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TERTS, a generic real-time gas turbine simulation environment

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Summary

Real-time simulation of gas turbine engine performance is used in a variety of aerospace applications. For simulation of propulsion system performance in flight-simulators, fidelity requirements become increasingly stringent. Significant improvements in simulation fidelity can be obtained when using thermodynamic models instead of the customary (piece-wise) linear real-time models. However, real-time thermodynamic models require sophisticated methods to efficiently solve the model equations on a real-time basis with sufficient speed.

NLR has developed the ‘Turbine Engine Real-Time Simulator’ (TERTS) generic real-time engine simulation environment for full thermodynamic simulation of various gas turbine engine configurations. At NLR’s National Simulation Facility (NSF[1]), research is performed on pilot-in-the-loop simulation of complex aircraft and helicopter configurations such as thrust-vectoring and Integrated Flight Propulsion Control (IFPC) concepts. For this application, high-fidelity real-time gas turbine models are required. TERTS has an efficient method for solving the engine model equations real-time. The system is implemented in Matlab-Simulink™, which offers advantages in terms of control system modeling flexibility. With TERTS, detailed thermodynamic real-time engine models can easily be implemented in NSF providing an excellent means to analyze a variety of engine effects on pilot-in-the-loop aircraft performance.
In this paper the TERTS modeling environment is described including the numerical solutions used to comply with the real-time requirements. A TERTS model of a military afterburning turbofan is presented including simulation results.

[1] http://www.nlr.nl/public/facilities/f115-03/index.html

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(20 pages in total)

1 Introduction

NLR's 'Turbine Engine Real-Time Simulator' (TERTS) is a component-based real-time modeling environment for gas turbines. With TERTS, full thermodynamic models of any kind of gas turbine configuration can be developed by establishing specific arrangements of engine component models in a model window.

TERTS is a powerful real-time tool for analysis of effects of malfunctions of control systems and other sub-systems on performance in pilot-in-the-loop simulations.

Since NLR is presented with a wide variety of gas turbine performance problems, simulation tools with a high degree of flexibility are required. As with NLR's Gas turbine Simulation Program GSP [1], TERTS was developed to allow rapid adaptation to various configurations, rather than being dedicated to a specific engine.

TERTS is implemented in the Matlab-Simulink[2] environment, offering excellent means to develop separate component and subsystem (especially control system) models. From Simulink, C-code can be generated for direct implementation of the model in the NSF simulation environment.

[2] Copyright © The MathWorks, Inc.

2 Real-time gas turbine simulation methods

With transient simulation, *off-line* models may accept undefined calculation times for iteration towards a transient operating point solution in a single time step. However, *real-time* models must employ special numerical methods to guarantee sufficient convergence at every time step within a predefined execution time.

Customary methodology of real-time gas turbine simulation is creating linear models obtained from system identification. Often ‘piece wise’ linear models are used where a series of separate linear models is used to cover the highly non-linear state space. Separate linear models are then determined for separate operating conditions (e.g. rotor speeds). This method is widely applied for flight simulators and control system design [2,3]. However, since this method is principally empirical, all operating condition effects on performance (such as failures, installation losses and deterioration) need to be implemented explicitly. For analysis of every new effect, additional code needs to be developed. Especially for research purposes where a large variety of effects is analyzed, this is unpractical.

Thus, instead of empirical models, higher-fidelity physical (thermodynamic) models are required in which most effects on performance are implicitly included in the model equations. These optimally are real-time derivatives of the customary 0-D component based engine models such as GSP [1] in which the equations for the conservation of mass, energy and momentum are solved for each component.

These models may use several methods to solve the non-linear set of equations representing a valid (quasi steady state) engine operating point during a transient [4,5]. Often, a Jacobian matrix is used to represent a linearized model (the sensitivity of the equation errors to the state deviations) in a particular operating point. The solver methods include Newton-Raphson based schemes [6], the Broyden Jacobian update method [7], and also different transient integration methods.

During iteration, new inverse Jacobians need to be determined to represent successive linearized models used to iterate towards the solution, due to the highly non-linear nature of a gas turbine system. Many pitfalls exist that can prevent successful solution, such as oscillation around the solution, ill-conditioned or singular Jacobians or dwelling in areas in the state space where most of the equation errors have a minimum. Stable, reliable convergence is hard to obtain, especially with generic engine simulation systems, where engine specific ‘fixes’ cannot be used.

The requirement of a limited execution time per time step for real-time simulation introduces an additional problem, since the execution time for the iteration is unknown in advance. A general approach here is “truncated iteration”: after a limited number of iteration steps (within maximum execution time per time step) the iteration is stopped and the accuracy accepted. It is assumed that succeeding time step iterations will further reduce any inaccuracies. This assumption is reasonable if the engine simulation involves high transient rates only at short intervals. In between where the engine runs “relatively steady”, any remaining errors in the equations are eliminated. This is normally the case, even with rather “violent” aircraft gas turbine operation.

Still, truncated iteration with re-determination of Jacobians during the simulation remains risky in unknown operating conditions. Extensive testing in all possible modes of operation is required to determine accuracy and execution speed requirements. Especially with complex thermodynamic engine models, the operating conditions are determined by so many variables that all combinations can never fully be tested.

3 TERTS Model description

3.1 Numerical method

With TERTS, the approach to avoid recalculation of inverse Jacobians during simulation is applied. It was recognized that a single inverse Jacobian is able to represent engine behavior in a limited part of the operating envelope, implying that a multiple of inverse Jacobians could represent the entire envelope. With many different variables defining the operating envelope however, this would be unpractical. An attempt was made to find a limited set of variables able to represent the engine envelope using dimensionless and reduced engine parameters.

Analysis of the inverse Jacobian indicated that corrected gas generator speed is the main factor responsible for deviations in the inverse Jacobian. This only applies if the Jacobian is determined for dimensionless and normalized state parameters. For a fixed corrected gas generator speed level, engine operation may well be simulated using a single Jacobian inverse (i.e. a single linear model, sufficiently able to provide convergence to various non-linear operating points). This would mean the entire operating envelope can be covered with a series of inverse Jacobians J^{-1} as a function of corrected gas generator speed N_{ggc}:

$$J^{-1} = F(N_{ggc})$$

For a real-time simulation this would entail pre-calculation and storage of an array of inverse Jacobians, while during simulation an inverse Jacobian is obtained by interpolation with gas generator speed. Hence, no inverse Jacobians need to be recalculated. To minimize the equation errors $\overline{E}$, one or more iteration steps per time step *i* can be performed for the states $\overline{S}$ using the interpolated inverse Jacobians:

$$\overline{S}_{i+1} = \overline{S}_i - J^{-1}.\overline{E}_i\,, \quad \boldsymbol{i=1\ldots}$$

If time step size is small enough (see section Stability), explicit Euler integration can be used:

$$\overline{S}_{t+1} = \overline{S}_t + \Delta t.\left(\frac{\partial \overline{S}}{\partial t}\right)_t$$

An important observation with gas turbine simulation is that rotor inertia is a major factor determining transient performance. The high frequency dynamics of thermodynamic states in the components (pressures, temperatures, flows etc.) only have small effects on rotor dynamics. This means the rotor speed dynamics can be ‘de-coupled’ from the component thermodynamics: with the explicit Euler integration, rotor speed states can be updated using the spool power errors for acceleration. The iteration updating the state at each time step therefore does not need to be applied to the rotor speed states. With a turbojet for example, 4 states and 4 errors would suffice to describe the engine system: one state represents rotor speed and therefore only 3 states need updating, requiring a 3x3 Jacobian.

Another issue is the limitation of the state update. With accurate off-line models where new Jacobians occasionally need to be re-determined and inverted repeatedly during single time steps, the state change often is limited for the linearization to remain valid. With single iterations per (small) time steps this limitation is unnecessary: the test models showed that best results (i.e. lowest equation errors and high stability) were obtained with state updates based on the full (unlimited) result of the product of J^{-1} and the error vector $\overline{E}$.

3.2 Stability

The stability of a TERTS model can be assessed using eigenvalues of the non-linear system. Real eigenvalues show state variables inhibiting first order behavior, while complex eigenvalues refer to at least second order responses of state variables. A stable system has eigenvalues with only negative real parts. Linearizing the non-linear system around an equilibrium point (a standard function in Matlab) allows determination of the eigenvalues. For a range of steady state operating points determined in advance, the stability of the system for small disturbances in input can be obtained. Figure 1 for example indicates the stability of a turboshaft engine model.

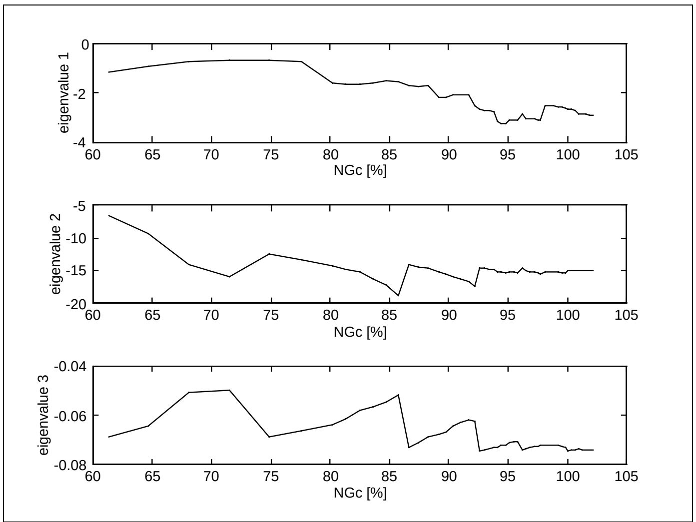

Figure 1 : Eigenvalue analysis example

With the explicit Euler method, time step size must be minimized in order to obtain maximum stability [6]. This implies a single iteration step per time step, as was found from test runs evaluating different iteration/integration schemes.

Some simple models were developed to test stability of the concept including a turbojet and a turboshaft. To improve the solver iteration stability, states and errors have been normalized. Best results were obtained with a single iteration step (state update) per integration time step at the smallest time step. At least 0.0333 (30Hz) is required to keep equation errors below 5%.

With more complex models, the time step requirements become more stringent: with the AB Turbofan model, at least 60 Hz is required to maintain accuracy with the afterburner control modeling. Figure 6 shows the equation errors during slam accels / decels. Stability was maintained at all conditions tested while the equation errors remained below 2% in most cases. With more computing power available, the best way to increase accuracy and stability is to just reduce time step size.

3.3 Accuracy

Both the equation errors and deviations of the thermodynamic model from known data affect accuracy of the simulation results. The previous section showed that the equation errors can be minimized by applying small time steps. Even if optimally tuned, the thermodynamic model has limitations in the 0-D component models. During (the quasi-steady state simulated) transients, the steady state component maps may not accurately represent component performance. If detailed control system simulations are involved, simulation time step size should correspond to (be at least smaller than) the smallest control update time step.

In some cases convergence (rate at which the equation errors disappear) is relatively slow, even during stable steady state. This is due to deviation of the Jacobian from the actual linear model in the particular operating point. In the example application at the end of this paper this is visible at IDLE power (Figure 6): the errors stay in the order of 1% for several seconds. Although this is sufficient for most applications, adding dimensions in the inverse Jacobian function for more precise representation of the entire state space can further improve convergence. This may well be required for simulations of particular failure effects, significantly affecting component performance. Adding T4/T2 (TIT over inlet temperature) as parameter representing the gas generator load would be the next step in this direction. Then the equation for J^{-1} would change into:

$$J^{-1} = F(N_{ggc}, T4/T2)$$

Additional errors in the thermodynamic model can be evaluated by comparing steady state performance results and errors minimized by fine-tuning the model. Finally, evaluation is required for transient performance, although often only limited transient data are available. In the AB Turbofan application example some validation data will be given.

3.4 Architecture

TERTS models are composed of configurations of component models similar to off-line 0-D gas turbine cycle models. Off-design transient gas turbine performance is calculated, relative to a reference operating report, usually the design point.

Matlab-Simulink offers the ability to decompose complex systems into smaller functional subsystems. A basic similarity between TERTS and GSP is therefore applicable and used to derive TERTS models from GSP. However, of the three object-oriented principles (encapsulation, inheritance and polymorphism), only encapsulation is supported by Matlab-Simulink.

3.5 User interface

TERTS employs the Simulink graphical user interface and reflects the component-based architecture for the gas turbine model. The main window manages the top-level model (Figure 2) and simulation, while lower level models (Figure 3) are accessed by zooming in on a system through double-clicking.

Input is provided in files listing input variables, off-design component maps, control schedules, etc. These files are simply accessed by any text file editor. Using scalable maps and control functions and dimensionless parameters, most component models are generic.

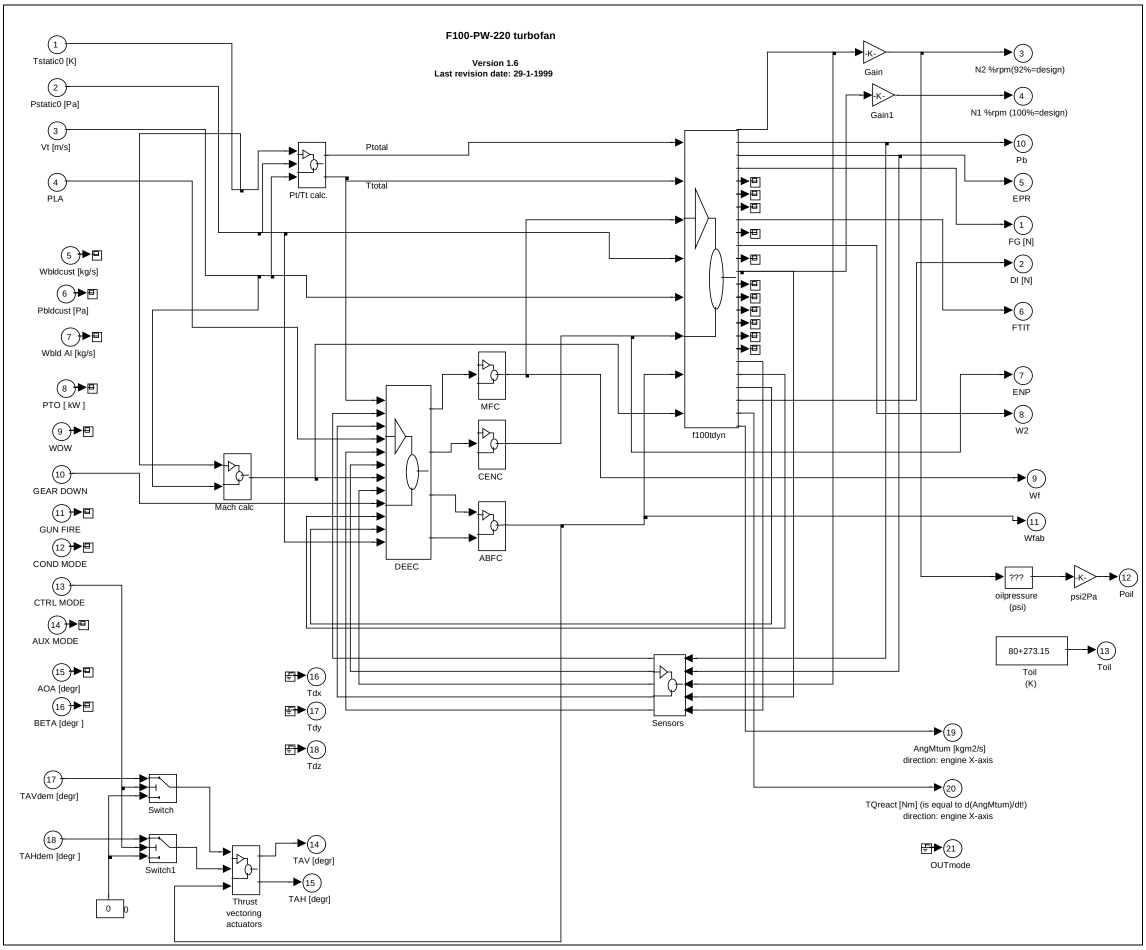

Figure 2 : TERTS top-level model of an afterburning turbofan

Matlab-Simulink's powerful graphical output features enable efficient presentation of results in many forms (see Figure 6 through Figure 9).

3.6 Component models

Calculation is performed on component level, using relations between component entry and exit gas properties based on component maps and thermodynamic equations. All component models are non-dimensional.

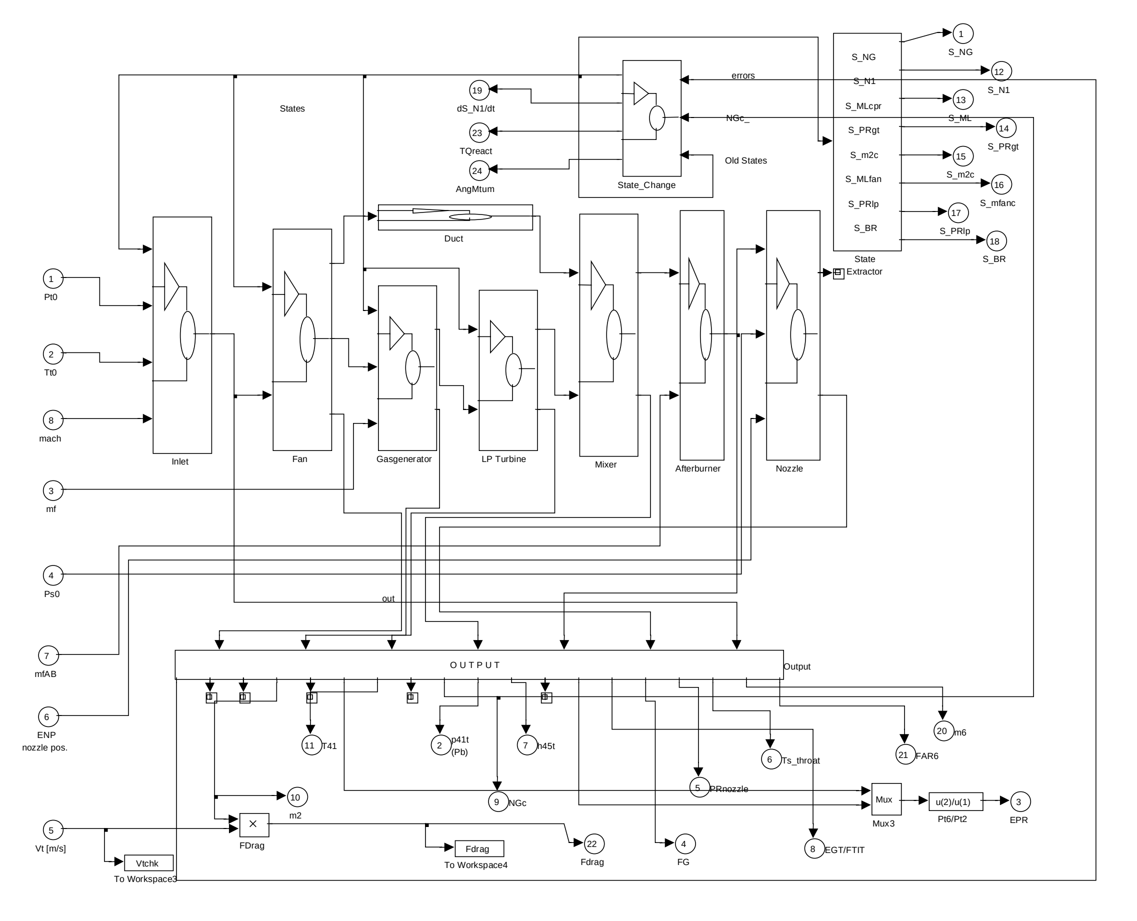

Figure 3 : TERTS afterburning turbofan - thermodynamic model level

To enable real-time simulation, any component detail not having a significant effect on operation or response of the system may be eliminated. Therefore, gas path component models generally do not include volume dynamics or heat soakage effects and for thermodynamics a "quasi steady state" method is applied. Exceptions are large volumes such as afterburners: the application example indicates volume effects are significant during AB light-up for example where relative large equation errors emerge (see section Validation, Figure 6).

The component models allow for simulation of secondary airflows, turbine cooling and variable (compressor) geometry if required for higher fidelity or accuracy. This often applies to high-performance engines where large turbine cooling flows have a significant effect on performance.

All components are modelled using the GSP [1] algorithms, except for the turbine, which employs:

- a simplified efficiency model based on a parabolic function of the loading parameter $\Delta H/U^2$,
- a rotor speed independent flow capacity map (function of pressure ratio only) .

If higher fidelity is required (volume and heat soakage effects, turbine model etc.), component models can easily be adapted at the cost of execution speed but without affecting the overall simulation concept.

4 Applications

TERTS has been used in several applications:

- The T700 turboshaft engine model [8]
- The EUROPA (European Rotorcraft Performance Analysis) tool, a common European helicopter performance prediction computer program [9]. The EUROPA code determines the dynamic performance of helicopters by simulating maneuvers, such as offshore platform takeoffs and landings. By simulating engine failures at the most critical time during the maneuver, the helicopter's safe maximum operating mass can be determined. A TERTS model of a small Allison 250 class turboshaft has been implemented in EUROPA.
- An afterburning turbofan engine model including detailed control system models. This more complex model is selected for demonstration of TERTS in the next section.

5 Twin-spool afterburning turbofan model

The engine used in this example is a twin-spool, afterburning turbofan with a low bypass ratio, a maximum thrust of approximately 110 kN and an overall pressure ratio of 25. Separate models are added for the electronic engine control (DEEC), the nozzle control and actuation, and the afterburner fuel control (Figure 2). Figure 3 shows the model one level deeper: i.e. the thermodynamic model that obtains inlet conditions and fuel flow from the top-level model. Many more sublevels exist for detailed simulation of components and subsystems.

In TERTS, a twin-spool afterburning turbofan engine model employs 8 states and 8 errors:
8 state variables representing:

- S_{N2} gas generator speed state
- S_{N1} fan speed state
- $S_{ML,3}$ compressor pressure ratio state
- $S_{PR,hpt}$ high pressure turbine pressure ratio state
- S_{m2c} inlet flow state
- $S_{ML,fan}$ fan state
- $S_{PR,lpt}$ low pressure turbine pressure ratio state
- S_{BPR} bypass ratio state

8 error variables calculated from:

- Fan entry corrected flow and map corrected flow
- Compressor entry corrected flow and map corrected flow
- HPT HPT power and compressor power
- HPT entry corrected flow and map corrected flow
- LPT LPT power and fan power
- LPT entry corrected flow and map corrected flow
- Mixer duct-to-core static pressure ratio
  (for conservation of momentum, constant duct-to-core entry flow static pressure ratio is assumed)
- Nozzle entry flow and exit flow

5.1 Validation

Steady state performance of the model was evaluated using engine manufacturer installed performance data (N1, N2, thrust and fuel flow across the entire flight envelope).
Figure 4 shows one of the validations at MIL power. In the relevant part of the flight envelope the errors remain within a 5% margin (beyond Mach 1.2 @ 0 ft, a large deviation occurs due to omission in the model of special control laws in that region).

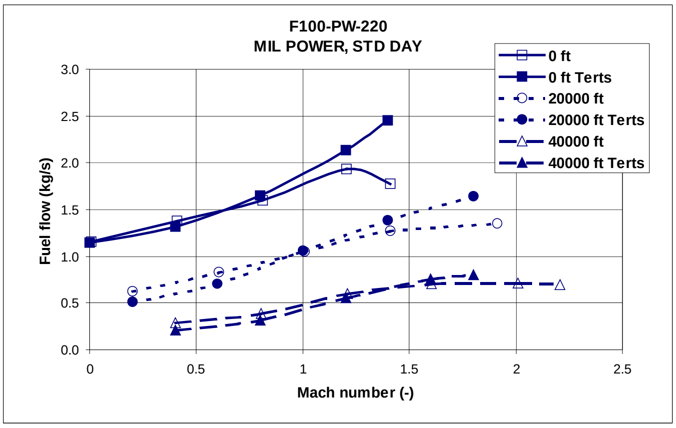

Figure 4 : Validation of steady state fuel flow at MIL power

Inaccuracies in the order of 5% were accepted at this stage, since the focus was put on a demonstration of the modeling concept. With additional fine-tuning using more engine data (obtained from off-line GSP models) the accuracy can be improved (see Accuracy section).

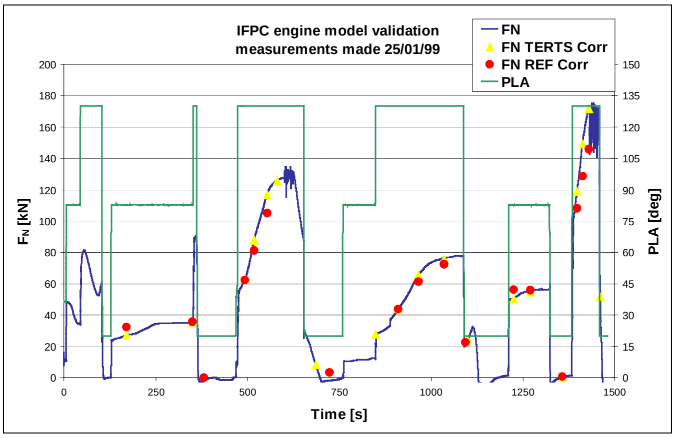

Figure 5 : Validation of net thrust at all throttle settings

TERTS determined thrust was also compared with steady state reference data during a test session in the NSF to assess inaccuracy during a typical F-16 mission simulation. The thrust-time history is displayed in Figure 5. Since the altitudes during the test session did not exactly match the reference data altitudes, the reference thrust data have been corrected for differences in pressure altitude. Results indicate a match well within 5% inaccuracy.

The oscillations in the thrust curve are the result of imperfections in implementation of afterburner permission control, which have been corrected after the test session.

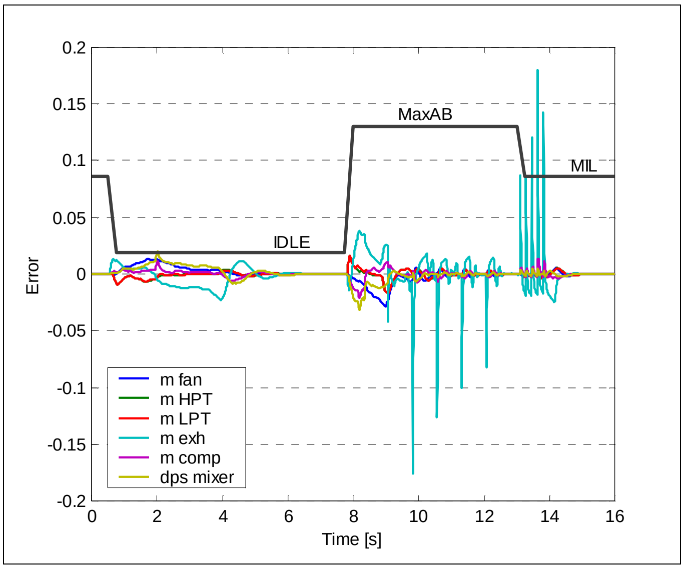

Figure 6 : AB turbofan equation errors during accel/decel

Figure 6 shows the response of the equation errors during slam decels and accels, also indicating the stability of the model. The errors remain within 4%, also during the accels. During stabilizing intermediate periods, the errors remain within 2%. During AB segment light-ups the exhaust mass flow error briefly exceeds 10%, which is corrected after a single time step and does not affect the performance parameter responses significantly as can be seen in Figure 7.

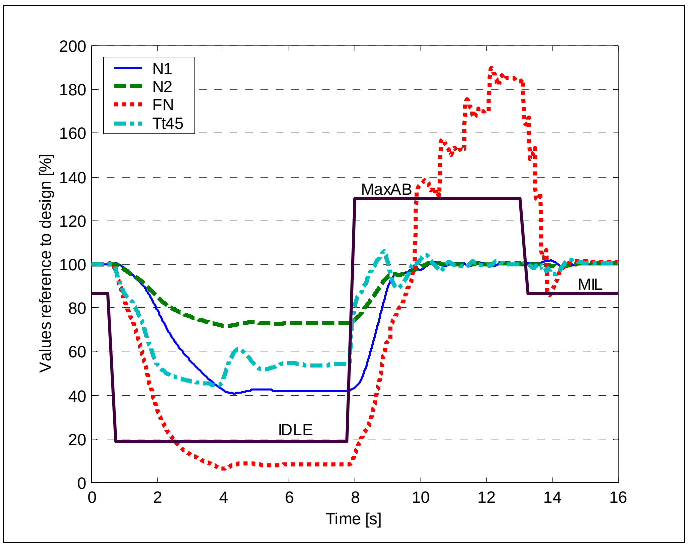

Figure 7 : Transient response example

During IDLE (2–8 s), convergence (although complete and fully stable) is rather slow (Figure 6: visible errors between 2-6 s). This effect is due to the limitations of the pre-calculated Jacobian approach and can be reduced by adding more dimensions to the inverse Jacobian function (see section Accuracy).

5.2 Transient performance

Transient performance has not been evaluated with test bed data at this stage. However, transient performance was found to correspond sufficiently with GSP calculated transients and with the test pilot experience in the NSF in all regions of the flight and engine power setting envelope.

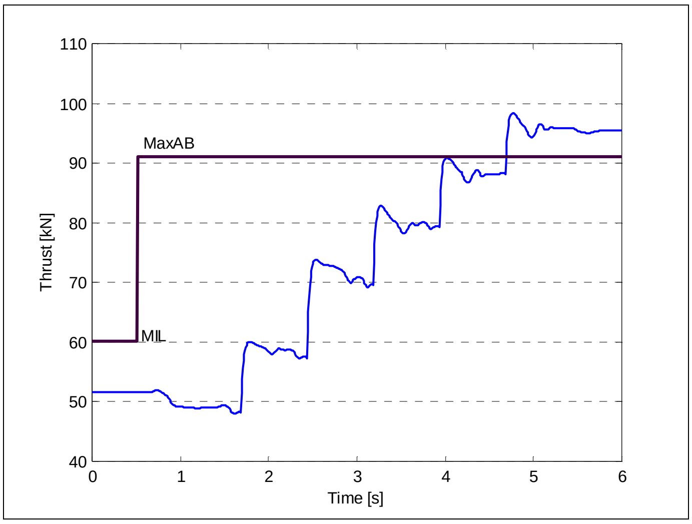

Figure 8 : MIL to MAX-AB thrust response

Figure 8 shows transient thrust response results for a MIL to MAX-AB slam accel (at ISA Static). The thrust shows the typical peaks at subsequent AB segment light-ups. These thrust peaks correspond to undesired pressure peaks that may cause fan stall. In practice, these must be avoided by adjusting the timing of change in exhaust nozzle position.

Figure 9 shows an IDLE - MAX-AB transient response (at ISA Static) of the fan rotational speed N1 and compressor rotational speed N2. Again the afterburner segment light-ups are visible through the effects of the pressure peaks on the fan rotational speed N1.

More validation work needs to be done to improve accuracy of both steady state and transient performance of the AB turbofan model. Apart from fine-tuning the present model, this may involve extending fidelity of component models (control system models, afterburner volume dynamics). This task can be performed using the existing TERTS component model library.

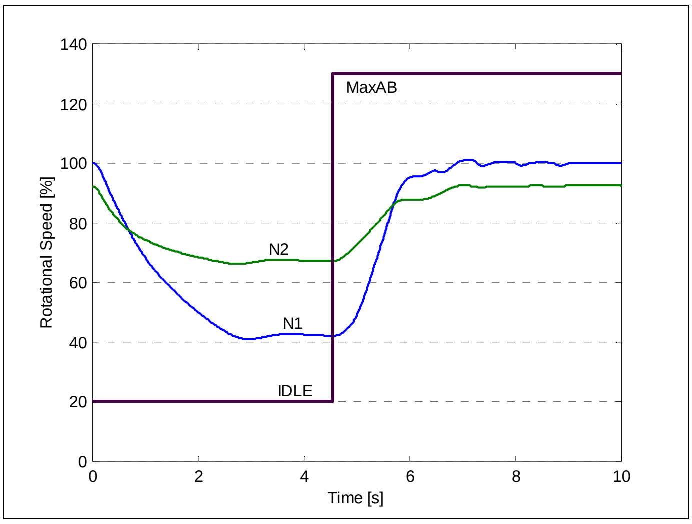

Figure 9 : IDLE to MAX-AB engine N1 and N2 response

5.3 Real-time execution speed

Using Matlab-Simulink's C-code generator, the AB turbofan model described was implemented in the NSF flight-simulator and used for Integrated Flight Propulsion Control (IFPC) and pilot-in-the-loop thrust vectoring concept research. For this purpose, flight control logic was integrated with engine control (not covered in this paper). At 100Hz (0.01s time steps), the engine model used up to about 20% of the available computing power (a 4-processor Silicon Graphics Challenge L computer, 180 Mwhetstones). Together with the aircraft model, this was well within the computing speed limitations.

6 Conclusions

The TERTS real-time gas turbine simulation environment is a powerful tool for development of high-fidelity thermodynamic (gas turbine) propulsion system performance models integrated in both off-line and pilot-in-the-loop flight simulation models.

The TERTS numerical method using pre-calculated inverse Jacobian functions provides high stability and accuracy, and minimizes execution time, even for complex models such as military afterburning turbofan engines.

The Matlab-Simulink environment offers efficient means to create new and adapt existing models using the component-based approach and Simulink's powerful control system modeling features.

With Matlab-Simulink's C-code generation tool, TERTS models are easily ported and embedded in aircraft modeling environments such as pilot–in-the-loop flight simulators.

TERTS has been successfully demonstrated in NLR's National Simulation Facility (NSF) as part of a project demonstrating Integrated Flight Propulsion Control (IFPC) and thrust-vectoring (TV) concepts.

TERTS flexibility will prove valuable to future applications such as detailed simulations of complex STOVL/TV propulsion systems, tilt-rotor and compound helicopter propulsion systems, integrated in research flight simulators.

Model inaccuracy of the current system is well within 5%. Further improvement is possible through:

- Obtaining more validation data, especially transient response data.
- Adding extra parameters such as T4/T2 to the inverse Jacobian function, thereby further reducing the equation errors.
- Extending the level of detail of the component models (e.g. the turbine).

This would require more computing power while the numerical concept can be maintained. This exercise is the subject of future research.

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