Volume Dynamics Modeling of a Turbofan Engine
&
Propulsion GUI Library Development

Fundamental Aeronautics – Supersonics Project
AeroPropulsionServoElasticity Task

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Outline – Volume Dynamics Modeling

• Introduction
• Description of Turbofan Engine
• Modeling Approach
• Steady State Simulation Results
• Dynamic Simulation Results
• System Identification Method and Results
• Future Work
• Conclusions
Introduction to Previous Work

• Work in this area started to develop a generic engine model that could be easily altered to a specific design

• A turbojet was chosen to begin development of simulation capability using available data for the GE J-85 engine
Turbofan Engine Description

• The engine modeled is a paper design medium size bypass turbofan model that is currently being studied for a business class jet
  – A turbofan engine is used as the likely candidate for supersonic aircraft, extending upon previous modeling work done for a turbojet
  – This engine can be scaled up with appropriate geometry and performances for a full size commercial vehicle

• The turbofan consists of:
  – A three stage fan and two stage low-pressure turbine connected by a low pressure shaft
  – A six stage high-pressure compressor and two stage high-pressure turbine connected by a high pressure shaft
  – A combustor in the core and terminates with a mixer/cold afterburner and exit nozzle
Turbofan Engine Schematic
Simulation Approach

• A nonlinear 1D lumped volume approach is used whereby each component is represented as a single volume using characteristic performance maps and conservation equations
  – The approach is used to meet expected performance challenges of future vehicles instead of a model based on just rotor dynamics
• The MATLAB/SIMULINK environment is chosen as the model platform for suitability of controls development and ease of model integration with NASA Langley vehicle simulation
• A built in explicit Runge-Kutta integration method is used

\[
\frac{d}{dt} \rho_{lpc,sv} = \frac{1}{V_{lpc}} \left( \dot{W}_{lpc} - \dot{W}_{hpc} - \dot{W}_{bypass} \right) \\
\frac{d}{dt} \dot{W}_{lpc} = \frac{A_{lpc}}{l_{lpc}} \left( P_{lpc,tc} - P_{lpc,sv} \right) \left\{ 1 + \frac{\gamma_{lpc} - 1}{2} M^2 \right\} \\
\frac{d}{dt} T_{lpc,sv} = \frac{\gamma_{lpc}}{\rho_{lpc,sv} V_{lpc}} \left( T_{lpc,tc} \dot{W}_{lpc} - T_{lpc,sv} \dot{W}_{hpc} - T_{lpc,sv} \dot{W}_{bypass} \right)
\]
Fan Lumped Volume Modeling Diagram

- Corrected Values Calculation
- Pressure Ratio Map
- Performance Map
- Efficiency Map
- Momentum
- Equation of State
- Energy
- Continuity

Variables:
- $P_{tv,n-1}$
- $T_{tv,n-1}$
- $N_c$
- $N$
- $P_{tv,n}$
- $P_{tc,n}$
- $T_{tv,n}$
- $T_{tc,n}$
- $\dot{W}_n$
- $\dot{W}_{n+1}$
- $\rho_{sv,n}$

Inlet

HPC
Steady State Simulation Results (SI units)

Table 1. Steady state performance for high-pressure components

<table>
<thead>
<tr>
<th>Model</th>
<th>Corr. Speed %</th>
<th>High Pressure Compressor</th>
<th>Combustor</th>
<th>High Pressure Turbine</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$P$</td>
<td>$T$</td>
<td>$\dot{W}$</td>
</tr>
<tr>
<td>Static</td>
<td>100</td>
<td>1269021</td>
<td>999.2</td>
<td>39.4</td>
</tr>
<tr>
<td>Dynamic</td>
<td>99.9</td>
<td>1277813</td>
<td>1043</td>
<td>39.3</td>
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<tr>
<td>Error %</td>
<td>0.1</td>
<td>0.69</td>
<td>4.38</td>
<td>0.25</td>
</tr>
</tbody>
</table>

- The SIMULINK model is compared to output from the Numerical Propulsion System Simulation (NPSS)
  - At the cruise condition of Mach 2.35 and 60,000 ft
- The model shows good matching for the steady state condition
  - The largest errors appear to be in the temperature
  - The error could be from generic maps or from a non-constant bleed

Table 1. Steady state performance for low-pressure components

<table>
<thead>
<tr>
<th>Model</th>
<th>Corr. Speed %</th>
<th>Low Pressure Compressor</th>
<th>Low Pressure Turbine</th>
<th>Mixer/Afterburner</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$P$</td>
<td>$T$</td>
<td>$\dot{W}$</td>
</tr>
<tr>
<td>Static</td>
<td>100</td>
<td>194707</td>
<td>579</td>
<td>80.8</td>
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<tr>
<td>Dynamic</td>
<td>99.94</td>
<td>193630</td>
<td>581</td>
<td>80.7</td>
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<tr>
<td>Error %</td>
<td>0.06</td>
<td>0.55</td>
<td>0.35</td>
<td>0.12</td>
</tr>
</tbody>
</table>
Dynamic Simulation Results

- The response of the fan speed and thrust show similar responses to a 1% step in fuel
  - Typically for the controller the fan speed is used as a proxy for the thrust
- The 1% step disturbance inlet pressure causes an overshoot in the Fan output pressure
- The results found are notionally similar to other dynamic engine studies, previous work was compared to dynamic results
Linearizing the Models

- Once confidence is obtained in the nonlinear simulation, linear models are required to allow for control algorithm development
  - To utilize the many tools available in linear control design the nonlinear models must be linearized about an operating point, here this will be cruise

- To obtain the linear models a logarithmic sinusoidal frequency sweep disturbance is used
  - The APSE effects are expected to produce freestream disturbances as high as 50Hz, thus the sweep must be able to capture dynamics in the order of 100 Hz to ensure no relevant dynamics are left out

- An example case of an inlet pressure disturbance and fan speed response will be presented here
Fan Speed to Pressure Disturbance

- Welch’s average modified periodogram is used to obtain the power spectral density (PSD): the transfer function is then the cross PSD over the input PSD

- A check on the coherence between the signals gives an indication of the adequacy of the estimate,

\[
T_{xy}(f) = \frac{P_{xy}(f)}{P_{xx}(f)}
\]

\[
C_{xy}(f) = \frac{|P_{xy}(f)|^2}{P_{xx}(f)P_{yy}(f)}
\]
Linearization and Comparison

• Used Matlab’s System Identification Toolbox to compare various order system models by investigating the bode plot
  – A sixth order system was found to provide the best fit
• The linear model is shown to have a favorable comparison to the nonlinear model as a final check
Conclusions

• A modeling strategy for a nonlinear turbofan engine is outlined using a 1D lump volume approach
  – Each component is treated as a separate volume using performance maps and conservation equations

• Preliminary investigations of the transient simulations revealed expected trends, however more verification and validation is required

• Using the simulation, a linearization method was also established to support later controls development
  – An example linear model is compared to the nonlinear response

• The work presented provides a reasonable approach to the propulsion-modeling element for the APSE task
Future Work

• The transient response of the turbofan engine needs to be more rigorously verified by comparison with other dynamic models and test data

• Finish obtaining all of the linear models to allow for the appropriate control algorithm development
  – Implement algorithms in the nonlinear model

• Integrate the turbofan engine model with the nonlinear inlet model and develop more comprehensive controls
  – The overall propulsion model can then be integrated with the vehicle model to create the APSE model

• Improve fidelity of the engine model to investigate surge and rotating stall
Outline – Propulsion GUI Library

- Introduction
- Modeling Goals
- Inlet Modeling
- Engine Modeling
- Modular Component Diagram
- Summary and Future Work
Introduction

• Simulations for a Turbofan and Turbojet engine model have been developed to meet expected engine design configurations for a supersonic commercial transport.

• Currently developing a single dynamic engine design platform in the MATLAB SIMULINK environment that is highly modular.
  – Work was conducted with the support of a summer intern.

• This will allow for:
  – Easier version control of the model
  – Streamlined ability to test multiple engine designs with a single tool.
Modeling Goals

• Inlet Model
  – Created linear models from LAPIN a heritage Fortran simulation
  – Objective is to create nonlinear model in the SIMULINK Environment to allow for consistent platform

• Engine Modeling
  – The first objective was to determine how to expand upon the model without dramatically increasing the run time of the simulation
    • Determined that the easiest approach to the problem would be to create switches to enable and disable subsystem blocks within the SIMULINK environment
  – The second objective was to ensure proper interconnections and flexibility to model not only the current models of the J-85 “like” engine and business class supersonic turbofan engine, but other engine designs as well
Supersonic Inlets

- Overall purpose of the inlet is to supply the engine with the required mass flow at the highest pressure and least distortion.
- Typically at or above Mach 2, a mixed compression inlet design is utilized.
- The inlet metric that is of paramount concern for safe flight operation is the inlet unstart probability.
- Bypass doors adjust downstream pressure to control shock position.
Inlet Modeling

- Large Perturbation Inlet (LAPIN) flow code in FORTRAN is used in this study
  - Nonlinear quasi1D code capable of modeling unstart and most control surfaces
  - Modeled as 134 separate volumes

- Continuity:
  \[ \frac{\partial (\rho A)}{\partial t} + \frac{\partial (\rho u A)}{\partial x} = M_s \]

- Momentum:
  \[ \frac{\partial (\rho u A)}{\partial t} + \frac{\partial [A(p + \rho u^2)]}{\partial x} = p \frac{\partial A}{\partial x} + F_s \]

- Energy:
  \[ \frac{\partial (\rho (e + \frac{u^2}{2}) A)}{\partial t} + \frac{\partial [A u (\rho (e + \frac{u^2}{2}) + p)]}{\partial x} = -p \frac{\partial A}{\partial t} + Q_s \]

Ultimately setup as a system of non-dimensional equations solved simultaneously.
SIMULINK Inlet Model

- Using the lumped volume approach similar to the Engine Models
- A Simulink library of the relevant volume dynamics is used to model each independent volume
- This allows for easy modifications while in the development phase
Turbojet to Turbofan

- Addition of Fan
- Addition of Low Pressure Turbine
- Low Pressure Rotor Dynamics
  - Connecting Fan and Low Pressure Turbine
- Allow for hot or cold Afterburner
- Account for Bypass Flow in Nozzle
- Account for Bypass Flow in Thrust Equation
Generic Simulation

LPC

LPT

Nozzle

Switching

High Pressure Components

Low Pressure Spool
Modular Modeling Approach

Volume Dynamics

Performance Characteristic Maps

High Pressure Compressor Subsystem
Summary and Future Work

- Demonstrated that an engine model with the flexibility to switch between a turbojet and turbofan model can be obtained with little cost in added run time

- Ensure adequate flexibility for other engine designs

- Develop a GUI for easier execution and modification

- Test modular approach by incorporating a stage-by-stage design subsystem

- Integrate propulsion model with airframe structural model