The International Journal Of Engineering And Science (IJES)
|| Volume || 5 || Issue || 12 || Pages || PP 111-119 || 2016 ||
ISSN (e): 2319 – 1813 ISSN (p): 2319 – 1805

Dynamic Modeling and Simulation on GE90 Engine

Shray Benawra & Jiqiang Wang
Jiangsu Province Key Laboratory of Aerospace Power System
Nanjing University of Aeronautics and Astronautics, Nanjing, 210016, China

ABSTRACT

The paper talks about a better numerical method for predicting on-design performance on a High-Bypass Turbofan engine GE90. A dynamic optimization turbofan engine for GE90 has been designed using MATLAB/Simulink software. Individual components including Ambient, Fan, Low Pressure Compressor (LPC), High Pressure Compressor (HPC), Combustion Chamber, High Pressure Turbine (HPT), Low Pressure Turbine (LPT), Exit Nozzle and Plenum volumes, Makes a combination to identify the performance characteristics of a turbofan engine throughout the flight condition. The specific engine characteristics are matched and adopted through the use of variables from developed a model. The results will validate through simulation with the software to look through for problems and understand the air flow from the intake to the nozzle. Good designs can intensify a better performance to the engine, which performance analysis can be applied and tested to each component of the GE90 engine during design point condition.

Keywords: *Dynamic Turbofan; GE90; Design Point; Modeling & Simulation; Performance Cycle Analysis*

Date of Submission: 03 December 2016 Date of Accepted: 30 December 2016

NOMENCLATURE

F - Uninstalled thrust
LPC - Low pressure compressor
HPC - High pressure compressor
HPT - High pressure turbine
LPT - Low pressure turbine
m- Mass flow rate
P - Pressure
R - Gas constant
SFC - Specific fuel consumption
T - Temperature
β - Bypass Ratio
A_n - Area of Core Nozzle
A_f - Area of Bypass Nozzle
V_f - Fan Velocity
V_j - Jet Velocity
f - fuel to air ratio
V_a - Air Velocity

I. INTRODUCTION

Commercial aircrafts are considering an increase in thermal challenges. Major reasons is that modern aircrafts contain extra components to provide power generation especially throughout years the power system loads grew in order to support these components to remove the internal heat functioned by the aircraft through a thermal management system (TMS) [1] [2]. Modeling and simulation software's would be helpful for engine designers to conduct design trade studies, to determine what parameters relent to optimize performance to the aircraft [3]. Dynamic models of General Electric GE90 engine were constructed and tested as part of B777 development program. In previous years advancement in technology has led to rapid increment in research of aircraft engine performance. Over these past years researchers in this area has developed new and innovative ways to deal with ever increasing demand of performance enhancement [4]. One of the areas that have gone through this phase is component modeling and simulation. Many researcher over the years drafted new designs and some of them come up with more creative solution to increase the overall performance of the jet engine. They developed a program for GE90 which includes testing of component besides other turbo machinery as well as the combustion chamber. Through simulation of the engine provides an advantage to this test. The components were analyzed and compare to the test data provided by GE to validate the design approach. The task was presented by Adamczyk and Turner et al. Turner et al job was to couple high and low pressure turbine and run it at these engine conditions [5]. Thereafter Turner et.al wanted to uncoupled fan and booster and couples the HPC, combustor, HPT and LPT and run it again these conditions [6-8]. A researcher named Roy as a consultant took part in the GE90 core compressor design to ensure that a successful performance of the E3 would be achieved in more suitable mechanical environment of the engine. This paper is presented to show the methods used to build a dynamic engine model, performance characteristic maps and simulate the components structure of the model which will support the conclusion that a successful simulation was accomplished [9] at design point through different flight conditions. Dynamical response data and static stability was isolated on the engine model, including the effect on the engine thrust, SFC and Mass flow at each station. The complexity of a gas turbine due to the dynamical analysis is multidisciplinary of the engine, which contains an understanding in mechanical, fluid mechanics and thermodynamics studies. We will derive the two basic types of dynamics on the GE90 model by using the first principle of physics. These types are the pressure dynamics and shaft dynamics. The basic dynamics are derived in forms of derivatives for gas turbine engines [10]. Fig 1 shows a cross sectional diagram of the GE90 engine.

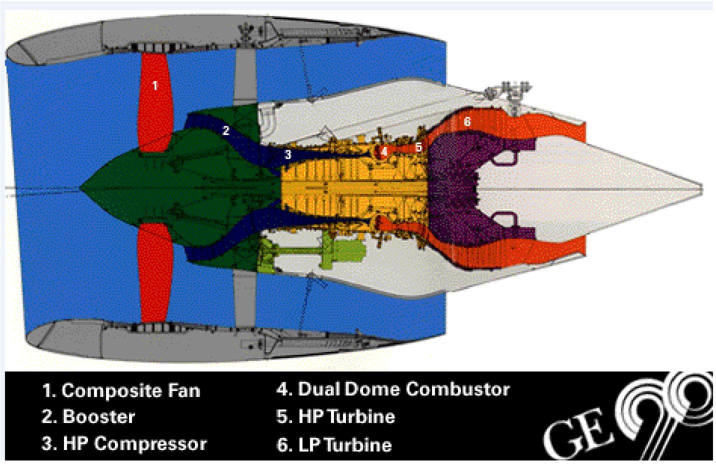
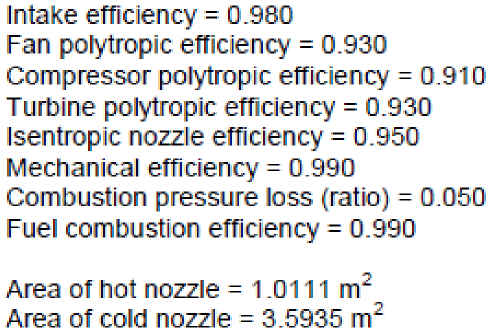


Fig. 1: GE90 Cross-section diagram [14]

II. GE90 MODEL COMPONENTS

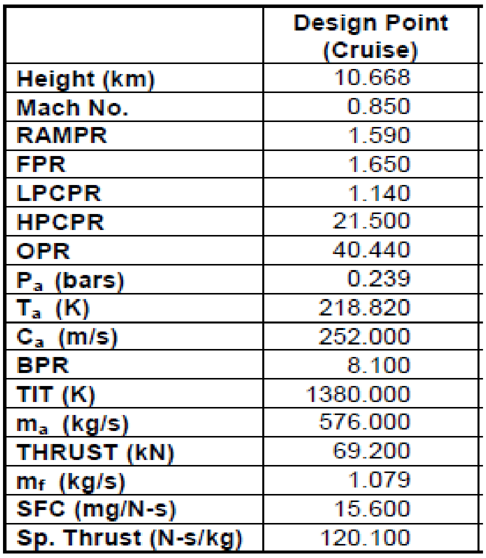
The GE90 engine model contain certain components, including the fan stage followed by the Low and High pressure compressor (LPC/HPC), combustor chamber, High and Low pressure turbines (HPT/LPT), and Nozzle. Certain consideration needs to be made for a generic engine; each component in the model is masked, which leads the user to insert specific calculations, geometry at design point situation. Emphases are put on capturing dynamic behavior in all stages of the engine. These can be achieved through two means, the inter component volumes and shaft inertial effect. Further details on these modeling techniques will then be considered and elaborated on the section [11]. The fan is the first stage of the compressors that calculates the correct mass flow rate when its pressure ratio and shaft speed are given. The total pressure calculation represents the inlet pressure. The total pressure we consider is the static pressure from the ambient, which is functioned by Altitude, Mach number as well as the aircraft velocity. Outputs of the fan contain mass flow rate, temperature and work. The LPC model functions the same as the Fan. HPC inputs contain HP shaft rotational speed, pressure outlet, temperature and mass flow rate coming from LPC model. Outputs of the HPC are mass flow rate, work, inlet pressure and temperature. Pressure flows back to the LPC as an input. Mass flow rate from the HPC enters the combustion chamber and then calculates temperature of fuel burned. Outputs of the burner are the mass flow rate, temperature of turbine inlet. HPT and LPT model have the same similarity to the HPC model. Differences between them are the shaft speed being fed into them. Section of the Nozzle is to obtain final air flow known as Thrust, exiting the engine. Therefore after considering the thrust we determine the SFC of the engine; the model was also built with additional blocks for the two shafts to calculate the rotation speed and work of the engine. Transient effects are created by the components of the engine which can be discussed further in detail. A block is also generated to see flow rate passing through the bypass duct outlet in the nozzle section of the engine [12]. Fig 2 and Fig 3 shows the engine parameters and configurations at design point condition that has conducted in the GE90 engine model [13].



Intake efficiency = 0.980
Fan polytropic efficiency = 0.930
Compressor polytropic efficiency = 0.910
Turbine polytropic efficiency = 0.930
Isentropic nozzle efficiency = 0.950
Mechanical efficiency = 0.990
Combustion pressure loss (ratio) = 0.050
Fuel combustion efficiency = 0.990

Area of hot nozzle = 1.0111 m^2
Area of cold nozzle = 3.5935 m^2

Fig2. Engine component configurations



	Design Point (Cruise)
Height (km)	10.668
Mach No.	0.850
RAMPR	1.590
FPR	1.650
LPCPR	1.140
HPCPR	21.500
OPR	40.440
P_a (bars)	0.239
T_a (K)	218.820
C_a (m/s)	252.000
BPR	8.100
TIT (K)	1380.000
m_a (kg/s)	576.000
THRUST (kN)	69.200
m_f (kg/s)	1.079
SFC (mg/N-s)	15.600
Sp. Thrust (N-s/kg)	120.100

Fig3. Engine data parameters

III. GE90 TRANSIENT DEVELPOMENT MODEL

The GE90 model transient behavior has been given attention and model fidelity increase with the dynamic behaviors, but also diminishes algebraic constraints by solving through advance numerical in turn reducing simulation time. There were two methods used for modeling the transients. Firstly the total mass flow being functioned by plenum volumes blocks that are allocated before the component model at each stage. Experimental data are mapped on generic performance contained on each component model. Pressure ratios, shaft speeds are map functions due to the behavior of inlet and outlet mass flows of the plenum volume model known, an equation is used to calculate the dynamic pressure of volume, as shown by equation (1).

$$P = \int \frac{\left(\dot{m}_{in} - \dot{m}_{out}\right) R T}{V} dt \tag{1}$$

The second method is considered the shaft moment of inertia for the High and Low pressure shaft. Changes are to be considered in the work signals from the engine to variations in shaft speed. The shaft inertia considered variation does not occur instantly. The model captures the delay in time demonstrating dynamic capabilities. In terms of physics Thrust is considered to be a mechanical force that is accelerates and contains a difference in velocity of gas passing through the engine. Total thrust calculation procedure is provided in equation. (2)- (4) [14]:

$$F_{bypass} = \frac{\dot{m}\,\beta}{1+\beta}[V_f - V_a] + A_f(P_{11} - P_{oa}) \qquad (2)$$

$$F_{core} = \frac{\dot{m}\,\beta}{1+\beta}[(1+f)V_j - V_a] + A_n(P_9 - P_{oa}) \qquad (3)$$

$$F_{total} = F_{bypass} + F_{core} \qquad (4)$$

Specific fuel consumption known as SFC is the mass fuel flow rate divided by the output thrust. For commercial engines, low cost of fuel is critical to the SFC typically about 15 to 25 % of aircraft operating costs [15]. SFC calculation is provided in equation (5) [16]:

$$SFC = \frac{3600\,\dot{m}_f}{F} \qquad (5)$$

Fig 4 shows the GE90 Engine model constructed using MATLAB/Simulink software to demonstrate dynamical analysis and simulations.

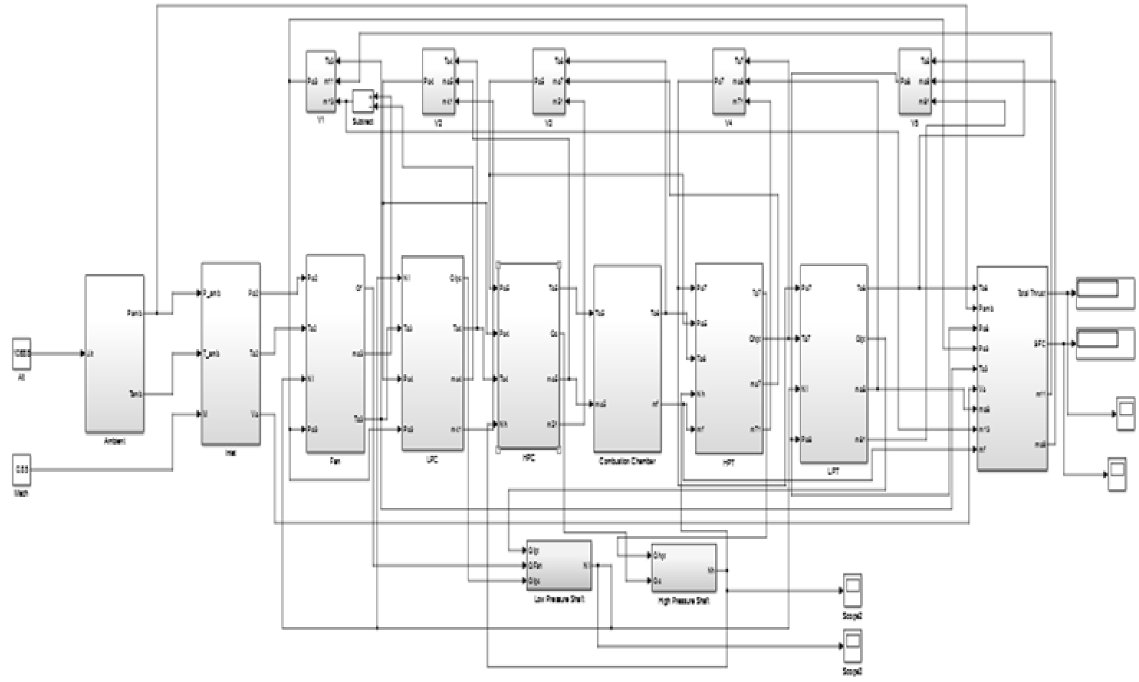


Fig4. Overview structure of the GE90 model

IV. SIMULATION RESULTS

Each component including the twin spools are compared to the data provided by GE in Fig2 before integrating the engine model. At the commencement stage the engine is simulated through the 200 second mission as per the GE90 research at design point conditions. Data points are reached for each component which includes the shaft speeds for both the spools for inlet and outlet conditions. The inputs provided are aircraft altitude 10688 m and Mach number 0.85. According to the simulation, Results were obtained through each cross-section of the GE90 engine. The results are provided in Table1 to show the compare the dynamic model with GE Data logbook.

Table 1 GE90 performance comparison

Design Point (Cruise)	**GE Data Logbook**	**Dynamic Model**	**Percentage Error**
FPR	1.650	1.650	0. 0%
LPCPR	1.140	0.963	15.5%
HPCPR	21.500	23.036	7.14%
Pa (bars)	0.239	0.238	0.42%
Ta (K)	218.820	218.678	0.06%
Ca (m/s)	252.000	251.974	0.01%
TIT (K)	1380.000	1421.524	3.00%

Ma (kg/s)	576.000	606.546	5.30%
THRUST (KN)	69.200	77.620	3.50%
SFC (mg/N-s)	15.600	13.900	10.8%

4.1 Fan

The requirement for the inputs for the fan model is the pressure outlet, LP shaft speed and mission profile. The outputs include mass flow rate and temperature. Reference to Fig 5 shows this simulation results.

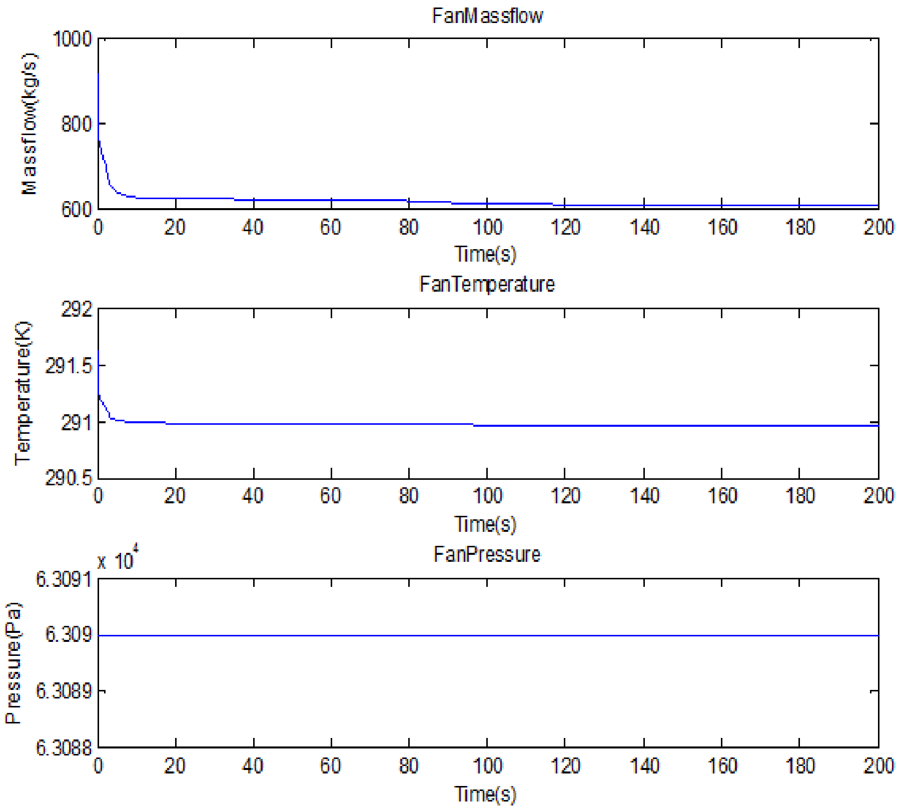


Fig5. Fan output conditions

4.2 Low Pressure Compressor (LPC)

The LPC model contains the same inputs and outputs as the fan. The results of this simulation are shown in Fig 6.

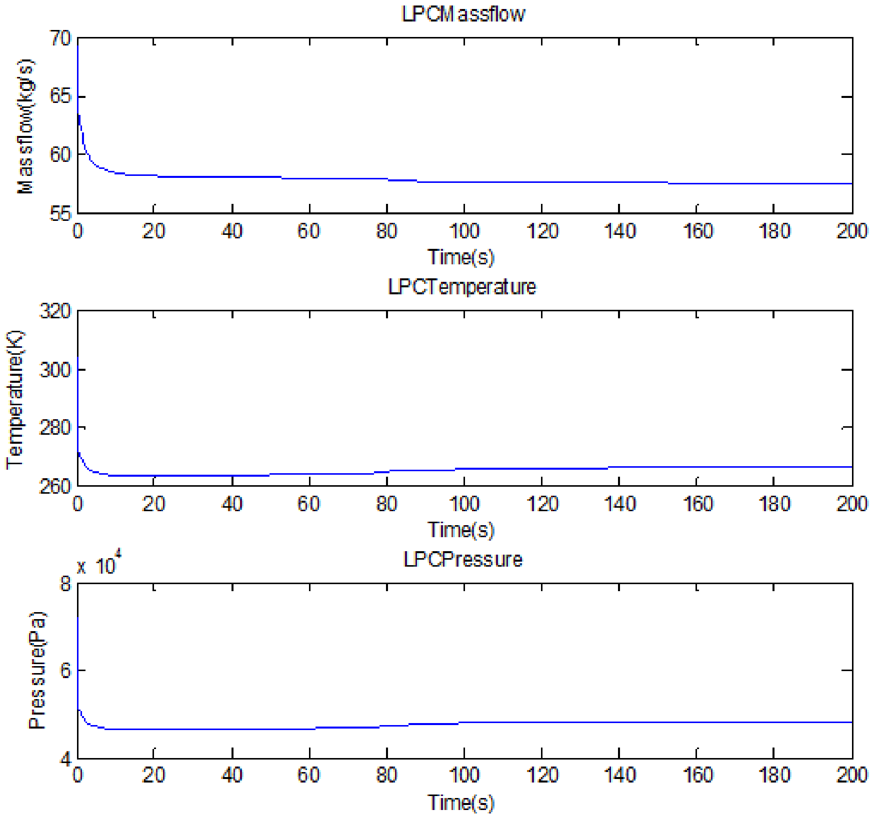


Fig6. LPC output conditions

4.3 High Pressure Compressor (HPC)

Inputs in the HPC model contain inlet pressure, mass flow; temperature, pressure outlet and HP rotational speed. Therefore the outputs contain the mass flow and temperature. The alternation of the pressure values depends on the dynamics coming from the plenum volume block; this influences mass flow rates passing through the HPC block. Temperature affects the driven efficiency that varies the flow rates. The results of this simulation are shown in Fig 7.

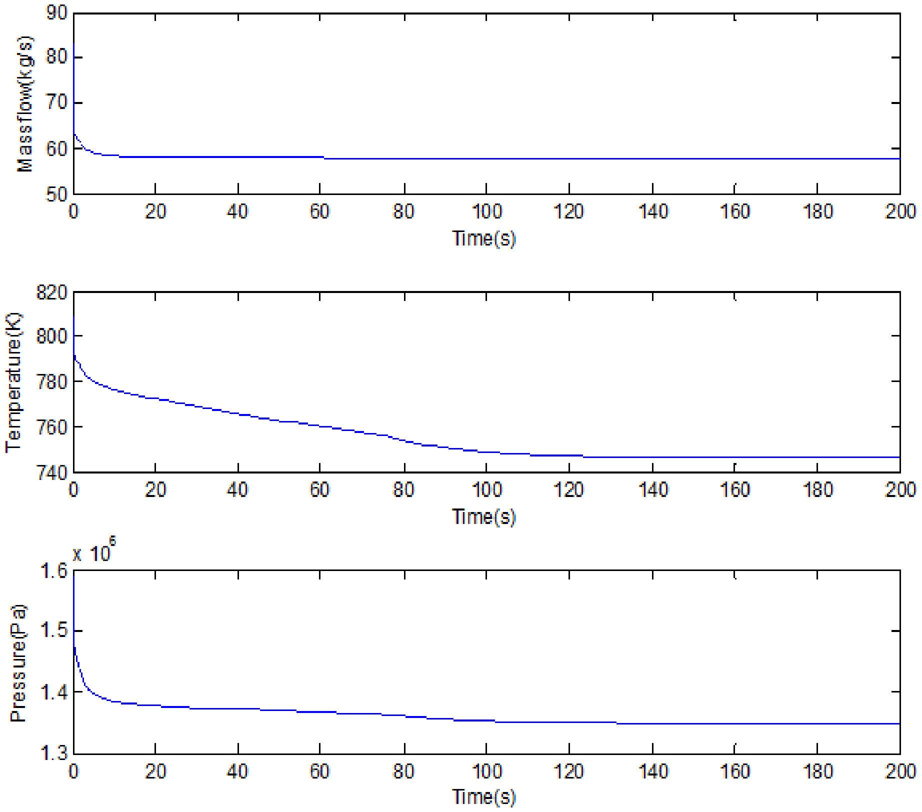


Fig7. HPC output conditions

4.4 Combustion Chamber

The Combustion Chamber model input contains a combination of fuel flow and mass flow rate with temperature. The output provides the turbine inlet temperature. The results are shown in Fig8.

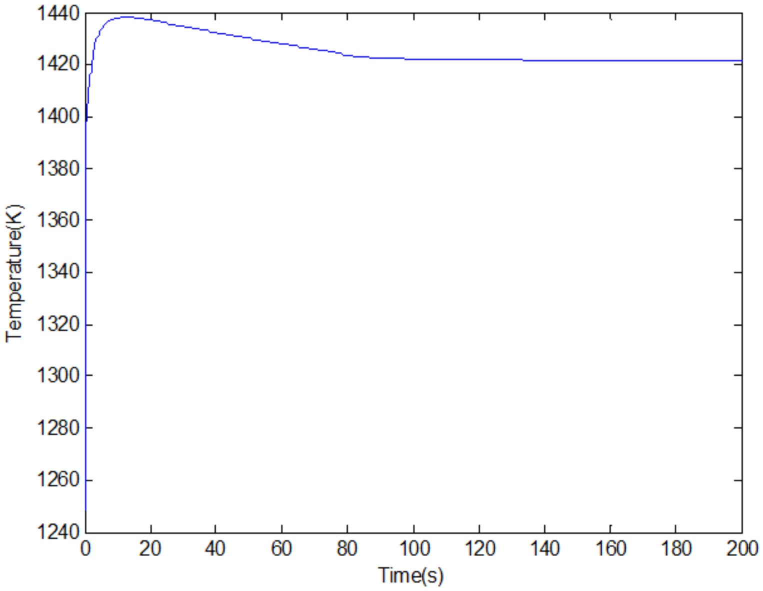


Fig8. Combustion chamber output conditions

4.5 High Pressure Turbine (HPT)

Inputs for the HPT section contain inlet mass flow rate, temperature, pressure and rotational speed from the high pressure shaft. Therefore outputs for the HPT consist of mass flow rate and o temperature. HPT temperature is a bit out of point due to the difference in efficiency maps. Results are shown in Fig9 respectively.

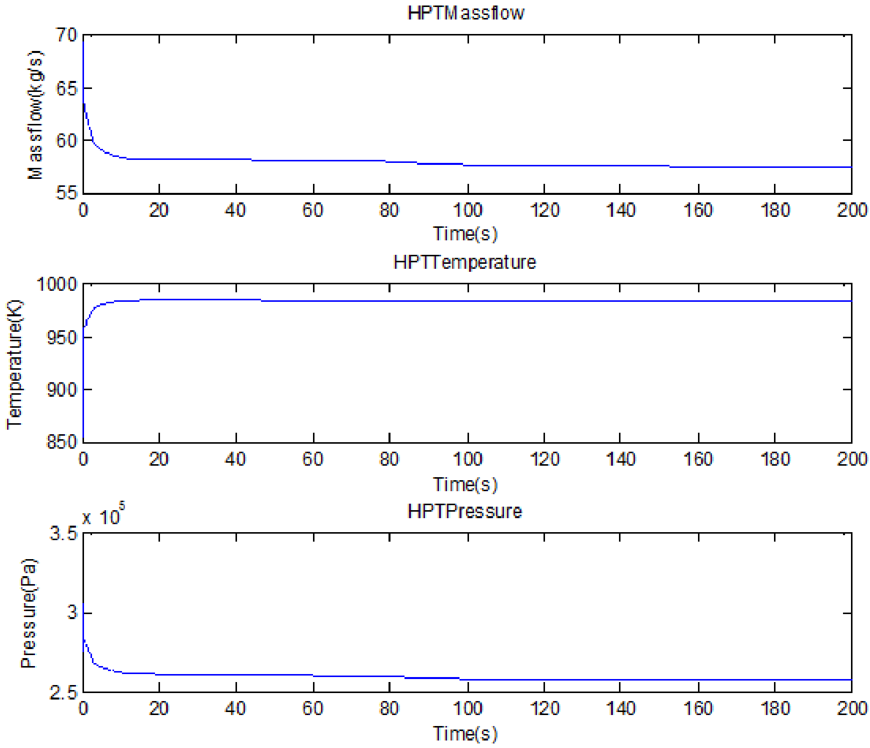


Fig9. High pressure turbine output conditions

4.6 Low Pressure Turbine (LPT)

Inputs for the LPT section contain inlet mass flow rate, temperature, pressure outlet and rotational speed from the low pressure shaft. Even with the HPT temperatures. The efficiency maps used within the LPT model are not the same to the HPT. The results are shown in Fig10.respectively.

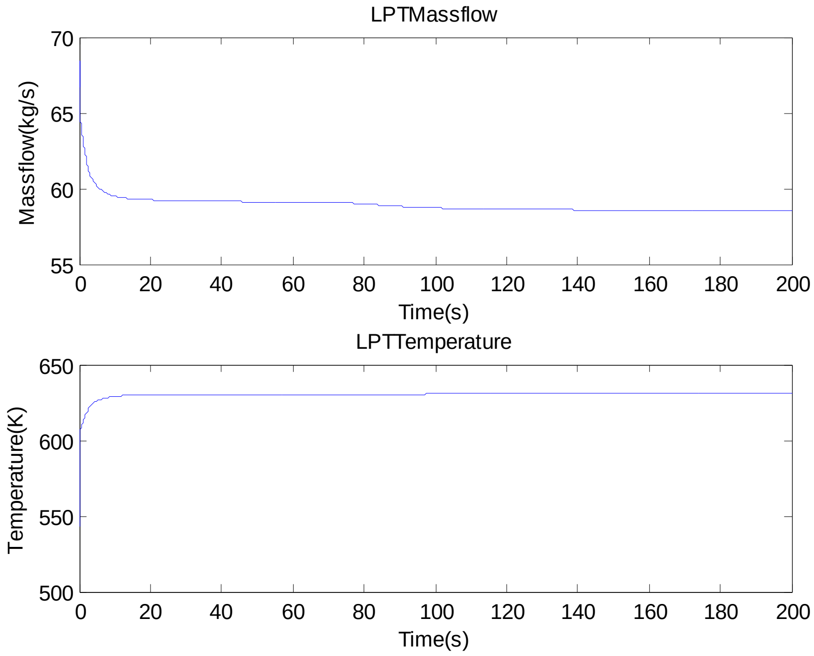


Fig10. Low pressure turbine output conditions

4.7 Exit Nozzle

Inputs for the Nozzle section refer to the flight condition and flow from the outlet of the LPT and flow from the Bypass duct outlet with flow from the fan. The nozzle outputs are Thrust, SFC and inlet pressure. Reference to this simulation for the nozzle is shown below in Fig 11 and Fig 12.

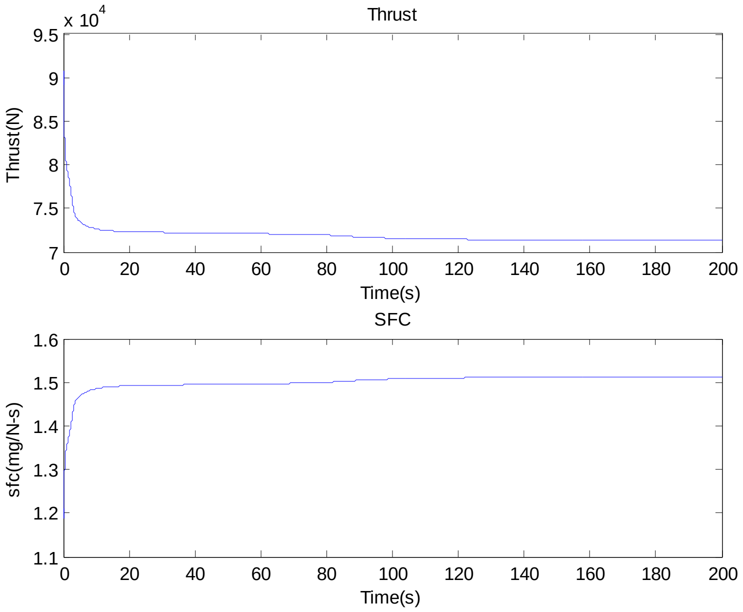


Fig11. Nozzle Thrust/SFC

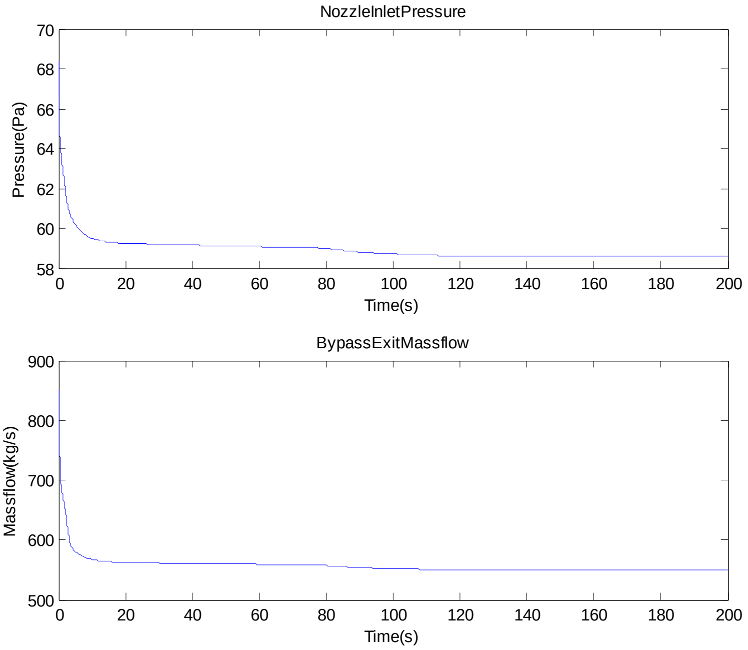


Fig12. Nozzle inlet pressure/Bypass exit mass flow

4.8 High and Low Pressure Shafts

The HP spool combined with HPC, Combustion Chamber, HPT and high pressure shaft. HPC airflow data inlet was provided to satisfy the engine baseline points were through look up tables. The Combustion Chamber provides the Mass fuel flow rate. Using engine results, the HPT turbine receives an outlet pressure. Analyses of other quantities include the High pressure shaft speed and given Moment of inertia (J) of 70 to the LP shaft and 39.712 to the HP shaft. The LP spool contains the Fan, LPC, LPT, and LP shaft. Airflow Data comes from the fan inputs, LPC inputs and LPT inlet conditions. Low pressure shaft model analyses the LP shaft speed. Reference to this simulation is shown in Fig13 respectively.

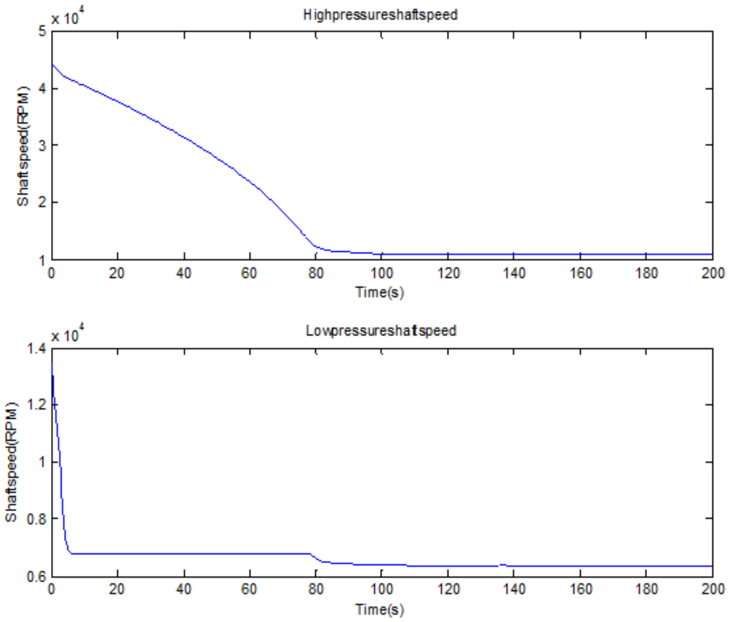


Fig13. High and Low pressure shaft speeds

V. CONCLUSION

MATLAB/Simulink software has been possible to develop modeling and simulation techniques in building and analyzing components for turbofan engines in providing dynamic effects. The model was built with aided individual information, allowing integration of the engine. Capturing of dynamic behavior was given more attention. The reduction of occurrence of algebraic constraints increases the model fidelity of these transients which leads to increase simulation speed. It is imperative that additional work would be required to reduce differences in smooth integrals between the spools and the entire engine. The GE90 Dynamic model will be considered useful for further upcoming research studies, in terms of engine cycle performance.

ACKNOWLEDGEMENTS

This work is supported by the Natural Science Foundation of Jiangsu Province (No. BK20140829), and the Fundamental Research Funds for the Central Universities (No. NS2016024).

REFERENCES

[1]. Scott Michael Eastbourn, *Modeling and Simulation of a Dynamic Turbofan Engine Using Matlab/Simulink* [D]. The University of Akron, 2010

[2]. Walters, E.A , Iden, S.M and Mc Carthy,K, etal. *Invent Modeling, Simulation, Analysis and Optimization*[R]. 48th AIAA Aerospace Sciences Meeting, 4-7 January 2012. AIAA 2010-287

[3]. K. McCarthy, E.Walters, A.Heitzel, etal. *Dynamic Thermal Management System Modeling of a more Electric Aircraft*[S]. SAE Paper 2008-01-2886

[4]. https://en.wikipedia.org/wiki/Turbofan#High-bypass_turbofan

[5]. Adamczyk, J.J.: *Aerodynamic Analysis of Multi-stage Turbomachinery Flows in Support of Aerodynamic Design*[J]. J. Turbo machinery, vol. 122, issue 2, 2000, pp. 189–217.

[6]. Turner, M.G., et al.: *Multi-stage Simulations of the GE90 Turbine*[S]. ASME 99–GT–98, 1999.

[7]. Turner, M.G.: *Full 3D Analysis of the GE90 Turbofan Primary Flowpath*[R]. NASA/CR—2000-209951, 2000.

[8]. Turner, M.G., et al.: *High Fidelity 3D Turbofan Engine Simulation With Emphasis on Turbomachinery-Combustor Coupling*[R]. AIAA–2002–3769, 2002.

[9]. J.C. Breaks etal. *Dynamic Modeling of High Bypass Ratio Turbofan Engines*[R]. AIAA/ASME/SAE.

[10]. Jack D. Mattingly, Link C.Jaw. *Aircraft Engine Controls Design, System Analysis and Health Monitoring* [M]. AIAA.Inc. 37-39

[11]. Scott M. Eastbourn, Rory A. Roberts, *Modeling and Simulaton of a Dynamic Turbofan Engine Using Simulink*[C], AIAA/ASME/SAE/ASEE, Joint Propulsion Conference & Exibit 31 July – 03 August 2011. AIAA 2011-6100

[12]. Rahman, Naveed U, Whidborne, James F, *"Real Time Transient Three Spool Turbofan Engine Simulation A Hybrid Approach"*[J], Journal of Engineering for Gas Turbines and Power, September 2009, Vol 131.

[13]. *The GE90 – An Introduction*[R]. Stanford University AA283 Course Material.

[14]. Benawra S., *Research Proposal on Novel Cycle Analysis based on GE90*[Z]. Nanjing University of Aeronautics and Astronautics, November 2015.

[15]. Rolls Royce. *The Jet Engine*[M]. 5th . UK, 1996. 76

[16]. Benawra.S. *Investigation of Design Parameters on Turbofan Engine PW4000*[D]. Nanjing University of Aeronautics and Astronautics, Nanjing, 2014.