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RESEARCH NOTE

Improved Turbine Engine Hierarchical Modeling and Simulation Based on Engine Fuel Control System

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Aircraft engines constitute a complex system, requiring adequate monitoring to ensure flight safety and timely maintenance. The best way to achieve this, is modeling the engine. Therefore, in this paper, a suitable mathematical model from the engine controller design point of view, for a specific aero turbine engine is proposed by the aid of MATLAB/Simulink software. The model is capable of reducing costs of actual engine tests and predicting some important controlled variables, which can usually not be measured directly (e.g. compressor surge margin, the turbine inlet temperature or the engine net thrust). The model has maximum accuracy for maximal variance of the fuel flow input command consistent with the engine control system specifications. So the model is strongly adaptable to engine control systems and real time applications. Simulation results which proved logical and well founded are obtained from applying an acquired fuel flow function to the engine model.

NOMENCLATURE

a	Sound speed
C_a	Air speed
C_{P3}	Specific heat in compressor
C_{P4}	Specific heat in turbine
C_V	Constant volume specific heat
C_{Vol}	Combustor volume
C_6	Exhaust gas speed
I_L	Polar moment of inertia of low pressure spool (LPS)
I_H	Polar moment of inertia of high pressure spool (HPS)
LHV	Fuel low heating value
M	Mach number
N	Spool speed
N_L	Low pressure spool speed
N_H	High pressure spool speed
P_{amb}	Ambient pressure (P_1)
P_2	Pressure at LPC inlet
P_{26}	Pressure at HPC inlet
P_3	Pressure at combustor inlet
P_{23}	Compressor pressure ratio
P_4	Pressure at HPT inlet
P_5	Pressure at nozzle inlet
P_{S6}	Static pressure at nozzle exit section
R	Universal gas constant
SFC	Specific fuel consumption
SM	Compressor surge margin
T_{amb}	Temperature at intake inlet (T_1)
T_2	Temperature at LPC inlet
T_{26}	Temperature at HPC inlet
T_3	Temperature at combustor inlet
T_4	Temperature at HPT inlet
T_{45}	Temperature at LPT inlet
T_5	Temperature at nozzle inlet
T_{S6}	Static temperature at nozzle exit section
u	Fuel mass flow ($\dot{m}_f(t)$)
V_{45}	HPT-LPT inter-component volume

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V_6	LPT-Nozzle inter-component volume
W_2	Mass flow rate through LPC
W_3	Mass flow rate through HPC
W_4	Mass flow rate through HPT
W_{45}	Mass flow rate through LPT
W_{noz}	Mass flow rate through nozzle
η_{mech}	Mechanical efficiency
γ	Specific heat ratio
ρ_{amb}	Ambient density
ρ_4	Density of fluid in combustor

INTRODUCTION

Aircraft engines constitute a complex system, requiring adequate monitoring to ensure flight safety and timely maintenance [1]. The best way to achieve this, is modeling the engine [2,3]. Modeling can reduce the costs with respect to actual engine tests and can predict some important variables that can't be measured directly (*e.g.* compressor surge margin, the turbine inlet temperature or the engine net thrust) [2,4]. So it can operate as a virtual test cell to investigate the engine behavior with the least possible error.

The aerothermal nonlinear model is the most accurate in simulating engine performance and thermodynamic parameters during transient operation [4-7].

There are several ways to do engine modeling and simulation. Traditional approaches have a long history of development using FORTRAN or other 4^{th} generation languages to calculate thermodynamics cycle parameters associated with the design and performance prediction of gas turbine engines. These cycle decks have been used extensively by developers of gas turbine engines and their customers to understand the behavior of jet engine designs before, during, and after the development of the physical engines [8].

In addition, MATLAB, Simulink, and associated tools have been applied in the development of detailed, physics-based, turbine engine models capable of execution on real-time hardware simulators [9].

Simulink provides an easy-to-use, graphical, modeling and simulation development environment for developing time-based simulations in a wide range of applications. And has the capability of code generation using associated tools. Add-on tools available from the MathWorks, Inc. enable the production of real-time code from Simulink models for execution on specialized, real-time, computing hardware [8].

As a result, a modeling capability called the Turbine Engine Simulator Model (TESM) has been developed for the purpose of supporting research in advanced turbine engine controls and health management.

TESM which operates as a virtual test cell, enables a user to investigate "what-if" scenarios at a fraction of the cost of an engine test cell or research aircraft.

In order to facilitate turbine engine and control system modeling and simulation, TESM implemented in Simulink has been developed.

Two goals are associated with the development of the TESM: 1) providing a capability for independent testing, verification and validation of propulsion system components and 2) providing a suitable engine model to be matched with a desired controller.

The requirements that have been considered in the design and developing of the TESM are:

1. Real-time engine simulation.
2. Operation over the entire flight envelope.
3. Credible transient behavior.
4. Easy modification for other engine cycles.
5. Simulated engine sensor measurements.
6. Environment, power lever angle (PLA) and engine load user inputs.

Based on the above requirements, we decided to develop a model having the following characteristics:

1. Physics based (*e.g.*, thermodynamic, inertias, *etc.*).
2. Modular/Component based.
3. Incorporating engine dimensions and component maps for sizing.

ENGINE CONTROL SYSTEM THEORY

With the increase in engine complexity, however, it is becoming more and more important to take interactions between the different engine systems and subsystems (core engine, reheat, air intake) into account.

One important research program in the field of jet engine control was conducted in the 90s in the USA. The program was called "Performance Seeking Control". Its goal was to integrate a simplified state space model into the engine control system of an F-15 aircraft to optimize the matching between supersonic air intake and engine operation [10]. The advantages were demonstrated in flight tests [11].

However, jet engines are, with the exception of malfunctions, stable dynamic systems. Therefore, it would be theoretically possible to control a simple jet engine manually, without the aid of a dedicated control system [2]. But without the aid of a control system, the pilots would have to manually check all engine operating limits and set the manipulated variables (e.g. fuel flow geometries) accordingly. To reduce pilot's workload, some of the early jet engines built around 1940 already featured control systems [2]. The most important advantages of controlled jet engines are:

1. Reduced pilot workload.

2. Constant thrust despite external disturbances.
3. Shorter response times to changed thrust demands.
4. More accurate adherence to operating limits, therefore increased engine life and safety.
5. Increased operating efficiency due to reduced fuel consumption.

The control systems typically featured loops to prevent engine over speeds, compressor surge and check turbine inlet temperature limit, either by scheduling the fuel flow ($\dot{m}$) during accelerations and decelerations or by controlling the acceleration and deceleration rates of engine spool.

There are two kinds of variables from a controller design point of view. First, Controlled variables: the most important variable to be controlled is the engine's thrust. Ideally, there would be no time delay between commanded thrust and the thrust delivered by the engine. This is however not possible due to different operating limits of the engine. Other controlled variables that are highly important for safe engine operation are turbine inlet temperature and the so-called surge margin (SM) of the compressor. According to the map data in Figure 6, SM can be defined as follows:

$$SM = \left(\frac{\left(\frac{P_{32}}{\dot{m}_{2a_{cor}}} \right)_{stall} - \left(\frac{P_{32}}{\dot{m}_{2a_{cor}}} \right)}{\left(\frac{P_{32}}{\dot{m}_{2a_{cor}}} \right)} \right)$$

$$P_{32} = \left(\frac{P_3}{P_2} \right) \qquad (1)$$

The controlled variables can be provided by the engine model and sent to controller.

Second, Manipulated variables: the expression " manipulated variables" shall denote variables which can be set by engine control system. The most important variable among them, is the fuel flow ($\dot{m}_f(t)$) provided to the combustion chamber. It is the main input to the engine model which is so sensitive to this kind of input.

In addition, it is possible for some engines to change the nozzle exhaust area or the angle of one or more stages of compressor blades, in order to control its operating point.

Since the objective of this paper is to evaluate the influence of controlling input functions on engine performance parameters, this would be obtained by considering the control system variables while modeling the engine.

TURBINE ENGINE SIMULATOR MODEL

A dynamic model of a turbofan engine is developed using the MATLAB simulation environment and its Simulink toolbox. The schematic configuration of the simulated turbofan engine, is shown in Figure 1.

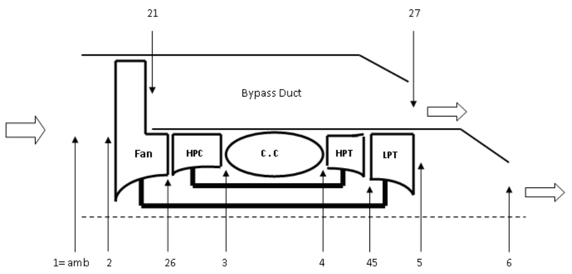


Figure 1. Layout of the turbofan engine.

The engine model is constructed with a component approach for ease of modification and replacement with different engine components. The precision of TESM results, depends on the precision of each component module results.

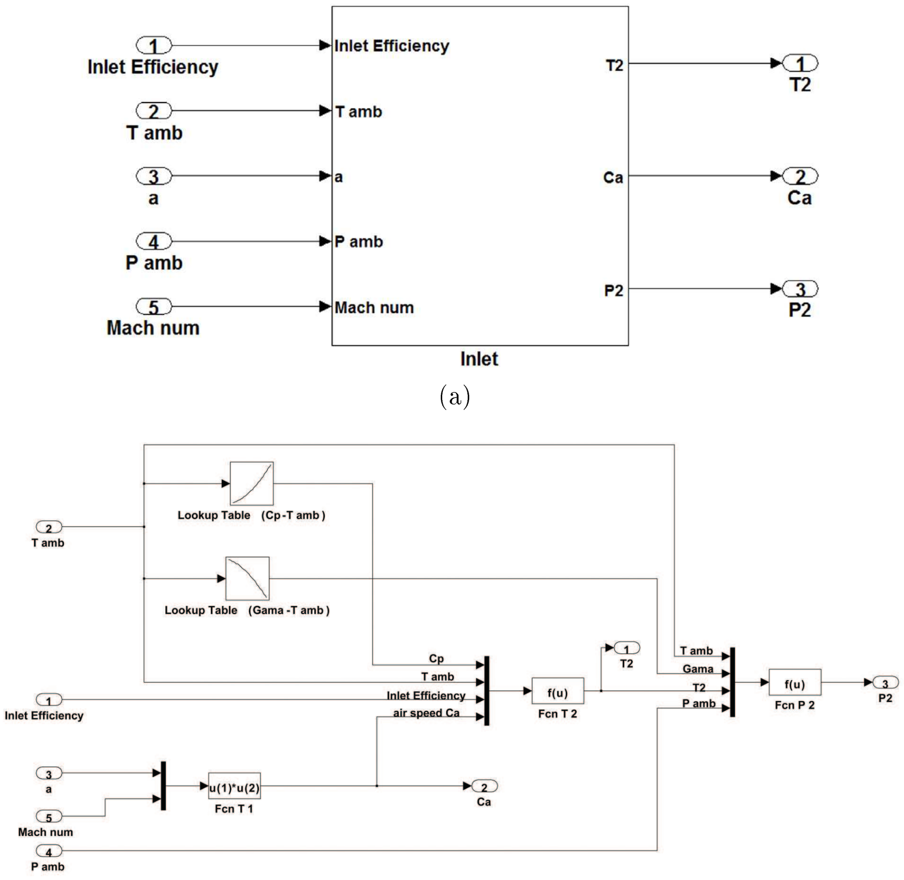
Each component can be instantiated from a software library module developed to represent the functions of that particular type of component. Each module is a functional unit with its own set of inputs and outputs (I/O). Each can function as an independent component.

For example the inlet module can be used as a stand-alone inlet component which can be used to instantiate inlet in the engine model. The inlet component and its I/O are shown in Figure 2.

The engine simulation model consists of the component modules such as: Inlet, Low Pressure Compressor (fan), High Pressure Compressor, Combustor, High Pressure Turbine, Low Pressure Turbine and Nozzle which are modeled as lumped parameter thermodynamic systems. This is to say that, a multiple stage compressor or turbine is simulated as one component. This approach is adopted because compressor and turbine maps are created to represent the performance of the overall component. The model can be developed to a stage-by-stage fashion, if we have required authentic performance data of each component.

The modules are developed based on fundamental laws of physics such as conservation of mass, momentum and energy. For example, the rotor dynamics (for both high and low speed rotors) is presented by the equation of conservation of angular momentum, *i.e.* based on moment of inertia of the components attached to the shafts. And the mixing volume dynamics are represented by the equations of conservation of mass and energy *i.e.* for a compressor or turbine the volume dynamics are based on the air in the volume after the module and before the next module.

The most important dynamical differential equations used in the TESM, are as follows (Eq. (2) through



(a)

(b)

Figure 2. Inlet module; a) subsystem, b) subsystem's contents.

Eq. (9)) [12,13]:

$$\dot{\rho}_4 = \frac{W_3 - W_4 + u}{C_{vol}} \tag{2}$$

$$\dot{T}_4 = \frac{C_{P3}T_3W_3 - C_{P4}T_4W_4 + uLHV}{C_{vol}\dot{\rho}_4 T_4 C_V} \tag{3}$$

$$\dot{N}_L = \frac{3600}{4\pi^2 N_L I_L}[W_{45}C_{P4}(T_{45} - T_5) - \frac{W_2 C_{P3}(T_{26} - T_2)}{\eta_{mech}}] \tag{4}$$

$$\dot{N}_H = \frac{3600}{4\pi^2 N_H I_H}[W_4 C_{P4}(T_4 - T_{45}) - \frac{W_3 C_{P3}(T_3 - T_{26})}{\eta_{mech}}] \tag{5}$$

$$\dot{P}_{26} = \left(1 + \frac{\gamma - 1}{2}M^2\right)^{\frac{1}{\gamma - 1}} RT_{26}\frac{W_2 - W_3}{V_{26}} \tag{6}$$

$$\dot{P}_3 = \left(1 + \frac{\gamma - 1}{2}M^2\right)^{\frac{1}{\gamma - 1}} RT_3\left(\frac{W_3 - W_4 - u}{V_3}\right) \tag{7}$$

$$\dot{P}_{45} = \left(1 + \frac{\gamma - 1}{2}M^2\right)^{\frac{1}{\gamma - 1}} RT_{45}\frac{W_4 - W_{45}}{V_{45}} \tag{8}$$

$$\dot{P}_6 = (1 + \frac{\gamma - 1}{2}M^2)^{\frac{1}{\gamma - 1}} RT_6\frac{W_{45} - Wnoz}{V_6} \tag{9}$$

In order to use individual components to create an engine model, all hardware component information such as flow, pressure ratio and efficiency maps, flow volume and area of some components are required.

Parameters Incorporation

The incorporation of turbo machinery map data (compressor and turbine maps) into the MATLAB workspace (Simulink related blocks) is a significant part of the tuning process required to match TESM performance with data for a specific engine.

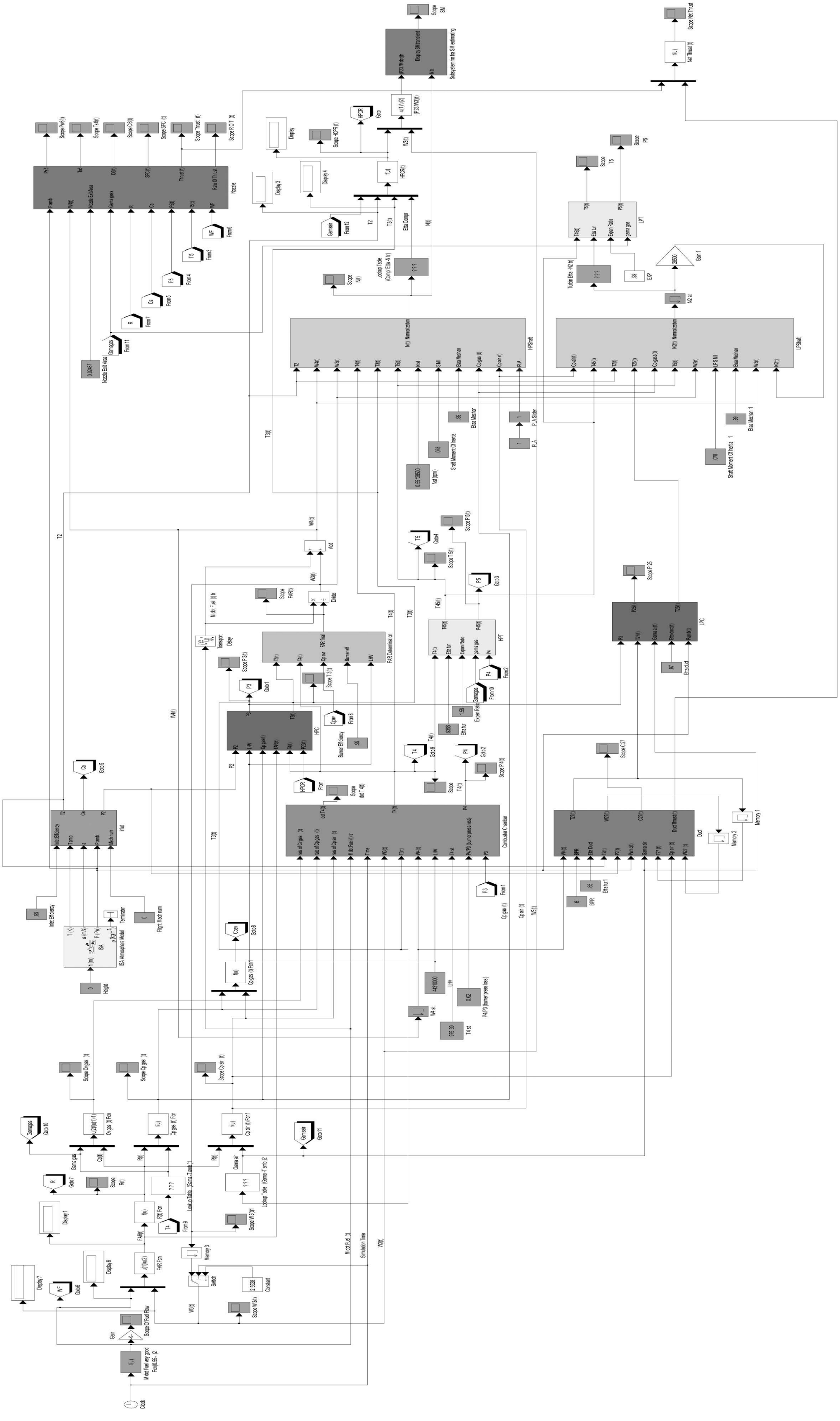


Figure 3. The Simulink model of TESM.

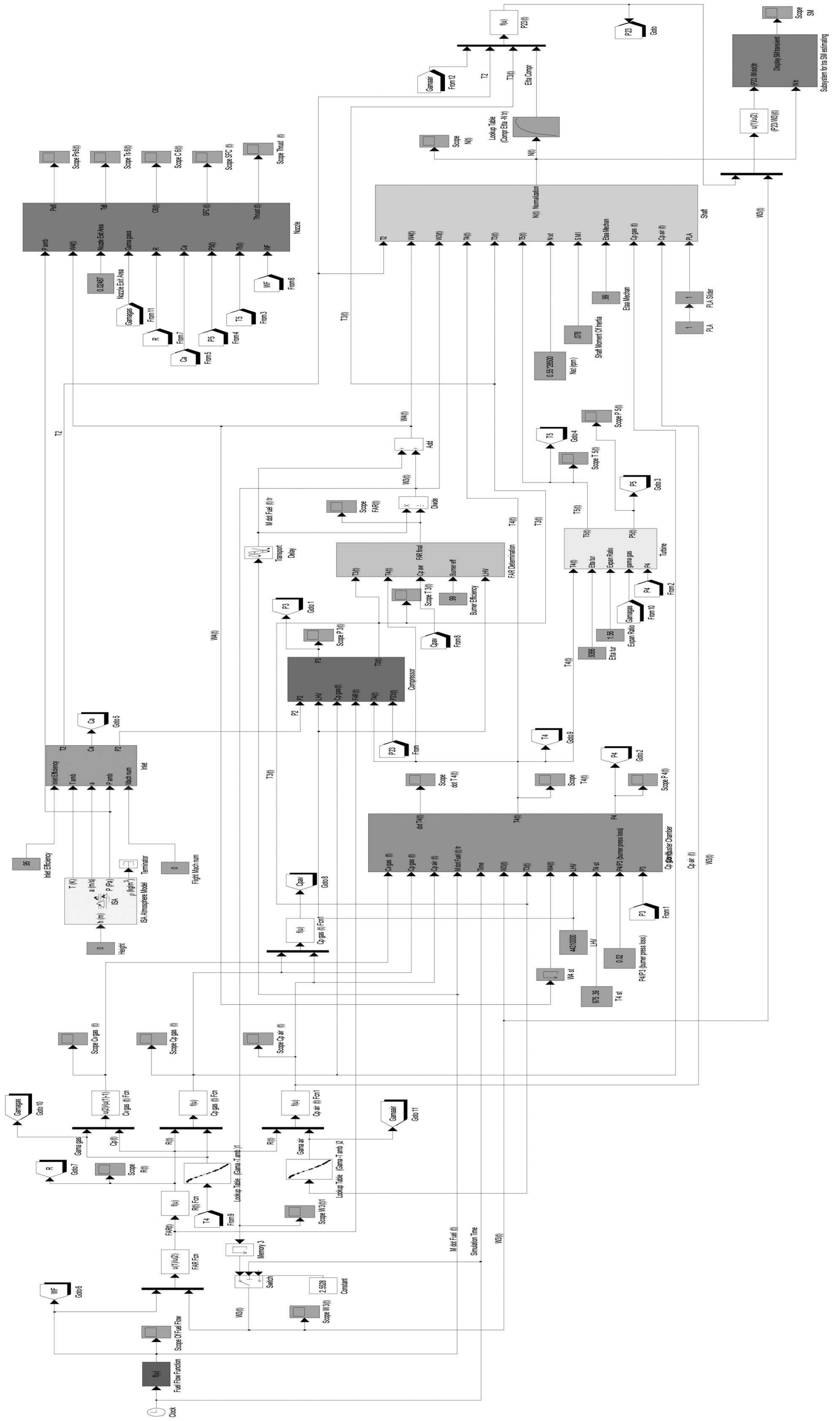
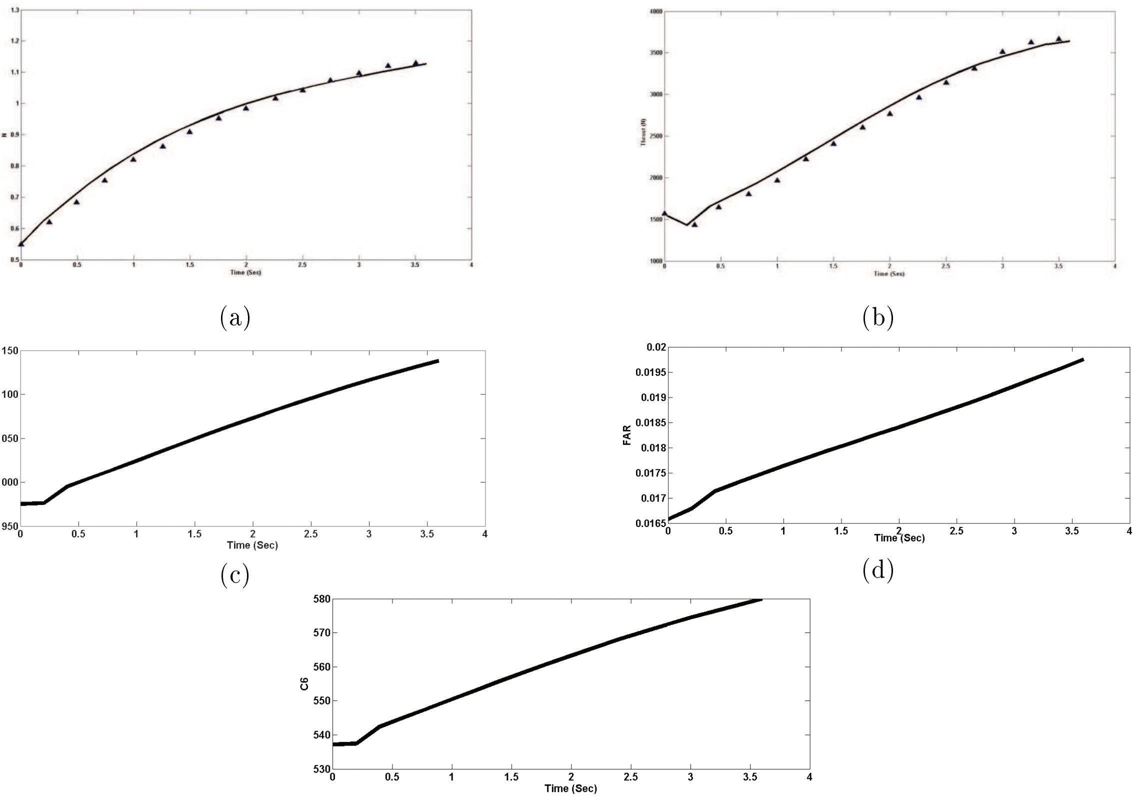


Figure 4. The Simulink model of the turbojet engine.



(a) (b) (c) (d) (e)

Figure 5. Trace of engine model responses (Lines) with PLA Movement at sea level, M=0 versus simulation time (Sec) in comparison with the similar engine testing operation (triangle points). (a) Normalized rotational speed. (b) Thrust (N). (c) Turbine inlet temperature (K). (d) Fuel-Air Ratio (FAR). (e) exhaust gas speed.

The other parameters to be incorporated into the MATLAB workspace, are characteristic lengths, volumes, moments of inertia, design constants, efficiencies, *etc*. Values for these tuning parameters must be determined from engine design documentation, experimentation or other simulation models. The model references these parameters at run-time.

Model Configuration

The Simulink model of TESM is shown in Figure 3. As can be seen, the relationships between components are easily understood and the gas path flow parameter connections between major engine components include, mass flow rate, total temperature and pressure, static pressure and fuel-air ratio (FAR).

This model provides a basic framework for both the development of engine component modules and analysis of component interactions at the system level within the engine. Component modules can be reused and the time and cost required to produce new models are significantly reduced.

SPECIFIC TURBOJET ENGINE CASE STUDY

TESM is reduced to a specific jet engine along with available parameters through omitting some components such as: Fan, HPC, HPT, HPS and Bleed air ducts. So we can have a single spool turbine engine simulator model. The Simulink model of the engine is shown in Figure 4.

Simulation Inputs & Outputs (I/O)

The simulation model has three user inputs. Altitude and Mach number are ambient inputs, and power is set by the PLA.

All user inputs can be changed by varying the associated Simulink slider blocks, while the model is running. The user inputs are detailed below:

- Altitude: this is an ambient input with a range of 10,000 feet for this type of engine which goes into the ISA atmosphere model block.
- Mach number: this simulates the speed of aircraft and it's effects on P_2, T_2 and C_a. The range for this type of engine mach number is 0 to 0.9.

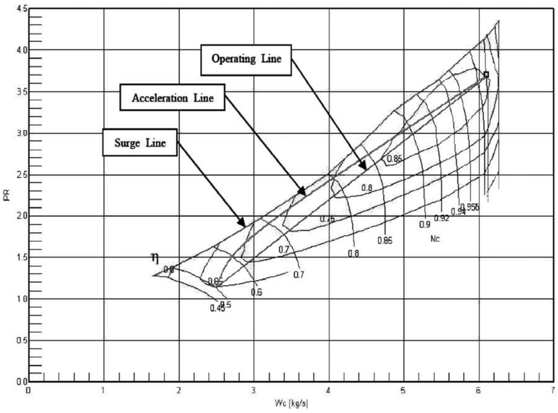


Figure 6. Model output acceleration line in the compressor map.

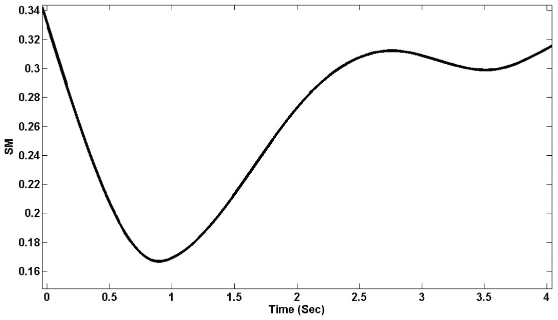


Figure 7. Compressor Surge Margin (SM).

- Power Lever Angle (PLA): this is the control input and shows the demanded spool speed. For full throttle condition, it creates 110% demanded spool speed.

This model has many outputs, and can indicate the engine continuous time operation. Table 1 shows some of these outputs.

Among the model outputs, three are the most important [2,3,10], including: Engine spool speed (N), Compressor surge margin (SM) and Turbine inlet temperature (T_4). These are important, because they should be controlled by the controllers.

TESTING & DEMONSTRATION

Since the specific engine is expected to achieve 3600 N thrust during maximum four seconds acceleration time, a test description is proposed according to some predefined fuel flow functions. After applying the fuel flow functions to the engine model, the simulation results are verified and a desirable function with allowable output parameters ($SM\rangle 0$, restricted turbine inlet temperature,...) is selected. The simulation results of engine model in comparison with the engine testing operation for achieving 3600 N thrust are presented in Figure 5(a,b), and proved logical and well founded. Figure 5(c), (d) and (f) indicate the Turbine inlet temperature, FAR and nozzle exhaust gas speed respectively, as other outputs of engine simulator model.

The simulations are run for a window of 4 seconds with the unit step PLA and constant zero values for Mach number and altitude. This window allows sufficient time for the system to transition through the flight envelope. Transient line, as the most important transient simulation result, is depicted in the compressor map in Figure 6.

As shown in Figure 6, at steady state operation, as the rotor speed increases, the surge margin reduces. So the engine moves toward instability but does not reach it.

At transient operation, mass flow increment causes the transient line to move away from the steady line. Thus, compressor surge would be more probable.

The simulation result of compressor surge margin as one of important outputs of simulator model is presented in Figure 7. The SM variations over acceleration time confirms the transient operation which is shown in Figure 6.

The comparison between engine acceleration times at model simulation phase and actual engine test is presented in Table 2.

CONCLUSION

One of the most useful design tools in control and engine health management is model simulation. Arguably, this is the most critical area in the process of design and analysis. As the interest in intelligent engine technology increases so does the demand for advanced methods of engine model simulation. Specifically, real-time model simulation that allows interface with physical hardware, such as sensors, actuators and valves, is very practical.

Undoubtedly, this element is very cost effective, in that, it can decrease test and experimentation hours significantly and these test procedures can be

Table 1. Jet engine model outputs.

Component Module	Output parameter(s)
ISA.Atms.Model	a, ρ, P_1, T_1
Inlet	C_a, P_2, T_2
Compressor	P_3, T_3, W_3
Combustor	P_4, T_4, W_4
Turbine	P_5, T_5
Nozzle	Thrust, SFC, P_{s6}, T_{s6}, C_6
Shaft	N
Surge Margin Model	SM

Table 2. Comparison of engine acceleration times (Sec).

Spool speed variation range	Acceleration time (Sec)		Error	Final Thrust (N)
	Simulation	Test		
0.55 to 1	2.07	2.12	2.3%	3000
0.55 to 1.1	3.65	3.55	2.8%	3550

conducted without any fuel consumption. In turn, overall cost can be reduced by millions. The key factor is to initiate this process with a high-quality model of the engine, itself. As with any system, the quality of the data obtained from simulation is only as good as the model in simulation.

Obviously, the characteristics of an engine and its control can be very meticulous and complex, as it pertains to modeling.

Therefore, a large amount of time and effort is spent in the developmental stages of a detailed engine model. However, in order to extract meaningful information for analysis, or allow external hardware to be tested, simulation of the model must be conducted in a real-time environment.

These tools produce more realistic data and allow a more accurate platform for control systems design.

The main contribution of this paper is the development of a nonlinear dynamical model of a turbine engine using MATLAB/Simulink environment. The model can be adapted to various engines by implementing appropriate component maps for the compressors and turbines.

According to data summarized in Table 2, the average percentage error is less than 3%. The model's behavior now approximates a real gas turbine and provides an ideal test bed for observing faults and failures, engine parameter variations, and degradation over time. This in turn provides a valuable tool in observing the symptoms of failure, developing diagnostics routines, and improving prognostic algorithms.

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