Performance analysis of J85 turbojet engine matching thrust with reduced inlet pressure to the compressor

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Performance Analysis of J85 Turbojet Engine Matching Thrust with Reduced Inlet Pressure to the Compressor

by

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Submitted to the Graduate Faculty as partial fulfillment of the requirements for the Master of Science Degree in Mechanical Engineering

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An Abstract of

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Jet engines are required to operate at a higher rpm for the same thrust values in cases such as aircraft landing and military loitering. High rpm reflects higher efficiency with increased pressure ratio. This work is focused on performance analysis of a J85 turbojet engine with an inlet flow control mechanism to increase rpm for same thrust values. Developed a real-time turbojet engine integrating aerothermodynamics of engine components, principles of jet propulsion and inter component volume dynamics represented in 1-D non-linear unsteady equations. Software programs SmoothC and SmoothT were used to derive the data from characteristic rig test performance maps for the compressor and turbine respectively. Simulink, a commercially available model-based graphical block diagramming tool from MathWorks has been used for dynamic modeling of the engine. Dynamic Look-up tables in Simulink were used to interpolate the real-time performance of the engine from rig-test data. Simulink model for the J85 turbojet engine was verified for performance accuracy with available test data of the engine.

A flow control mechanism that produces a pressure drop across inlet is assumed and
the analysis is carried with reduced compressor inlet pressure for matching thrust. Compressor inlet pressure is reduced to a percentage of atmospheric pressure and to produce the desired thrust with reduced inlet pressure, the engine operates at a higher shaft rpm. With increase in shaft rpm, pressure and temperature ratio values across the compressor-turbine assembly increases. Performance parameters of the engine are analyzed with the increase in compressor pressure ratio and shaft rpm.

Specific fuel consumption, specific thrust, component pressure ratios, thermal and propulsive efficiencies are the performance parameters of the engine that are analyzed on the model with reduced inlet pressure for the real-time test cases of desired thrust range. Limitations of the analysis are discussed along with possible industrial applications of this flow control mechanism.
To my parents, siblings and friends, who have been supporting and encouraging me throughout my years of education.
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<td>$A_{nz}$</td>
<td>Effective cross-sectional area of the nozzle (m$^2$)</td>
</tr>
<tr>
<td>$a$</td>
<td>Speed of sound (m/s)</td>
</tr>
<tr>
<td>$alt$</td>
<td>Altitude of engine operation (m)</td>
</tr>
<tr>
<td>Bld</td>
<td>Compressor bleed flow rate (kg/s)</td>
</tr>
<tr>
<td>$C_v$</td>
<td>Nozzle velocity coefficient</td>
</tr>
<tr>
<td>$c_v$</td>
<td>Specific constant at constant volume (J/(kg − k))</td>
</tr>
<tr>
<td>$c_{vp}$</td>
<td>Specific constant at constant volume at the combustor interpolated temperature (J/(kg − k))</td>
</tr>
<tr>
<td>$c_p$</td>
<td>Specific constant at constant pressure (J/(kg − k))</td>
</tr>
<tr>
<td>$c_{po}$</td>
<td>Specific constant at constant pressure at the combustor interpolated temperature (J/(kg − k))</td>
</tr>
<tr>
<td>FN</td>
<td>Net thrust produced (N)</td>
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<tr>
<td>$f_1$</td>
<td>Function for the corrected mass flow rate of the compressor</td>
</tr>
<tr>
<td>$f_2$</td>
<td>Function for the isentropic efficiency of the compressor</td>
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<tr>
<td>$f_3$</td>
<td>Function for the corrected mass flow rate of the turbine</td>
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<tr>
<td>$f_4$</td>
<td>Function for the isentropic expansion efficiency of the turbine</td>
</tr>
<tr>
<td>HVF</td>
<td>Lower heating value of fuel = 43120 (KJ/kg)</td>
</tr>
<tr>
<td>h</td>
<td>Total enthalpy</td>
</tr>
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IN  Polar moment of inertia of shaft \((N \cdot m \cdot s^2)\)

M  Mach number

\(\dot{m}_f\)  Mass flow rate of the fuel \((kg/s)\)

\(\dot{m}_b\)  Mass flow rate in the combustor \((kg/s)\)

\(\dot{m}_{3'}\)  Mass flow rate at the entrance of the compressor plenum \((kg/s)\)

\(\dot{m}_{3\text{ corr}}\)  Corrected mass flow rate in the compressor

\(\dot{m}_3\)  Mass flow rate at the exit of the compressor plenum \((kg/s)\)

\(\dot{m}_4\)  Mass flow rate in the combustor \((kg/s)\)

\(\dot{m}_{5'}\)  Mass flow rate at the entrance of the turbine plenum \((kg/s)\)

\(\dot{m}_{5\text{ corr}}\)  Corrected mass flow rate in the turbine

\(\dot{m}_5\)  Mass flow rate at the exit of the turbine plenum \((kg/s)\)

N  Shaft speed (RPM)

N_{corr \text{ comp}}  Corrected speed for the compressor

N_{corr \text{ turb}}  Corrected speed for the turbine

N_{des}  Shaft speed at design point

P_{amb}  Ambient static pressure \((N/m^2)\)

P_b  Nozzle back pressure \((N/m^2)\)

P_{cr}  Critical pressure ratio for the nozzle

P_{ref}  Reference pressure at sea level = 101324 \((N/m^2)\)

P_{Wc}  Compressor power (KW)

P_{Wt}  Turbine power (KW)

P_0  Ambient total pressure \((N/m^2)\)
\( P_2 \) Total pressure at compressor inlet \((N/m^2)\)

\( P_3 \) Total pressure at compressor exit \((N/m^2)\)

\( P_4 \) Total pressure at combustor exit \((N/m^2)\)

\( P_5 \) Total pressure at turbine exit \((N/m^2)\)

\( P_7 \) Total pressure at nozzle exit \((N/m^2)\)

\( R \) Universal gas constant = 287 \((N·m/kg·K)\)

\( R_b \) Pressure drop constant in the combustor \((N·s^2/kg^2·m^2)\)

\( T_{amb} \) Ambient static temperature (K)

\( T_b \) Interpolated temperature in the combustor (K)

\( T_{ref} \) Reference temperature at sea level = 288.15 (K)

\( T_0 \) Ambient total temperature (K)

\( T_2 \) Total temperature at compressor inlet (K)

\( T_{2des} \) Total temperature at compressor inlet at design point (K)

\( T_3' \) Total temperature at compressor inlet plenum (K)

\( T_3 \) Total temperature at compressor plenum exit (K)

\( T_4 \) Total temperature at combustor exit (K)

\( T_{4des} \) Total temperature at combustor exit at design point (K)

\( T_5' \) Total temperature at turbine plenum inlet (K)

\( T_5 \) Total temperature at turbine plenum exit (K)

\( u \) Total internal energy

\( v_e \) Exit velocity of jet from nozzle (m/s)
\( v_o \) \quad \text{Inlet velocity of the air into the engine (m/s)}

\( V_3 \) \quad \text{Compressor volume (m}^3\text{)}

\( V_4 \) \quad \text{Combustor volume (m}^3\text{)}

\( V_5 \) \quad \text{Turbine volume (m}^3\text{)}

\( W_3 \) \quad \text{Mass of the air in the compressor (kg)}

\( W_4 \) \quad \text{Mass of the air in the combustor (kg)}

\( W_5 \) \quad \text{Mass of the air in the turbine (kg)}

\( \gamma \) \quad \text{Ratio of specific heats}

\( \gamma_b \) \quad \text{Ratio of specific heats at the combustor interpolated temperature}

\( \beta_b \) \quad \text{Temperature interpolation constant in combustor}

\( \beta_c \) \quad \text{Temperature interpolation constant in compressor}

\( \eta_l \) \quad \text{Inlet efficiency}

\( \eta_{\text{Is Comp}} \) \quad \text{Isentropic compression efficiency in the compressor}

\( \eta_{\text{Is turb}} \) \quad \text{Isentropic expansion efficiency in the turbine}

\( \eta_b \) \quad \text{Combustor efficiency}

\( \eta_{ov} \) \quad \text{Overall efficiency of the engine}

\( \eta_p \) \quad \text{Propulsive efficiency of the engine}

\( \eta_{th} \) \quad \text{Thermal efficiency of the engine}

\( \rho \) \quad \text{Density (kg/m}^3\text{)}
Chapter 1

Introduction

Jet engines are highly non-linear plants with a complex range of operation described by a flight envelope. Altitude and Mach number defines the operational set points for the engine. The main task for these systems is the production of adequate thrust while maintaining safe and stable operation. Performance requirements for the engines vary according to mission characteristics. Civil aircraft operation requires minimum running and maintenance costs. Military aircraft require maximum available thrust in a minimum response time. (Valceres V.R. Silva, Wael Khatib, Peter J. Fleming, 2005)

However, increasing the efficiency and minimizing running cost by reducing fuel consumption is an important criterion for any jet engine. Even a small percent decrease in fuel consumption translates to a significant saving of running costs over the life of a typical jet engine. Similarly, with the slight increase in the efficiency could increase the operational life of the engine. This work is an approach to analyze the performance of jet engine with an alternative flow control mechanism.

1.1 Objective

This work analyzes the feasibility of a thrust control mechanism by regulating the flow at the engine inlet to increase the engine rpm for the same value. This approach adds
value to the design process with the aim of increasing performance levels in the engine operation. A flow control mechanism in the inlet produces a pressure drop across the inlet section and compressor inlet pressure is reduced. Performance characteristics for a J85 turbojet engine is analyzed with reduced inlet pressure to the compressor and matching thrust. Pressure drop across the inlet is defined theoretically assuming the real-time possibility with a flap-actuator mechanism inside the inlet section. Engine must run at a higher rpm to produce the same thrust with reduced inlet pressure leading to higher pressure and temperature ranges across the compressor-turbine assembly. Thermal efficiency of the engine is function of pressure ratio across the compressor and also isentropic efficiency is integrated to the component pressure ratio with shaft rpm values. This work describes the variation in the performance characteristics of the engine with reduced compressor inlet pressure compared to that of the normal operation. Limitations to stability of the engine regarding to compressor surge condition, shaft rpm and turbine inlet temperatures with pressure reduction are considered a limiting factor to these parameters are set.

1.2 Engine Design Point and Off Design Performance Calculations

The operating condition where an engine will spend most time has been traditionally chosen as the engine design point. Design point performance must be defined before analysis of any other operating conditions is possible. With the engine geometry fixed by the design point calculation, the performance at other key operating conditions can be evaluated. In this instance, the calculation procedure is the off design performance calculation. Here geometry is fixed and operating conditions are changing. The off-design performance calculations are used in this analysis. A real-time
computational model for a J85 turbojet engine is built with the actual design data and the overall component performance maps from rig tests.

1.3 Computational Modeling

Designing and developing new aircraft engine is time-consuming and expensive. There is increasing pressure to reduce the time, cost and risk of aircraft engine development and maintenance. To compete effectively in global marketplace, innovative approaches to reducing aircraft engine design-circle span, manufacture and maintenance cost are needed. (Yuan Caoa, Xianlong Jina, Guang Menga, Jay Fletcher, 2004). An opportunity emerged to realize this point with computational simulation and Virtual Prototyping. As modeling techniques have improved, and computers have progressed, simulation has assumed an essential role in planning, executing, and evaluating operations. So too, in the design, manufacturing, and operating of aircraft turbine engines, accurate performance simulations have become essential. Therefore, throughout the years, many computer-based models for the simulation of the operational characteristics of the aircraft gas turbine engine have been structured and evolved into a very wide range of applications.

Computational simulation is a promising means for alleviating this cost, but it requires a flexible software simulation system capable of integrating advanced multidisciplinary and multi-fidelity analysis methods, dynamically constructing arbitrary simulation models, and distributing computationally complex tasks. (John A. Reed and Abdollah A Afjeh, 1999). Also constructing and evaluation of integrated aircraft engine system architectures is a tough task. Many block-oriented programming tools like Matlab/Simulink, Dymola and Modelica along with the procedural programming like
FORTRAN and C were available for the real-time modeling and the simulation of
dynamic systems. The present work employs Matlab/Simulink for the modeling of the
dynamic turbojet engine to the steady-state and transient simulation.

Simulink is an object-oriented modeling language and provides a graphical user
interface for building math models as block diagrams. It is designed to allow convenient,
component-oriented modeling of complex physical systems including mechanical,
electrical, electronic, hydraulic, thermal, control, electric power or process-oriented
subcomponents. Object orientation is viewed as a structuring concept that is used to
handle the complexity of large system description. Simulink model developed has
followed the top–down structured design approach, in which the whole system can be
divided into several sub-systems; each sub-system consists of various components. Each
component uses the defined dynamic mathematical equations of the system for the
dynamic behavior of the components for the modeling. All the components are integrated
together by connecting the variables for each component according to the dynamic flow
directions.

Simulink model developed in the thesis is an extensible generic model for the
turbojet engine that may be used to evaluate the dynamic performance of integrated
power system architectures during conceptual and preliminary design. The model can be
employed to any turbojet engine with integration of the design data, component
performance maps of the respective engine to the model. This model can be used in
steady-state and transient analysis of the aero-engine.
Chapter 2

Jet Engine

2.1 Introduction

Jet Engine is the gas turbine application for aircraft propulsion. Basic principle in a jet engine is to accelerate a mass of fluid in the direction opposite to motion and thereby propelling the aircraft forward by the thrust generated. Schematic differences between the Turbojets, Turbofans and Turboprop/Turbo shaft Engines are explained here.

Turbojet is the earliest and simplest form of jet engines and produce thrust by greatly accelerating a small mass of fluid. Figure 1 shows a conventional single spool turbojet above the centre line, and one with the addition of an afterburner, convergent–divergent (con-di) intake, and con-di nozzle below the centre line.

Figure 2.1 Turbojet engine configurations [Source: Gas Turbine Performance]
Ambient air passes from free stream to the flight intake leading edge and the air accelerates from free stream if the engine is static, whereas at high flight Mach number it diffuses from the free stream, ram conditions. Usually, it then diffuses in the flight intake before passing through the engine intake to the compressor face with a small loss in total pressure. The compressor then increases both the pressure and temperature of the gas. Work input is required to achieve the pressure ratio; the associated temperature rise depends on the efficiency of the compressor. The compressor exit diffuser passes the air to the combustor. Here, fuel is injected and burnt to raise exit gas temperature. The diffuser and combustor both impose a small total pressure loss. The hot, high pressure gas is then expanded through the turbine where work is extracted to produce shaft power; both temperature and pressure are reduced. The shaft power is that required to drive the compressor and any engine auxiliaries. On leaving the turbine, the gas is still at a pressure typically at least twice that of ambient. This results from the higher inlet temperature to the turbine. Downstream of the turbine the gas diffuses in the jet pipe. This is a short duct that transforms the flow path from annular to a full circle at entry to the propelling nozzle. The jet pipe imposes a small total pressure loss. The propelling nozzle is a convergent duct that accelerates the flow to provide the high velocity jet to create the thrust. Engine cooling system uses the relatively cool air from the compression system that bypasses the combustor via air system flow paths to cool the turbine nozzle guide vanes and blades to ensure acceptable metal temperatures at elevated gas temperatures.

For high flight Mach number applications an afterburner is often employed, which offers produces higher thrust from the same configuration. This is also called reheat, and
involves burning fuel in an additional combustor downstream of the jet pipe. Turbojets are quite inefficient compared to other engine types at lower Mach numbers but has dominant role for the supersonic flight modes and military applications.

Turbofans are widely used engines for the modern civil-aircraft propulsion. A turbofan engine is based on the principle that for the same power, a large volume of slower-moving air will produce more thrust than a small volume of fast-moving air. Turbofan engines are of the types separate jets turbofan and mixed turbofan with afterburner. Figure 2 shows the configuration of the separate jets turbofan above the centre line and mixed turbofan with afterburner below the centre line.

![Turbofan engine configurations](Source: Gas Turbine Performance).

In the turbofan engine, the first compressor is termed a fan and supplies flow to a bypass as well as a core stream. The core stream is the same as that of a turbojet and provides the hot thrust; however, the core turbines also provide power to compress the fan bypass stream. The bypass stream passes through the bypass duct, incurring a small
total pressure loss. It then enters the cold nozzle in the case of separate jets. The total thrust is the sum of those from both the hot and cold nozzles. The purpose of the bypass stream of air is to generate additional thrust with a high mass flow rate than to the low jet velocity, which improves specific fuel consumption (SFC) relative to a pure turbojet. However, this results in lower ratios of engine thrust to frontal area and weight. In the case of the mixed turbofan engine, the core gas and the by-pass air streams are combined in a mixer upstream of a common jet pipe with an afterburner and convergent–divergent nozzle to provide high jet velocities for supersonic flight. It is often also beneficial to mix the two streams for turbofans without afterburners.

Turbo shaft and Turboprop engines have the core turbojet components, power turbine of the turbofan engine without the fan. The main difference is that all the available pressure at entry to the turbine is expanded to ambient to produce shaft power. After diffusion in the exhaust duct, the gas exit velocity is negligible. This results in turbine power substantially greater than that required to drive the compressor, hence excess power drives the load, such as a propeller for a turboprop engine or an electrical generator for a turbo shaft.

![Figure 2.3 Turbo shaft engine configurations](Source: Gas Turbine Performance)
2.2 Thermodynamic Cycle

Thermodynamic working cycle for the jet engine is based on Brayton cycle. It is an open cycle (but usually represented as closed for thermodynamic analysis) designed for a piston engine and it is basis for the gas turbine engine cycle. T-s diagram of ideal Brayton cycle is shown here in Figure 4 with processes associated.

![T-s Diagram for the ideal closed Brayton cycle](Source: Cengel (2002)).

2.3 Ideal Turbojet Cycle

Temperature-entropy (T-s) diagram of the ideal jet engine cycle is shown in Figure 5. The pressure of the air rises slightly as it is decelerated in the diffuser. Then, air is compressed by the compressor. It is mixed with fuel in the combustion chamber, where the mixture is burned at constant pressure. The high-pressure and high-temperature combustion gases partially expand in the turbine, producing enough power to drive the compressor and other auxiliary equipment. Finally, the gases expand in a nozzle to the ambient pressure and leave the aircraft at a high velocity [Source: Cengel (2002)].
2.4 Work Done

For the ideal jet engine, work done on the turbine is assumed to be equal to the compressor work and the processes in the diffuser, the compressor, the turbine and the nozzle are assumed to be isentropic. So the net work done in a turbojet engine is zero. However, for the actual cycle analysis, the irreversibility associated with in the compressor, turbine, nozzle and diffuser should be considered. Therefore, in a steady state operation of the jet engine, the turbine and the compressor work should be equal. Any difference in these parameters runs engine into the transient mode of operation.

2.5 Performance Parameters

The performance parameters for an aero-engine are defined in this section. Each parameter has its formula.

2.5.1 Specific thrust

This is the amount of output thrust per unit of mass flow entering the engine. It is particularly important to maximize specific thrust in applications where engine weight or...
volume is crucial for aircraft that fly at high Mach numbers where the drag per unit frontal area is high.

### 2.5.2 Specific Fuel Consumption

This is the mass of fuel burnt per unit time per unit of output power or thrust. It is important to minimize SFC for applications where the weight and/or cost of the fuel are significant. When specifying the SFC values, it is important to state whether the lower or higher calorific value of the fuel is used.

### 2.5.3 Thermal Efficiency

Thermal efficiency for jet engines is defined as the rate of addition of kinetic energy to the air divided by the rate of fuel energy supplied, usually expressed as a percentage. The energy in the jet is proportional to the difference in the squares of jet and flight velocities. Generally thermal efficiency increases as pressure ratio and SOT increase together, as these results in a higher jet velocity for a given energy input.

\[
\eta_{th} = \frac{\text{increase in kinetic energy}}{\text{heat energy added}}
\]

### 2.5.4 Propulsive Efficiency

Propulsive efficiency for jet engines is defined as the useful propulsive power produced by the engine divided by the rate of kinetic energy addition to the air, again usually expressed as a percentage. The net thrust is proportional to the difference in the jet and flight velocities. Since power is force times velocity, propulsive power is proportional to the flight speed times the difference in the jet and flight velocities. From the formula, propulsive efficiency is improved by low jet velocities, due to lower energy wastage as jet kinetic energy. This requires high pressure ratio and low SOT. However,
low jet velocities produce lower thrust output, hence to achieve high propulsive efficiency, as well as a required thrust, high engine mass flow must be coupled with low jet velocities. This leads to engines of low specific thrust, which are large and heavy. Turbofan engines are based upon this principal.

\[ \eta_p = \frac{FN \cdot v_0}{\text{increase in kinetic energy}} \]

**2.5.5 Overall Efficiency**

Overall efficiency of a jet engine is the product of the thermal and the propulsive efficiencies of the engine.

\[ \eta_{ov} = \eta_{th} \cdot \eta_p \]
Chapter 3

Simulink

3.1 Simulink Introduction

Simulink is a software package for modeling, simulating, and analyzing dynamical systems. It supports linear and nonlinear systems, modeled in continuous time, sampled time, or a hybrid of the two. Systems can also be multi-rate, i.e., have different parts that are sampled or updated at different rates. MATLAB and Simulink are integrated; you can simulate, analyze, and revise your models in either environment at any point.

For modeling, Simulink provides a graphical user interface (GUI) for building models as block diagrams, using click-and-drag mouse operations. With this interface, you can draw the models just as you would with pencil and paper (or as most textbooks depict them). This is a far cry from previous simulation packages that require you to formulate differential equations and difference equations in a language or program. Simulink includes a comprehensive block library of sinks, sources, linear and nonlinear components, and connectors. We can also customize and create your own blocks by writing our own S-Functions.

Models are hierarchical, so we can build models using both top-down and bottom-
up approaches. We can view the system at a high level and then double-click on blocks to go down through the levels to see increasing levels of model detail. This approach provides insight into how a model is organized and how its parts interact.

After defining a model, it can be simulated using a choice of integration methods, either from the Simulink menus or by entering commands in MATLAB’s command window. The menus are particularly convenient for interactive work, while the command-line approach is very useful for running a batch of simulations. Using scopes and other display blocks, we can see the simulation results while the simulation is running. In addition, we can change parameters and immediately see what happens, for “what if” exploration. The simulation results can be put in the MATLAB workspace for post processing and visualization. Model analysis tools include linearization and trimming tools, which can be accessed from the MATLAB command line, plus the many tools in MATLAB and its application toolboxes.

3.2 Simulink Real-Time Workshop

The Simulink Real-Time Workshop automatically generates C code directly from Simulink block diagrams. This allows the execution of continuous, discrete-time, and hybrid system models on a wide range of computer platforms, including real-time hardware. The Real-Time Workshop can be used for:

**Rapid Prototyping:** As a rapid prototyping tool, the Real-Time Workshop enables you to implement your designs quickly without lengthy hand coding and debugging. Control, signal processing, and dynamic system algorithms can be implemented by developing graphical Simulink block diagrams and automatically generating C code.

**Real-Time Simulation:** You can create and execute code for an entire system or
specified subsystems for hardware-in-the-loop simulations. Typical applications include training simulators (pilot-in-the-loop), real-time model validation, and testing.

**Stand-Alone Simulation:** Stand-alone simulations can be run directly on your host machine or transferred to other systems for remote execution. Because time histories are saved in MATLAB as binary or ASCII files, they can be easily loaded into MATLAB for additional analysis or graphic display.

### 3.3 How Simulink Works

Each block within a Simulink model has these general characteristics: a vector of inputs, \( u \), a vector of outputs, \( y \), and a vector of states, \( x \):

![Block Diagram](image)

The state vector may consist of continuous states, discrete states, or a combination of both. The mathematical relationships between these quantities are expressed by these equations.

\[
\begin{align*}
  y &= f_0(t, x, u) \quad \text{Output} \\
  x_{d_{k+1}} &= f_u(t, x, u) \quad \text{Update} \\
  x' &= f_d(t, x, u) \quad \text{Derivative}
\end{align*}
\]

where \( x = \begin{pmatrix} x_c \\ x_{d_k} \end{pmatrix} \)

Simulation in Simulink consists of two phases: Initialization and Simulation.

**Initialization phase:**

1. The block parameters are passed to MATLAB for evaluation. The resulting numerical values are used as the actual block parameters.

2. The model hierarchy is flattened. Each subsystem that is not a conditionally executed
subsystem is replaced by the blocks it contains.

3 Blocks are sorted into the order in which they need to be updated. The sorting algorithm constructs a list such that any block with direct feed through is not updated until the blocks driving its inputs are updated. It is during this step that algebraic loops are detected.

4 The connections between blocks are checked to ensure that the vector length of the output of each block is the same as the input expected by the blocks it drives.

**Simulation phase:**

A model is simulated using numerical integration. Each of the supplied ODE solvers (simulation methods) depends on the ability of the model to provide the derivatives of its continuous states. Calculating these derivatives is a two-step process. First, each block’s output is calculated in the order determined during the sorting. Then, in a second pass, each block calculates its derivatives based on the current time, its inputs, and its states. The resulting derivative vector is returned to the solver, which uses it to compute a new state vector at the next time point. Once a new state vector is calculated, the sampled data blocks and Scope blocks are updated.

3.4 **Simulink User Interface and Modeling Systems**

Simulink opens from the Matlab interface by either

- clicking the icon on the Matlab toolbar
- typing Simulink command on the Matlab prompt

**Simulink Library Browser**

Simulink Library Browser pops up as soon as Simulink starts and has all the defined libraries with the list of blocks in each library. Each block has a special purpose
and is the bricks in building the model in Simulink. There are separate block sets and toolboxes define in Simulink for definite applications like aerospace toolbox, communications block set etc.

Figure 3.1 Simulink library browser

**Simulink Window**

Simulink window is the workspace for Simulink and opens from the library browser.

Figure 3.2 Simulink window
Creating New System:

We can start building a new model in Simulink by adding the blocks required into the Simulink workspace and connecting the input and the output vectors for each block as the modeling equations demand. Each block has its parameters and cam defined by clicking on it.

Simulation

After completion of the model, the required solver, time step parameter and other simulation parameters can be defined in the configuration parameters icon from the simulation in the Simulink window toolbar. The results can be viewed in the scope block in the graphs or else in the Matlab workspace by To Workspace block.

3.5 Simulink in this Thesis

Turbojet engine model using the non-linear component dynamics in a continuous time sample is developed in Simulink workspace. Component dynamics and the non-linear equations are explained in the later chapters. Some of the Simulink concepts used for building the model other than the basic modeling are explained below.

Subsystems:

As the model increases in size and complexity, we can simplify it by grouping blocks into subsystems. Using subsystems has these advantages:

- It helps reduce the number of blocks displayed in your model window.
- It allows you to keep functionally related blocks together.
- It enables you to establish a hierarchical block diagram, where a Subsystem block is on one layer and the blocks that make up the subsystem are on another.
Example for the subsystem application:

After creating a subsystem, the model shrinks to

**Masked Subsystems:**

Masking is a powerful Simulink feature that enables you to customize the dialog box and icon for a subsystem. With masking, you can:

- Simplify the use of your model by replacing many dialog boxes in a subsystem with a single one. Instead of requiring the user of the model to open each block and enter parameter values, those parameter values can be entered on the mask dialog box and passed to the blocks in the masked subsystem.
- Provide a more descriptive and helpful user interface by defining a dialog box with your own block description, parameter field labels, and help text.
- Define commands that compute variables whose values depend on block parameters.
- Create a block icon that depicts the subsystem’s purpose.
- Prevent unintended modification of subsystems by hiding their contents behind a customized interface.
- Create dynamic dialogues.
Look-Up Table (2-D):

The Look-Up Table (2-D) block maps the block inputs to an output using linear interpolation of a table of values defined by the block’s parameters. We define the possible output values as the Table parameter. We define the values that correspond to its rows and columns with the Row and Column parameters. The block generates an output value by comparing the block inputs with the Row and the Column parameters.

Algebraic Loops

Some Simulink blocks have input ports with direct feed through. This means that the output of these blocks cannot be computed without knowing the values of the signals entering the blocks at these input ports. An algebraic loop generally occurs when an input port with direct feed through is driven by the output of the same block, either directly, or by a feedback path through other blocks with direct feed through. When a model contains an algebraic loop, Simulink calls a loop solving routine at each time step. The loop solver performs iterations to determine the solution to the problem (if it can). As a result, models with algebraic loops run slower than models without them.
Chapter 4

Mathematical and Simulink Modeling of Engine

4.1 Introduction

A basic turbojet engine with an inlet, axial compressor, combustor, axial turbine and a converging nozzle is built in Simulink. Complete description of these components and their dynamics is explained in this chapter.

The engine model is based on component volume dynamics. Isentropic processes are assumed for the diffuser and the converging nozzle. Actual performance of the components in the form of performance maps for the compressor and turbine are used. Every component is described by the steady state characteristics, followed by a fictitious volume where mass and energy storage takes place. Figure 4.1 shows the station numbering of the mathematical model for the engine.

![Figure 4.1 Station numbering for the engine modeling](image)
A mathematical model, based on the lumped parameter approach is used from the unsteady one dimensional conservation laws described by a set of first-order differential and algebraic equations. Programs SmoothC and SmoothT were used for representing the component performance characteristics from the performance maps and this data is used for the interpolation of the real-time performance in Simulink model. Simulink representation for each component is explained along with their dynamics.

4.2 Surrounding Atmosphere model

The air flowing into the engine diffuser is taken from the outside surroundings. Ambient air temperature and pressure are determined by the altitude as described by the International Standard Atmosphere ISA.

4.2.1 Standard Atmospheric Parameter Calculation

Given the flight altitude, static temperature and static pressure values of the surrounding air (assumed to be perfect gas) can be calculated using ISA model.

ISA, Mean Sea Level Conditions:

\[ T_{amb} = 288.15 \]
\[ P_{amb} = 101325 \]
\[ a = 340.294 \]
\[ \rho = 1.225 \]

ISA, Sea level to 11000m Altitude:

\[ T_{amb} = 288.15 - (0.0065 \times \text{alt}) \]
\[ P_{amb} = 101325 \times \left[ \frac{T_{amb}}{288.15} \right]^{0.2561} \]

ISA, 11000 m to 25000 m Altitude:
With the known value of the flight Mach number, the stagnation values of the temperature and pressure of the ambient air is calculated from the equations,

\[ T_0 = T_{amb} \left[ 1 + \left( \frac{\gamma - 1}{2} \right) * M^2 \right] \]

\[ P_0 = P_{amb} \left[ 1 + \left( \frac{\gamma - 1}{2} \right) * M^2 \right]^{\frac{\gamma}{\gamma - 1}} \]

Simulink representation for the atmosphere calculations is represented along with inlet model. Altitude is given as the input for the model and output will be total temperature and pressure values available for the engine inlet.

### 4.3 Inlet

Intake diffuser is used to bring the free stream air into the engine. It does no work on the flow and guides the flow to the compressor. However, the performance of the inlet is defines by the pressure recovery from the free stream to the engine. An isentropic process is assumed for the air flow in the inlet diffuser. Heat transfer and the friction between the air and the diffuser walls are not considered. Also the flow in the diffuser is modeled as a quasi steady state and so the dynamic behavior of the air in the diffuser is not considered. The stagnation values of the temperature and pressure at the diffuser exit are calculated from the equations,

\[ T_2 = T_0 \]

\[ P_2 = \eta_l * P_0 \]

Pressure recovery in the diffuser is calculated using the US military standard as

\[ \eta_l = 1.0 \text{ if } M \leq 1 \]
\[ \eta_l = 1.0 - 0.075 \times [(M - 1)^{1.35}] \] if \( M > 1 \)

4.3.1 Atmosphere and Inlet model in Simulink

Figure 4.2 Simulink model of inlet

4.4 Compressor

The purpose of a compressor is to increase the total pressure of the gas stream to that required by the engine while absorbing the minimum shaft power possible. Temperature of the incoming air also increases with pressure in the compressor. The work done by the compressor on the gas is extracted from the turbine. In the reference engine model, the compressor is an axial compressor with 8 stages. But while modeling the engine in Simulink, compressor is modeled as a single block by stacking all the stages of the compressor into a single block. Dynamic behavior of all the individual stages is also stacked into a single block with only the inlet and final exit conditions of the compressor. Overall compressor performance map is used for the compressor behavior.

4.4.1 Compressor Map

Compressor performance maps are obtained from the actual rig test of the engines and plotting the results on the map. Compressor map are plotted between the corrected flow parameter and pressure ratio with corrected speed lines. Efficiency contours could
be on the same plot or separated onto another plot between efficiency and pressure ratio with corrected speed lines. Characteristics are termed in corrected parameters in order to eliminate the dependence of the performance characteristics on the values of the inlet temperature and pressure. With the corrected parameters performance maps can be plotted in simple curves for a wide range of operating conditions. Definition for the corrected parameters is explained in the calculation for steady state characteristics.

For every compressor map there are two critical regions, the surge line and the choke line. Along the surge line, the rotational speed contours become nearly horizontal. To the left and above of the surge line, the speed contours drop with respect to the pressure ratio. This may cause an unstable phenomenon, surging. Surge is associated with a drop in the pressure ratio, i.e. the delivery pressure, which can lead to pulsations in the mass flow and even reverse it. It can cause considerable damage to the compressor, i.e. blade failure. As the pressure ratio decreases and the mass flow rate increases, the radial velocity of the flow must also increase, in order for the compressor to move enough gas through it. At some point, the compressor cannot accelerate the flow to a high enough radial velocity for the given motor speed. Maximum mass flow rate is then reached and choke is said to occur. Rotation stall is also an undesirable event. It occurs when cells of separated flow form and block a segment of the compressor rotor. Performance is decreased and the rotor might become unbalanced, also leading to failure (Source: Fox, 1998). The area enclosed by the surge line and the choke line is the normal operating range for the compressor. These regions are the ones carried out in the model.
Ignoring second-order phenomena such as Reynolds number effects, for a fixed inlet flow angle and no rotating/tertiary stall or inlet distortion for the compressor the following apply:

- For fixed compressor geometry the map is unique.
- The operating point on the compressor map is primarily dictated by the components surrounding it as opposed to the compressor itself.
• Any two out of the three parameters may be used as the ordinates for the map.

In the present work, flow rate and isentropic compression efficiency are calculated from the map.

4.4.2 How to Read Compressor Maps

The accuracy of the map representation is very important for simulation calculations. Here we employ a special purpose tool Smooth C developed by J. Kurzke exclusively for the compressor map representation. A brief introduction about the tool Smooth C (Source: J. Kurzke, Copyright 2002, Germany) is provided.

4.4.2.1 Smooth C

Computer programs that calculate the compressor performance need to input a description of the compressor maps. Usually producing compressor characteristic data by hand is a cumbersome task that takes a large amount of time because of the scatter in the data. Moreover, the data from the compressor rig tests are not usually evenly distributed over the tested speed range, or the distance between speed lines is substantial. Thus, interpolation and extrapolation of the measured data are required. Figure 4.3 shows the working window of the tool Smooth C.

The program Smooth C is a tool that quickly produces high quality compressor characteristics from measured data. Such characteristics can be used to provide information in addition to performance calculations. One can also evaluate small differences between different compressor types, for example the effects of inter-stage bleed, Reynolds’s number, tip clearance, re-staggered blades and vanes, distortion, etc. Smooth C can be a valuable tool for dealing with information other than measured data. It can also be used to check the quality of any compressor map. One can use, for example,
existing compressor maps as input. Various cross-plots offered by the program allow a judgment as to whether the map is a reasonable description of the compressor physics or not. Deficiencies can be corrected and physically meaningful interpolations and extrapolations of the map are possible.

Figure 4.4 Working windows for the tool SmoothC

The output of the program is tabulated data with the same number of equally spaced points for all speed lines. This type of data is suitable as input into performance programs simulating gas turbine engines. So choosing Smooth C can greatly enhance efficiency and accuracy of data processing.
4.4.3 Corrected Parameters for the Compressor

Mass flow rate and the shaft speed for the compressor are represented in corrected parameters in the map. These corrected parameters are defined by the following expressions:

\[ \dot{m}_{3\text{ corr}} = \frac{\dot{m}_3 \cdot \sqrt{\frac{T_2}{T_{\text{ref}}}}}{\frac{p_2}{p_{\text{ref}}}} \]

\[ N_{\text{corr comp}} = \frac{N}{N_{\text{des}}} \sqrt{\frac{T_{2\text{des}}}{T_2}} \]

4.4.4 Steady State Characteristics

With the data obtained from the map using the tool SmoothC, the isentropic compression efficiency and the corrected mass flow rate of the compressor can be computed as functions of the pressure ratio and the corrected rotor speed expressed as below.

\[ \dot{m}_{3\text{ corr}} = f_1 \left( \frac{p_3}{p_2}, N_{\text{corr comp}} \right) \]

\[ \eta_{\text{is comp}} = f_2 \left( \frac{p_3}{p_2}, N_{\text{corr comp}} \right) \]

Functions \( f_1 \) and \( f_2 \) can be calculated by applying curve fitting function. Another alternative to find the corrected mass flow rate and compressor efficiency is to apply the compressor data to the 2D Look Up tables in Simulink. In this thesis, both the methods are tested and worked out very well. For the curve fitting function, a tool called LABFit is used for finding the accuracy of the curve fittings.

From the values of the corrected mass flow rate and the compressor efficiency, the
actual mass flow rate and the temperature can be calculated from the expressions,

\[
\dot{m}_3' = \frac{\dot{m}_{3\text{corr}} \cdot \frac{P_2}{P_{\text{ref}}}}{\sqrt{\frac{T_2}{T_{\text{ref}}}}}
\]

\[
T_{3'} = T_2 \left\{ 1 + \frac{1}{\eta_{\text{Is Comp}}} \left[ \frac{P_3}{P_2} \frac{\gamma - 1}{\gamma} - 1 \right] \right\}
\]

Work done by the compressor to increase the pressure and temperature of the air can be calculated from the expression

\[
P_{W_c} = \dot{m}_3' \cdot c_p \cdot (T_{3'} - T_2)
\]

The value for the \( c_p \) in the above expression is calculated at the interpolated temperature value for the compressor given by

\[
T_c = \beta_c \cdot T_3 + (1 - \beta_c) \cdot T_2
\]

4.4.5 Compressor Volume Dynamics

In the transient process, the compressor is modeled as a mixing volume in which the mass and energy can be accumulated. The gas dynamics associated in the compressor stages are calculated by applying the continuity, energy and Ideal gas equations to the inter component volume between the compressor and the combustor.

Continuity equation:

\[
\frac{d}{dt} (W_3) = \dot{m}_3' - \dot{m}_3 - Bld
\]

Energy equation:

\[
\frac{d}{dt} (T_3) = \frac{1}{W_3 c_v} \left\{ \left[ \dot{m}_3' \cdot (c_p T_3' - c_v T_3) \right] - \left[ (\dot{m}_3 + Bld) \cdot R \cdot T_3 \right] \right\}
\]

Ideal Gas equation:
$$P_3 = \frac{W_3 \ast R \ast T_3}{V_3}$$

These mathematical equations are used for modeling the inter component volume for the compressor in Simulink.

### 4.4.6 Simulink Model for Compressor and Compressor Plenum

![Simulink model for compressor and compressor inter component volume](image)

**Figure 4.5** Simulink model for compressor and compressor inter component volume

### 4.5 Combustor

Combustion process in this engine model is simplified for the performance calculations and assumed to be instantaneous and complete after the fuel injection to the combustor. However, the actual process of burning the fuel in the combustor is a complex process. After the injection of the fuel into combustor, fuel droplets are engulfed into the air stream and transported to the burning zone. During transportation, the fuel droplets are heated and evaporated due to surrounding air. Then the fuel vapors diffuse and mix with the hot air and then burn at a finite rate. All the factors like mixing of the fuel vapors to the air, combustion rate and combustion efficiency are to be considered for
combustor modeling.

4.5.1 Pressure Drop in the Combustor

Unlike the theoretical combustion process where the inlet pressure and outlet pressure of the chamber are equal, there is a pressure drop in the combustion for the actual process. Because of this pressure drop, the gases can flow in the correct direction and mass flow rate through the combustion chamber is calculated. Expression for the pressure drop across the combustor is given by,

\[ \dot{m}_b = \dot{m}_3 = \sqrt{\frac{P_3 - P_4}{R_b}} \]

Where \( R_b \) is the calculated combustor pressure loss coefficient and is calculated from the steady state values of the engine at various speeds.

4.5.2 Combustor Volume Dynamics

The combustor is lumped into a single equivalent one dimensional volume. Model is developed in Simulink from the mathematical expressions of the continuity, energy equation and the ideal gas equation along with the algebraic expression for pressure drop in the combustor.

Continuity equation:

\[ \frac{d}{dt} (W_4) = \dot{m}_b + \dot{m}_f - \dot{m}_4 \]

Energy balance:

\[ \frac{d}{dt} (T_4) = \frac{1}{W_4 c_{vb}} \left[ \dot{m}_3 \left( c_{pb} T_b - c_{vb} T_4 \right) \right] + \left[ \dot{m}_f \left( \text{HVF} \times \eta_b - c_{vb} T_4 \right) \right] - \left[ \dot{m}_4 \times R \times T_4 \right] \]

Ideal Gas equation:

\[ P_4 = \frac{W_4 \times R \times T_4}{V_4} \]
where $T_b$ in the above equation is the combustor interpolation constant calculated from the expression:

$$T_b = \beta_b \cdot T_3 + (1 - \beta_b) \cdot T_4$$

The values for the specific heats of the combustor are calculated at the interpolated temperature of the combustor.

### 4.5.3 Efficiency of the combustor

Combustor efficiency is calculated from the map below with the value of the combustor parameter calculated from the values of the pressure drop and the temperature rise in the combustor.

![Figure 4.6 Combustor efficiency](image)

**Figure 4.6 Combustor efficiency**

### 4.5.4 Simulink Model for Combustor

![Figure 4.7 Combustor model in Simulink](image)

**Figure 4.7 Combustor model in Simulink**
4.6 Turbine

Turbine is used to extract sufficient energy from the hot gases of the combustor to drive the compressor and other auxiliary power equipment. In the reference engine model, the turbine is an axial turbine with 2 stages. But while modeling the engine in Simulink, turbine is modeled as a single block by stacking the two stages of the turbine into a single block. Dynamic behavior of all the individual stages is also stacked into a single block with only the inlet and final exit conditions of the turbine. Overall turbine performance map is used for the turbine behavior.

4.6.1 Turbine Map

Turbine performance maps are obtained from the actual rig test of the engines and plotting the results on the map. Flow rate and isentropic expansion efficiency are calculated from the map.

Turbine map is plotted between the corrected flow parameter and pressure ratio with corrected speed lines. Efficiency contours could be on the same plot or separated onto another plot between efficiency and pressure ratio with corrected speed lines. Characteristics are termed in corrected parameters in order to eliminate the dependence of the performance characteristics on the values of the inlet temperature and pressure. With the corrected parameters performance maps can be plotted in simple curves for a wide range of operating conditions. Definitions for the corrected parameters are explained in the calculation for steady state characteristics.

4.6.2 How to Read Compressor Maps

The accuracy of the map representation is very important for simulation calculations. Here we employ a special purpose tool Smooth T developed by J. Kurzke
exclusively for the turbine map representation. A brief introduction about the tool Smooth T (Source: J. Kurzke, Copyright 2002, Germany) is provided.

Figure 4.8 Overall performance map of turbine (Source: NASA-TM-2008-215172)

4.6.2.1 Smooth T

The accuracy of the turbine map representation is essential for precise cycle calculations. Similar to SmoothC for compressor, the program Smooth T is a tool that can quickly produce high quality turbine characteristics from experimental data. Such characteristics have other uses in addition to performance calculations. One can also
evaluate small differences between different turbine types, for example to show the
effects of Reynolds number, tip clearance, re-staggered blades and vanes, cooling air
injection etc. Smooth T has application beyond dealing with just experimental data. It can
also be employed to check the quality of any turbine map. One can use existing turbine
maps as input. Various cross-plots offered by the program allow one to exercise judgment
as to whether the map is a reasonable description of the turbine physics or not.
Deficiencies can be corrected and physical, meaningful interpolations and extrapolations
of the map are possible. Instead of genuine measured data - that seldom is available
outside industry and research facilities – one can take data from figures published in the
open literature by using this program.

The output of the program is a listing of tabulated data with the same number of
points for all speed lines. This data is suitable as input into performance programs
simulating gas turbine engines.

Figure 4.9 Working windows of the SmoothT
4.6.3 Corrected Parameters for Turbine

Mass flow rate and the shaft speed for the turbine are represented in corrected parameters in the map. These corrected parameters are defined by the following expressions:

\[
\dot{m}_{5'\,\text{corr}} = \frac{\dot{m}_{5'} \sqrt{\frac{T_4}{T_{\text{ref}}}}}{\frac{P_4}{P_{\text{ref}}}}
\]

\[
N_{\text{corr \, turb}} = \frac{N}{N_{\text{des}}} \sqrt{\frac{T_{4\,\text{des}}}{T_4}}
\]

4.6.3 Steady State Characteristics

Mass flow rate and rotor speed are represented in corrected parameters in the map. From this map, the isentropic expansion efficiency and the corrected mass flow rate of the turbine can be computed as functions of the pressure ratio and the corrected rotor speed expressed as below.

\[
\dot{m}_{5'\,\text{corr}} = f_3 \left( \frac{P_4}{P_5}, N_{\text{corr \, turb}} \right)
\]

\[
\eta_{\text{is \, turb}} = f_4 \left( \frac{P_4}{P_5}, N_{\text{corr \, turb}} \right)
\]

Functions \( f_1 \) and \( f_2 \) can be calculated by applying curve fitting function. Another alternative to find the corrected mass flow rate and turbine efficiency is to apply the turbine data to the 2D Look Up tables in Simulink. In this thesis, both the methods are tested and worked out very well. For the curve fitting function, a tool called LABFit is used for finding the accuracy of the curve fittings.

From the values of the corrected mass flow rate and the turbine efficiency, the
actual mass flow rate and the temperature can be calculated from the expressions,

$$\dot{m}_5' = \frac{\dot{m}_{5\text{corr}} * \frac{P_4}{P_{\text{ref}}}}{\sqrt{\frac{T_4}{T_{\text{ref}}}}}$$

$$T_5' = T_4 * \left\{ 1 + \eta_{\text{ls turb}} * \left[ 1 - \left( \frac{P_5}{P_4} \right)^{\frac{\gamma_b - 1}{\gamma_b}} \right] \right\}$$

Work done on the turbine by the hot gases from the combustor can be calculated from the expression:

$$Pw_t = \dot{m}_5' * c_{pb} * (T_5 - T_4)$$

4.6.4 Turbine Volume Dynamics

In the transient process, the turbine is modeled as mixing volume in which the mass and energy can be accumulated. The gas dynamics associated in the turbine stages are calculated by applying the continuity, energy and the Ideal gas equations to the inter component volume between the turbine and the convergent nozzle.

Continuity equation:

$$\frac{d}{dt}(W_5) = \dot{m}_5' - \dot{m}_5 + Bld$$

Energy equation:

$$\frac{d}{dt}(T_5) = \frac{1}{W_5c_{\text{vb}}} \left[ \left( c_{pb}T_5' - c_vT_5 \right) \right] - \left[ \dot{m}_5 * R * T_5 \right]$$

Ideal Gas equation:

$$P_5 = \frac{W_5 * R * T_5}{V_5}$$

Turbine inter component volume is built in Simulink using these mathematical equations.
4.7 Nozzle

A convergent nozzle is considered in modeling the engine. The partially expanded gas coming from the turbine at a relatively high pressure is accelerated to a high velocity in the nozzle. Finally, the gases expand to the ambient pressure and provide the thrust to propel the aircraft. Gas flow in the nozzle is considered to be quasi steady state and so the dynamics in the nozzle are not considered.

Modeling of the convergent nozzle for the engine is based on the following mathematical equations. The mass flow rate through the nozzle depends on two factors: nozzle back-pressure $P_{\text{back}}$ and the nozzle exit critical pressure $P_{\text{cr}}$.

For a specific inlet pressure to the nozzle, there exists a critical back-pressure defined by the expression
Depending on the value of the critical pressure the flow through the nozzle is defined below.

**Case 1:** If the back pressure is greater than the critical pressure value, the flow is subsonic at the exit and the exit pressure is equal to the back pressure. The flow rate, exit velocity and the Thrust produced is calculated with the expressions below.

If \( P_b > P_{cr} \),

Exit pressure from the nozzle,

\[
P_{exit} = P_b
\]

Mass flow rate in the nozzle,

\[
\dot{m}_5 = \frac{P_5}{\sqrt{RT_5}} A_{nz} \left[ \frac{P_e}{P_5} \right]^{\gamma_b/\gamma_b-1} \sqrt{\frac{2 \gamma_b}{\gamma_b-1}} \left[ 1 - \left( \frac{P_e}{P_5} \right)^{\gamma_b-1/\gamma_b} \right]
\]

Thrust produced,

\[
\text{Thrust} = C_v \dot{m}_5 \sqrt{2 c_p T_5 \left[ 1 - \left( \frac{P_e}{P_5} \right)^{\gamma_b-1/\gamma_b} \right]}
\]

Jet velocity at the exit of the nozzle,

\[
V_e = \sqrt{\frac{2 \gamma_b}{\gamma_b-1} \frac{RT_5}{\gamma_b-1} \left[ 1 - \left( \frac{P_e}{P_5} \right)^{\gamma_b-1/\gamma_b} \right]}
\]

**Case 2:** If the back pressure is less than the critical pressure, the flow is sonic or choked at the exit and the exit pressure is equal to the critical pressure. Flow rate, exit velocity, and the Thrust produced is calculated from the expressions below.
If $P_b < P_{cr}$,

Exit pressure from the nozzle,

$$P_{exit} = P_{cr}$$

Mass flow rate in the nozzle,

$$\dot{m}_5 = \frac{P_5}{\sqrt{RT_5}} A_nz \sqrt{\gamma_b \left[ \frac{2}{\gamma_b + 1} \right]^{\gamma_{b+1} \gamma_{b-1}}}$$

Thrust produced,

$$\text{Thrust} = C_v \dot{m}_5 \sqrt{2c_p T_5 \left[ 1 - \frac{P_{cr}}{P_5} \frac{\gamma_{b-1}}{\gamma_b} \right] + A_nz [P_{cr} - P_e]}$$

Jet velocity at the exit of the nozzle,

$$V_e = \frac{2\gamma_b}{\gamma_b - 1} RT_5 \left[ 1 - \frac{P_e}{P_5} \frac{\gamma_{b-1}}{\gamma_b} \right]$$

### 4.7.1 Nozzle Model in Simulink

![Nozzle Model in Simulink Diagram](image-url)

Figure 4.11 Nozzle model in Simulink
4.8 Rotor Dynamics

The steady state performance of a turbojet engine matches the operating points of the compressor with that of turbine. A mismatch between these components produces unbalanced torque that is integrated with the dynamic relations to find the new steady state match. Therefore, the change of the rotor speed is a function of the energy differential of the work extracted by the turbine and the work done by the compressor given by,

\[ \frac{d}{dt}(N) = \left(\frac{301}{\pi}\right)^2 \frac{1}{\Pi N} [P_{\text{turb}} - P_{\text{comp}}] \]

Figure 4.12 Rotor dynamics model in Simulink

4.9 Fuel Controller

The transient response in the engine is due to the response from the fuel controller. The control is set according to the output demand for each case.

Figure 4.13 Simulink model for fuel controller
Figure 4.14 Turbojet engine model in Simulink
Chapter 5

Simulation and Model Verification

Before starting simulation of the model, all the parameters for components and control volumes are to be adjusted to an initial steady state condition the engine is operated. These initial conditions are to be specified with care because ill initial conditions might lead the simulation to the case with no result and longer duration of simulation. With a specific fuel scheduling and with the initial steady state conditions, transient behavior of the engine from one steady state to other can be simulated.

5.1 Steady-State Algorithm

Steady state conditions for the given operating conditions can be calculated using the following algorithm. With the known values of the altitude, the operating Mach and selected values of the shaft rotational speed, mass flow parameter for the compressor, values for the compressor pressure ratio, efficiency is noted from the values of the performance map. Also values for the mass flow rate, temperature, pressure and compressor work are calculated from the equation set. An initial guess is made for the turbine inlet temperature and the mass flow parameter in the turbine is calculated from the flow compatibility equations. Now the values for the turbine pressure ratio and the expansion efficiency are taken from the turbine performance map with the known values.
of the shaft rotational speed, turbine inlet temperature and mass flow parameter of the turbine. Values for the exit temperature, pressure of the turbine and the turbine work are calculated from the equation set. Now the compressor work and the turbine work are compared and if they are within the difference of 3% variation, they are considered to be valid. Or else another guess is made for the value of the turbine inlet temperature and the steps thereafter are repeated until the compressor and the turbine work matches. Final exit conditions from the nozzle are calculated from the defined equations. Flow chart for the steady state algorithm is shown in the Figure 5.1.

![Flow Chart for Steady State Algorithm](image)

Figure 5.1 Steady state algorithm

### 5.2 Fuel Schedule

Engine model developed here has a separate fuel controller through which the transient phenomena from one steady state to the other occur with variation of the turbine inlet temperature and shaft rotational speed. This fuel scheduler is an input block of the
types step, ramp, from workspace, random etc. Fuel controller is set before running a simulation for a particular case according to the desired output.

**5.3 Design Point Transient Simulation**

The present developed engine model is to be verified for the parametric values to the NASA TM X-3014 model at the design conditions. For the simulation initiation, the initial steady state condition of the engine is set to be around 70% of the design speed and at sea level zero Mach condition.

Fuel schedule for the engine is as shown in the graph. Acceleration and the deceleration schedule the schedule is just to verify the transient response. Schedule is set for 30 seconds, but after reaching the required criteria (in this case: design RPM = 16540) model concludes to the steady state condition at that point.

![Fuel Schedule Graph](image)

**Figure 5.2 Fuel schedule for the engine**

Transient condition simulation results are explained below in response to the fuel schedule. Dynamic response in the shaft rotational speed is the important factor that determines the engine’s dynamic behavior from one steady state to another state. This
dynamic change with respect to fuel flow rate is shown in the Figure 5.3.

Figure 5.3 Shaft rotational speed (RPM)

The present criteria is to verify the developed model at the design point conditions, so at the design RPM of 16540, fuel controller controls the fuel flow rate and the model concludes to the steady state condition at the design point. Figure 5.4 shows the fuel flow rate.

Figure 5.4 Actual fuel flow rate
Flow rate in the compressor increases as the shaft speed increases with the fuel flow. Compressor flow rate for the given parameters must be defined accurate as it determines the flow properties in the later components. Dynamic response in the compressor flow rate with the shaft speed and fuel flow rate is shown in the Figure 5.5.

![Comp flow rate](image)

Figure 5.5 Compressor flow rate

Compressor pressure ratio increases with an increase in compressor flow rate and shaft rotational speed. Compressor surge is an important phenomenon to be observed in the engine modeling. Operating pressure ratio of the compressor should always maintain the specified surge limit to the surge line. Figure 5.6 gives the transient simulation for the compressor pressure ratio and surge pressure ratio.
The compressor works on the incoming air and subsequently the air pressure at the compressor outlet increases. The pressure increase of the compressor outlet is determined by the shaft rotational speed and fuel mass flow rate. Figure 5.7 shows the transient response in the compressor outlet and the inlet pressure.
With the increase in the outlet pressure, outlet temperature also increases and the increase is shown in the Figure 5.8.

![Figure 5.8 Compressor exit pressure](image)

In the compressor map, with the increase in the compressor flow rate and pressure ratio, the isentropic efficiency also increases until a certain value and thereafter it begins to decrease. Thus, the maximum efficiency line is crossed during the transient. Figure 54 shows the change of compressor isentropic efficiency during the simulation. The same is the result in the transient simulation as shown in the Figure 5.9.
Figure 5.9 Compressor isentropic efficiency

With the addition of the fuel in the combustion chamber, the outlet temperature of the combustor increases and this is an important criterion in the engine design such that it should be within the limit for the turbine material property. The increase in the combustor exit temperature with the fuel and combustor inlet temperature is shown in Figure 5.10.

Figure 5.10 Combustor inlet and exit temperatures
Unlike the ideal combustion in which the pressure at the inlet and exit of the combustor is equal, there is a pressure drop in the actual combustion from the inlet to the outlet. This pressure drop is calculated from the specific values from the engine design data and is used to calculate the flow rate in the combustion chamber. Figure 5.11 shows the inlet and outlet pressure of the combustion chamber.

![Combustor inlet and exit pressure](image)

**Figure 5.11 Combustor inlet and exit pressure**

The air-fuel mass ratio in the combustion chamber is shown in the Figure 5.12. During the transient simulation, it usually runs on lower values during acceleration and higher on deceleration.
Higher the turbine inlet temperature higher will be the final thrust developed by the engine. But this temperature is limited by the turbine metal material. During the expansion process, the outlet temperature of the turbine decreases doing work on the turbine. Inlet and the exit temperatures of the turbine is shown in the Figure 5.13.
Flow rate in the turbine should match to the flow rate of the compressor plus the flow rate of the fuel according to the flow compatibility equations. Figure 5.14 shows the response in the turbine flow rate with the fuel schedule.

Figure 5.14 Turbine flow rate

Expansion ratio across the turbine is shown in the Figure 5.15. This pressure ratio is a little less than the pressure ratio of the compressor.

Figure 5.15 Turbine pressure ratio
Isentropic expansion efficiency of the turbine in response to the fuel schedule is shown in the Figure 5.16.

The dynamic response in the engine simulation is due to the rotor dynamics by the difference in the turbine and compressor work. Figure 5.17 shows the response in the turbine and the compressor work that drives the engine simulation.
Thrust developed by the engine model is shown in the Figure 5.18. With the increase in the fuel flow and shaft speed, thrust produced by the engine increases consequently.

Figure 5.17 Turbine and compressor power

Figure 5.18 Thrust produced
Exit velocity of the jet at the nozzle exit determines the thrust produced and is a key in the determination of the propulsive efficiency of the engine model. Figure 5.19 shows the variation of exit jet velocity with time.

Figure 5.19 Exit jet velocity

5.4 Model Verification

Simulation results from the Simulink engine model are verified to the actual engine data. The data from the model of NASA TM X-3014 single spool turbojet engine is used to verify the simulation results. Final engine model developed here is not for a specific turbojet engine model as the compressor and turbine performance maps used are a close proximate to the available engine design data and are not the actual performance maps. The simulation results were mainly verified within the reasonable range that one would expect. Steady state performance values for the turbojet engines are available for the conditions

- 100% of design shaft speed and 101324 value of P2
• 100% of design shaft speed and 68950 value of \( P_2 \)

The parameter values are tabulated below:

**Steady-State Data for the Turbojet Engine at \( P_2 = 101324 \)**

Table 5.1 Simulink model comparison with reference model at \( P_2 = 101324 \)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Engine</th>
<th>Simulink model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor flow rate, ( \dot{m}_3 )</td>
<td>19.92</td>
<td>19.99</td>
</tr>
<tr>
<td>Combustor flow rate, ( \dot{m}_b )</td>
<td>19.37</td>
<td>19.99</td>
</tr>
<tr>
<td>Compressor Inlet Pressure, ( P_2 )</td>
<td>101324</td>
<td>101324</td>
</tr>
<tr>
<td>Combustor Inlet Pressure, ( P_3 )</td>
<td>678500</td>
<td>701052</td>
</tr>
<tr>
<td>Turbine Inlet Pressure, ( P_4 )</td>
<td>627200</td>
<td>646239</td>
</tr>
<tr>
<td>Turbine Outlet Pressure, ( P_5 )</td>
<td>225000</td>
<td>227417</td>
</tr>
<tr>
<td>Compressor Inlet Temperature, ( T_2 )</td>
<td>288.15</td>
<td>288.15</td>
</tr>
<tr>
<td>Combustor Inlet Temperature, ( T_3 )</td>
<td>537.5</td>
<td>538.1</td>
</tr>
<tr>
<td>Turbine Inlet Temperature, ( T_4 )</td>
<td>1139</td>
<td>1118</td>
</tr>
<tr>
<td>Fuel Flow rate, ( \dot{m}_f )</td>
<td>.3168</td>
<td>.3616</td>
</tr>
<tr>
<td>Percentage of Shaft speed</td>
<td>.9988</td>
<td>1.0037</td>
</tr>
<tr>
<td>Total Thrust</td>
<td>12606</td>
<td>12552</td>
</tr>
</tbody>
</table>
Steady-State Data for the Turbojet Engine at $P_2 = 68950$

Table 5.2 Simulink model comparison with reference model at $P_2 = 68590$

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Engine</th>
<th>Simulink model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor flow rate, $\dot{m}_3$</td>
<td>13.55</td>
<td>13.64</td>
</tr>
<tr>
<td>Combustor flow rate, $\dot{m}_b$</td>
<td>13.03</td>
<td>13.64</td>
</tr>
<tr>
<td>Compressor Inlet Pressure, $P_2$</td>
<td>68860</td>
<td>68860</td>
</tr>
<tr>
<td>Combustor Inlet Pressure, $P_3$</td>
<td>456000</td>
<td>46985</td>
</tr>
<tr>
<td>Turbine Inlet Pressure, $P_4$</td>
<td>432800</td>
<td>44324</td>
</tr>
<tr>
<td>Turbine Outlet Pressure, $P_5$</td>
<td>159800</td>
<td>161525</td>
</tr>
<tr>
<td>Compressor Inlet Temperature, $T_2$</td>
<td>288.15</td>
<td>288.15</td>
</tr>
<tr>
<td>Combustor Inlet Temperature, $T_3$</td>
<td>536.6</td>
<td>536.9</td>
</tr>
<tr>
<td>Turbine Inlet Temperature, $T_4$</td>
<td>1164</td>
<td>1198</td>
</tr>
<tr>
<td>Fuel Flow rate, $\dot{m}_f$</td>
<td>.2266</td>
<td>.2352</td>
</tr>
<tr>
<td>Percentage of Shaft speed</td>
<td>1</td>
<td>0.9943</td>
</tr>
<tr>
<td>Total Thrust</td>
<td>6765.7</td>
<td>6982</td>
</tr>
</tbody>
</table>

From the comparison with the NASA TM X-3014 model, dynamic transient parametric values for the Simulink model are in a proximate reasonable range. The variation in the values is less than 2% of the actual and could be the reasonable approximation for the transient simulations. Therefore, the developed Simulink model can be adapted for a reasonable approximation to the performance analysis of turbojet engine.
Chapter 6

Engine Performance Test

Performance of the real-time engine is analyzed from the virtual engine tests for the desired test cases on the Simulink model. The validity of the Simulink model is made sure for real-time analysis and performed the simulations. Data from the test cases are analyzed and plotted the performance characteristics of the engine with reduced inlet pressure across the desired thrust ranges.

6.1 Ambient Pressure and Pressure Reduction at Compressor Inlet

Intake diffuser is used to bring the free stream air into the engine. It does no work on the flow and guides the flow to the compressor. An isentropic process is assumed for the air flow in the inlet diffuser. Pressure recovery in the inlet neglecting heat transfer and friction between the air and the inlet walls is studied in the preceding chapters.

For the performance analysis, the pressure in the compressor inlet is theoretically dropped to a percent of atmospheric pressure. In the real-time, this possibility is assumed by a flap-actuator mechanism. The following cases are analyzed for the pressure drop across the inlet:
Table 6.1 Test cases for analysis with percentage of inlet pressure to supposed actual case

<table>
<thead>
<tr>
<th>Case</th>
<th>% of atmospheric pressure at compressor inlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>90</td>
</tr>
<tr>
<td>3</td>
<td>80</td>
</tr>
<tr>
<td>4</td>
<td>70</td>
</tr>
</tbody>
</table>

6.2 Desired Thrust Levels in the Analysis

The design point thrust for the engine is 12.537 KN at 100% design RPM. With this value as the maximum thrust capacity of the engine, the following cases are considered for the performance analysis engine to get an overall idea across the full operation range.

Table 6.2 Test cases for analysis with target output thrust

<table>
<thead>
<tr>
<th>Case</th>
<th>Thrust (KN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>4</td>
<td>12</td>
</tr>
</tbody>
</table>

6.3 Analysis of Test Results

Trends to the operational and performance characteristics have been plotted below with a brief description of the significance of the change.

To produce the same thrust with reduced inlet pressure, engine works at a higher
rpm. Density of the air drops with reduced inlet pressure and mass flow rate of air goes down demanding more work from the compressor. Compressor work is attained from the increase shaft rpm to produce same thrust to the engine. Figure 6.1 shows the variation of the engine rpm for the reduced pressure at desired thrust levels.

Figure 6.1 Shaft speed variation with reduced inlet pressure

Variation of the compressor mass flow rate for reduced inlet pressures is shown in the Figure 6.2. Mass flow rate in the compressor goes down due to decrease in the density of the air.
Corrected mass flow rate in the compressor increases with reduced inlet pressure due to increase in shaft rpm and compressor pressure ratio. It is particularly important to have higher corrected mass flow rate values to produce higher thrust to weight ratios for the engine. Figure 6.3 shows the increase in the corrected mass flow rate values in the compressor.
Compressor pressure ratio of the engine increases with reduced inlet pressure to produce the same thrust as shown in the Figure 6.4. Compressor pressure ratio plays major part for the engine thermal efficiency. Usually higher compressor pressure ratio indicates higher cycle efficiency of the engine.

![Compressor pressure ratio variation with reduced inlet pressure](image)

Figure 6.4 Compressor pressure ratio variation with reduced inlet pressure

Fuel consumption is also increased to produce the desired thrust with reduced compressor inlet pressure values. Consequently, turbine entry temperature also increases. Turbine inlet temperature is key term in the engine design and is limited by the structural characteristics of the engine. Figure 6.5 shows the variation of the Turbine inlet temperature with reduced inlet pressure to produce the desired thrust levels.
Generally, exhaust nozzles are choked in supersonic flights of turbojets. With reduced compressor inlet pressure, exit velocity of the jet from the nozzle increases. This affects the thermal efficiency and specific thrust values of the engine. Figure 6.7 shows the variation of the exit jet velocity with reduced inlet pressure.
Compressor efficiency of the engine goes down for higher thrust values and increases for lower thrust ranges with reduced inlet pressure to produce desired thrust. This increase in the efficiency of the compressor for lower thrust operation is particularly significant and discussed later. Figure 6.8 shows the change in the compressor efficiency.
6.4 Analysis of Engine Performance Characteristics

Operation of the engine with reduced compressor inlet pressure to produce the desired thrust is particularly significant in the lower thrust ranges of the engine. As shown in the Figure 6.9 and 6.10, the engine steady state operation line shifts into efficient zone for lower thrust ranges. For higher thrust values, even though the operation line shifts to the right lowering the efficiency, it has the advantage of running at higher rpm.

![Engine steady state operation lines for 100% and 90% atmospheric pressure to produce thrust of 3KN, 6KN, 9KN and 12 KN](image)

**Figure 6.9 Engine steady state operation line for the actual and 90% of atmospheric pressure at compressor inlet**
Specific thrust of the engine increases in a significant proportion with reduced inlet pressure than the normal operation. Desired thrust is produced with lower mass flow rate and higher exhausts jet velocity, leading to a higher specific thrust. Figure 6.11 shows the increase in the specific thrust values with reduced inlet pressure to produce the desired thrust.
Specific fuel consumption increases with reduced inlet pressure to produce the same thrust with the increase in the fuel flow rate. Figure 6.12 shows the increase in the SFC with reduced inlet pressure to produce the same exhaust thrust. The increase is significant for the higher thrust values. But, it doesn’t increase much in upper middle thrust ranges. So, the engine can employ this pressure drop across the inlet in the upper-middle thrust ranges with a reasonable performance gain.
Thermal efficiency of the engine is decreasing with the reduced compressor inlet pressure operation. This decrease is significant in higher thrust range and doesn’t show a significant variation in the upper-middle thrust range. This change in the thermal efficiency can be spent for certain military applications at the cost of fuel consumption. Even the work output increases with reduced inlet pressure, the net work decreases leading to an efficiency drop. Figure 6.12 shows the decrease in the thermal efficiency with the pressure reduction for the desired thrust levels.

Figure 6.12 SFC variation with reduced inlet pressure
Figure 6.13 Thermal efficiency variation with reduced inlet pressure

Propulsive efficiency also decreases with reduced inlet pressure because most of the increase in the kinetic energy is released to the exhaust than to produce the required thrust. Figure 6.14 shows the variation of the propulsive efficiency.

Figure 6.14 Propulsive efficiency variations with reduced inlet pressure
Lines of constant rpm are shown across the constant thrust values with reduced compressor inlet pressure in the Figure 6.15.

Percentage change in the value for various performance parameters of the engine for a test case of 7KN thrust value with different percentage pressure drops in the inlet is shown in the Figure 6.16.
Figure 6.16 Cumulative graph showing the % change in the parameter values to produce 7 KN thrust with reduce compressor inlet pressure
Chapter 7

Conclusion and Future Work

7.1 Conclusion

Overall performance of the turbojet engine decreases with reduced compressor inlet pressure for the same thrust if the engine is operated continuously with this mechanism. But has significant importance for applications where a certain amount of efficiency could be spent for the power demands.

It is observed that the thermal efficiency and fuel flow rate do not have a significant change in lower thrust range of operations. But the engine has the advantage of operating at a higher rpm. This particular application can be applied to any aircraft engine during the time of descent and landing. There will be cases where the aircraft need to gain maximum power from lower thrust range in the minimum time. For an example, consider the case where the aircraft is in its approach to landing. Engine at this point operates in the lower thrust range. At the times like a runway overshoot or a go-around landing case, the engine needs to regain its maximum thrust from the lower range in the minimum amount of time. It is at this particular case, the concept of flow control with reduced inlet pressure has a real-time application. Starting at the time of descent the flow control mechanism to reduce compressor inlet pressure is employed and
the efficiency of the engine doesn’t change much with this application. But the engine id operated at a 10% higher rpm than normal operation with 10% pressure drop across the inlet. If the engine needs to regain the maximum power for the cases as discussed, it could be achieved faster than the normal operation just by deploying the flow control mechanism.

With the reduction in the inlet pressure, the engine works at a higher rpm to produce the same thrust. This results with increase in the work output but decrease in the net work. Therefore, even with the increase in the compressor pressure ratio and turbine inlet temperature, the engine thermal efficiency goes down in a small proportion. With the higher exit jet velocities, propulsive efficiency of the engine also goes down in a very small proportion. SFC, Thermal and propulsive efficiencies are the major performance parameters for commercial engines. But for military engines, situations demand higher Specific Thrust.

Specific thrust for engine increases with reduced compressor inlet pressure. This is particularly important for the cases of shorter runways and higher climb rate. With increase in the specific thrust value, the frontal area of the engine could be decreased and it is extremely important for the military applications.

Thrust specific fuel consumption value increases with reduced inlet pressure. With increase in the specific fuel consumption value for an engine, the range value for the engine decreases. Thermal and Propulsive efficiencies are also decreasing with reduced inlet pressure. However, if the flow control mechanism is employed for certain time of flight such as landing or takeoff, performance decrease in these actors doesn’t affect the engine operation. It is advantageous to employ the reduced compressor inlet
pressure approach if the situation demands engine power to efficiency.

7.2 Future Work

Engine model built here is a simple turbojet engine. The characteristic maps used are a close assumption to the original model and are not the exact of the engine. The analysis would be more accurate if it is done with the engine exact performance maps. Also it would be more practical approach with the consideration of afterburner, supersonic inlets and cooling technologies. Also with the consideration of variable inlet and exhaust areas, the analysis could be more helpful.

The pressure drop across the inlet is defined theoretically assuming a flap-actuator mechanism inside the inlet. The work can be continued in designing such a mechanism.
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Appendix A

Basic Gas Dynamics

The relations for representing the gas dynamics is derived from the continuity and energy balance equations. Mathematical manipulations required to formulate these equations in terms of the chosen variables are given in this appendix.

Continuity and energy balance for quasi-one dimensional flow is given by the following equations

\[
\frac{d}{dt} (\rho A) + \frac{d}{dx} (\rho Av) = 0 \quad \text{equation 1}
\]

\[
\frac{d}{dt} (\rho A u) + \frac{d}{dx} (\rho A v h) = 0 \quad \text{equation 2}
\]

With the expression \( \dot{m} = \rho Av \)

**Continuity equation:**

Equation 1 transforms to

\[
\frac{d}{dt} (\rho A) = \frac{d}{dx} (\dot{m})
\]

\[
\frac{d}{dt} (\rho) = \frac{1}{A} \frac{d}{dx} (\dot{m})
\]

Lumping the spatial variable, the equation transforms to

\[
\frac{d}{dt} (\rho) = \frac{1}{V} (\dot{m}_1 - \dot{m}_2)
\]
\[
\frac{d}{dt} (\rho V) = (\dot{m}_1 - \dot{m}_2)
\]
\[
\frac{d}{dt} (W) = (\dot{m}_1 - \dot{m}_2)
\]

This is the expression used for the Continuity equation for the system components.

**Energy equation:**

Equation 2 transforms to

\[
\frac{d}{dt} (\rho Au) + \frac{d}{dx} (\dot{m} h) = 0
\]

This equation later transforms to

\[
\frac{d}{dt} (\rho A c_v T) = -\frac{1}{A} \frac{d}{dx} (\dot{m} c_p T)
\]

Again lumping the spatial variable leads to

\[
\frac{d}{dt} (\rho T) = \frac{1}{V} (\dot{m}_1 T_1 - \dot{m}_2 T_2)
\]

\[
\frac{d}{dt} (W T) = (\dot{m}_1 T_1 - \dot{m}_2 T_2)
\]

This equation is further simplified and used for the energy balance relation for the system components in the modeling.
Appendix B

Simulink Models

Below are the figures that explains the engine component modeling in its hierarchy

Compressor and Compressor plenum Model
Compressor model inside the subsystem

Compressor plenum model inside the subsystem
Energy balance in the compressor inside the subsystem

Combustor Subsystem
Combustor modeling inside the subsystem

Energy balance in the combustor subsystem
Turbine and Turbine plenum Subsystems

Turbine model inside the subsystem
Turbine plenum modeling inside the subsystem

Simulink model energy balance for the turbine
Nozzle model in Simulink

Simulink model for the nozzle dynamic inside the subsystem