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

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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

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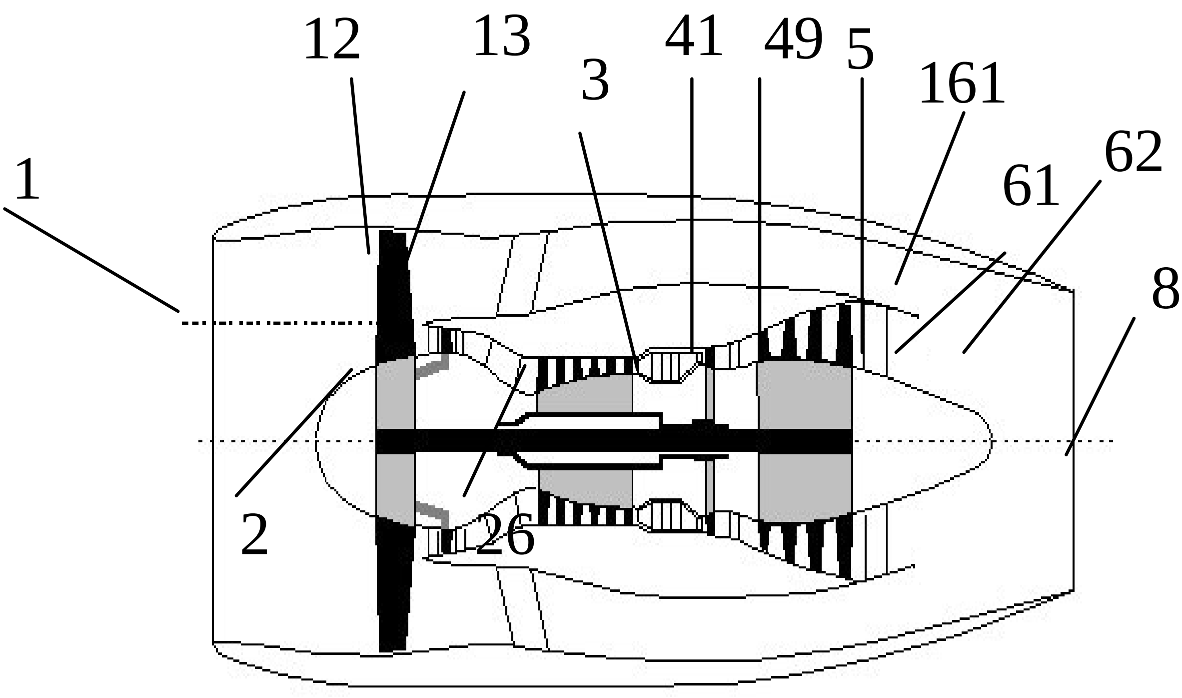
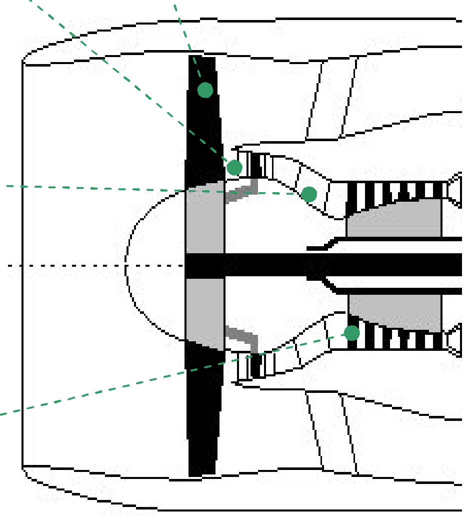
Layout of Large (partially) mixed Turbofan



Component Modelling (I)

The fan

- Characteristics separate for Fan Root and Fan Tip
- Separate surge lines.
- Sufficiently large size Þ Reynolds number effects neglected.



The Swan neck

- Modeled by a pressure loss ΔP

The compressor

- Characteristics
- Separate surge lines.
- IGV scheduled as a function of Relative N/ÖT.
- Effects for IGV changes using Deltas
- Reynolds Number corrections

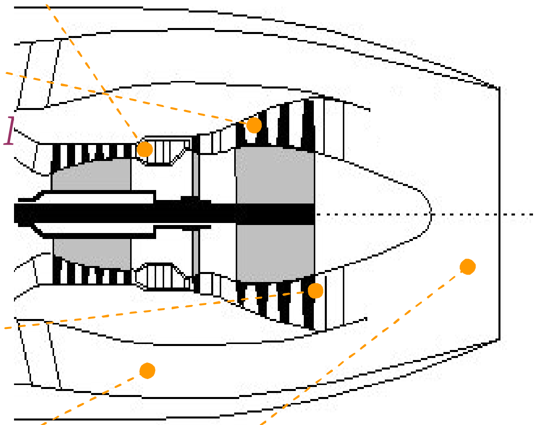
Component Modelling (I)

Combustion

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

The HP and LP Turbines

- *Characteristics*
- *Cooling bleed mixing after the expansion. I 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

$$SW_i = \frac{W_i \cdot \sqrt{T_i}}{p_i} \Bigg/ \left(\frac{W_i \cdot \sqrt{T_i}}{p_i} \right)_{ref}$$

Efficiency factor:

$$SE_i = \frac{h_i}{(h_i)_{ref}}$$

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 PQ *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**

$$\begin{cases} f\left(\dot{X}, X, Y, U\right) = 0 \\ g\left(X, Y, U\right) = 0 \end{cases}$$

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

$U_t \rightarrow$

$$g\left(X_t, Y_t, U_t\right) = 0$$
$$f\left(\dot{X}_t, X_t, Y_t, U_t\right) = 0$$
$$h\left(\dot{X}_t, \dot{X}_{t-1}, X_t, X_{t-1}, dt\right) = 0$$

$\rightarrow Y_t$
$\rightarrow X_t$

Time integration scheme

Explicit integration

For example using Euler forward: $\boldsymbol{X}_t = \boldsymbol{X}_{t-1} + \boldsymbol{dt}\,\dot{\boldsymbol{X}}_{t-1}$

Implicit integration.

For example using Euler backward $\boldsymbol{X}_t = \boldsymbol{X}_{t-1} + \boldsymbol{dt}\,\dot{\boldsymbol{X}}_t$

Explicit: ***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: ***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)

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- **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).

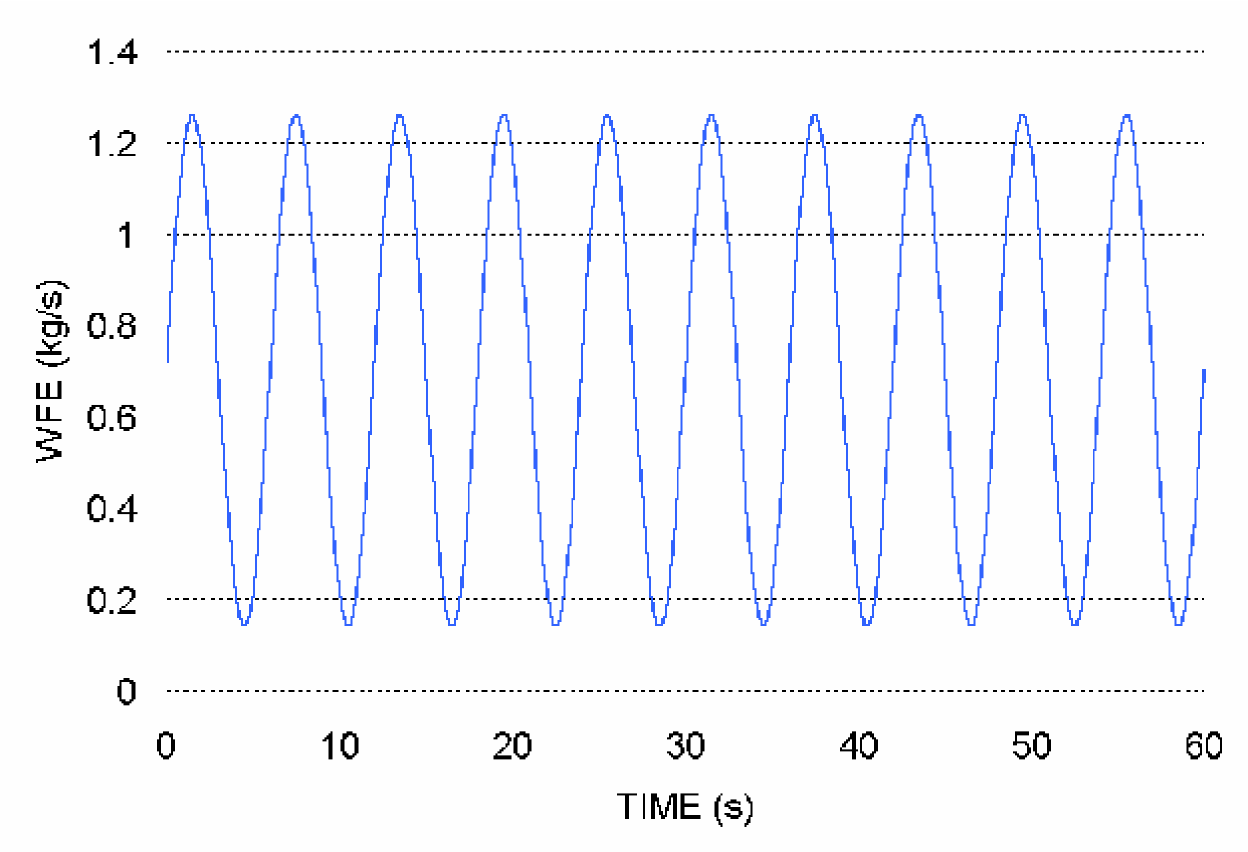
- **Robustness**

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

- **Thermodynamic subroutines optimized**

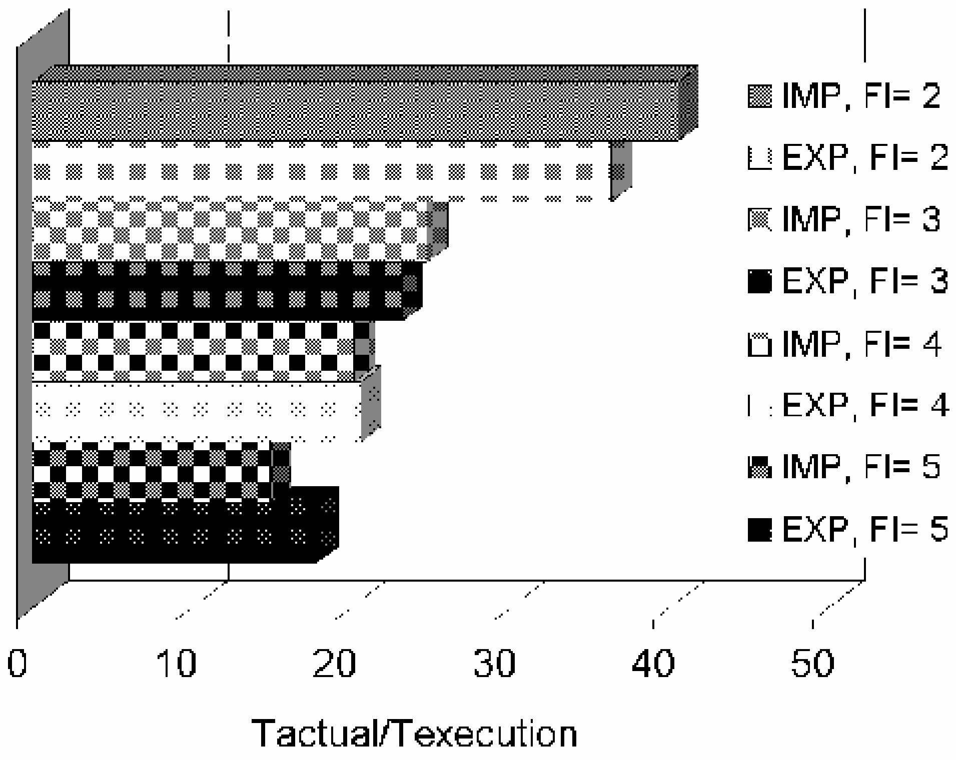
Investigations & Validation

Transient Fuel Input



Timing Investigations

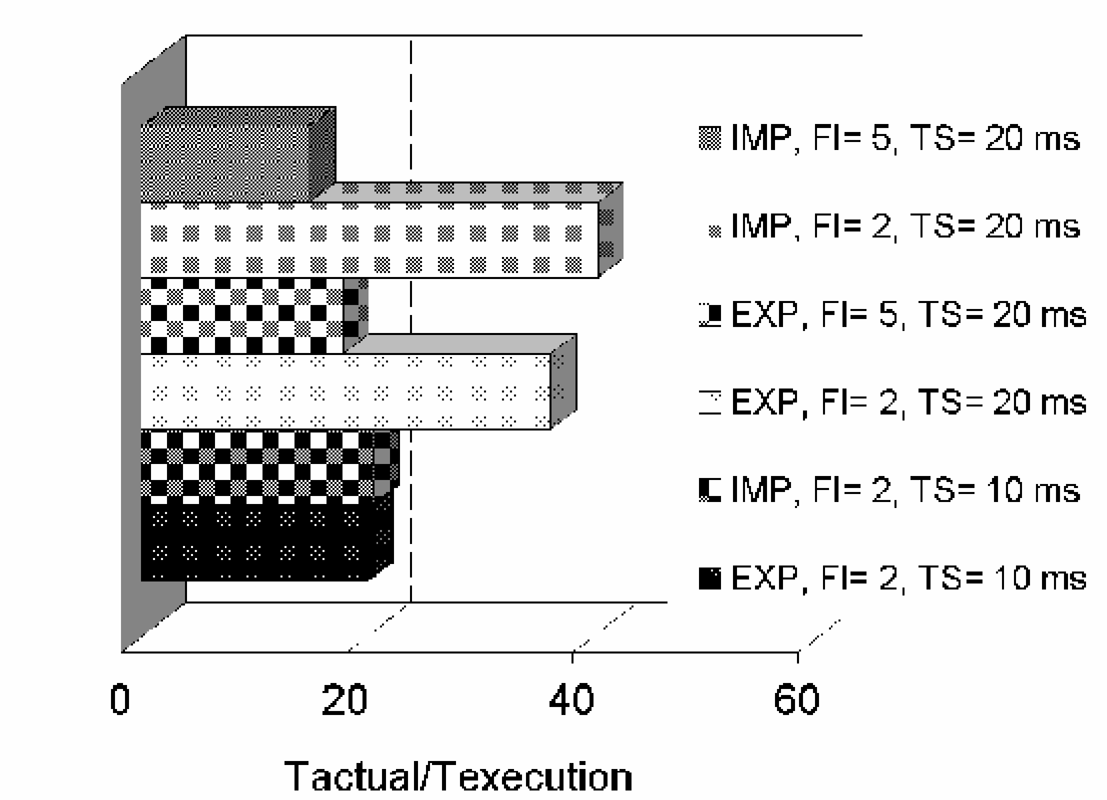
Different Number Of Fixed Iterations



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

Timing Investigations

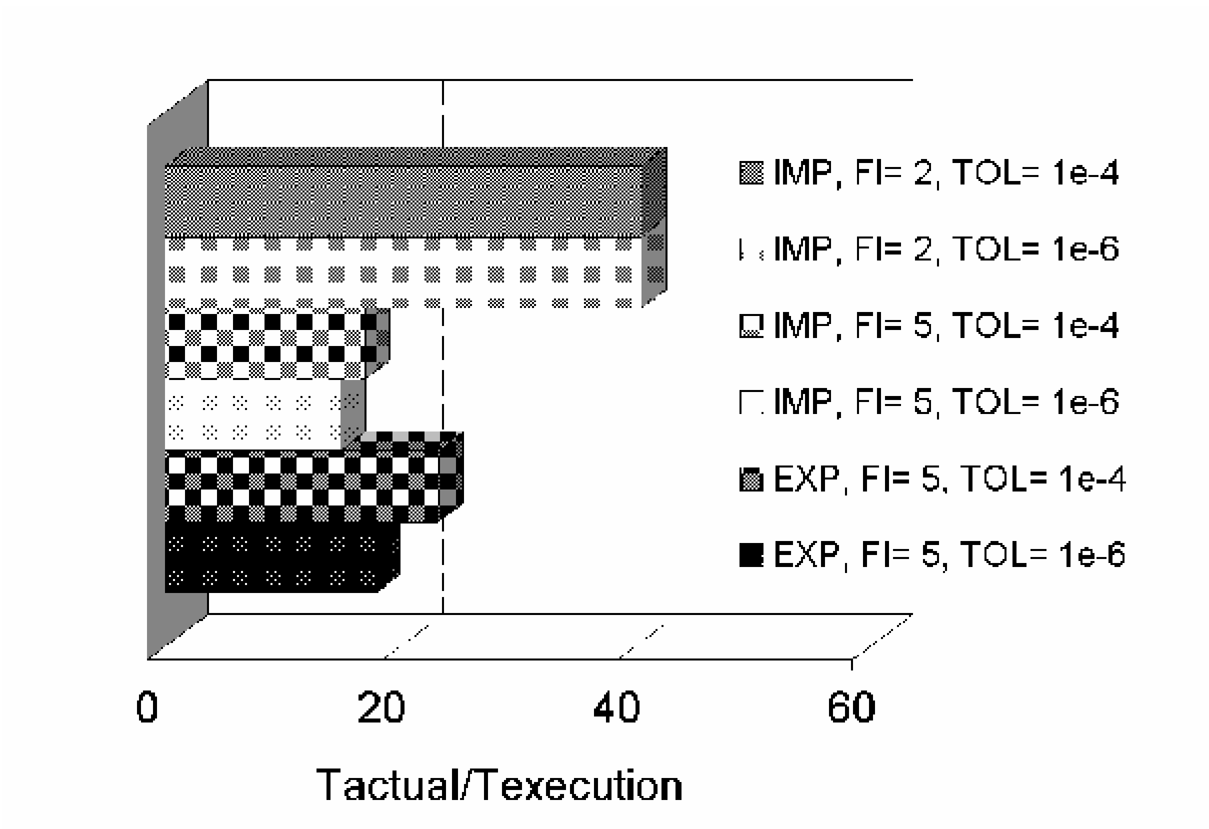
Different time steps



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

Timing Investigations

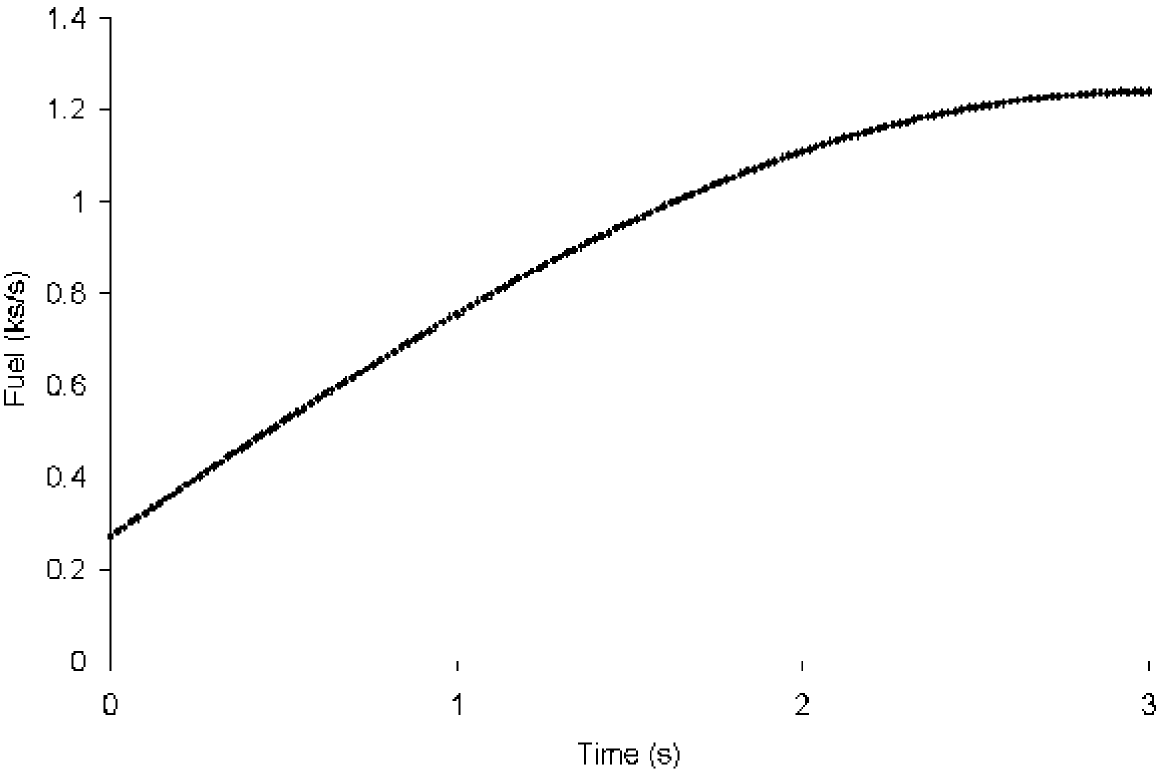
Effect of Convergence Tolerance



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

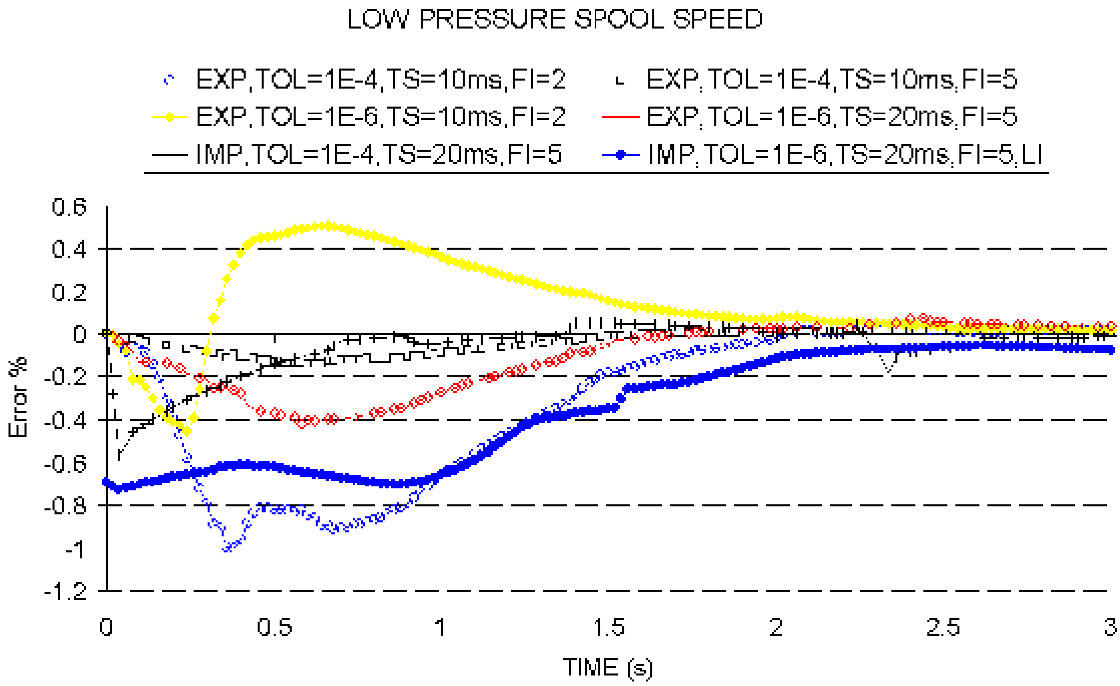
Accuracy Studies

Transient Input for accuracy testing



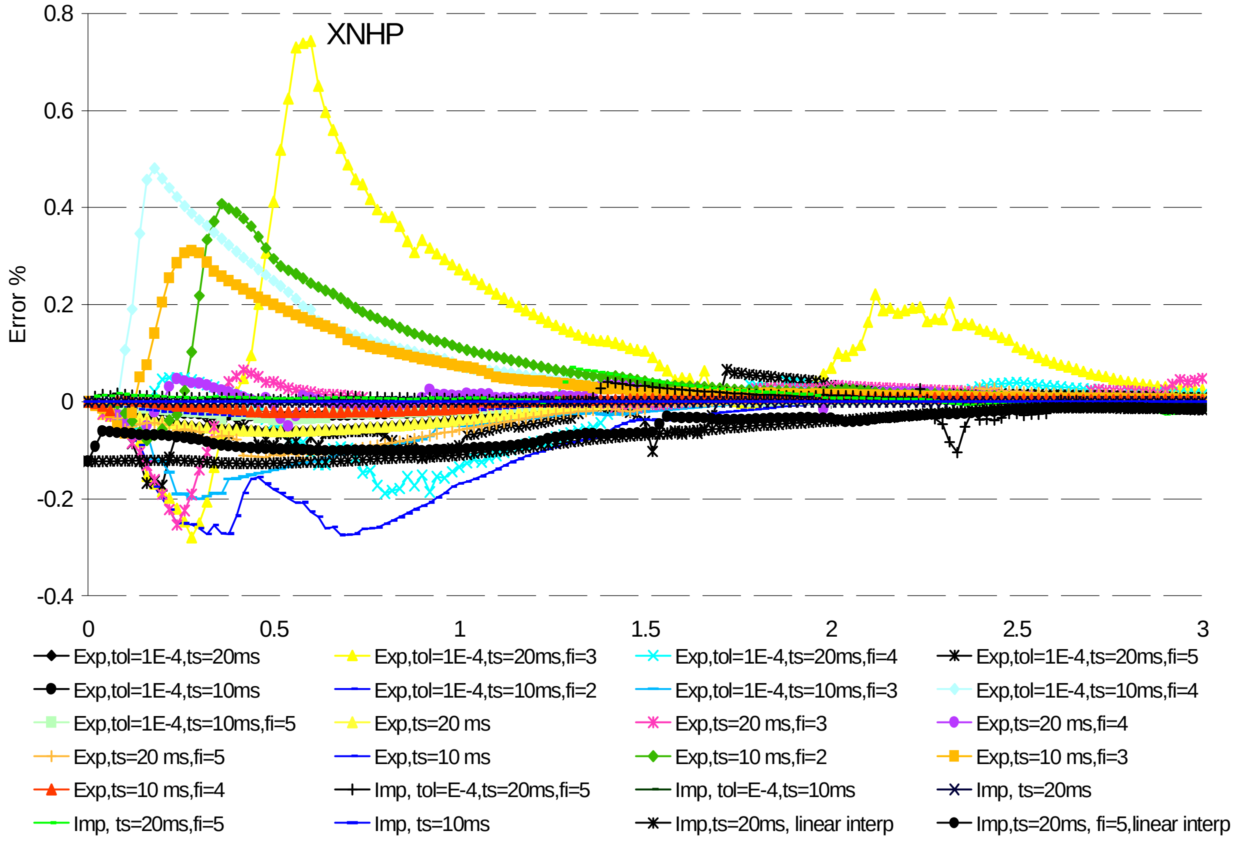
Accuracy Studies

Low pressure shaft speed prediction error



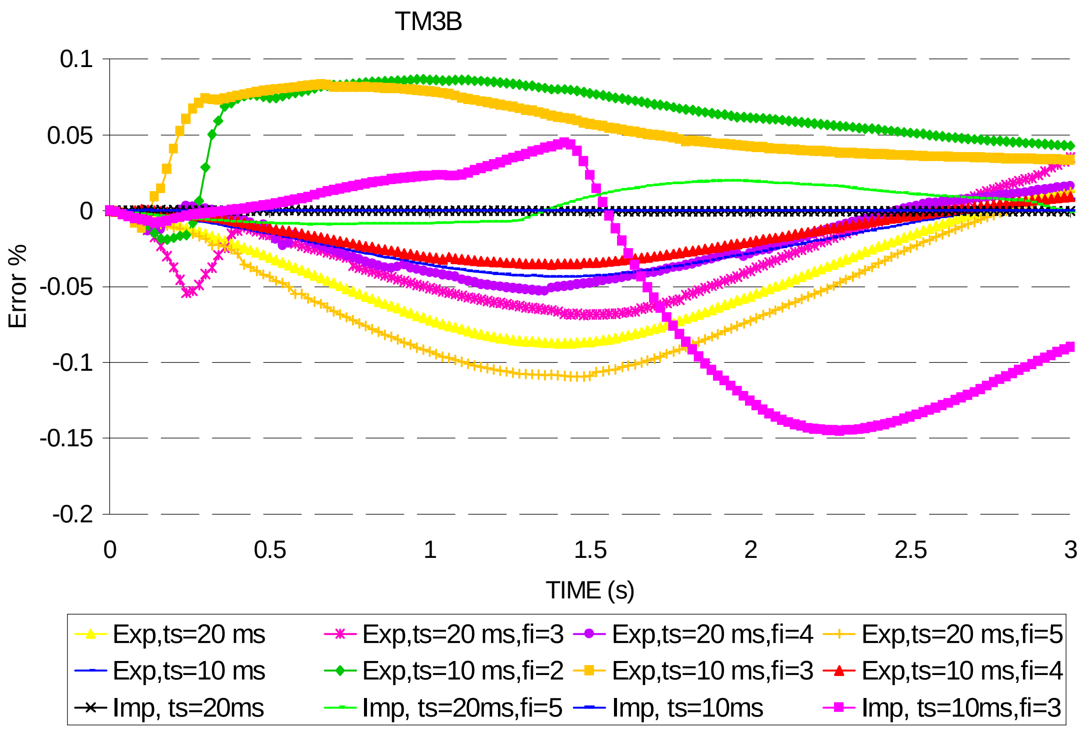
Accuracy Studies

High pressure shaft speed prediction error

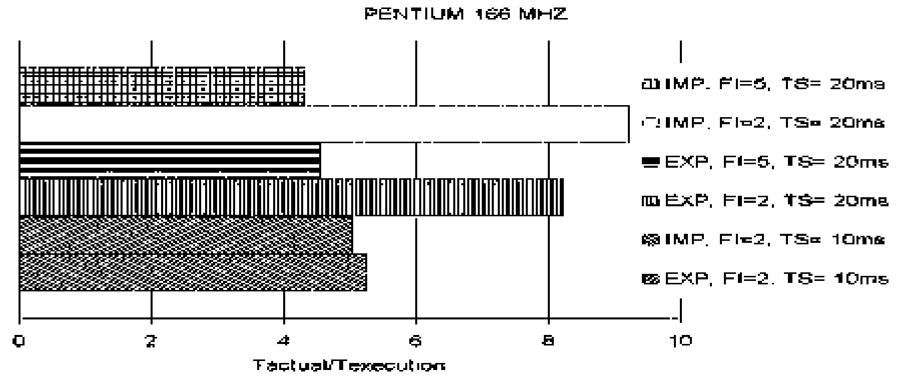


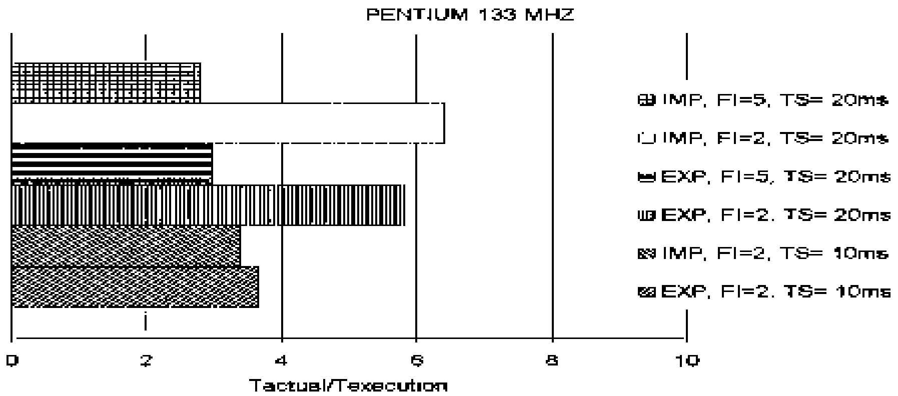
Accuracy Studies

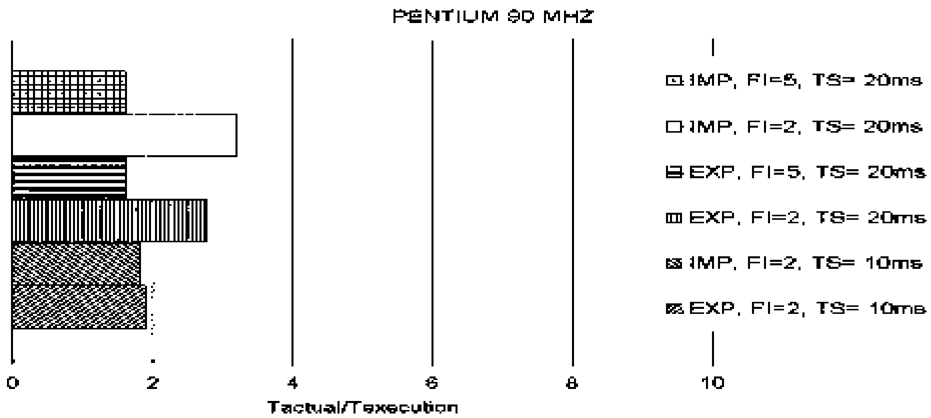
Temperature prediction error



Timing investigations using different processors







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*