REAL TIME ENGINE MODEL
IMPLEMENTATION FOR ADAPTIVE
CONTROL & PERFORMANCE MONITORING
OF LARGE CIVIL TURBOFANS

A. Stamatis, K. Mathioudakis
Lab. Of Thermal Turbomachines
National Technical University of Athens

J. Ruiz
SNECMA

B. Curnock
Rolls-Royce
Real Time Engine Model Implementation for Adaptive Control & Performance Monitoring of Large Civil Turbofans

• Requirements  
• Modelling Methods  
• Implementation Issues  
• Validation-Parametric Studies  
• Summary - Conclusions
Requirements For A REAL Time Engine Model

General requirements: SAE AIR4548.

Time dependent behavior:
  • Heat soakage, Shaft dynamics, and Gas dynamics.

Update rate 10 to 20 times > highest frequency

Requirements for a model supporting a controller:
  • a highly accurate and detailed model
  • trade-off between computer cost, speed, and performance.

Cycle rate smaller than the engine controller,
  • ( i.e. ~20 [ms] for an advanced turbofan engine controller)

Robustness and predictability.
  • Numerical exceptions prevented
  • predictable execution time.
  • Limit number of iteration passes for completion in the controller cycle time

To meet requirements:
  -Model all the crucial effects
  -Use any advances that help reducing calculation time and ensure robustness.
Modelling Methods

Layout of Large (partially) mixed Turbofan
Component Modelling (I)

The fan
- Characteristics separate for Fan Root and Fan Tip
- Separate surge lines.
- Sufficiently large size $\Rightarrow$ Reynolds number effects neglected.

The Swan neck
- Modeled by a pressure loss $\Delta P$

The compressor
- Characteristics
- Separate surge lines.
- IGV scheduled as a function of Relative $N/\sqrt{T}$.
- Effects for IGV changes using Deltas
- Reynolds Number corrections
Component Modelling (I)

Combustion
- Fixed burning efficiency. Cold pressure loss, hot loss, No dissociation

The HP and LP Turbines
- Characteristics
- Cooling bleed mixing after the expansion. No friction or windage losses on the shafts.
- Reynolds Number effects

The Exhaust unit
- Pressure loss based on axial Mach number and swirl angle.

The By-pass duct
- (a) Fan Outlet Guide Vane (OGV), (b) duct loss

Nozzle Performance
- A 3-stream mixing method: Mixed, Hot and Cold
Model Adaptation

Adaptation factors expressing condition of components

Flow factor for a component

\[
SW_i = \frac{\frac{W_i \cdot \sqrt{T_i}}{p_i}}{\left(\frac{W_i \cdot \sqrt{T_i}}{p_i}\right)_{\text{ref}}}
\]

Efficiency factor:

\[
SE_i = \frac{\eta_i}{(\eta_i)_{\text{ref}}}
\]

The values of the factors for determining condition of an engine derived using data from measurements.

Derivation based on the solution of a multidimensional minimization problem
Dynamic Modeling

• Heat transfer between the gas and the metal applied separately to compressor and turbine blades and casings. 
  
  Heat transfer in a compressor or turbine has an effect on the thermodynamics, changing the pressure ratio $P_Q$ for a fixed work.

• Shaft dynamics incorporated in two energy balance equations, one for each shaft.

• No gas dynamics
Solver and Integrator

• System of non-linear equations

\[
\begin{align*}
    f\left(\dot{X}, X, Y, U\right) &= 0 \\
    g\left(X, Y, U\right) &= 0
\end{align*}
\]

- \(U\) : control and flight condition variables
- \(X\) : shaft and temperature dynamics variables
- \(Y\) : performance and thermodynamic parameters

• Steady state calculations

Demand \(dX/dt=0\). Solve non-linear system

• Dynamic modeling:

System of equations is to be integrated in time

\[
\begin{align*}
    U_t \rightarrow \\
    f\left(\dot{X}_t, X_t, Y_t, U_t\right) &= 0 \\
    g\left(X_t, Y_t, U_t\right) &= 0 \\
    h\left(\dot{X}_t, \dot{X}_{t-1}, X_t, X_{t-1}, dt\right) &= 0 \\
    \rightarrow \\
    X_t \rightarrow \\
    Y_t
\end{align*}
\]
Time integration scheme

Explicit integration

For example using Euler forward: \[ X_t = X_{t-1} + dt \dot{X}_{t-1} \]

Implicit integration.

For example using Euler backward: \[ X_t = X_{t-1} + dt \dot{X}_t \]

Explicit: \textit{simplicity} – speed

(when number of states is comparable to number of guessing variables the reduced system is solved twice as fast if a Newton type method requiring Jacobian calculation of the linearized system is to be used)

Implicit: \textit{more stable}

when stiff set of equations are involved permitting thus bigger time steps to be used.
Particular Dynamic Modeling issues for the real time implementation

- Map interpolation routines optimized
  (Minimum number of operations, advanced search, recent table look up reference location index etc)

- Accurate guessing
  Scaling of the guessing variables and error equations has been introduced in order to improve the condition number of the compatibility equations system matrix and thus improve further convergence characteristics.

- Solution based on Broyden update of the inverse Jacobian
  (Advantage: ability to exploit past information during transient, avoiding costly Jacobian evaluations in each time step, allowing fixed model execution time to be imposed if desired. Efficient modified Newton Raphson solution algorithm has been incorporated as well, which could be sufficient for non real time models)

- Predictability
  Flags for update policy control it is easily controlled (i.e calculation or not of Jacobian in each time step as well as the number of updates).

- Robustness
  Damping schem in Broyden method, provisions to inhibit mathematical exceptions,

- Thermodynamic subroutines optimized
Investigations & Validation

Transient Fuel Input

![Graph showing transient fuel input over time](image-url)
Timing Investigations

Different Number Of Fixed Iterations

Comparison of execution time in a PENTIUM II (450 MHz)
Timing Investigations

Different time steps

Comparison of execution time in a PENTIUM II (450 MHz) for
Timing Investigations

Effect of Convergence Tolerance

Comparison of execution time in a PENTIUM II (450 MHz)
Accuracy Studies

Transient Input for accuracy testing

![Graph showing fuel flow rate over time]

- Y-axis: Fuel flow rate (kg/s)
- X-axis: Time (s)

The graph illustrates the transient input for accuracy testing, showing how fuel flow rate changes over time.
Accuracy Studies

Low pressure shaft speed prediction error

LOW PRESSURE SPOOL SPEED

- EXP, TOL=1E-4, TS=10ms, FI=2
- EXP, TOL=1E-6, TS=10ms, FI=2
- EXP, TOL=1E-4, TS=20ms, FI=5
- EXP, TOL=1E-6, TS=20ms, FI=5
- IMP, TOL=1E-4, TS=20ms, FI=5.5

Error %

TIME (s)
Accuracy Studies

High pressure shaft speed prediction error

![Graph showing high pressure shaft speed prediction error with various error percentages and time intervals.]
Accuracy Studies

Temperature prediction error

![Temperature prediction error graph]

- Exp, ts=20 ms
- Exp, ts=20 ms, fi=3
- Exp, ts=20 ms, fi=4
- Exp, ts=20 ms, fi=5
- Exp, ts=10 ms
- Exp, ts=10 ms, fi=2
- Exp, ts=10 ms, fi=3
- Exp, ts=10 ms, fi=4
- Imp, ts=20 ms
- Imp, ts=20 ms, fi=5
- Imp, ts=10 ms
- Imp, ts=10 ms, fi=3
Timing investigations using different processors

PENTIUM 166 MHZ

PENTIUM 133 MHZ

PENTIUM 33 MHZ
Discussion

- One iteration of the code costs about 0.25-0.3 ms using implicit or explicit Euler in Pentium 450MHz and 2-3 ms in a Pentium 90MHz.

- 5 iterations (< 1.5 ms in Pentium 450 and < 15ms in Pentium 90) are sufficient to produce accurate enough solution in each operating point (or time step).

- The code is robust enough in terms of its ability to run efficiently even in abrupt accelerations and decelerations.

- Adaptation possibility can be useful for an improved control capability.
  - Adaptation to incoming measurement data can be performed by running the model in adaptive mode, during the time remaining after execution of the model, since execution time is only a small fraction of the real time.

- There are still aspects to be optimized.
  - Further code optimization such as more efficient calculations of gas properties (usage of pre-calculated tables).
  - Elimination of software overhead, e.g. data copying between Common-Blocks. Replacement of divisions and power arithmetic by multiplications wherever possible and maybe reduction of the number of iteration variables could also be beneficial.
Conclusions

- A real time engine model has been developed.
- Non linear physical structure (identical with a detailed transient model which represent the real engine)
- Ability to adapt to the engine condition.
- General and specific requirements for the targeted model have been set, evolution of the model was presented and various investigations concerning the ability to satisfy these requirements have been done.
- The developed model is faster than real time in terms of a realistic time step (20ms for current turbofan engines controllers) using a processor (Pentium 90MHz) with computing power about ten times less than the current existing processors in the market.
- Speed is achieved without sacrificing model accuracy