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Surge and Rotating Speed Control for UAV Turbojet Engine using LabVIEW

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Abstract

In this paper, we propose to prevent compressor surge and control rotating speed for UAV turbojet engine. Turbojet engine controller is designed by applying PID control algorithm and it was applied to the linearized turbojet engine model. To prevent any surge or a flame out event during the engine acceleration or deceleration, the PID controller effectively controls the fuel flow input of the control system. PID results are used as the fuel flow control inputs to prevent compressor surge and flame-out for turbojet engine and the controller is designed to converge to the desired speed quickly and safely. Using LabVIEW to perform computer simulations verified the performance of the proposed controller. The simulation result using the designed PID controller verified that quickly converge to the desired speed and properly control fuel flow rate while preventing the surge and flame out event.

Keywords*: Turbojet Engine, Surge Control, PID Controller, LabVIEW*

1. Introduction

Unmanned aerial vehicle (UAV) refers an aircraft which performs autonomous flying without pilots, according to the program input in advance, recognizing obstacles and determining a route. A turbojet engine for small unmanned aerial vehicles requires a system to be implemented in digital electronic. Also, its air inlet, guide vane of nozzle, air bleed valves, turbocharger lubrication system and braking system needs a variety of control methods [1]. However, to simplify the system, the exhaust nozzle area is to be fixed, so that we can control the rotation speed of the rotor, which is the thrust of the unmanned aircraft turbojet engine, only with the fuel flow rate and reach an optimal engine performance [2].

The turbojet engine for unmanned aerial vehicles requires short take-off and landing distances and fast mobility. It results in a sharp increase in the fuel flow. Due to the increase, the components of the engine are safe from the engine operating limitations, such as compressor surge or flame-out. Especially, the surge is a factor that causes a compressor stall as it makes the pressure of the air flow increase and the air flow rate flowing into the engine decrease. In addition, it may increase the turbine inlet temperature excessively due to the reduced air flow rate of the engine [3].

The goal of designing the engine control system is to ensure safety and reliability, to give the engine idling prevention and thrust control functions. In addition, the transient response performance of engine acceleration and deceleration is to be optimized and the engine should have several engine protecting functions such as surge prevention and temperature rise prevention. Also, it is important to optimize the fuel flow consumption and include error detection and diagnosis functions into the engine control system. The safety level has to meet the guidelines from the authorized agencies. Also, the acceptable failure rate for all the assemblies and components should be reliable. The components include various electrical devices, electronic devices and hydraulics. In addition, the engine control system is supposed to guarantee it reaches the control goals even if a disturbance occurs the engine system or the system parameter changes.

Many researches are working on how to control the engine to extend the lifespan of an aircraft engine and minimize the fuel consumption [4-5]. The previous research on aircraft turbojet engines focused on controlling engine thrust through the fuel flow rate and the exhaust nozzle area control. Also, other studies dealt with surge control in engine acceleration process. As it is difficult to measure engine thrust directly, thrust control is performed by controlling the fuel flow rate and the exhaust nozzle area. When these are controlled, the compressor, which is proportional to the thrust, rotates in a desired speed. Since kinetics equation of an engine is nonlinear, a linear model which is linearized in the operating point of the engine has been adopted to configure a multivariate control system.

An important factor to consider in the design of the engine control system is to make sure engine surge and flame-out do not occur when the engine is accelerated or decelerated. Also, it is important to keep the engine not to exceed the allowable limit temperature with a protection system. Surge, the phenomenon that injected air unexpectedly flows backward, could happen when the aircraft requires strong thrust in a short time, for example, when the aircraft takes off. Surge is the main cause of aircraft accidents and quasi-accidents. Therefore, for a passenger plane and a fighter aircraft, the engine performance is determined by prevention of surge flame-out. Surge control is implemented by changing the exhaust nozzle area or adjust the air flow rate to keep the proper pressure ratio according to the compressor rotation speed. If the exhaust nozzle area is fixed, the rotation speed of the compressor is to be adjusted for surge control[6].

This study adopts PID control method for a single input-output system turbojet engine which inputs the fuel flow rate[7]. The aims of the study are to control the speed of the turbojet engine using PID control method and to prevent surge and flame-out which can occur during acceleration and deceleration by controlling the fuel flow rate. The proposed method proves the performance of the controller which is designed by simulation using the LabVIEW.

2. Turbojet Engine Control Systems

2.1. Turbojet Engine and Surge Control

Turbojet engine is composed of a compressor, a combustion chamber, a turbine, a nozzle as shown in Figure 1. Controller was designed as a target model for small unmanned aircraft with turbojet engine. The turbojet engine can do damage to components such as thermal shock or operation caused by surge or flame out. Performance of engine acceleration and deceleration controller for a turbojet engine is obtained by controlling the fuel flow. The engine may be damaged as the surge, flame-out phenomenon to decreasing the compressor pressure is generated in accordance with the rapid increase in air flow rate when the engine is decelerated. Therefore the controller should be designed to note the surge operating point without causing surge and flame out phenomenon as shown in Fig 2.

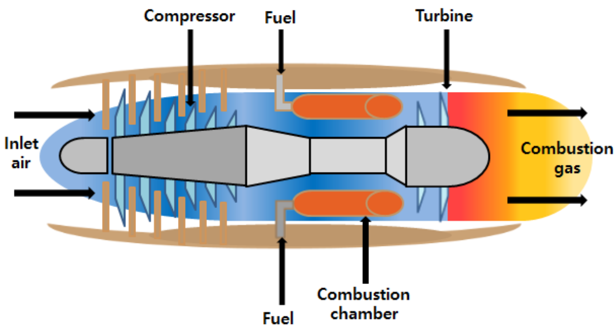


Figure 1. Turbojet Engine Structure

Surge operating point of small turbojet engine compressor is found to be very close proximity to the surge control line. To maximize the performance of the engine, the engine acceleration should be controlled to follow the surge control line in which the surge margin line is closely positioned.

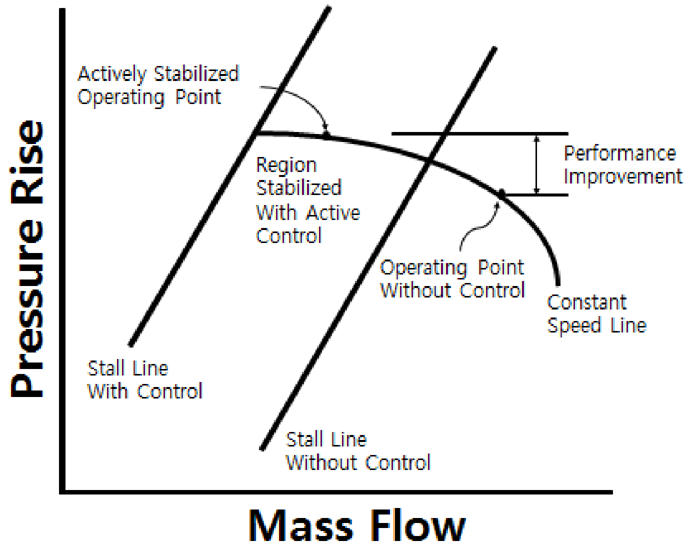


Figure 2. Surge Operation Point

The surge control line can be expressed by the following equation in accordance with the compressor rotating speed above 24000rpm below 29500rpm. Also, the flame-out control line can be expressed by the following equation in accordance with the compressor rotating speed above 27000rpm below 29500rpm

$$P_{surge} = \begin{cases} \frac{(2.912-2.082)(N-20000)}{4000} + 2.082, & N < 24000 \\ \frac{(3.622-2.912)(N-24000)}{3000} + 2.912, & 24000 \leq N < 27000 \\ \frac{(3.938-3.622)(N-27000)}{1000} + 3.622, & 27000 \leq N < 28000 \\ \frac{(4.088-3.938)(N-28000)}{1000} + 3.938, & 28000 \leq N < 29000 \\ \frac{(4.135-4.088)(N-29000)}{1000} + 4.088, & 29000 \leq N < 29500 \\ 4.135 & 29500 \leq N \end{cases} \quad (1)$$

$$P_{frame-out} = \begin{cases} \frac{(2.5835-1.5250)(N-20000)}{7000} + 1.5250, & N < 27000 \\ \frac{(2.8920-2.5835)(N-27000)}{1000} + 2.5835, & 27000 \leq N < 28000 \\ \frac{(3.0260-2.8920)(N-28000)}{1500} + 2.8920, & 28000 \leq N < 29500 \\ 3.0260 & 29500 \leq N \end{cases} \quad (2)$$

2.2. Linear Modeling of Turbojet Engine

Dynamic governing equation of turbojet engine can obtain dynamically unsteady equation of thermodynamical equilibrium from equilibrium equation of power, energy, flow rate. The non-linear equations are linearized by using a perturbation method from the reference operating point in the form of component matching program solution.

State space equation of engine can be expressed as the following equation,

$$\dot{x} = f(x,u) \quad (3)$$

Where x is a state vector of engine, u is a control input vector of engine. The system has linear relation as the following equation because actually it includes multiple state variables and input variables.

$$\Delta\dot{x} = A\Delta x + B\Delta u \quad (4)$$

When there are n number of state variables and m number of control inputs, each matrix can be expressed as the following equation,

$$[A] = \left[\frac{\partial \dot{x}_i}{\partial x_j}\right]_0 \qquad where \begin{pmatrix} i = 1, n \\ j = 1, n \end{pmatrix}$$
$$[B] = \left[\frac{\partial \dot{x}_i}{\partial x_j}\right]_0 \qquad where \begin{pmatrix} i = 1, n \\ j = 1, m \end{pmatrix} \quad (5)$$

In this paper, the state variable vectors are used for the compressor rotation speed (Δx_1), the turbine inlet temperature (Δx_2), the compressor outlet temperature (Δx_3), the fuel flow rate (Δx_4).

2.3. PID Controller

The PID control has been one of the control system design methods of the longest history. PID controller is mainly to adjust an appropriate proportional gain (K_P), integral gain (K_I), and differential gain (K_D) to achieve the optimal control performance [8]. The relationship between the input e(t) and output u(t) can be formulated in the following,

$$U(t) = K_P e_N(t) + K_I \int_0^t e_N(t)dt + K_D \frac{de_N(t)}{dt} \quad (6)$$

A general PID controller system block diagram is shown in Figure 3,

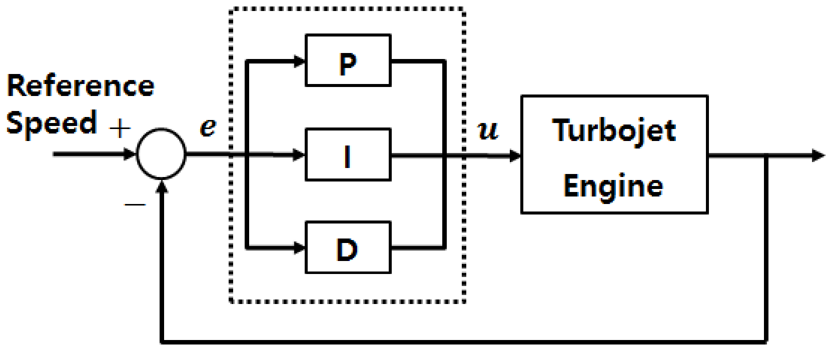


Figure 3. Block Diagram of PID Controller

The simulation model in LabVIEW is shown in Figure 4, 5. The Simulation use control & simulation loop of LabVIEW. On the left side of the Figure 4, it sets an initial RPM, pressure, temperature and flow rate. And to prevent any surge or a flame out event during the engine acceleration or deceleration, the PID controller effectively controls the fuel flow input of the control system. On the right side of the Figure 4, It constitutes a state space using the compressor rotational speed, turbine inlet temperature, compressor discharge pressure, fuel flow rate in the state vector.

We define that as the error of rotate acceleration speed of reference accelerations.

$$e_N = \dot{N}_d - \dot{N} \tag{7}$$

Where e_N is an error of rotation acceleration speed of reference acceleration, $\dot{N}_d$ is reference acceleration speed and $\dot{N}$ is compressor rotation acceleration measured.

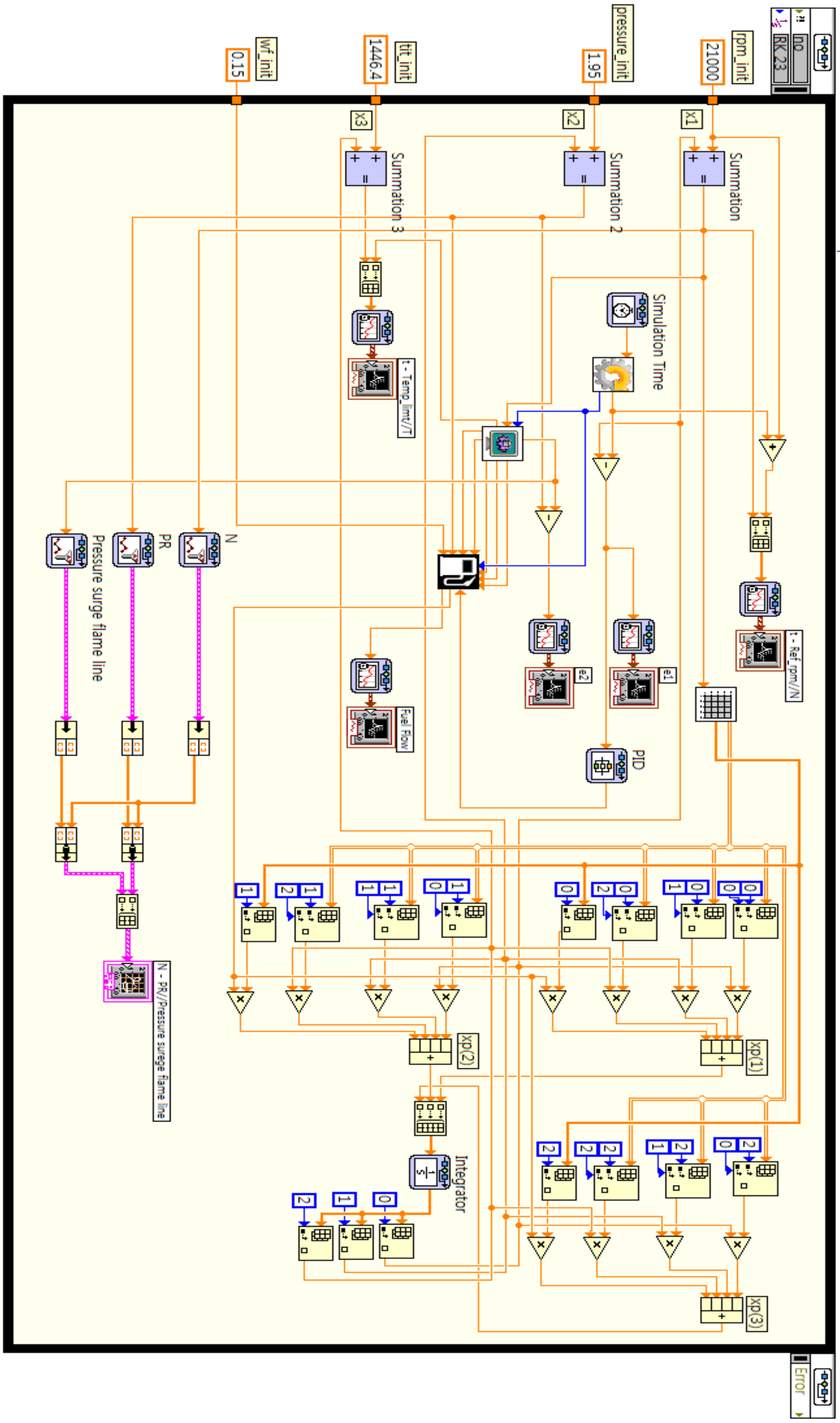


Figure 4. Simulation Block Diagram of the Proposed System in LabVIEW

3. Simulation

The performance of proposed PID engine control method presented in this paper is shown by simulation using LabVIEW. We use a linear model expressed with state space equation in the following equation,

$$\dot{x_{p1}}(t) = A_p x_p(t) + B_p u_p(t) \quad (8)$$

Where, $x_p = [x_{p1} \;\; x_{p2} \;\; x_{p3}]^T$

x_{p1} : compressor rotation speed

x_{p2} : turbine inlet temperature

x_{p3} : compressor outlet pressure

u_p : fuel flow

Once the maximum compressor rotating speed is 100%, we can have the system matrix and input matrix after linearization at each point 50%, 60%, 70%, 80% and 90% as follows,

Case 50%

$$A_p = \begin{bmatrix} -7.0893E+00 & 3.6768E+04 & 5.0478E+01 \\ 1.6640E-01 & -1.0930E+03 & 1.4680E+00 \\ 3.3399E+00 & -5.0885E+04 & -3.4759E+02 \end{bmatrix}$$

$$B_p = [-2.3449E+04 \quad 3.2640E+02 \quad 5.9776E+05]$$

Case 60%

$$A_p = \begin{bmatrix} -6.9746E+00 & 2.9849E+04 & 4.6627E+01 \\ 1.5664E-01 & -9.9804E+03 & 1.4095E+00 \\ 3.2662E+00 & -4.0854E+04 & -3.6907E+02 \end{bmatrix}$$

$$B_p = [3.5270E+03 \quad 1.2231E+02 \quad 5.6693E+05]$$

Case 70%

$$A_p = \begin{bmatrix} -6.8155E+00 & 2.6187E+04 & 4.6301E+01 \\ 1.5248E-01 & -9.2628E+03 & 1.4118E+00 \\ 3.5340E+00 & -4.9804E+04 & -3.8205E+02 \end{bmatrix}$$

$$B_p = [-1.7240E+03 \quad 1.6267E+02 \quad 5.6502E+05]$$

Case 80%

$$A_p = \begin{bmatrix} -6.1171E+00 & 2.2374E+04 & 4.5137E+01 \\ 1.1650E-01 & -7.9733E+02 & 1.4274E+00 \\ 3.9098E+00 & -5.0108E+04 & -3.9057E+02 \end{bmatrix}$$

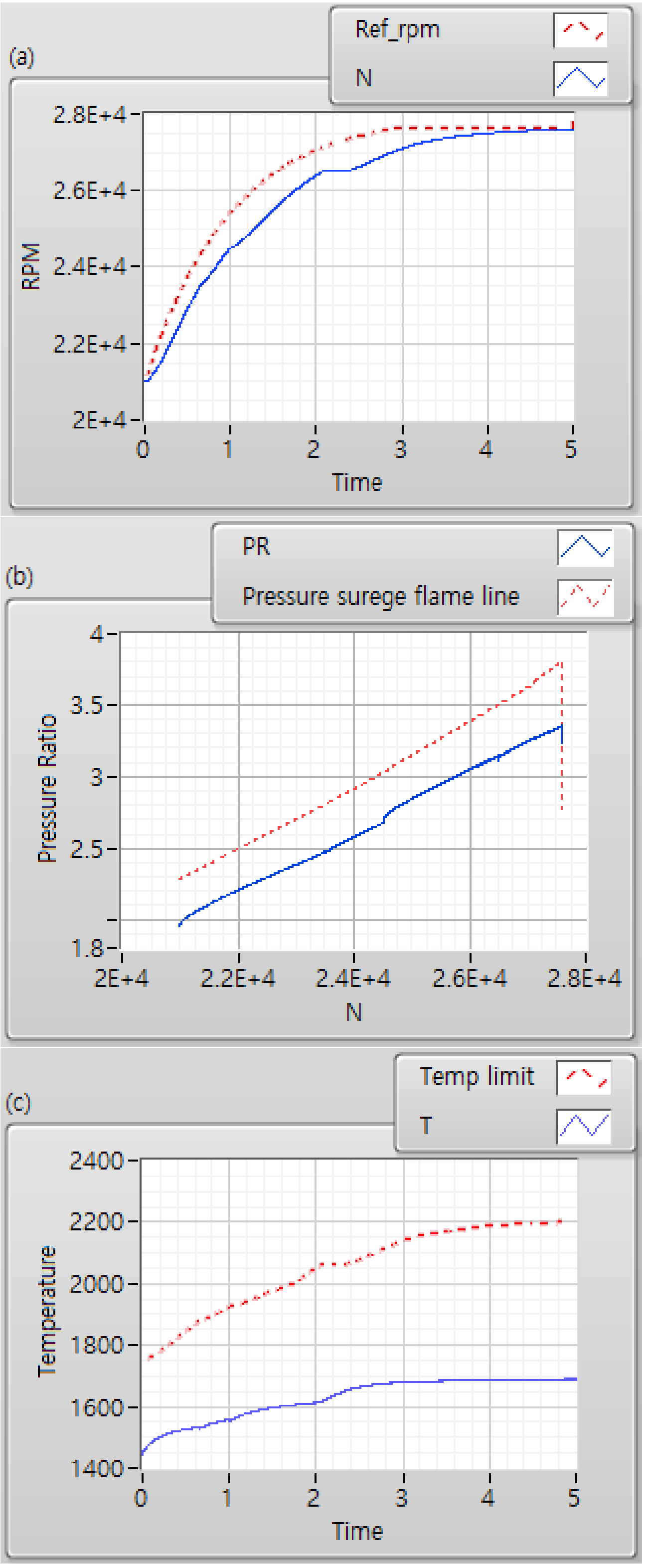
$$B_p = [-7.5395E+03 \quad 1.8614E+01 \quad 5.5251E+05]$$

Case 90%

$$A_p = \begin{bmatrix} -6.1182E+00 & 1.9087E+04 & 4.0209E+01 \\ 8.6668E-02 & -7.4336E+02 & 1.3260E+00 \\ 4.4379E+00 & -5.1329E+04 & -4.0410E+02 \end{bmatrix}$$

$$B_p = [-2.0238E+04 \quad 4.8370E+02 \quad 5.5324E+05]$$

As shown in Figure 5, 6, the engine adopting the PID controller operates successfully without any surge or flame out event. The rotor rotating speed at the initial state is set to 21000 rpm, and accelerated until reaching to 27650 rpm for 3 seconds, and it maintains this state for 2 seconds, and then reduces the speed by 21000 rpm for 3 seconds. Compressor rotation speed shows a quick response characteristic to the reference speed. Compressor outlet pressure and turbine inlet temperature show that they maintain performance within a stable range without exceeding the limit. The control gains of the proposed PID controller are K_P = 0.00005, K_I = 0.00007, K_D = 0.000001.


(a)
Ref_rpm
N
RPM
2.8E+4
2.6E+4
2.4E+4
2.2E+4
2E+4
0
1
2
3
4
5
Time
(b)
PR
Pressure surege flame line
Pressure Ratio
4
3.5
3
2.5
1.8
2E+4
2.2E+4
2.4E+4
2.6E+4
2.8E+4
N
(c)
Temp limit
T
Temperature
2400
2200
2000
1800
1600
1400
0
1
2
3
4
5
Time

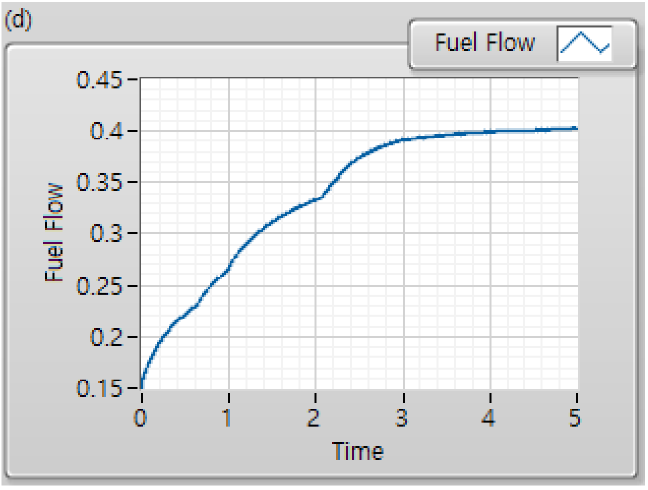
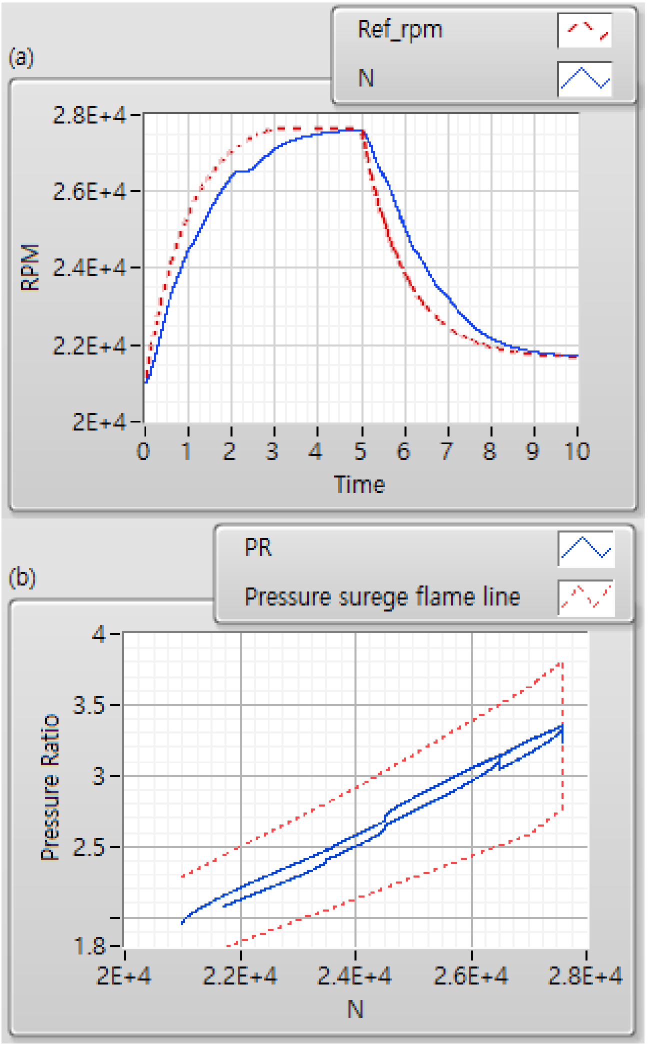


Figure 5. Simulation Results (a) Compressor Rotation Speed (b) Compressor Outlet Pressure Ratio (c) Turbine Inlet Temperature (d) Fuel Flow Rate



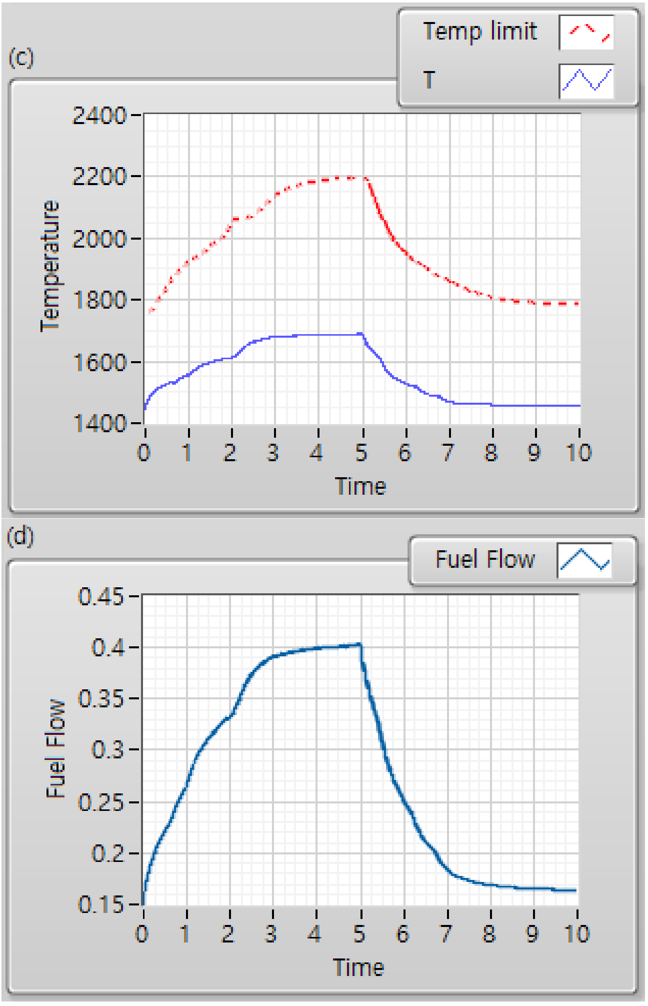


Figure 6. Simulation Results (a) Compressor Rotation Speed (b) Compressor Outlet Pressure Ratio (c) Turbine Inlet Temperature (d) Fuel Flow Rate

4. Conclusion

In this paper we propose a turbojet engine controller of unmanned aircraft based on PID controller. The controller which is designed for the fast response was confirmed for the reference speed while maintaining the required performance in the steady state for the velocity, pressure, temperature, and fuel flow through the simulation using the LabVIEW. To prevent any surge or flame out event during the engine acceleration or deceleration, the PID controller effectively controls the fuel flow input of the control system. Computer simulations applied to the linear model of a turbojet engine show that it quickly converges to the desired speed and properly control fuel flow rate while preventing the surge and flame out event.

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