuel is added to the combustion chamber, and therefore, more heat is released. The difference of temperature between the working fluid and metal parts during transient implies that part of the fuel energy is wasted as heat. Heat soakage, the net heat transfer from the working fluid to the metal parts, has a significant effect on engine performance.

As quoted by Walsh and Fletcher (1998), during the acceleration from idle to full power ou thrust , the engine casing must soak to a new higher steady state operanting temperature, which absorbs typically 30% of the excess fuel energy.

As quoted by Alves (1989), investigation of gas the heat starage into the combustor wall has been shown that the effect has no significant influence during gas turbine transient. Even at static high altitude conditions or during a step fuel flow transien, where this effect is more prominent, it has been found no influence at all.

The difference of temperature between the working fluid and the metal parts causes heat transfer from the working fluid to the metal parts or the inverse. Temporarily, blade tip clearance variation may be caused by heat transfer because the thermal growth of the compressor and turbine discs is slower than the thermal growth of casings.

Tip clearance in compressor affects its geometry, therefore change its performance characteristics map. This increased tip clearance causes mainly the downwards movement in surge line, limiting the fuel that could be added for a given acceleration.

2.1.3 Volume transient

When considering steady state operation the fluid properties are not changed with time then the inlet mass flow in a component at a given instant is equal to the outlet mass flow. During transient operation fluid properties are changed with time, for example, flow density, pressure and temperature. These fluid properties changes cause a difference in the mass flow at inlet and outlet of a given gas turbine component. These effects are more significant in components that have large volumes as combustion chamber, duct and heat exchangers and must be considered mainly in transient.

The mass flow difference in a given volume will contribute to power unbalance between compressor and turbine and variation in parameters such as pressure and temperature.

Due to the fact that the combustion chamber generally has the largest volume, in this work, only volumes related to combustion chamber will be considered.

3. Gas turbine performance Models

A gas turbine performance model is made with the use of engineering, mathematics, programming knowledge and appropriate agreement of model objectives.

The speed and accuracy of model are parameters that must be considered in the performance model. The model must supply information at an adequate speed for the objective. According to SAE AIR4548 (1995), the accuracy of the model will reflect the intended objectives. The accuracy still must be defined taking into consideration the operation mode.

In the steady state, the evaluation of the accuracy is relatively simple and is specified in terms of outlet variables.

In transients, the evaluation of the accuracy is more complex because it is necessary to consider the time. The minimum accuracy that is expected in transients can be set based on a comparison of the calculated values and the expected ones.

There is a trade-off between the speed and the model accuracy. Smaller time steps are required to obtain greater accuracy, therefore lesser time steps, what it will require greater model processing time. The model adjustment depends on engines test data for the simulation. With continuation of the project and acquisition of more data, the model can be adequately adjusted. According to the SAE AIR4548 (1995) the factors of risks in developing a model are: a) the possibility of the time of the execution of the implemented algorithm exceeds the target limit; b) numerical divergence of the algorithm and; c) inconsistency among the calculated results and the data used for the validation. The transient is modelled in levels depending on the intended applications. Basically there are two types of models: thermodynamic model, the more complete and precise, however slow and heavy; and real time models, that are er, however of more limited application and less accurate. The model used in this work is of the thermodynamic type.

3.1 Thermodynamic model

This is a steady state model defined in terms of conservation equations, thermodynamic relations and engine components maps. Figure 1 shows a compressor map. For this reason, the thermodynamic model has almost no limitation in its simulation capacity. The existing limitations are those due to the processor used in model calculations and those due to the risk factors that appear in model project procedure that can be adequately solved.

The thermodynamic model uses the input data, the restrictions and requirements of mass, moment and energy conservation for an adequate thermodynamic match of the cycle components that represent the engine and supply the performance and engine operation parameters.

The algorithm for implementation of this model is initiated with the calculation of the steady state engine performance. In transient mode the time is increased and the routines of shaft, thermal and volume transients are activated.

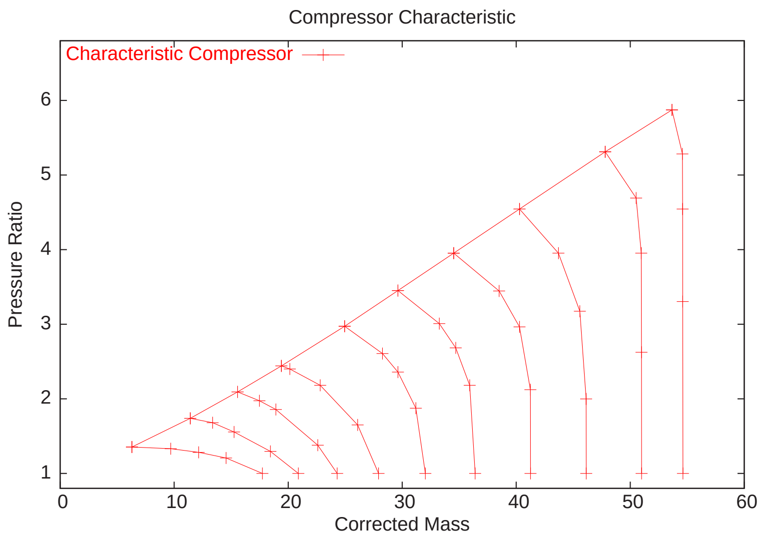

Figure 1. Compressor maps

Due to its modular conception, each component and operation mode can be represented by a code block. Therefore the thermodynamic model can be buil from already developed elements, so that the commitment among speed, precision and cost will have been resolved in previous technology development.

The operation modes of performance model are:

Steady state mode - In this operation mode the heat transfer, the shaft and volume dynamics are off and the engine is calculated for values such as speed, temperature and flow of fuels at design point.

Transient mode - The transient mode considers the unbalancing between the torques of turbines and compressors together with the inertia to define the rates of acceleration and deceleration that determine the shaft transient. The heat transfer between the components and flow is added to simulate thermal transient and to determine its influence on the engine performance. Finally, the volume dynamic is integrated to simulate cycles at the presence of long ducts, great volumes and events of high frequency such as surge.

The consistency of the thermodynamic models at transient mode is easily achieved if the model was consistently developed with steady state because stead state mode is the base for transient calculations.

Starting and stops - the operation simulation at starting and stops are necessary in many cases. The thermodynamic model can be easily modified for this mode.

Simulation of failure - In this operating mode, the model must possess commutation resources to simulate different events of failure, since each failure type requires, in the majority of cases, different logics for its simulation.

A model does not need to predict the transient in all the engine operation modes. A model of simulation for each operation modes can exist; we can have one model to simulate starts and another to simulate stops, for example (Onions and Foss, 1983).

3.2 Use of thermodynamic model

This model can easily be modified for new applications, modes and operation ranges and is used for engine design and development. It is heavy and slow and it is not used directly in control systems.

The model becomes more adequate as more complex is the cycle used for the study of transient and engine starting, as well as in the programming development of control system.

Thermodynamic models, according to Walsh and Fletcher (1998) are usually used for:

- Transient performance examination during the phase of engine design, before the engine is available for tests;
- The engine performance estimate at points of operational envelope where the engine tests are not done due to the danger of damages in engine or due to high costs;
- Fail analysis for manoeuvres that can be too expensive or not practical to test, such as the shaft rupture.

When using thermodynamic model, the time increment for calculations must be possibly in the range of 10 to 30 ms, or less if it is important to evaluate the influence of small volumes during the transient or phenomena of high frequency as stall, this demanding increments of time of 1 ms or less.

The environment conditions, control variables and required power are generally the basic inlet requirements for the thermodynamic model and the variable universally used in the evaluation of the transient is the shaft speed.

Coupling of the standard thermodynamic model with the engine control system is not possible, due to the much smaller time for the convergence required for the former. According Walsh and Fletcher (1998), to obtain the execution in real time an thermodynamic model must be strongly simplified, with consequent loss in accuracy.

4. Numerical simulation of transients

The software used in this work is able to simulate at steady state almost all types of gas turbine. It is a software developed at ITA (Bringhenti, 1999), modular in the sense that the engine is made of functional blocks. A managing program perform the block calculation and the engine overall parameters.

The accuracy of the results of this program has been validated from several engines data and from the calculates performed by other similar softwares. It is the basics for the transient mode repeated in this work. Additional blocks were designed and the management scheme modified accordingly. Simplicity of input data, a characteristic of stead state program, has been maintained.

Validation of the program was carried out for the most common gas turbine configurations, of 1 to 3 shafts using another validated computer program (Alves, 2003; Alves and Barbosa, 2003).

4.1 Input data

The input data file necessary for the steady state analysis consists of three sections: a) identification of engine under study; b) assembly of the engine by blocks, when the user supplies the design point components data and c) off-design, when the user requests off-design calculations.

Below are shown the results of transient calculations using the GTAnalysis computer program. In all cases the engine is decelerated from design point by means of an instantaneous turbine inlet temperature reduction, giving enough time for the engine stabilization at the new point of operation. Steady state is achieved after it is stabilized at the given temperature. The Fig. 2 to Fig. 8 show, instead of parameter values, the ratio between the transient parameter value and the design point parameter value for the sake of better visualization.

4.2 Single shaft turbojet (subsonic flight)

Figure 2 shows the speed variation during the transient. In this case, the step of temperature applied in deceleration and acceleration is of 100 K. The nominal thrust of the engine is of 10 kN.

Figure 3 shows the specific fuel consumption (SFC) and thrust variations. Initially, during the deceleration, a fall in SFC occurs due to the reduction in fuel flow required for the negative temperature step. The thrust is strongly dependent on turbine inlet temperature and is equally reduced. The reduction of mass flow and cycle efficiency with the rotation provokes the increase of SFC causing the fall of the thrust, until the stabilization at stead state. The acceleration process follows an inverted pattern (Fig. 3).

Single shaft turbojet running line is similar to the running line of a single shaft turboshaft. At the points where the propeller nozzle is choked, the running line is single, approaching the surge line at low rotational and low flight speeds.

On the compressor characteristics in Fig. 4 is shown the influence of combustor chamber volume in the operation line during the transient. In fast decceleration, caused by the temperature step, the pressure at exit of the combustion chamber

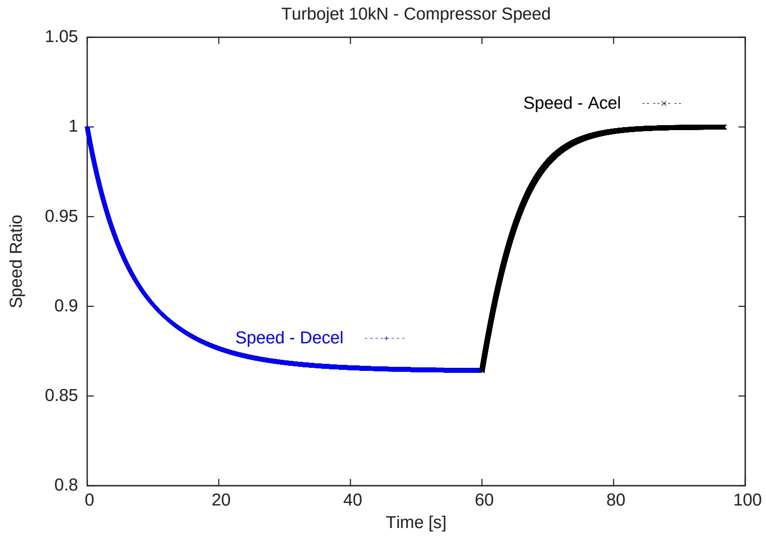

Figure 2. Shaft speed transient

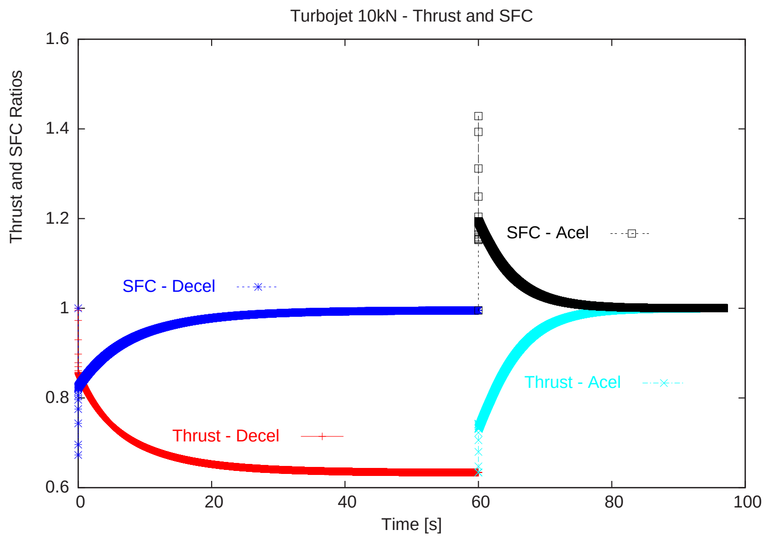

Figure 3. Thrust and SFC transients

volume diminishes, what causes the mass flow, which leaves the volume and enters in turbine, to increase. The temperature reduction decreases less than the mass flow increases, resulting in an increase of turbine power. The compressor answers then with an increase in compression ratio and reduction of mass flow, moving the operation point closer to the surge line. Torque unbalance causes the shaft speed to alter, forcing the mass flow to equalize between turbine and compressor, what results in shaft speed and pressure ratio decrease.

During the acceleration, to keep the turbine capacity, the mass flow must be diminished to accommodate the step in temperature. The inertia of rotating set hinders rotation change and mass flow reduction will occur at constant speed.

4.3 Twin-shaft engine with free turbine

According to Saravanamuttoo et al. (2001), when load variation is frequent and there is a need to quickly accommodate speed variations due to load fluctuation, turboshaft with free power turbine is the most appropriate engine. They are used when the flexibility of operation is necessary, e. g., compressor drive, maritime propeller and automotive vehicles, due to the fact that the power turbine speed can vary widely. Specific fuel consumption and power depends on the power turbine efficiency.

The engine behavior depends on the type of the load: cubic for maritime propellers and constant speed for electrical generation.

During acceleration, the gas generator supplies additional power to the free power turbine through gas generator

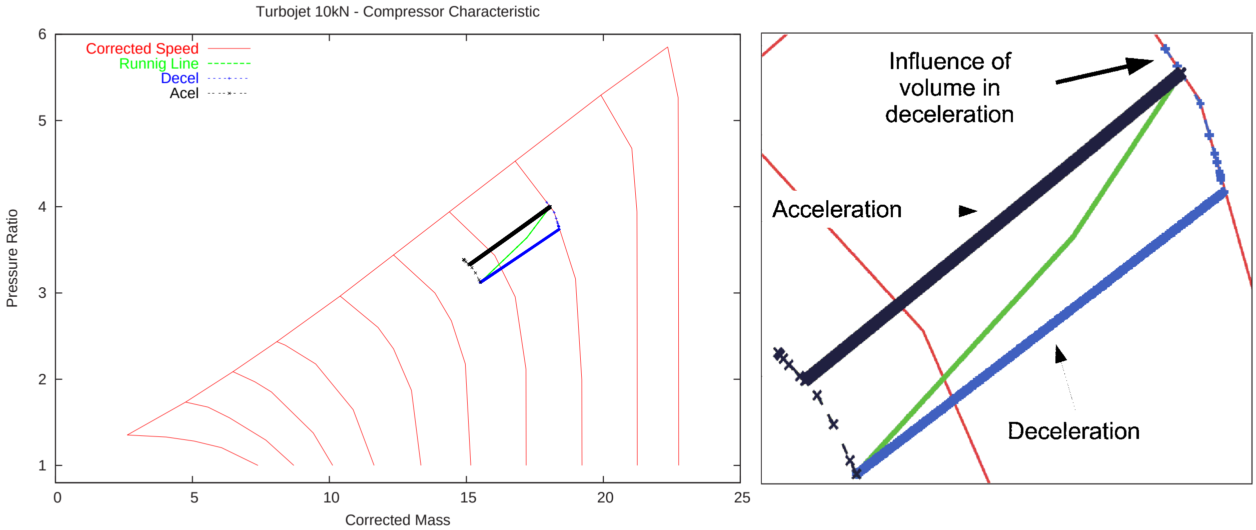

Figure 4. Compressor characteristic with running line during transients for a turbojet

exhaust gas. This power increases proportionally to the gas generator speed.

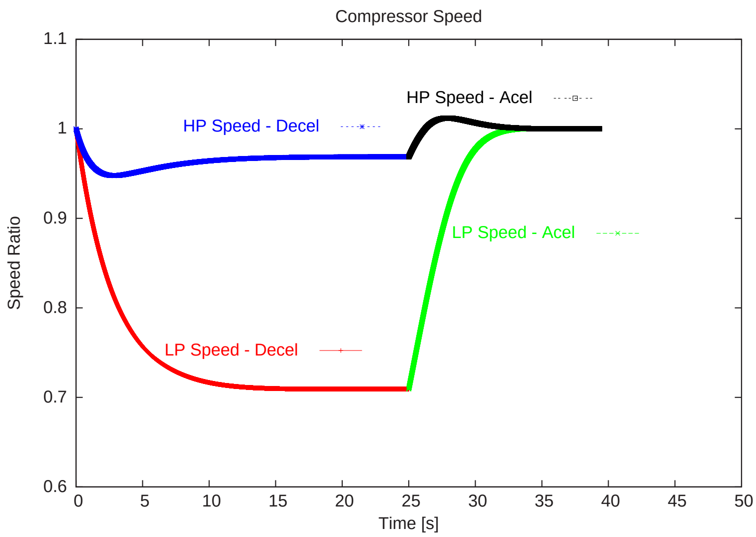

Figure 5. Twin-shaft with free power turbine transients

The twin-shaft engine with free power turbine comprises of three rotating sets: high and low pressure spools and power turbine plus driven equipment. Twin-shaft engines usually are more efficient and load flexible. It is this type of engine characteristics that the expansion in the high pressure turbine is almost unaltered, therefore minimal speed variation. As a consequence, surge during operation at part load is not a problem. The influence of the power turbine is greatest when it is unchoked, what reduces the expansion through the low pressure turbine, thus reducing power.

Engine behavior is similar to the single shaft free power turbine. Major cycle parameters depend directly on the power turbine performance.

Figures 5, 6 and 7 refer to 11.7 MW twin-shaft, free power turbine during transients, at SLS (sea level, static). Figure 5 shows the speed transients and Fig. 6 shows the transient running lines plotted on the compressor map. The temperature steps are of 200 K for both acceleration and deceleration.

4.4 Three shaft turbofan (subsonic flight)

Turbofans have been designed aiming at low specific fuel consumption and engine noise reduction. By-pass and fan pressure ratio have major influence on the engine performance, as well as on the propulsive efficiency.

In this study, the engine transients are associated with temperature changes in the combustion chamber.

An increase in the chamber outlet temperature, thus in the turbine entry temperature, causes the turbine to generate

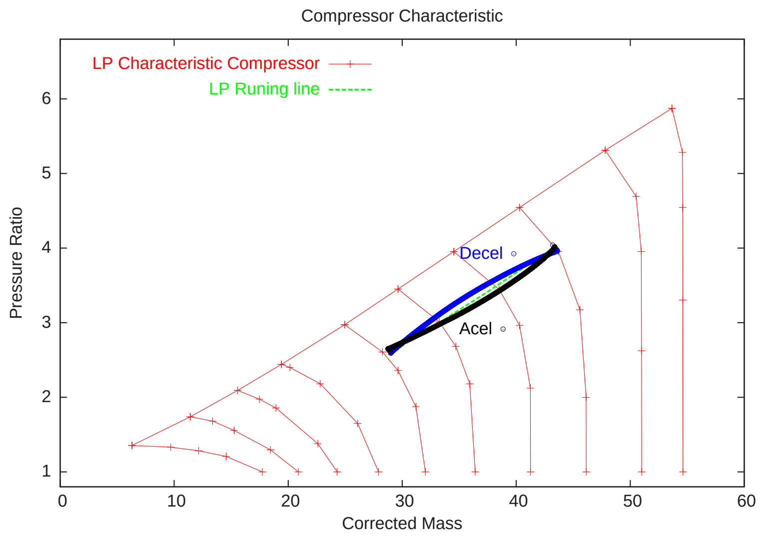

Figure 6. LP compressor characteristic and running line at transient

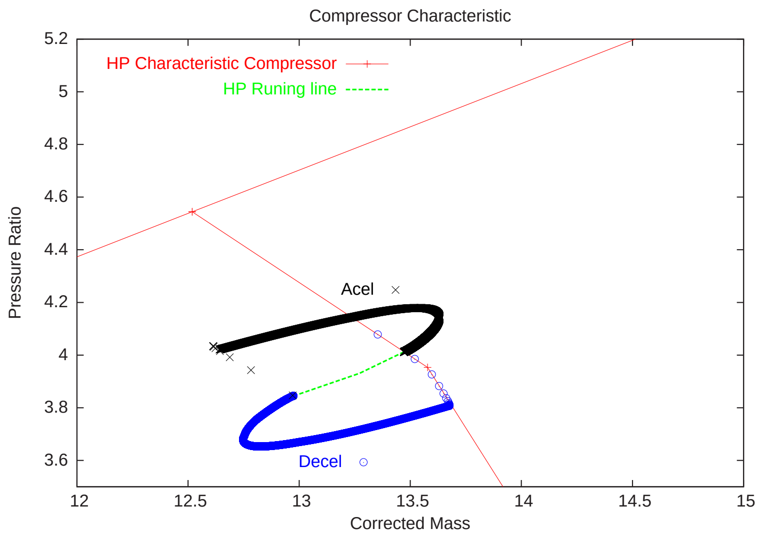

Figure 7. Component maps example

more power than the required by the compressor, auxiliaries and mechanical losses at the same instant. The extra power causes increase in the shaft speed. Similarly, a decrease in the turbine entry temperature causes a reduction in shaft speed.

Figure 8 shows speed variation for LP (low pressure), IP (intermediate pressure) and HP (high pressure) compressors for a three-shaft turbofan during transient, operating at SLS. The temperature steps are of 200 K for both acceleration and deceleration and total mass flow is 1179 kg/s.

5. Conclusion

The gas turbine transients can be numerically calculated using a block decomposition of the engine. The development of a computer program that is able to numerically simulate almost all type of gas turbines during shaft and volume transients was reported. As expected during the transient simulation, the inertias of the rotating spools, as well as the component volume, have significant effects in the running lines. Despite they happen during very short intervals, as in the volume case, they may drive the compressor to surge, even when the engine is decelerated.

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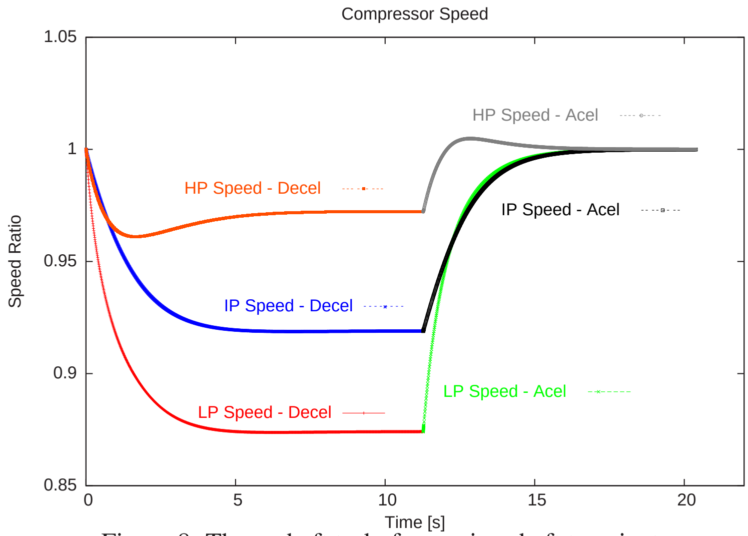

Figure 8. Three-shaft turbofan engine shaft transients

7. References

Alves, M. A. C., 1989, "The Influence of Combustion Chamber Heat Transfer During Gas Turbine Transients", M.Sc. Thesis, Cranfield Institute of Technology, England.

Alves, M. A. C., 2003, "Transitório Não-Adiabático de turbinas a Gás" , Ph. D. Thesis, ITA, Brazil.

Alves, M. A. C., J. R. Barbosa., 2003, "A step further in gas turbine dynamic simulation". Proceedings of the Instituto Tecnologico de Aeronáutica, Energy Department, São José dos Campos, Brazil.

Barbosa, J. R., Bringhenti, C., 1999, "Simulação Numérica do Desempenho de Turbinas a Gás", Proceedings of COBEM 1999, Engenharia Aeroespacial S8, Águas de Lindóia - SP, 22 a 26 de novembro, Brazil.

Barbosa, J.R., Bringhenti, C., 2000, "Simulação Numérica em Sala de Aula", CONEM, paper EC8840, Ensino de Engenharia Mecânica, pp. 2-9, Natal - RN, Brasil.

Bringhenti, C. 1999, "Analysis of Steady State Gas Turbine Performance", M. Sc. Thesis, ITA, Brazil (In Portuguese).

Bringhenti, C. 2003, "Variable Geometry Gas Turbine Performance Analysis", Ph. D. Thesis, ITA, Brazil.

Bringhenti, C., and Barbosa, J.R. 2002 a, "Effects Of Variable-Area turbines Stators Over The Important Parameters Of Gas Turbine Performance", proceedings of the CONEM, CPB0272, João Pessoa - PB, Brazil.

Bringhenti, C., and Barbosa, J.R. 2002 b, "Performance Evaluation Of Different Types Of Gas Turbines For Power Generation", proceedings of the CONEM, CPB0292, João Pessoa - PB, Brazil.

Bringhenti, C., and Barbosa, J.R. 2002 c, "Study Of An Industrial Gas Turbine With Turbine Stators Variable Geometry", proceedings of the ENCIT, CIT02-0885, Caxambu - MG, Brazil.

Bringhenti, C., and Barbosa, J.R. 2003, "Analysis of Gas Turbine Off-Design Safe Operation Using Variable Geometry Compressor", proceedings of the COBEM, COBEM2003-0230, São Paulo - SP, November 10-14, Brazil.

Bringhenti, C., and Barbosa, J.R. 2004, "Part-Load Versus Down rated Industrial Gas Turbine Performance", proceedings of ASME TURBO EXPO 2004, Power for Land, Sea, and Air, GT2004-54147, June 14-17, Austria Center Vienna, Vienna, Austria.

Bringhenti, C., and Barbosa, J.R., 2001, "An Overview Of Variable Geometry Gas Turbines", Proceedings of the COBEM, Energy and Thermal Systems, Uberlândia - MG, Brazil, Vol. 4, pp. 97-105.

Bringhenti, C., Barbosa, J.R., and Carneiro, H.F. de França Mendes, 2001, "Variable Geometry Turbine Performance Maps For The Variable Geometry Gas Turbines", Proceedings of the COBEM, Energy and Thermal Systems, Uberlândia - MG, Brazil, Vol. 4, pp. 87-96.

Onions, R. A., Foss, A. M., 1983, "Improvements in the dynamic simulation of gas turbines", AGARD Eng. Handling, 16p (SEE N83-29241 18-07), International Organization.

Saravanamuttoo, H. I. H., Rogers, G. F. C., Cohen, H., 2001., "Gas Turbine Theory". Practice Hall, England.

Society of Automotive Engineers, 1995. "Real-Time Modelling Methods for Gas Turbine Engine Performance", AIR4548, Warrendale, PA, December.

Walsh, P. P., and Fletcher, P., 1998, "Gas Turbine Performance", Blackwell Science.

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