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Modeling and Timing Simulation of Micro Turbine engine in Starting Process

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Abstract. The stability of start-up process of turbine engine is the foundation of its operation. The process of starting performance optimization is very complex, and the experiment is dangerous, so it is very necessary to make the simulation study on the turbine engine starting process. In this paper, the mathematical model of turbine engine in starting process was established, according to the JetCat-P400 turbine engine starting process principle, using the experimental data of engine ground operation and the actuator voltage data. The simulation results showed the validity of the model.

1. Introduction

Turbine engine is a nonlinear, time-varying and complex pneumatic thermodynamic system, and the longevity of engine is influenced by the performance of the starting process. It is difficult to get the component characteristics of turbine engine at low rotate speed, particularly characteristics of combustion chamber, compressor and turbine. In [1-2], a component-level ground start-up model of turbine engine is established, but it is difficult to obtain the characteristics of the components. In [3-4], a Simple Three Segment Integral Method is put forward to build the model of turbine engine in start-up process. According to the working process of turbine engine ground starting, the starting process includes three phases: engine rotor is driven by starter motor only, engine rotor is accelerated by the both starter motor and turbine together, and the turbine works alone. In [5], Radial Basis Function(RBF) neural network is proposed to build the model of turbine engine in start-up process. However, its physical meaning is not clear. Above all, in the process of starting performance optimization, these three models cannot effectively describe the impact to the turbine engine' performance with the change of actuator state.

Research of this paper was based on the JetCat-P400 turbine engine system. Firstly, the turbine engine starting process sequence was analysed in detail, and then the rotor speed mathematic model of turbine engine starting process was established based on analysing its load condition. Finally, the accuracy of the model was verified by timing simulation of turbine engine in starting process.

2. Ground operation of a turbine engine and analysis of the starting process

The starting process of turbine engine involves five actuators: starting motor, ignition, pump, main fuel solenoid and starting fuel solenoid, which work together. The starting process of engine is carried out by controlling the actuator in accordance with the timing sequence, thus, how to obtain the time sequence of actuators is the foundation of modeling and analysing the start-up process. In this paper, the engine ground operation, aiming at acquiring experimental data, was executed firstly. Then, the actuator state of each stage was obtained through analysing the experimental data. Finally, the time sequence of start-up process was detailed analysed according to the actuator state.

2.1. Turbine engine experiment platform

The ground operation of the turbine engine experiment platform was based on JetCat-P400 turbine engine, shown as Figure 1. The system consists of two parts, one part is the JetCat-P400 turbine engine system, including turbine engine, ground support unit (GCU), electronic control unit (ECU), fuel pump, battery, the other part is a voltage monitoring system [6-7], in which a simple and cheap development board with stm32 is used to monitor the voltage of the four actuators, the starter motor, ignition, the main fuel solenoid and the starting fuel solenoid.

Figure 1. Experiment platform

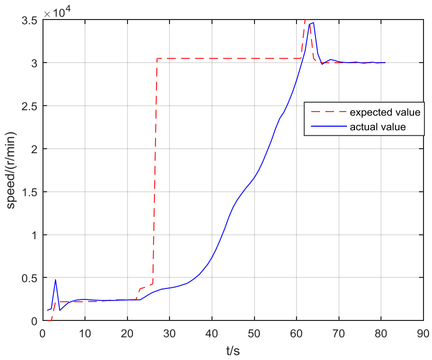

Figure 2. Engine speed curve

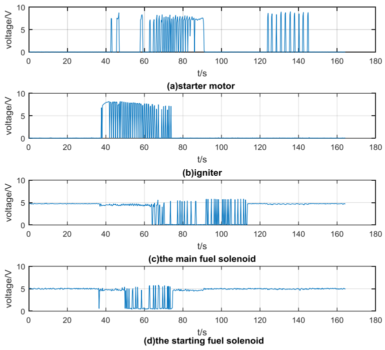

Figure 3. Actuator voltage

2.2. Turbine engine ground operation experiment

The aim of the ground operation experiment is to obtain the experimental data of the turbine engine actuator. Data has two sources. One part of data comes from the turbine engine ECU, shown as Figure 2, in which dashed lines are used for the expected value of turbine speed and solid lines are used for its actual measured value. And the other part of data comes from the voltage monitoring system, from which the voltage of the actuator, the starter motor, ignition, the main fuel solenoid and the starting fuel solenoid can be obtained, as shown in Figure 3. In Figure 3 a set of turbine engine successful data is listed and the engine starts from 30 seconds. Figure 3(a) shows the voltage value of starter motor and the value of 0 express the starter motor not works. From the voltage value, the status of the motor can be known. The status of the ignition is the same as the starter motor, however, the main fuel solenoid and the starting fuel solenoid are just the opposite.

3. Modeling of micro turbine engine in starting process

The ground starting process of turbine engine musts rely on the outside motive power, because that the ignition will only cause the engine damage, does not make accelerate, when the engine speed is zero. When going up to a certain rotate speed and temperature, the fuel can be pumped and ignited. The gas created by combustion chamber makes the turbine work, and increases the engine speed. With increasing of the engine speed, the resistance of the turbine goes up. In conclusion, starter motor and gas created by combustion chamber does work to the rotor, thus generates a positive acceleration. On the other side, the resistance of the turbine itself makes the engine speed decrease. So the acceleration of engine rotor can be expressed as:

$$a = a_q + a_T - a_C \tag{1}$$

where the a_q is the acceleration from starter motor, and its value is 0 when motor turn off. The a_T is the acceleration from oil inflame, and its value is 0 when the main fuel solenoid closed. The a_C is the reverse acceleration from the friction or air resistance.

Thus, the engine speed model of turbine engine can be described by the following equation:

$$n = n_0 + \int_0^t a\,dt \tag{2}$$

where the n_0 is initial speed of engine, in the condition of ground experiment, the engine speed is 0.

3.1. Calculation of a_C

When the ground operation experiment being finished, the starter motor, oil pump and oil valve is turned off, the reverse acceleration of engine rotor comes from the frictions and air resistance. So a_C can be identified using the data from engine shut down process. When the engine works with high speed, its mainly resistance comes from the air. Ignoring the driving accessories registers and frictional resistance, then a_C could be considered directly as proportional to the square of the engine speed [8]. It can be described as follows:

$$a_C = C \cdot n^2 \tag{3}$$

where the C is a constant related to motor type.
The experiment data is obtained from the stage of automatic stop in turbine engine ground operation experiment, shown as Figure 4. In automatic stop stage, the starter motor and fuel are not doing any work to engine, and the engine speed reduces slowly. The acceleration of the turbine rotor can be calculated by doing derivation to the engine speed. Finally, the constant can be calculated:

$$C = 2.6921 \times 10^{-5} \tag{4}$$

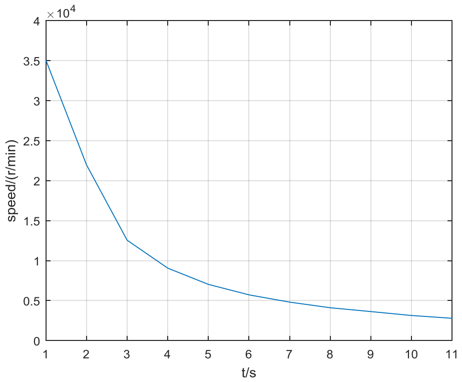

Figure 4. Engine speed curve

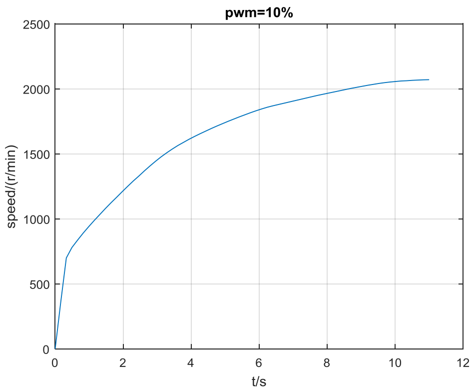

Figure 5. Engine speed curve

3.2. Calculation of a_q

The JetCat-P400 turbine engine uses a direct-current (DC) motor for starter motor. DC motor has a small armature resistance. When DC motor being in an energized state, the motor will generate a large starting current which will bring the motor spins and generates the reverse electromotive force. Then, the current and the motor torque start to decrease, so does the corresponding acceleration. Finally, it will be stable in a certain rotating speed. The common DC motor equation shows as follow [9]:

$$T_m \frac{dw_m(t)}{dt} + w_m(t) = K_m u_a(t) - K_c M_c(t) \tag{5}$$

where the $w_m(t)$ is the motor speed and $w_m(t) = n$. The T_m is the time constant of motor. The K_m is a constant related to the motor type. The $u_a(t)$ is the motor voltage. The $K_c M_c(t)$ is the motor load torque.
Acceleration given by load torque can be calculated as follows:

$$\frac{K_c}{T_m} M_c(t) = C \cdot n^2 \tag{6}$$

The motor voltage is calculated as:

$$u_a(t) = U \cdot pwm\_motor \tag{7}$$

where $U = 9.9V$, which pwm_motor is the motor driver board voltage. The pwm_motor is the duty ratio of motor which varies between 0 and 1.
Combining Eq. (6), (7) with Eq. (8) yields can be obtained:

$$\frac{dn}{dt} = \frac{K_m}{T_m} \cdot U \cdot pwm\_motor - \frac{n}{T_m} - C \cdot n^2 \tag{8}$$

The acceleration given by motor can be expressed as:

$$a_q = \frac{K_m}{T_m} \cdot U \cdot pwm\_motor - \frac{n}{T_m} \tag{9}$$

In order to obtain the parameters of starter motor, the turbine engine ground operation experiment is carried out. In the condition of zero motor speed, the pwm_motor is 10%, when motor speed keeps going up, record the current data, show as Figure 5. Make derivation to motor speed, find $\frac{dn}{dt}$, then the correlation coefficient can be obtained as follows:

$$\frac{K_m}{T_m} \cdot U = 8130 \quad \frac{1}{T_m} = 0.05 \tag{10}$$

3.3. Calculation of a_T

For simplify the problem, a linear relationship between the turbine acceleration and rotate speed is considered as follow [8]:

$$a_T = \frac{C \cdot n_r^2}{(n_r - n_1)} \cdot (n - n_1) \tag{11}$$

where n_1 is the engine speed before the ignition, n_r is the balanced speed of engine between the turbine and the compressor power in contemporary oil supply condition.

After turbine engine being ignited, the stable speed of engine in different fuel injection conditions are different. Based on the analysis on experimental data, the stable speed of engine has a linear relationship with oil pump, and the relationship can be expressed as:

$$n_r = k \cdot U_{pump} \tag{12}$$

where the k is constant. The U_{pump} is voltage of oil pump.

Through the turbine engine ground operation experiment, the stable rpm corresponding to oil pump can be extracted. In the situation of voltage keeping stable, each rpm is processed by average filter. The relationship between the engine speed and oil pump is shown in Figure 6. Using MATLAB Fitting toolbox, we get the parameter as:

$$k = 2.708 \times 10^4 \tag{13}$$

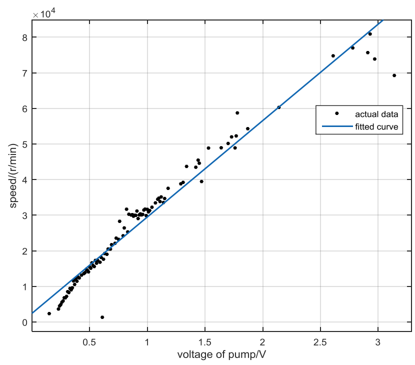

Figure 6. Steady speed relations with oil pump voltage

4. Timing simulation of micro turbine engine in starting process

The starting process of turbine engine is done strictly according to the timing. From the above analysis we can see, the starting process is not only power on the starter motor and fuel pump, but also includes a few steps in chronological. In different stages, the status of actuator is not the same. Even in the same stage, the starter motor and fuel pump voltage at different time is also different. So the start process of turbine engine should take the time sequence as consideration.

In this paper, the simulation of turbine engine in starting process was achieved based on the software MATLAB/Stateflow [10-11]. Stateflow is good at realizing the logical transfer & event-driven FSM (finite state machine). Such graphical utility can improve the efficiency of turbine engine in starting

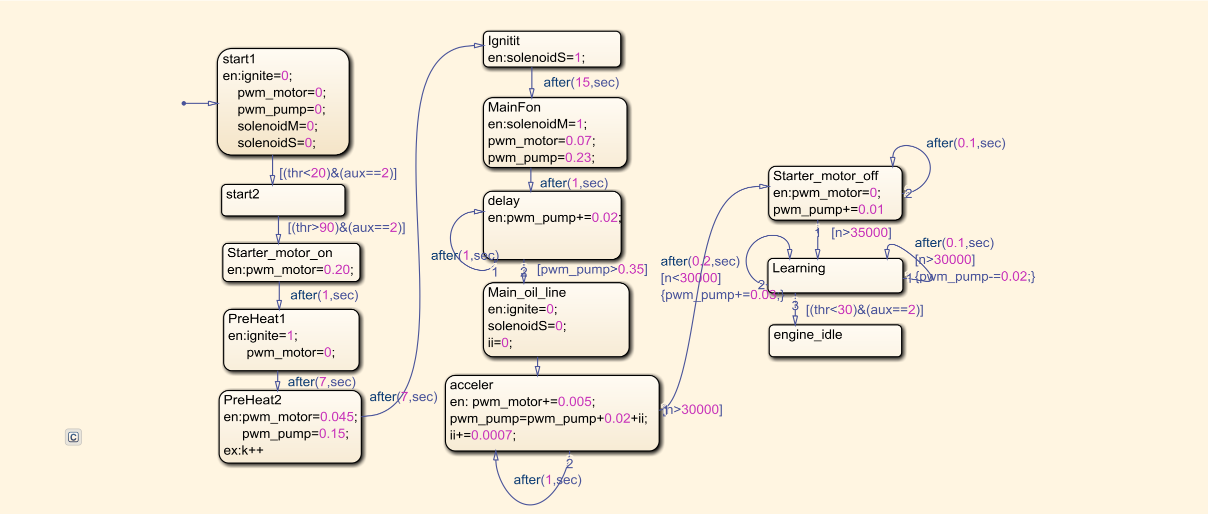

Figure 7. Stateflow chart of turbine engine controller

Figure 7 is the subsystem of the "Turbine engine controller". It as can be seen from the Figure 8, when simulation begins, the system enters into the stage of "start1", and all the actuators will be turned off. Then, waiting for the start-up signal, the throttle stick is moved from minimum to maximum and the auxiliary stick keeps in the start state. After the start signal has been received, the starter motor is activated within one second. With the model of turbine engine in starting process, the engine speed of the moment can be calculated. Then, the starter motor is turned off, the engine steps into the next state after 7 seconds, the engine speed of this moment can also be calculated, and so on, the turbine engine rotor speed can be calculated. The simulation curve is shown in Figure 8.

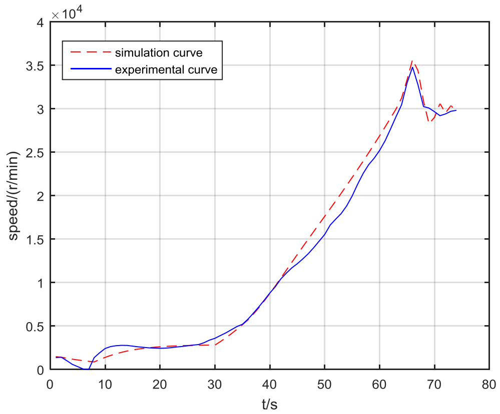

Figure 8. Engine speed curve in starting process simulation

In Figure 8, the solid line represents the turbine engine ground experiment data, while the dotted line shows the predictive value. In this paper, there are two sets of experimental data, the first is used to build the model of turbine engine in starting process, and the second is used to validate the correction of the model. From this figure, the simulation data is well in accordance with the experimental data, and the trend goes to the same direction. Thus, the advantage of modeling according to the timing sequence can be embodied.

5. Conclusion

In this paper, an analytical study about JetCat-P400 turbine engine's starting process sequence was carried out based on the experimental data of engine ground operation. Firstly, the mechanical properties of turbine engine rotor were studied. Then, the start process mathematical model was established. Meanwhile, relevant parameters were identified through analysing the experimental data. Finally, a timing sequence simulation of turbine engine was put forward.

Simulation results showed that the simulation data suited experimental data well. The turbine engine mathematical model and timing sequence simulation method adopted in this paper has be of significance in research guidance of the turbine engine control system.

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7. References

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