About 0-D Transient Performance Simulation

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ABSTRACT

Modelling transient gas turbine performance and operability is of lasting interest for teaching at universities and for supporting the development of control systems. The simplest transient performance models consider only rotor inertia, the more sophisticated simulations take additional effects into account as there are volume packing, the heat exchange between the gas and the hardware, as well as compressor and turbine tip clearance variation.

Steady state performance calculations are feasible without knowing much about the geometry of the engine. The engine performance during off-design operation is essentially described by the cycle design point and the compressor and turbine maps. With the simulation of transient manoeuvres this is different: a model of the engine geometry is indispensable if more than only the inertia of the rotors is to be considered.

For calculating tip clearances, one needs - besides dimensions of disks, blades, and casings - procedures for determining how these dimensions change with spool speed and temperature. Modelling the heat transfer between gas mass flow and the hardware is a special challenge.

The main benefit of the tip clearance model is a much-improved prediction of the engine operability, i.e., whether the compression system surges during or shortly after a transient manoeuvre. For models as they are used for control system development is the progression of fuel flow over time equally important.

Transient performance models are developed with different objectives. A model for teaching gas turbine performance must be easy to operate and allow many views on the results. A simple controller is sufficient and whether the simulation runs in real time or not is of secondary importance.

That is different if the performance model is to be used for control system development. It must be able to run in real time, describe the functioning of bleed valves, compressor guide vanes and nozzle accurately as well as the transient behaviour of temperature and pressure sensors. It is essential that the response of the engine to a change in fuel flow is realistic.

This paper discusses the relative importance of various transient performance model details on the simulation results by means of example calculations for typical aircraft engine. The main drivers for model accuracy are identified.

Keywords: Turbofan Performance, Transient, Heat Soakage, Volume Packing

1.0 NOMENCLATURE

CMF Continuous Mass Flow method
FADEC Full Authority Digital Engine Control
ICV Inter-Component Volume method
$\dot{N}$ spool speed change per time
N_L low pressure spool speed
N_H high pressure spool speed
$N_{H,corr}$ corrected HP spool speed
SAS secondary air system
t time
T temperature
W mass flow
W_F fuel mass flow

2.0 INTRODUCTION

The simulation of aircraft engine transient performance has been a topic of interest for a long time. For a comprehensive overview of this subject, one may refer to Ref. 1, which cites 164 publications on the topic, including physics-based methods and black-box approaches that employ neural networks. This paper focuses on physics-based models that utilize an engine geometry model. Simplified transient simulations that only consider the spool inertia are of limited value.

Ref. 2 outlines a generic heat soakage and tip clearance model that requires a significant amount of input data. GasTurb's methodology for heat soakage, initially presented in Ref. 3, utilizes straightforward first-order lags along with a relatively simple engine geometry representation, and needs much less input data.

In transient performance modeling, the key considerations are the time required for a change in thrust and the prevention of engine surge. The quantity of fuel consumed during the brief period of a sudden acceleration is of secondary importance.

This paper focuses on brief time intervals, which are of paramount importance with regard to engine operability. During this time span, the expansion of the disk due to thermal effects is insignificant; however, disk diameter alterations resulting from centrifugal stress are not. It is advisable to include at least an approximate disk stress calculation when developing an ambitious transient performance simulation program.

As already mentioned above, the majority of the methods described in literature require a significant amount of input data, particularly when heat soakage and tip clearance changes are to be considered. When modeling, it is essential to consider the balance between the complexity and accuracy of an engine model.

A comprehensive description of the engine geometry is typically accessible only to engine manufacturers or engine maintenance facilities. However, such a vast repository of data is unnecessary and potentially detrimental. Even if a comprehensive CAD model were available, it could not be utilized for transient performance calculations due to the exorbitant computational resources required to run a model with such intricate details. Replacing the actual geometry with a surrogate is a crucial necessity.

References 4 and 5 outline the process for acquiring the essential data for heat transfer modeling from advanced 2D/3D whole engine aerothermal models. Ref.5 highlights that a streamlined heat transfer model comprising a minimal number of components can effectively retain the primary characteristics of a more comprehensive model.

This paper builds upon this concept and employs the geometry model initially introduced by the author in GasTurb in 2012 for estimating engine weight. In addition to the data necessary for calculating the thermodynamic cycle design point, only a limited amount of additional input data is required for defining the engine geometry. This is due to the task-oriented software design of GasTurb, which works with pre-defined engine configurations.

3.0 TRANSIENT PHENOMENA

This section provides an overview of the processes occurring in an aircraft engine during transients, as well as guidance on how to model these processes in a 0-D performance program.

3.1 Spool Inertia

The principal effect during transients is the imbalance of work between the components on the same shaft. In order to estimate the power required for spool speed changes, it is necessary to know the spool inertia. In the absence of an engine geometry model, rotor inertia data can only be derived from similar engines or through statistical analysis.

3.2 Heat Soakage

It is important to note that even at steady state, the thermodynamic processes in an engine are not adiabatic. However, the actual heat flow is negligible with respect to the energy transfer in the components. During transients, there is a notable difference in the rate of change between the gas and the metal temperatures. This delta leads to significant heat transfers.

Once the rotor speed change has ceased in an engine acceleration to take-off thrust, the heat flow persists via heat conduction into the thick-walled components. This process can be approximated by a delay element with a time constant of approximately 10 seconds.

In terms of computational effort, it is not feasible to account for all the individual heat flows of the thousands of components in an engine in simulations. Even for sophisticated simulations, it is sufficient to record the heat exchange in the most important components, such as compressors and turbine blades, casings and disks, as a lump sum.

The heat transfer during transients has various aspects: there is a direkt effect on the thermodynamic cycle, and some indirect effects as compressor and turbine efficiencies change due to the tip clearance variations caused by differences in the thermal expansion of parts.

3.2.1 Turbomachines

The transfer of heat during the compression process alters the shape of a compressor map for a number of reasons, which are discussed in detail in Ref. 1. At the conclusion of the respective section summary, it is stated: “With regard to modifications to the component map, there is no consensus among researchers, and a range of opinions exists.” Consequently, this phenomenon is typically excluded from 0-D performance programs.

3.2.2 Combustor

References 2 and 5 goes into a lot of detail about heat transfer between the combustor hardware and the gas, looking at both convection and radiative heat transfer. It's worth questioning whether this level of detail is necessary. It's probably more important to focus on the dynamics of the fuel injection process.

As stated in Ref. 6, the fuel injection and evaporation processes can be modeled with time constants of 12 milliseconds (acceleration) and approximately 5 milliseconds (deceleration) following a sudden increase or decrease in fuel.

3.3 Tip Clearance

Compressor and turbine efficiencies are sensitive to changes in running tip clearance. More important - from an engine operability point of view - is the effect on the compressor surge line.

Be aware that tip clearances are different depending on whether the simulation begins at idle (with a cold engine) or at high power (with a hot engine). At the begin, all metal parts have their steady state temperatures, and the centrifugal forces that affect the disk diameters are different between idle and take-off thrust.

3.4 Volume Packing
How does volume packing affect the result? This will certainly depend on the size of the engine components and thus on the type of engine. One question is: do we need a volume packing simulation at all, and if so, what kind of model is best?

The most simplistic simulation option is the Continuous Mass Flow (CMF) method, which just ignores volume packing. The Inter-Component Volume (ICV) method considers the dynamics in a volume between adjacent components, where the mass entering the volume may be different from the mass leaving the volume, resulting in accumulation or dispersion of mass in the volume. The method requires smaller time steps than the CMF methods and has convergence problems (Ref. 1).

It should be noted that the two methods result in different compressor operating lines if the transient simulation is controlled by fuel flow as a function of time. The effect on the operating lines will only be seen while spool speed is changing, not in the stabilization phase after the transient.

Considering the typical duration of the transient manoeuvres discussed here and the volumes within the engine, Ref. 5 concludes that volume dynamic effects are negligible. This finding is in alignment with the outcome of the analysis in Ref. 6 and the findings in section 5.3 of this paper.

3.5 Secondary Air System
Ref. 4 uses a steady-state model of the secondary air system that considers engine geometry changes, like seal clearances, with spool speed, temperature, and pressure across the entire flight envelope. However, it doesn't account for the time needed to fill and empty the large SAS volumes inside the HP compressor and combustion chamber.

This effect has been studied in Ref. 7 where the SAS model is an integral part of a transient performance program that can simulate volume packing not only in the mainstream but also in the SAS. It is clear that volume packing within the SAS has a significant effect on the SAS airflows. While there is no notable volume dynamics in the main gas path, the percentage of turbine cooling flow shows a significant reduction at the beginning of an acceleration. By the time the burner exit temperature reaches its peak value, the percentage of cooling flow still remains at a relatively low level, which is a potential hazardous thermal load on the engine parts.

3.6 Turbine Flow Capacity
The mass flow capacity of a turbine is directly dependent on the throat area of the nozzle guide vane, which changes in line with metal temperature. During a transient, the metal temperature unquestionably follows the gas temperature with a time delay. In the simulation, one only needs to consider the difference between the steady-state temperature and the delayed temperature. Since the blade temperature time constant is small, so the change in turbine flow capacity will be minimal. This could be incorporated into the transient performance model, however, that is not a worthwhile pursuit.

4.0 A SIMPLE TRANSIENT PERFORMANCE MODEL

The principles of the transient simulation methodology used for writing this paper are summarized in References 3 and 9. Section 5 of this paper describes the details of the application of this methodology to a numerical example.

The gas turbine performance software developed by the author since 1995 originally did not allow for volume packing, as this program attempts to minimize the number of input data. Getting numbers for the component volumes seemed to be too cumbersome. After the conceptional design feature was implemented into GasTurb 12, however, the situation changed since component volumes are a fall-out of the geometry model. It is recognized that the assumption, volume packing can be ignored in transient performance calculations, needs to be re-visited.

The experimental performance program ExPP23, which was used to write this paper, describes what happens in the inter-component volumes with the following equation:

$$W_{out} - W_{in} = \frac{Vol}{\gamma RT} \frac{dP}{dt}$$

The gas in the ICV is assumed to have uniform pressure and temperature. The minor temperature variation is ignored when the change in pressure is calculated.

The changes in disk diameter resulting from stress are calculated using a model consisting of rings, see Ref. 9 for details. The disk diameter changes due to thermal expansion, however, are ignored in simulations of transients with GasTurb because the amount of disk cooling air is relatively small, and the disk mass is large. It is assumed that the mean disk temperature remains constant within the short duration of the examined manoeuvre.

When it comes to practical simulations, it's important to understand how the control system works. In many papers, a prescribed fuel flow over time controls the event. How fast the engine accelerates with such a control system depends on whether the hardware is cold or hot at the beginning of the transient. When accelerating a cold engine, more fuel is needed because some of the energy goes into heating up the metal.

Modern aircraft engines are controlled via FADEC units, which employ the so-called "N dot" control ($\dot{N}$=dN/dt). This compensates for the effects of the initial engine temperature status by using more or less fuel, thereby making the acceleration time independent of the temperature of the engine hardware, fuel heating value, and burner efficiency.

In the following studies, the equation $\dot{N} = f(N_{H, corr})$ is employed to regulate accelerations. This represents an indirect method for prescribing the compressor operating line. Consequently, simulations conducted with or without consideration of heat soakage yield nearly identical surge margins until the HP spool speed approaches the targeted value.

The specifics of the off-design iteration setup and the engine control model utilized in transient simulations with ExPP23 are outlined in detail in Ref. 9. These algorithms are applied not only to the normal operational range between idle and maximum power, but also to simulations of engine start, run-down, and windmilling.

Note that for the engine run-down simulation described in section 5.4 of this paper, one needs compressor and turbine maps that include the sub-idle region down to a few percent corrected spool speed. Ref. 9 explains how to extend the usually available compressor and turbine maps which are valid for idle and above down to very low speeds.

5.0 BR 710 EXAMPLE

General descriptions of the transient behavior of jet engines are all well and good, but they do not answer the question of how important the individual elements of the simulation (inertia, volume filling, heat soakage, etc.) are for the accuracy of a model. The BR 710 - a medium bypass ratio mixed-flow turbofan - is used as an example to demonstrate the quality that can be achieved with a derivative of the GasTurb software. This engine was chosen because of the public availability of sufficiently accurate geometry and thermodynamic data as well as test results for an acceleration from idle to maximum thrust.

The following phenomena can be considered by the software used:

- spool inertia
- volume packing
- heat soakage
- tip clearance and the resulting changes in efficiency and surge margin
- combustion delay

Compressor map shape changes due to heat transfer, changes in the SAS due to changing seal clearances and filling the SAS volumes, as well as changes of turbine flow capacities due to thermal expansion are not considered for the reasons previously outlined.

5.1 Engine Geometry

Figure 8 in Ref. 4 shows a cross-section of the BR710, supplemented by 3 ellipses and 3 arrows indicating special features. The supplements can be easily removed using an appropriate image processing program. However, this alone does not provide an accurate representation of the BR 710 engine geometry, as the diameter-to-length ratio is not correct. But this can also be easily corrected because it is known that the compressor is a scaled version of the V2500 compressor, for which the ratio of diameter to length can be taken from drawings available on the internet.

The illustration in Ref. 4 is missing one crucial piece of the puzzle: a representation of the flow channel between the engine end and the nozzle. However, getting dimensions for that part of the engine is not a problem because the diameter of the nozzle throat is a result of the cycle calculation. And the total length of the engine, from the spinner tip to the nozzle, can be derived from the data provided in Ref. 8.

GasTurb makes it easy to create a reasonable geometry model. The author's experimental performance program provides additionally the volumes of the flow path for each component and allows thus to study volume packing effects in the simulation of transients.

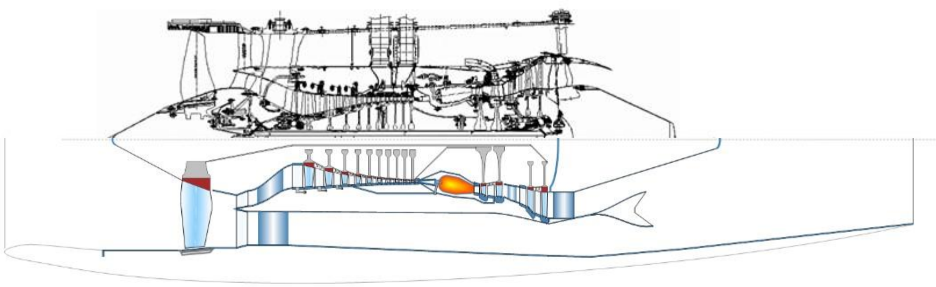

Figure 1: Geometry model of the BR710 compared to the crosscut from Ref. 4

5.1.1 Heat Flows in the Flow Path

The transition from the engine hardware to the simplified heat storage model is problematic. In GasTurb, there are three parts: the blades, the blade attachment to the disk, and the housing.

The blades can be replaced with plates of a constant thickness that are representative of their heat storage capacity. The blade attachment is part of the disk geometry model. Replacing the real casing with a constant thickness casing representative of the heat flow is challenging because the geometry of the real casing is very complex. The casing thickness representative of the heat storage capacity can only be found through trial and error.

The second input property that describes the heat flow during transients is the assumed time constant. There are three different values used in GasTurb: a small number describing the heat transfer to and from the blades, a medium number which is applicable to the blade attachment and the inner air seal, and a larger number which is representative for the casing. The following time constants and casing thicknesses are used in the BR710 model; they have been found by trial and error in such a way that the calculated heat flows are similar to those shown in figure 13 of ref. 4.

	Time Constant [s]			Casing Thickness [m]
	Blade & Vanes	Platform	Casing	
HPC	1	3	7	0.005
Burner Can			3	0.004
HPT	1	2	5	0.024
LPT	2	3	15	0.025

The HPT casing thickness is much bigger that the HPC casing thickness due to the turbine tip clearance control geometry

The time constants and the casing thicknesses required for modeling the LPT heat transfer are larger than those required for modeling the HPT because the LPT incorporates a massive inlet guide vane (which is integrated with the inter-turbine duct) as well as substantial outlet guide vanes.

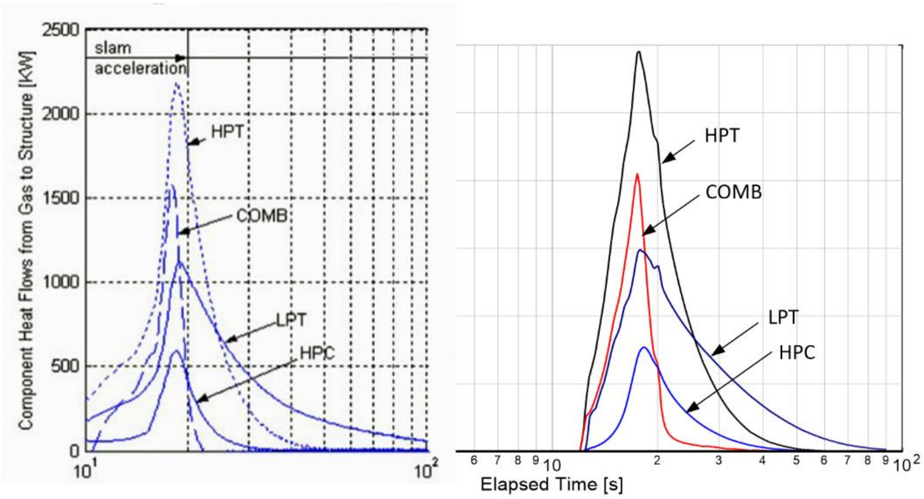

Figure 2: Comparison of the calculated heat flows with Ref. 4

5.2 Results

Fig. 2 demonstrates that the heat flows from the gas to the structure, which in Ref. 4 were calculated with a sophisticated state space model whose parameters were derived from highly complex FE and SAS models, can be reproduced with a high degree of accuracy using the comparatively simple GasTurb program.

This result was essentially achieved through the careful selection of the time constants and the equivalent casing wall thicknesses. Since the simple model of the heat flows is based on physical principles, it can be assumed that it is not only suitable for the slam acceleration example considered here but also for the simulation of other transient events.

Please note that the heat flows shown in Fig. 2 have been calculated rather than measured directly. However, Ref. 4 contains also actual measured values that can be used for comparison with the simulation results. We will begin with Fig. 12 from Ref. 4 which illustrates the fuel flow overshoot at the end of the acceleration phase. As the simplified model can only simulate the first 90 seconds of a transient process, the following comparisons are limited to the period from 10 to 100 seconds.

The sophisticated model matches the measured values very well in the time span from 18 to 26 seconds, after that the match is less good. The simple simulation initially underestimates the fuel flow but matches the measured values quite well in the time span from 30 to 90 seconds.

The next figure shows the pressure ratio of the HPT. The very detailed model of Ref. 4 agrees somewhat less well with the measured values than the simple model, especially in the initial phase up to 30 seconds.

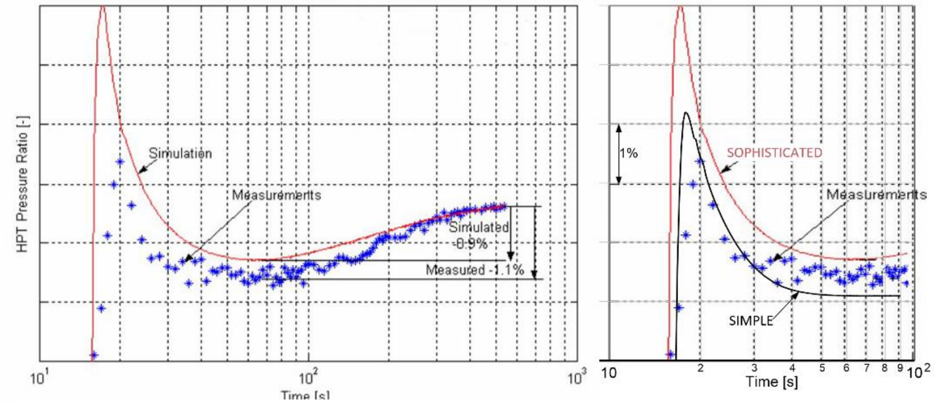

Figure 3: Predicted and measured HPT pressure ratio

Figure 5 shows how well the two calculation models match the measured values from fig. 11 in Ref. 4. While the results of the sophisticated model are higher than the measured values in the time span from 22 to 50 seconds, the simple model generates too low temperature values at the beginning for the time before 32 seconds.

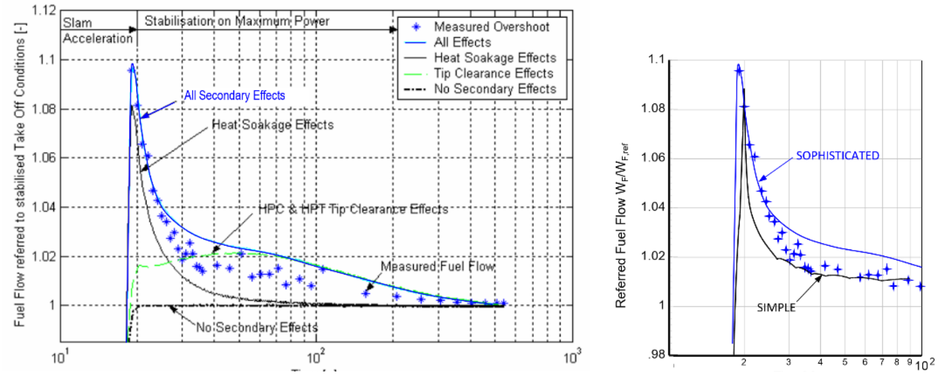

Figure 4: Simulated and measured fuel flow overshoot.

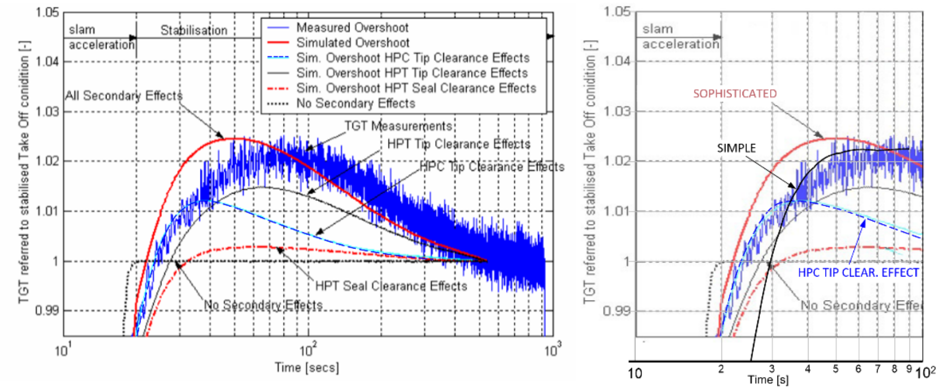

Figure 5: Simulated and measured TGT overshoot

There is another figure in Ref. 4 that shows measured data. It is dedicated to the HPC surge margin change during transients. In the first phase of the acceleration, the shift of the HPC operating line towards the surge line depends on how the controller controls $\dot{N}$, the variable guide vanes, and the bleed valves. We don't know exactly how this happens, so we can't reproduce it in the simple model.

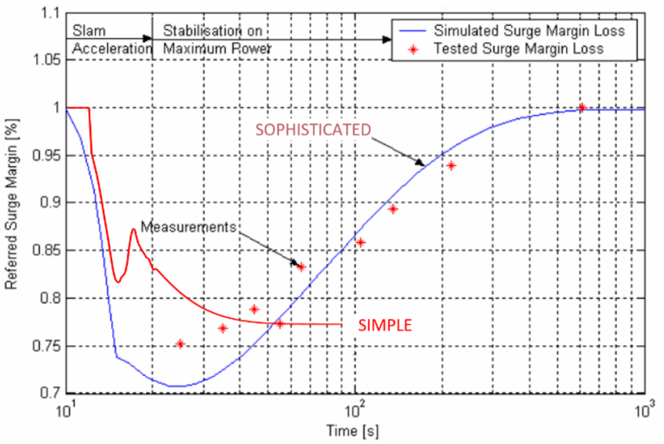

Figure 6: Predicted and measured surge margin change

Once the slam acceleration is complete, the tip clearances keep growing because heat transfers to the casing. This makes efficiency worse and moves the surge line down, which means a loss of surge margin. This is reflected in the results of the simple model. The sophisticated model uses the real compressor map with its surge line. The map in the simple model, however, is just an approximation, so the results for surge margin over time are expected to be different.

The surge margin predicted by the simple model flattens out at the end of the simulation period. This is because the simple model doesn't account for the thermal expansion of the disks. This long-term effect reduces the tip clearance and thus restores the surge margin over time.

It is important to note that the BR710 performance model, created by the engine manufacturer, aligns for sure well with steady state engine test data. The simple performance model, however, is based on a limited number of published data and utilizes scaled compressor and turbine maps taken from open literature. Under these circumstances, it is astonishing how well the results of the sophisticated model and the measured data can be reproduced with the simple model.

5.3 Volume Packing

The modeling of transient volume filling and emptying processes takes up a lot of space in the literature, and the question arises as to whether this is justified.

This question can be easily answered if one has a geometric model of the engine, as in GasTurb, which provides the volumes of the individual components as a by-product. The performance program can easily be extended from a constant mass flow program to an inter-component volume program.

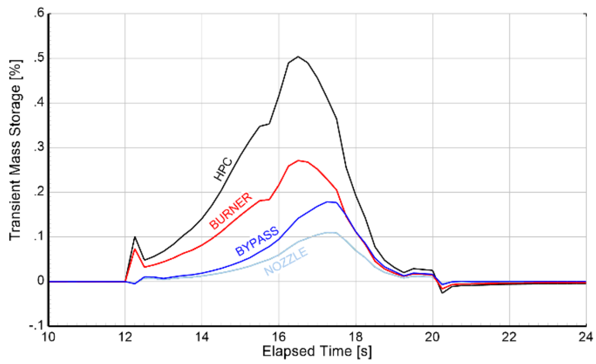

Figure 7: The largest transient mass storages in the BR 710 model

Figure 7 shows how large the transient mass flows into the components are during the slam acceleration we have examined before. Even the largest, that of the HPC, is less than half a percent. Such small mass flows are barely visible in the graphical output of the main performance parameters.

The conclusion, at least for turbofan transient simulations, is that volume packing effects need not be considered in turbofan operability studies.

5.4 Engine Run-down

Besides ordinary transient manoeuvres like acceleration and deceleration may also the run-down time of interest. This is important with respect to the question: How long is power from the generator available after a flame-out, for example.

The following two figures compare two run-down simulations beginning at stabilized idle. One of them considers only rotor inertia, the other heat soakage and component efficiency losses due to the increasing tip clearance.

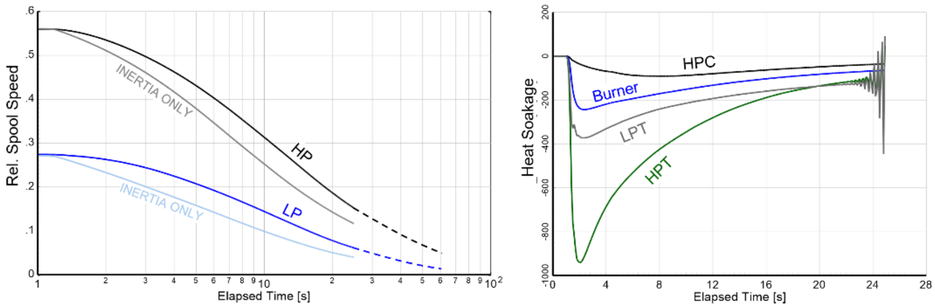

Figure 8: Engine run-down simulation

The simulation of a run-down with consideration of the stored heat causes convergence issues, which manifest as oscillations in the heat flows of the HPT and LPT, commencing after 23 seconds. Whether volume packing is considered or not makes no difference. If the heat exchange is disregarded, the calculation proceeds without complications and ends after 90 seconds with 1.25% N_L and 3.15% N_H.

Engine run-down simulations may be a useful tool for calibrating the heat soak model by adjusting the imaginary casing thicknesses used for estimating the energy storage capacity of the engine hardware.

6.0 OUTLOOK

Simulating transients using only rotor inertia is a rough approximation of reality and may lead to erroneous conclusions. This is similar to optimizing the thermodynamic cycle using equations with constant isentropic exponents or ignoring the variability of the fuel heating value with temperature in combustion calculations. To ensure the accuracy of results from a transient performance simulation program, it is essential to consider the heat exchange between the gas and the engine hardware, as well as the effect of changes in tip clearance on component efficiencies and surge margin.

In order to calculate compressor and turbine tip clearances, it is essential to have a model of the engine that is responsive to changes in gas temperature and pressure, as well as to spool speed. Accurately modeling the rotating components is simpler than describing the heat storage capacity of casings, inter-compressor ducts, turbine center frames, and other structural components that are in direct contact with the main gas stream.

Several research organizations have recently developed tools for preliminary engine design which may be of use for future advanced transient performance models, see References 10 to 12. The results of these developments can certainly be used to improve also software that is easy to use, easy to learn, and visually appealing.

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