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Thermodynamic Modeling and Simulation of a Geared Turbofan Engine with Hydromechanical Control System

Amin Imani[1*], Ali Rasti Jahromi[2]

[1]Assist. Prof., Department of Mechanical Engineering, Faculty of Engineering, Bu-Ali Sina University, Hamedan, Iran
[2]PhD, School of Mechanical Engineering, Iran University of Science and Technology, Tehran, Iran
*Corresponding author: a.imani@basu.ac.ir

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Abstract

In this paper, in order to investigate the performance of a geared turbofan engine and its control system, the thermodynamic modeling of the engine along with the modeling of the corresponding hydromechanical controller is conducted. Engine test data is used for validation of engine performance simulation. The maximum difference between engine modeling outputs and engine data in take-off conditions is 3.2% and with engine test data in different rotor speeds is 7.6%. In order to model the controller, a comprehensive structure is extracted for the controller by using the engine data and the governing logic. The simulation results of the engine performance along with the control system according to the throttle commands from the maximum degree to the minimum, indicate the accurate performance of the controller model in fulfilment of thrust and limit protection. In addition to analyzing the performance of the engine in different operating conditions, the results of this research can also be used to examine the strengths and weaknesses of the existing control system. Since the capabilities of hydromechanical control systems for managing engine fuel, bleed system and peripheral systems are limited, therefore, simulating the existing controller structure in connection with the engine model is important to develop the hydromechanical type controller to an autonomous electronic type containing condition monitoring, health management and fault-tolerant control.

Keywords: Geared Turbofan Engine, Thermodynamic Modeling, Hydromechanical Control System, Fuel Control, Bleed System.

1. Introduction

Turbofan engines with high bypass ratio have lower specific fuel consumption than turbojet engines, because most of the thrust produced by these engines is provided by the air passing through the engine bypass. In order to have a high bypass ratio and increase thrust and reduce specific fuel consumption, the engine fan speed should be several times lower than the engine core speed. Using a gearbox is an effective solution to reduce the engine's spool speed [1]. Several researches have been done in the field of design and analysis of different parts and performance analysis of geared turbofan engines. In two studies, the opportunities and challenges of using geared turbofan engines have been investigated [2,3]. According to their results, the use of a gearbox to reduce the engine's low-pressure spool speed leads to an increase in the bypass ratio, an improvement in propulsion efficiency, and a reduction in noise and weight compared to the conventional turbofan engines. In other researches in this field, the solution of geared turbofan engines with ultra-high bypass ratio has been analyzed in order to reduce the pollutant emissions and improve specific fuel consumption [4-6]. The design of a geared turbofan engine as the propellant of a small unmanned aircraft has been done by Kelly et al. [7]. Considering that their goal was to convert a small turbojet engine into a geared turbofan engine, the design, production and testing of the fan module for the new engine was considered. The specific fuel consumption of the developed engine is lower than that of the turbojet engine, and its speed and flight altitude are higher than that of the equivalent turboprop engine.

The issue of controlling geared engines has captured the attention of certain researchers as well [8]. In a research by Chapman and Litt, a controller was designed for a geared turbofan engine [9]. They considered a two-spool engine in the thrust class of 130 kN with an ultra-high bypass ratio that had a variable fan nozzle area. The control structure included a PI controller and a set of regulators for the engine's bounded variables so that the engine has a safe operation in the entire flight envelope. Kratz and Chapman also addressed the active turbine tip clearance control of a geared turbofan engine [10]. First, they performed a modeling for the high-pressure turbine tip clearance. Then, they investigated how to use actuators to achieve active control of the turbine tip clearance. According to the studies done, although the issue of analyzing the performance of geared turbofan engines and their components to enhance the design and increase efficiency has been the focus of researchers, the modeling of the hydromechanical controller system used in a group of geared turbofan engines and its effectiveness in connection with the engine model has not been performed so far. This process is important for finding the strengths and weaknesses of the existing controller and facilitates the path to convert it into an autonomous electronic control system containing engine condition monitoring, health management and fault-tolerant control.

In the current study, the performance analysis of a geared turbofan engine along with its control system is performed. For this purpose, after examining the structure of the engine and determining its specifications, a thermodynamic modeling is carried out for the engine. Then, according to the characteristics of the engine hydromechanical controller and the test data, a comprehensive structure is extracted to model the behavior of the controller. In the simulation section, the performance of the engine and the control system model will be evaluated.

2. Specifications of the Studied Geared Turbofan Engine

In this research, ALF502 two-spool geared turbofan engine is investigated. The core of this engine consists of an annular combustion chamber, 7 stages of axial high pressure compressor and one stage of centrifugal compressor, which are driven by 2 stages of axial high pressure turbine [11]. This engine uses a bleed system to prevent compressor surge, whose actuator is installed on the axial high pressure compressor housing. The bleed system facilitates the acceleration of the engine rotor. Fan and an axial low pressure compressor stage are also driven by two low pressure turbine stages through a speed reduction gearbox. In this way, the speed of the fan and the low pressure compressor are the same. The engine design point specifications are presented in Table 1.

Table 1. Specifications of the engine design point [11]

Parameter	Unit	Value
Outer fan pressure ratio	-	1.44
LPC pressure ratio	-	1.25
Axial HPC pressure ratio	-	3.63
Radial HPC pressure ratio	-	2.5
Bypass ratio	-	5.7
Burner outlet temperature	K	1464
Low pressure spool speed	rpm	7602
High pressure spool speed	rpm	20000

3. Engine Thermodynamic Modeling

The thermodynamic cycle modeling equations are based on the Brayton cycle and establish the conservation of energy and momentum of the system. The performance of the compressor and turbine is described and simulated by their performance maps.

The structure of the model built in the MATLAB Simulink environment is a modular type in which the calculations of engine components including inlet, fan, compressor, combustion chamber, turbine and nozzle are performed separately and placed in individual blocks and the inputs and outputs of the blocks are connected to each other. In order to validate the engine model, its results have been compared with the real engine data in the two conditions of take-off and ground test. The engine simulation results in the Matlab-Simulink environment and Gasturb13 software have acceptable agreement with the engine manual data. The maximum mismatch for the take-off condition is 4.6% for Gasturb13 software, and it is 3.2% for MATLAB simulation. In Figures 1-3, the results of the simulations performed by Gasturb13 and MATLAB-Simulink software are compared with the ground test data. According to Figure 1, the maximum error for low pressure spool speed is about 7.6% for two simulations. Based on Figure 2, the maximum error of the low pressure turbine inlet temperature (T45) is about 4.7% for Gasturb13 software, and it is about 1.6% for MATLAB simulation. According to Figure 3, the maximum fuel flow error is about 15% and 5.8% for Gasturb13 and MATLAB, respectively.

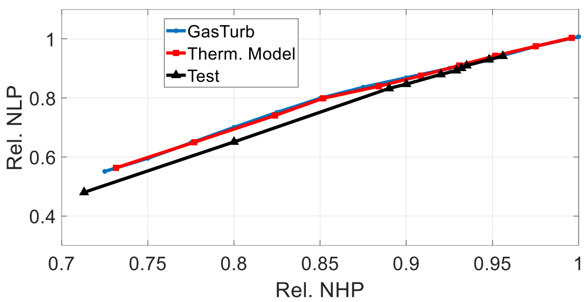

Figure 1. Comparing the simulations with the ground test data: LP spool speed vs. HP spool speed

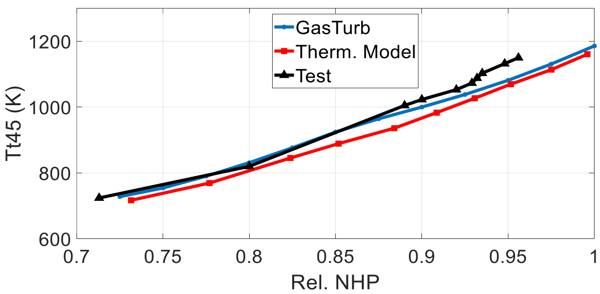

Figure 2. Comparing the simulations with the ground test data: LPT inlet temperature vs. HP spool speed

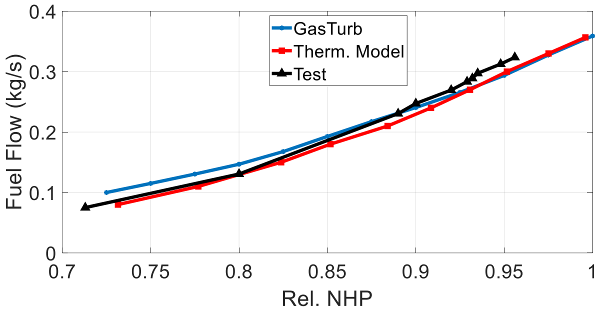

Figure 3. Comparing the simulations with the ground test data: Fuel flow vs. HP spool speed

4. Engine Control System

The control system of the studied engine operates hydromechanically and is responsible for regulating the fuel flow and the performance of the bleed system. In addition to the hydromechanical system, there is an overspeed control system to limit the maximum speed of the low pressure spool. Some methods have been provided for engine control based on core speed, which are usually related to hydromechanical controllers. One of these structures is shown in Figure 4. In this research, the structure of Figure 4 has been developed and the structure of Figure 5 has been extracted for modeling the ALF502 engine fuel control unit. To model the controller, the data related to PLA degree, T12 temperature, compressor outlet pressure (P3), core speed (NH), and fuel flow are considered.

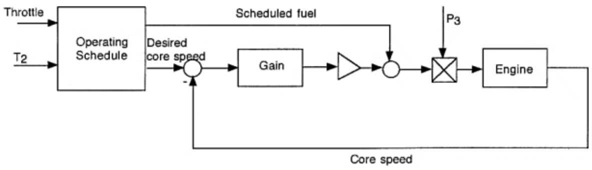

Figure 4. A core speed control structure [12]

Considering that in the ALF502 engine, the core speed is controlled as the thrust representative, a lookup table is extracted to determine the NH equivalent speed according to the throttle degree and the ambient temperature. As the engine controller operates based on Wf/P3, a steady-state control part as a function of throttle degree and ambient temperature is utilized in the form of a feedforward mechanism for Wf/P3. A PI controller is necessary to ensure that the engine speed reaches the desired value. The output of this controller is added to the feedforward section at any time. When the core speed reaches the desired amount, the output of the PI controller becomes zero, and at the new steady state point, the value of Wf/P3 is obtained only from the lookup table. After determining the value of Wf/P3, in order to take into account the restrictions related to acceleration/deceleration and prevent the compressor surge and the combustion chamber blow-out, the resulting value is limited within the limits of a saturation function. In order to determine the required fuel for the engine, the value of Wf/P3 is finally multiplied by the P3 amount that enters the controller through a port. On the hydromechanical controller, there is a maximum/minimum fuel adjustment screw, which is included as a saturation function in the controller model.

5. Simulation Results

In order to check the performance of the studied engine despite the changes in ambient temperature and throttle degree, a comprehensive simulation is carried out in this section. Figure 6(a) illustrates the variation of the throttle angle in the time interval [0-50]s. According to Figure 6(b), in order to consider the change of ambient temperature on the performance of the control system, it is assumed that the ambient temperature will increase linearly from 15°C to 45°C in the time period of [10-30]s.

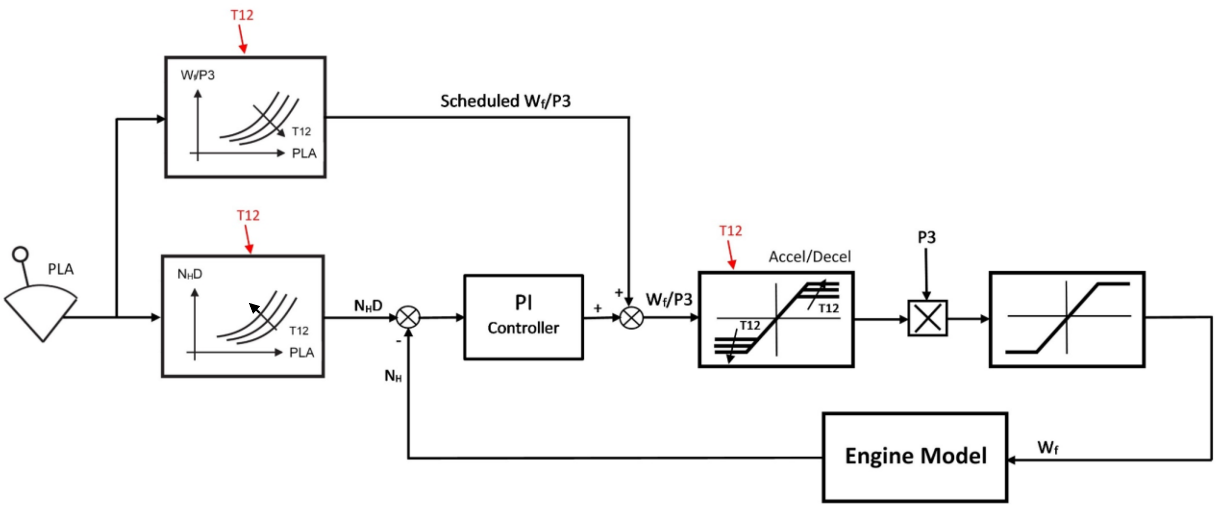

Figure 5. Model structure of the studied engine fuel control system

The changes of the desired thrust are shown in Figure 7(a). In this figure, the engine thrust resulting from the controller's performance is also shown, which indicates the accurate performance of the controller in following the requested thrust. Figure 7(b) shows the desired relative speed of the high pressure spool as well as the actual value, and indicates the precise performance of the controller in tracking the engine speed. The changes of the low pressure spool speed are demonstrated in Figure 7(c). Based on the result, the speed of this spool does not exceed the corresponding limit and this demonstrates the effective performance of the overspeed controller. The changes of the low pressure turbine inlet temperature (T45) are shown in Figure 7(d). The amount of fuel flow determined by the controller is illustrated in Figure 7(e). The changes of the ratio unit (i.e., Wf/P3), which is the basis of the hydromechanical controller operation, are depicted in Figure 7(f). The value of Wf/P3 at any moment is the sum of the steady state part (or the scheduled value) and the dynamic part (from the PI controller). The final value of Wf/P3 remains within the saturation limits.

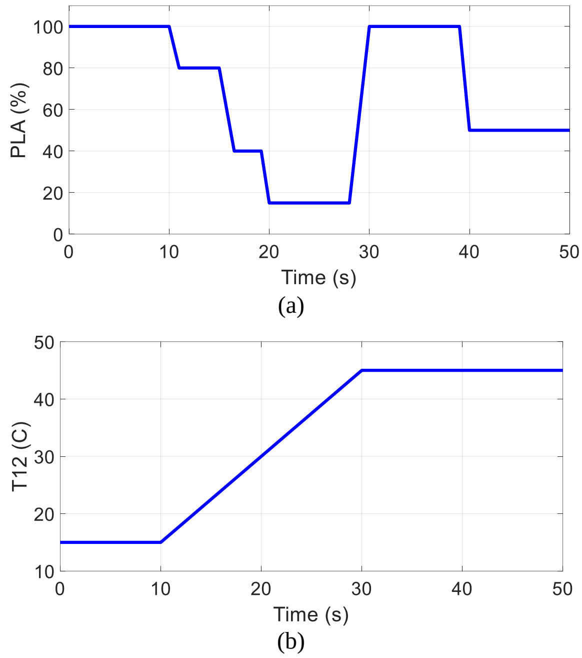

Figure 6. a) Throttle degree variations, b) Ambient temperature variations

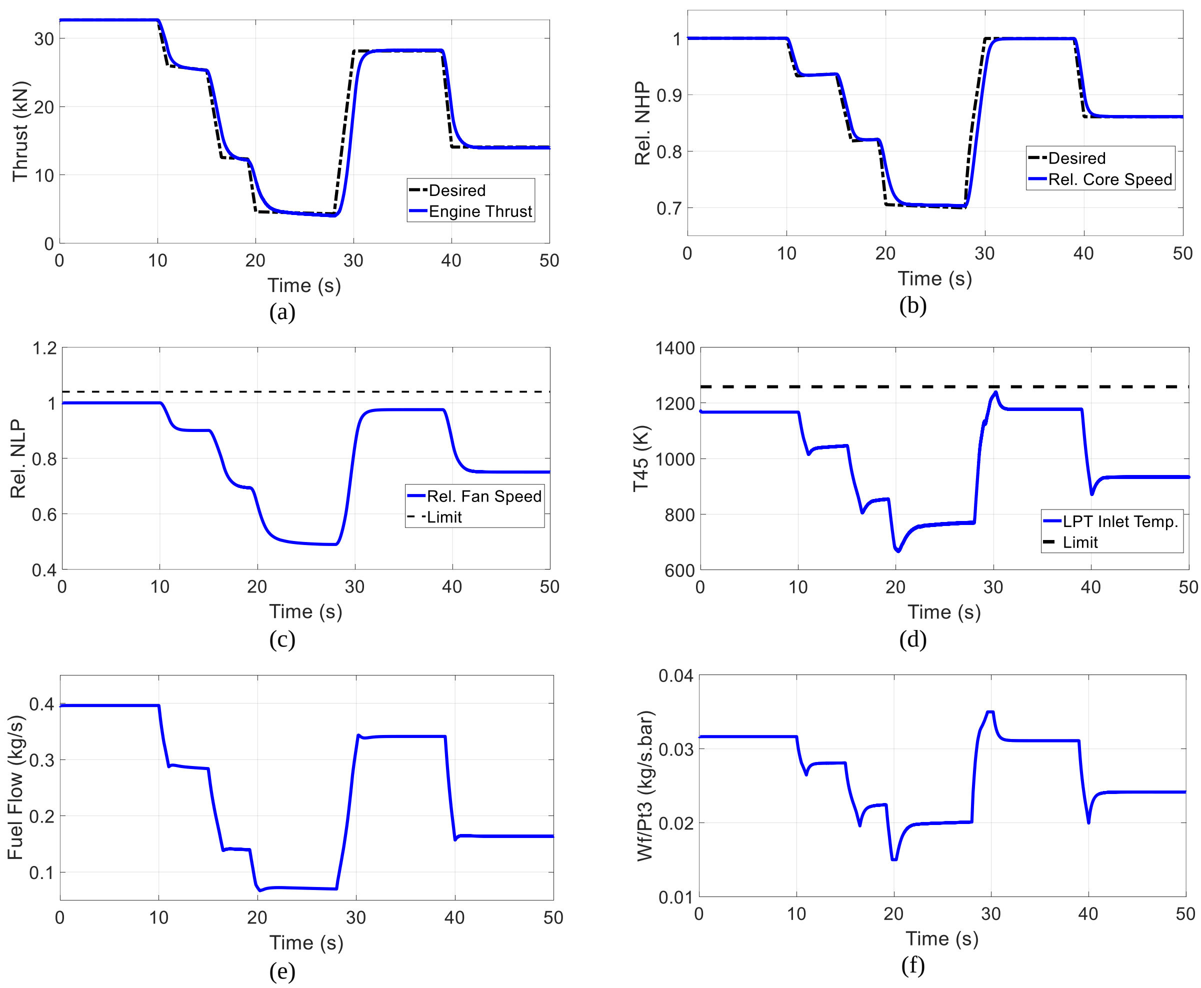

Figure 7. a) Engine thrust, b) Relative core speed, c) Relative LP spool speed, d) LP turbine inlet temperature, e) Fuel flow, f) Ratio unit (Wf/P3)

According to the obtained results, the performance of the modeled controller in providing the requested thrust is efficient and at the same time, the limits that can be controlled by the hydromechanical system are also met.

6. Conclusion

In the present research, to investigate the performance of a geared turbofan engine, a thermodynamic modeling was done along with the modeling of its hydromechanical control system. The maximum mismatch between the engine model outputs and engine data in the take-off condition was 3.2%. It was also 7.6% for engine ground test data at various speeds. By evaluating the behavior of the engine's hydromechanical control system and examining the governing logic and input and output signals, a comprehensive structure for modeling of the controller was extracted. The performance of the engine model along with the controller was assessed using a simulation study. The findings of this study, in addition to analyzing the behavior of the engine in different operating conditions, can also be used to convert the control system from hydromechanical type to electronic type.

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