

GAS TURBINE ENGINE SIMULATION AT NLR

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ABSTRACT

An important aspect of aircraft simulation is the modelling of the propulsion system. At NLR aircraft propulsion system models are used for real-time aircraft simulation and for aircraft and propulsion system performance analysis. This paper describes the NLR approach towards engine modelling for both real-time engine simulation and (off-line) performance analysis and the relation between these two. For performance analysis NLR has developed GSP (Gas turbine Simulation Program). With GSP, both steady-state and transient performance of any type of gas turbine can be analysed. With respect to real-time engine modelling, NLR follows an approach towards non-linear models with thermodynamic relations instead of using linear models resulting from conventional system identification. In the presentation, both GSP and the real-time modelling approach will be described and an overview of applications will be given.

SYMBOLS AND ABBREVIATIONS

AJF	- Variable exhaust throat area
BPR	- ByPass Ratio
Cf	- Bypass ratio effect factor (GSP Fan component)
CFD	- Computational Fluid Dynamics
dTs	- Deviation from standard temperature
EGT	- Exhaust Gas Temperature
EPR	- Engine Pressure Ratio
FN	- Net thrust
GSP	- Gas turbine Simulation Program
fN2min	- maximum N2 deceleration rate function
fN2max	- maximum N2 acceleration rate function
fN1cmin	- maximum N1c deceleration rate function
fN1cmax	- maximum N1c acceleration rate function
FTIT	- Fan turbine inlet temperature
HP	- High Pressure (compressor or turbine)
LP	- Low Pressure (compressor or turbine)
m	- mass flow
Ma	- Mach number
N1	- Fan rotational speed
N2	- Gas generator rotational speed
N2S	- N2 as sensed by fuel control system
NLR	- Nationaal Lucht- en Ruimtevaart Laboratorium (National Aerospace Laboratory, the Netherlands)
Pb	- Burner pressure (pressure in combustor)
PLA	- Power Lever Angle
PTO	- Power take-off
SQRT	- square root
Theta	- ratio of temperature and sea level standard temperature
TT2	- Total engine inlet temperature
TT2.5	- Total HP compressor entry temperature
TT4	- HP turbine entry temperature
WCFC	- Fan core corrected mass flow
PRFC	- Fan core pressure ratio
Wf	- Fuel flow
WFPB	- fuel control variable = Wf/Pb
Zp	- pressure altitude

subscripts:

c	- corrected to sea level standard inlet conditions
core	- related to core engine (i.e. gas generator) flow
dBPR	- due to change in BPR
dem	- demanded by fuel control unit
des	- design point
duct	- related to bypass (fan) duct flow

1 INTRODUCTION

During the past decades, computer simulation has become a powerful tool for analysis of the processes in gas turbine engines. Nowadays computer models are indispensable for research and development in the gasturbine world.

Computer models are also useful for the gasturbine engine user/operator or aircraft company installing engines in their aircraft. For optimization of installation, usage, diagnostics, health monitoring and maintenance, extensive analysis of engine performance is necessary. In these cases a computer model is very useful. For some analysis types a computer model is essential; for other types it may replace expensive test programs on a real engine.

At NLR, gas turbine engine modelling is performed for both off-line and real-time simulation. Off-line gas turbine engine simulation is applied for:

- performance analysis: needed for diagnostics, solving handling and performance problems experienced by engine/aircraft operators. A new application is performance sensitivity analysis for defining condition monitoring systems which use gas path analysis techniques.
- performance prediction: providing data for aircraft performance calculations, other (real-time) simulation models and emission calculations.

The latter application receives rapidly increasing attention.

Real-time gas turbine engine models are developed for use in flight simulator models. Flight simulator models at NLR are generally used for research purposes, like development of flight control systems.

Both off-line and real-time models exist in a variety of types, with different levels of complexity, fidelity, accuracy and computer performance requirements.

2 OFF-LINE MODELS

Off-line models range from simple calculations by hand to 3D-CFD calculations. CFD computations cannot be performed throughout an entire gas turbine, but are limited to local areas in the gas turbine. However, by combining local CFD modelling with less complex overall gas turbine models, CFD analysis can be performed which directly interacts with the performance of the entire gas turbine (in reference 1 this concept is applied in a much broader sense). For overall gasturbine performance analysis at NLR, less complicated models generally are sufficient. An approach still resulting in accurate performance data throughout the complete engine is component stacking. Such models exist of compositions of component models that are based on component characteristics.

3 GASTURBINE SIMULATION PROGRAM

For (off-line) propulsion system performance analysis NLR has developed GSP (Gas turbine Simulation Program). GSP is a component stacking model capable of calculating both steady-state and transient gas turbine performance, including detailed calculation of secondary effects such as compressor bleed, turbine cooling and power off-take. Besides being a performance prediction tool, GSP is especially suitable for parameter sensitivity analysis such as: ambient (flight) condition effects analysis, installation (losses) effects analysis, analysis of effects of certain engine malfunctioning (including control system malfunctioning) and component deterioration effects analysis.

3.1 History

The development of GSP was started at the Delft Technical University (TUD, Aerospace dept.) in 1986. At TUD, NASA's DYNGEN (Ref. 2) program was used for jet- and turbofan engine simulation. However, DYNGEN appeared to have many problems with numerical stability and had a poor user interface. As a consequence, GSP was developed, inheriting features from DYNGEN. Significant deficiencies of DYNGEN were fixed in GSP; especially the stability, the speed of the numerical iteration processes and the user interface were improved. Development continued at NLR, where GSP has been converted to standard ANSI FORTRAN-5 and implemented on a powerful mainframe computer. It appeared that an additional amount of improvements, adjustments and extensions to the GSP program were necessary before useful simulation of a jet engine was possible.

Now, processes in the gasturbine are modelled with more detail, which has improved the accuracy. The most significant improvement has been the development of a fan model calculating the separation into duct- and core air, described in section 3.3.

An *extension* has been added in the form of a power turbine module, enabling turboshaft engine simulation. Further, the user interface has been improved and a number of output presentation features have been added.

In its present state, GSP version 6.0 is a well-proven tool for detailed performance analysis of any kind of gasturbine (turbojet, turbofan, turboshaft engines and generic designs like variable cycle gas turbines).

3.2 Modelling approach

Gasturbine simulation with GSP is based on one-dimensional modelling of the processes in the different gasturbine components with thermodynamic relations and steady-state characteristics ("component maps"). With one-dimensional modelling, air and gas properties, thermodynamically averaged over the flow cross-areas, are used in the calculations.

A gasturbine model is created by arranging ("stacking") different predefined components (like fans, compressors, combustors, turbines and nozzles) in a configuration similar to the specific gasturbine type to be simulated. The exit gas condition of a component then forms the inlet gas condition of the next component in the configuration.

The processes in gasturbine components are determined by relations among 2 up to 5 parameters defined by component maps and thermodynamic equations. These parameters are air or gas properties and other parameters such as rotor speeds and efficiencies determining the component operating point.

GSP is an "off-design" model. A predefined design point is calculated first from a set of user specified design point data. The deviation from the design point is calculated by solving a set of non-linear differential equations (see section 3.4). The equations are determined by the mass balance, the heat balance and the power (energy) balance for all components.

In case of a transient simulation, the differential equations include time-derivatives. Then, in each time step, the solution represents a quasi-steady state operating point.

3.3 Fan model

With the early GSP versions, significant deviation from reality occurred with simulation of turbofan engines. This was due to the fact that particularly in the fan, gas properties vary significantly over the cross flow area. Due to the relatively long fan blades (resulting in a large difference in blade speed from root to tip) there is a substantial variation in local fan characteristics along the blades. For a compressor model, this is not a problem, since the air exits into a single subsequent component, which requires the same averaged air properties as input.

With a fan however, part of the exit flow enters the bypass duct and part flows into the core engine. The separated flows have been subject to compression processes with different characteristics. Neglecting this effect caused inaccuracies of up to 10% in fan and (consequently) overall gasturbine performance parameters. Therefore, the process in the fan should be described separately for the core- and the duct flows using two separate maps. However, then the problem arises how to divide the fan inlet flow

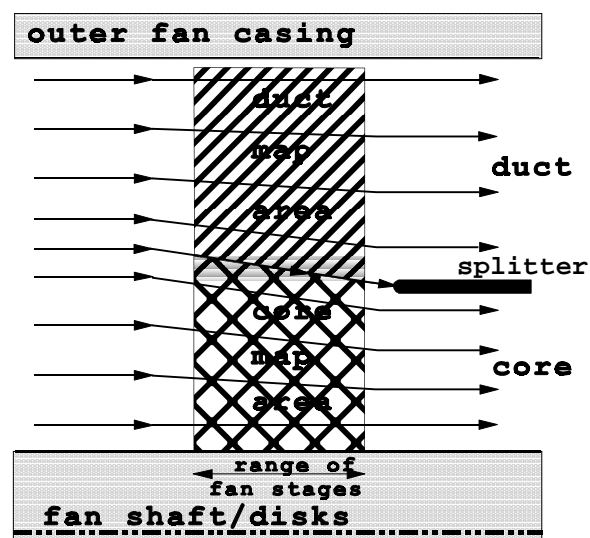


Figure 1 Fan stream lines in design point

into a flow using the core- and a flow using the duct map characteristics. These two flows are referred to as the *effective map flows*. Simply using the bypass ratio (BPR) for this division is not the answer, because the bypass ratio varies significantly with changing engine operating point. For example, the duct flow for a severely decreased (off-design) BPR can become very small. If this flow would be taken as the effective flow for the duct map, the map operating point is likely to exceed the stall limit.

In reality, this effect is compensated for by flow somehow (radially) flowing from duct to core side after being partly compressed by the duct side of the fan, thus smoothing the flow pattern along the radius (and as a result decreasing the effective core map flow and increasing the duct side stall margin). In GSP, the following approach has been used to model this effect. If uniform fan inlet flow (undisturbed, uniform density, speed, and pressure) is assumed, imaginary streamlines can be drawn indicating which part of the inlet flow eventually will enter the duct or the core (Fig. 1). Behind the fan there always is a *splitter* of some form, dividing the flow. The streamline hitting the stagnation point on the splitter's leading edge, indicates the boundary between the core- and duct flows in the inlet and fan; this is referred to as the *flow dividing streamline*.

As a reference, the flow dividing streamline in the gasturbine design operating point (with the design BPR, see figure 1) is used, from which the core- and duct effective flows have to be adjusted for off-design operation.

In the off-design case the flow dividing streamline will change position with varying BPR. This means there is flow across the design point dividing streamline, partly being compressed by the duct side and partly by the core side of the fan (Δm_{dBPR} in figure 2). This part of the total flow is equal to the difference between the flow which would have entered the duct with a BPR equal to BPR_{des} , and the actual flow according to the off-design BPR:

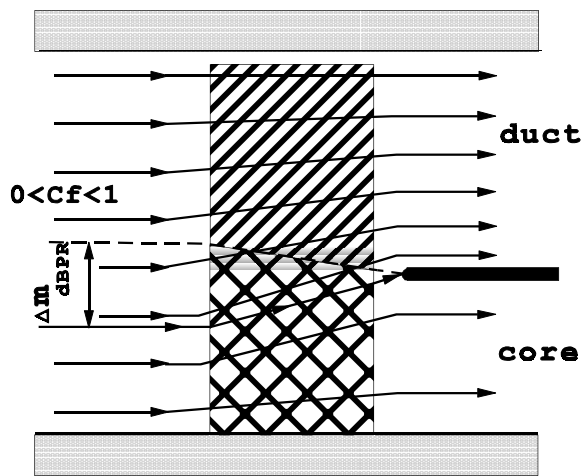


Figure 2 Off-design fan stream lines

$$\Delta m_{dBPR} = m_{in} \cdot \left(\frac{BPR}{BPR + 1} - \frac{BPR_{des}}{BPR_{des} + 1} \right) \quad (1)$$

The ratio at which the core- and duct side of the fan each contribute to the total compression of Δm_{dBPR} can be represented by a factor Cf. Then Cf determines the effective map flows as follows:

$$m_{duct} = m_{in} \cdot \frac{BPR_{des}}{BPR_{des} + 1} + Cf \cdot \Delta m_{dBPR} \quad (2)$$

$$m_{core} = m_{in} \cdot \frac{1}{BPR_{des} + 1} - Cf \cdot \Delta m_{dBPR} \quad (3)$$

Cf can be considered representing the *position* of the dividing streamline. For off-design conditions, a part of Δm_{dBPR} proportional to Cf is "shifted" to the other map. There are two extreme cases:

In the case of Cf=1 (Fig. 3), Δm_{dBPR} is entirely shifted to the other map flow so that the dividing streamline remains equal to the design dividing streamline. In effect, there are two totally separate compressors, both taking air from the same inlet and BPR is the ratio of the effective duct- and core

map flows.

In the other extreme case of $C_f=0$ (Fig. 4), no part of Δm_{dBPR} is shifted. Δm_{dBPR} remains included in the map flow of the side where it entered the inlet and the dividing streamline follows a line determined by the actual (off-design) BPR, only directing toward the splitter after having passed the last fan stage. This means that Δm_{dBPR} is fully compressed by the side of the fan it would flow through if the BPR would be equal to its design value and only then flows to the other side to yield the specific off-design BPR. The effective duct- and core flows for the maps are only dependent on the design BPR and the total inlet flow, and independent of the varying off-design BPR. In effect, both maps use the same uniform total inlet flow, only scaled to their design values according to the BPR_{des} constant.

The reality will generally be somewhere between these extremes ($0 < C_f < 1$, see figure 2), depending on fan and splitter design. A splitter located relatively far behind the last stage of the fan would allow radial flow between the last stage and the splitter. This flow compensates pressure differences between the two flows and causes a deviating off-design BPR. This case, where the effective map flows are relatively independent of the BPR, is represented by a small C_f value. A splitter close to the last fan stage will prevent radial flow behind the fan and result in a stronger relation between BPR and the effective map flows (i.e. a higher C_f value). When building a turbofan model, the C_f constant resulting in the best model match must be determined using trial and error.

With the new fan model, significant accuracy improvements have been achieved. Particularly with the model of a military afterburning turbofan engine, inaccuracies in fan related parameters were reduced from around 10% down to a 2.5% average (using a C_f of 0.1).

3.4 Solution method

The set of non-linear differential equations is solved using the multi-variable Newton-Raphson method. The integration of the transients is performed using a modified Euler method, providing sufficient integration stability. These features were inherited from DYNGEN (see section 3.1). In GSP, the method by Broyden (Ref. 3) is used to update the differential equations' Jacobian matrix instead of recalculating this matrix for each iteration step. This significantly reduces calculation time.

The effects of power off-take, compressor bleed and turbine cooling are included in the model in detail. For transient simulation, also heat transfer and internal volume effects are calculated.

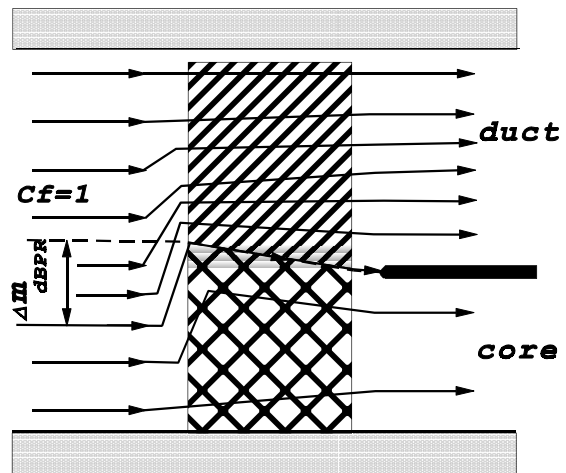


Figure 3 Off-design fan stream lines with $C_f=1$.

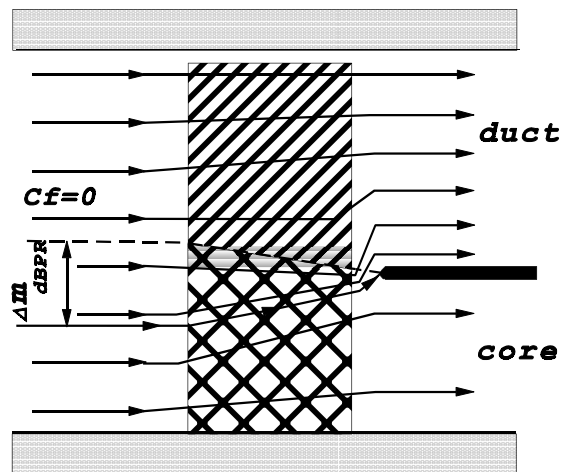


Figure 4 Off design fan stream lines with $C_f=0$.

3.5 Experience

At NLR, GSP has been used for performance analysis of a variety of gas turbine engines types, i.e.:

- J85-GE-15 (turbojet, General Electric)
- P&WC JT15D-1 and JT15D-4 (turbofan, Pratt & Whitney Canada)
- F100-PW-200 and F100-PW-220 (afterburning turbofan, Pratt & Whitney)
- RTM 322 (turboshaft, Rolls-Royce Turboméca)
- TAY 620 (turbofan, Rolls-Royce)

Typical applications include analysis of installation and flight conditions effects, calculation of exhaust conditions (as input for other models calculating infra-red signatures and exhaust emissions) and parameter sensitivity analysis to determine feasibility of condition monitoring methods. An important application is performance calculation for validation of real-time flight simulator models. These activities have provided NLR with significant experience in performing gas turbine performance analysis with GSP. With this experience NLR has the ability to quickly build GSP-models of specific gas turbines. The major effort with building a model often is collecting engine data. Especially component characteristics are usually not available and have to be derived from performance data. Once the effort has been taken to build a model for a specific gas turbine, steady-state and transient performance can be quickly analysed using GSP's user-friendly interface. Engine steady-state and transient performance are presented in the form of a variety of surveyable alpha-numerical and graphical output. Particularly the F100-PW-200 and JT15D-4 engines have been modelled in detail. With these models, steady-state parameter inaccuracies of 1% have been achieved. A small amount of test bed measured transient data have been available for comparison; these data did not deviate more

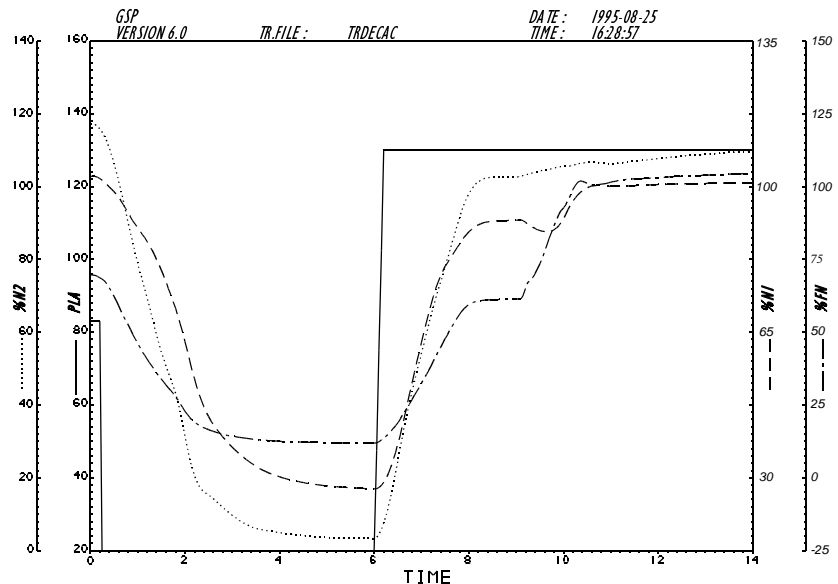


Figure 5 Afterburning turbofan slam decel from max dry followed by slam accel to max AB.

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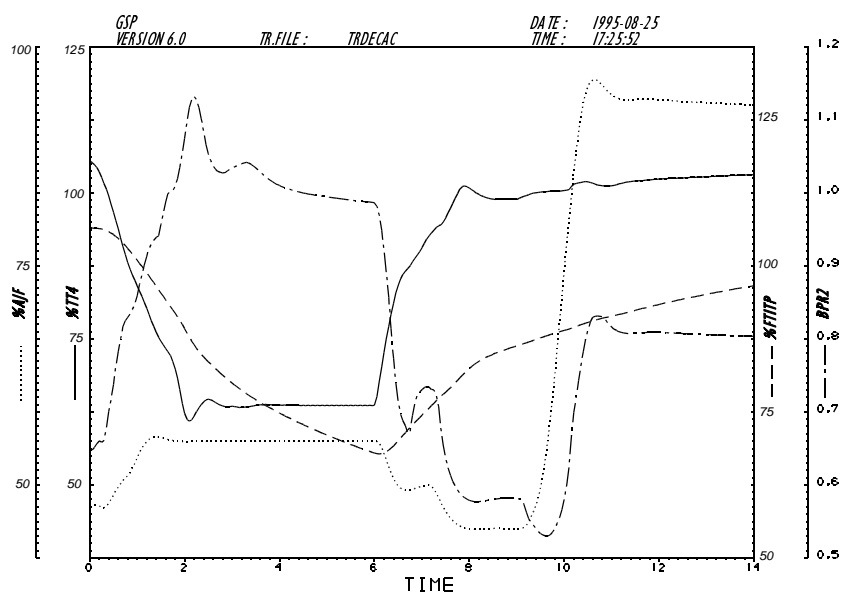


Figure 6 Slam decel and accel into AB: nozzle area, turbine temperatures and bypass ratio.

than 5% from the model results. The models include detailed control system models, enabling accurate analysis of transient performance. Effects of several forms of engine and control system malfunctioning can be determined.

Figures 5 through 8 show the simulated responses typical for an afterburning variable geometry turbofan with a complicated control system like the F100 engine. Figure 5 shows a slam decel from max dry power down to idle, after 6 seconds followed by a slam accel to maximum

afterburner power at sea level standard conditions. For the same case, figure 6 shows nozzle area, turbine temperature and bypass ratio responses. Figure 7 shows how the fan duct operating point travels through the duct map. Map plots like figure 7 can be generated for all component types and include an optional number of curves at user specified constant efficiency values. With a fan core map (not shown here) different from the fan duct map, an accurate fan model was obtained. With a Cf factor equal to 0.1 (see section 3.3) the best match was obtained. Performance parameters can also be plotted along both x- and y-axis in order to analyse relations among parameters. In figure 8 this option is used to show basic fuel control characteristics. The Wf/Pb value for the above mentioned case is plotted during decel and accel. Also the max Wf/Pb accel schedule is shown, indicating that in this case the fuel control has limited the accel Wf/Pb to a level lower than maximum governor Wf/Pb. The unstable Wf/Pb signal during deceleration is caused by unstable input from electronic supervisory control algorithms. For this model, the total number of performance and control system parameters available for presentation exceeds 120, enabling detailed diagnostic analysis. Accurate models for transient performance analysis are also valuable tools for developing and validating real-time engine models. The GSP model of the JT15D-4 engine was specifically set up for this purpose (see the next section).

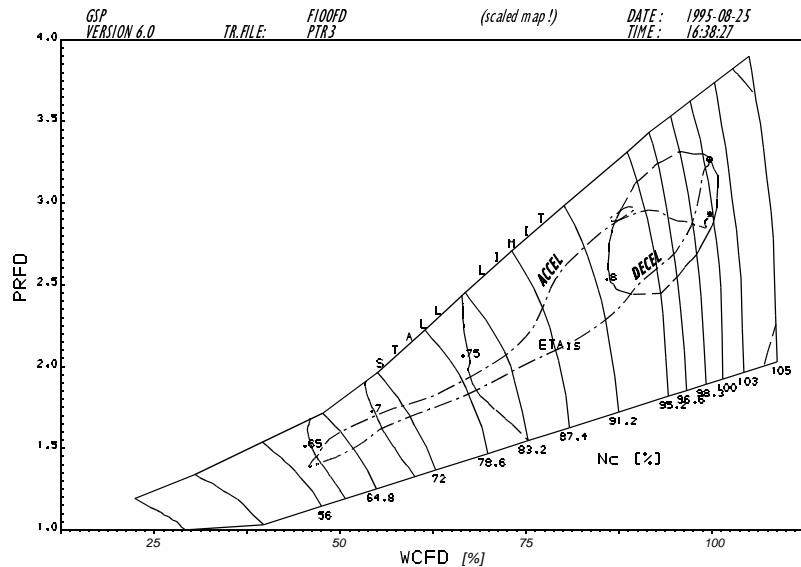


Figure 7 Decel-accel in fan duct map

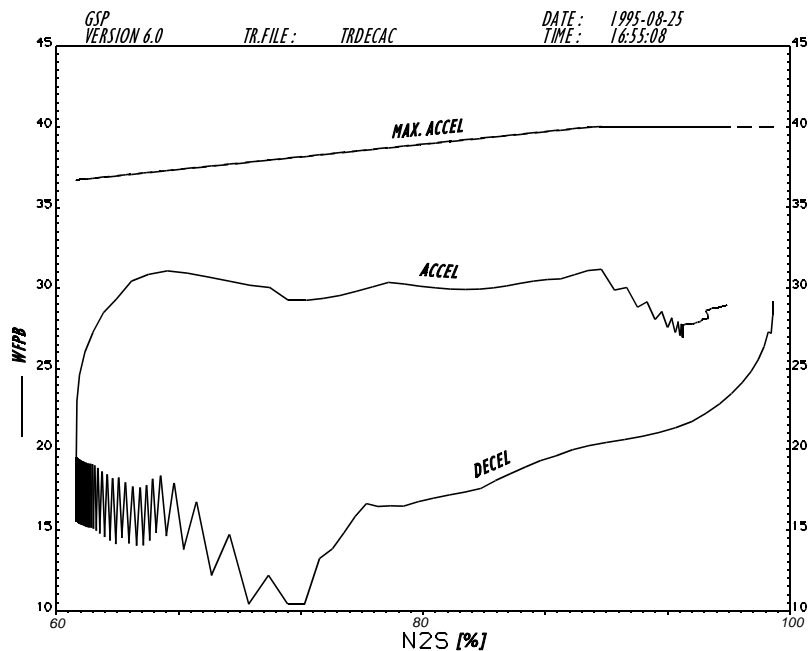


Figure 8 Decel-accel fuel control governor characteristics

4 REAL-TIME GASTURBINE ENGINE MODELLING AT NLR

NLR is active in the development of flight simulators and flight control systems. One of the main modules in a flight simulator real-time aircraft model is the engine model. Naturally, the fidelity of the engine model affects the overall flight simulator's fidelity. Especially with high thrust-to-weight ratio aircraft, effects of inaccurate thrust values on simulator fidelity are significant. Simulators for modern fighter aircraft (having thrust-to-weight ratios in the order of 1) should therefore have propulsion system models with accuracies comparable to the aerodynamic aircraft model accuracy. Moreover, detailed flight simulator engine models are necessary for integrated flight control system development (Ref. 4, 5).

Up to 1990, NLR's flight simulator models were obtained using system identification techniques, resulting in linear engine models with, compared to the aerodynamic aircraft models, relatively low fidelity. During the last few years, NLR has improved the propulsion system model fidelity by using "piecewise" linear models like in reference 6, 7.

Increasing accuracy and detail with linear models remains difficult and time consuming because in order to represent secondary effects such as installation and temperature deviation effects, a large amount of extra data tables are necessary.

4.1 Towards thermodynamic real-time engine models

A new approach towards real-time engine modelling is using non-linear thermodynamic relations instead of linear models obtained from system identification. A major problem with non-linear models is how to establish fixed calculation times per integration time step while guaranteeing numerical stability and acceptable accuracy. Iteration loops with an undefined number of passes within a single time step (like in GSP) are not allowed. However, the differential equations can be solved also *during integration*, calculating only one iteration step per time steps ("one pass per time step"), resulting in a stable small error after a few time steps. Several publications exist on this subject (Ref. 4, 5, 8, 9, 10, 11). Efforts in this direction originated from an increasing demand for high-fidelity gas turbine models, both for flight simulator- and gasturbine control system development. Besides improving model fidelity, this approach has the potential to reduce the amount of empirical engine performance data tables. By also developing separate reusable modules (e.g. fan, gas generator and control system modules), this will lead to a reduction in model development effort. However, when explicitly modelling components such as turbines and compressors, extra data tables will be necessary to represent component characteristics.

At NLR, currently a step-by-step approach towards thermodynamic real-time engine models is followed.

4.2 Case study

In 1993, development of a flight simulator model for the NLR Cessna Citation research aircraft was started as part of the AFC/NFT¹ project. For the P&WC JT15D-4 engines of this aircraft, as a case study, a simple non-linear real-time gas turbine model was developed with only limited thermodynamics. However, a high degree of modularity was required right away to allow an evolutionary development towards more detailed models from the start.

The JT15D-4 engine is a small turbofan engine with a single stage fan, a single booster stage and a radial HP compressor. For steady state data, a performance deck program was used; transient data were available in the form of flight test measurements of engine throttle responses. MATLAB-SIMULINK² simulation software was used to develop the JT15D-4 model as this was also the

¹ Automatic Flight Control / National Fly-by-Wire Testbed project; NLR-TUD cooperation on autothrottle, autopilot and flight control system development.

² MATLAB and SIMULINK are registered trademarks of The MathWorks Inc. Natick, Mass. USA.

flight simulator model development tool. SIMULINK allows quick evaluation of different modelling concepts and easy integration into SIMULINK flight simulator models. Further SIMULINK enables the user to build a module library, which is desirable in view of the modularity and reusability requirements. The model flow charts are shown in figures 9, 10, 11. The global engine model is shown in figure 9. It incorporates 2 sub-models: the gas generator model (Fig. 10) and the fan model (Fig. 11). Both sub-models can easily be reused. The gas generator module determines the overall engine operating point as well as the acceleration and deceleration rates of both gas generator and fan using blocks with max. accel and decel schedules (i.e. the "fN..." blocks).

Engine model

The current model has the power lever angle (PLA) and the flight conditions as input and thrust and the two rotor speeds as output. The two rotor speeds are appropriate to represent the engine operating point and thrust setting. Besides a fan and a gas generator module, the -4 version of the JT15D engine has a booster stage on the fan spool. However, only after the model explicitly calculates fan exit and compressor entry air conditions, a separate booster model is needed. The modular lay-out provides a means to effectively assess the accuracy of simulated engine behaviour with different modelling concepts. Start-up, shut down, windmilling, PTO and compressor bleed effects have not yet been included in the model.

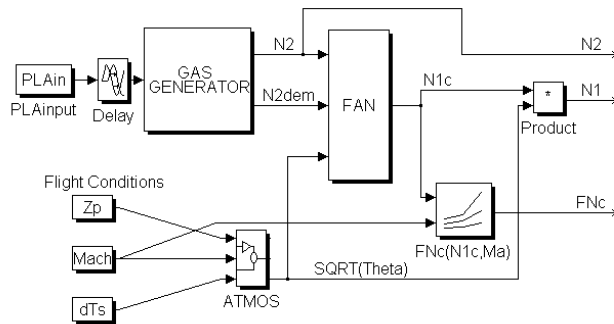


Figure 9 JT15D-4 SIMULINK model

Gas generator model

The gas generator steady-state performance is represented by a table with the relation between power level angle (PLA) and rotor speed. Depending on the type of fuel-control, the rotor speed signal is corrected for compressor inlet temperature. In the case of the JT15D engine the rotor speed-PLA relation (the "N2dem" block) is uncorrected. However, corrected gas generator speed (N2c) is a practical parameter to represent gas generator operating point and it (thermodynamically) determines steady-state performance of the rest of the engine (fan speed, EPR, EGT, thrust etc.). Since the TT2.5 parameter was not available, gas generator speed was corrected with the closely related TT2 instead.

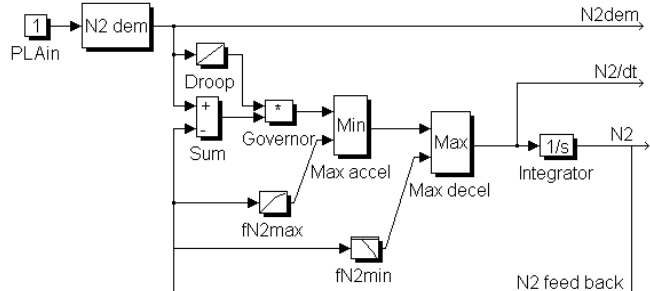


Figure 10 JT15D-4 Gas generator model

For transient simulation the control system characteristics have to be modelled. Gas generator speed usually is controlled by varying a parameter which corrects for different flight conditions. In most cases this parameter is the fuel flow - burner pressure ratio (Wf/Pb). Wf/Pb is a good measure for fuel air ratio which determines the acceleration rate of the spool. Acceleration and deceleration are controlled by limiting Wf/Pb. Maximum accel and decel Wf/Pb schedules are usually functions of corrected gas generator speed and flight conditions. Because of the strong link between N2 acceleration rate and Wf/Pb, dynamic performance of the gas generator can very well be modelled using maximum spool acceleration and deceleration rate schedules instead³ (i.e. the "fN2..." blocks). With future improvements the

³ Modern digital gas turbine control systems also limit spool rotational acceleration and deceleration with "Ndot control".

actual Wf/Pb schedules may be used once models with explicit calculation of Pb and turbine power have been realized.

Fan model

The fan obtains thermodynamic power from the gas generator. Therefore the operating point of the fan (and fan turbine) should be a function of the gas generator operating point (i.e. corrected gas generator speed $N2c$). This means steady state corrected fan speed $N1c$ is a function of $N2c$ (the " $N1c/N2c$ " block). Dynamic performance of the fan is principally determined by

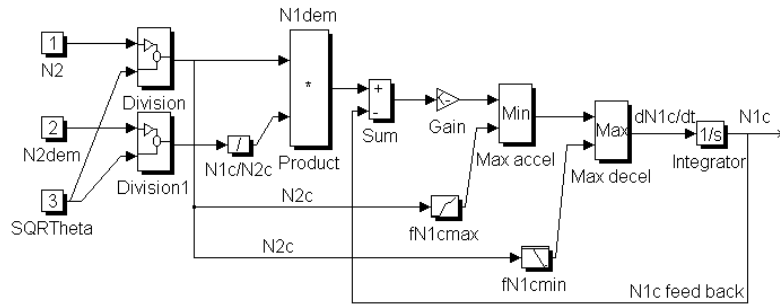


Figure 11 Fan-model

(dynamic) performance of the gas generator. Up to now, dynamic fan performance is represented by acceleration/deceleration to a "demanded fan speed" which is a function of demanded gas generator speed (i.e. a function of PLA). Maximum accel and decel rates are functions of $N2c$.

Results

In-flight measurement data have been used to assess the validity of the model. Measured dynamic PLA inputs have been input to the model for different flight conditions. The fuel-control model functions have subsequently been adjusted in order to match the model output ($N1$ and $N2$) with the measured responses. With little effort, accel and decel schedule functions could be adjusted in order to obtain a match as depicted in figure 12. After repeating this process for different flight conditions, it appeared that some control-model functions (like accel and decel schedules) were dependent on flight conditions. By using a number of flight condition dependent control function tables, a model valid for the entire flight envelope was obtained. The engine model then was successfully implemented in the Cessna Citation flight simulator model.

Further development

The approach used to model the JT15D-4 results in a good match with the data. However, further study has to show to what extent tables (empirical models) can and need to be replaced by thermodynamic equations. Currently, the thermodynamic relation between inlet, fan/fan-turbine and gas generator is only modelled by tables with relations between corrected speeds. If, for example, performance with deviating installation losses must be simulated, this model will not be adequate.

Further investigation will be focused on the use of thermodynamic equations to improve model fidelity and minimize the size (and dimension) of the tables and other specification data. The equation algorithms may be derived from GSP. "One pass per integration time step" methods will be evaluated

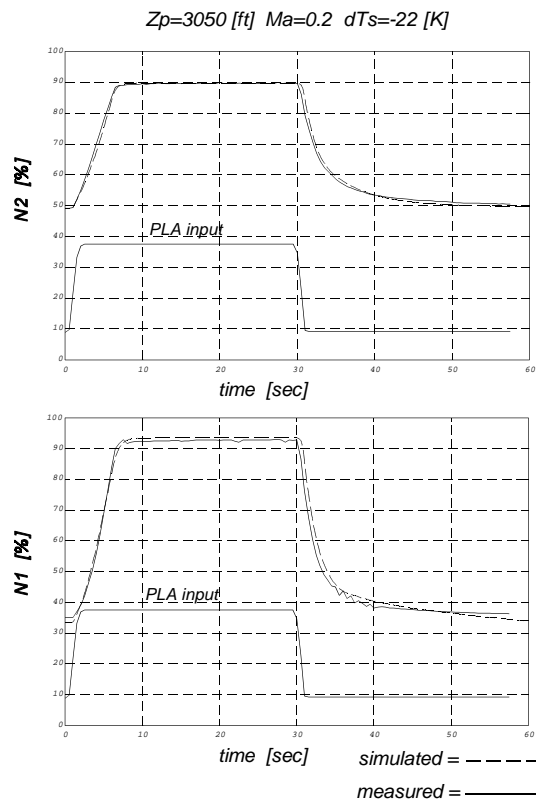


Figure 12 Comparison simulated $N1$ and $N2$ responses with measurement data

and applied for solution of the equations.

The fuel control unit should be modelled in more detail by actually calculating fuel flow. It would more effectively separate the fuel control and gas generator models, increasing the potential accuracy of the model and providing more generic modules. With a thermodynamic approach, start-up, shut down, windmilling, PTO and compressor bleed effects will implicitly be included in the model.

Conclusion

The approach of building simple non-linear gasturbine models with SIMULINK has proved to be beneficial. With little effort, parameters and tables of the generic model can be matched to a particular engine, resulting in a relatively detailed and accurate model. Extending the model with thermodynamic equations for individual component models is expected to be feasible with algorithms inherited from GSP and the "one pass per time step" method. It is important to continue development of the JT15D SIMULINK model, not only in order to obtain an accurate real-time engine model for the Cessna Citation research aircraft, but also to obtain a generic engine model, to be used for flight simulators and flight control system design at NLR in the future.

5 FUTURE DEVELOPMENTS

At present, GSP is a mature tool, able to serve users in most gas turbine performance analysis needs. Plans for future improvements include modelling effects of variable stator vanes position in compressor maps and modelling component deterioration effects in order to perform sensitivity analysis to support development of diagnostic algorithms in condition monitoring systems. More urgent is the development of high-fidelity modular real-time gas turbine engine models since flight simulator development is one of NLR's key activities. Therefore, extending the currently developed real-time SIMULINK modules with thermodynamic equations now has priority.

6 CONCLUSIONS

With GSP, NLR has a powerful tool to analyse gasturbine performance for various purposes. GSP has been successfully applied for a number of engine types. GSP models can generate the data necessary for real-time model development and subsequently be used for real-time model validation. NLR's real-time gas turbine models need further improvement. The achievements with the simple JT15D-4 engine model prove that the non-linear approach with SIMULINK is feasible and offering reusable modules. However, although model fidelity has been improved, most secondary effects still have to be represented in separate tables. Therefore, the next step will be extending the real-time model with thermodynamic equations for individual component models, solved with the "one pass per time step method". Thermodynamic equation algorithms and component map tables and functions then can be inherited from GSP.

7 REFERENCES

- 1) Russel W. Claus, et al., Multi disciplinary Propulsion Simulation Using NPSS, AIAA-92-4709-CP.
- 2) J.J. Sellers, C.J. Daniels, DYNGEN - A program for calculating steady-state and transient performance of turbojet and turbofan engines, NASA TN D-7901, 1975.
- 3) C.G. Broyden, Quasi Newton methods and their application to function minimization, Mathematics of Computation, vol.21, July 1967, pp. 568-581.
- 4) Drummond, C.K.; Ouzts P.J., Real-Time Simulation of an F110/STOVL Turbofan Engine, NASA TM 102409.
- 5) Szuch, J.R., Advancements in Real-Time Engine Simulation Technology, AIAA-82-1075.
- 6) Mihalow, J.R.; Roth, S.P., A Piecewise Linear State Variable Technique for Real-Time Propulsion system simulation, NASA TM 82851.

- 7) Davies, W.J.; Jones, C.L.; Noonan, R.A., Real Time Simulators for Use in Design of Integrated Flight and Propulsion Control Systems, ASME Paper No. 88-GT-24.
- 8) French, M.W., Development Of A Compact Real-Time Turbofan Engine Dynamic Simulation, SAE Paper No. 821401.
- 9) Mihalow, J.R., A Nonlinear Propulsion System Simulation Technique for Piloted Simulators, NASA TM 82600
- 10) McLaughlin, P., A Technique for the Implementation of Nonlinear Models as Real-Time Digital Simulations, Proceedings of Summer Computer Simulation Conference, Seattle WA, USA Aug. 1980, pp. 111-115.
- 11) Sugiyama, N., Generalized High Speed Simulation of Gas Turbine Engines, ASME Paper No. 90-GT-270.