Study on Regulating Law of Two-stage Turbo charger System of Piston Aircraft Engine

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Abstract

The power of engine can be recovered at high altitude by matching turbocharger, however, if the mass flow of turbine is not accurate, it will result in under power or boost pressure exceed engine required strength of structure, therefore the mass flow of turbine should be regulated exact. A certain type of piston aircraft engine was selected as a testing engine and its two-stage turbo charger model was built based on GT-Power software and the model's effectiveness was demonstrated by a large number of experiments. The regulating law of turbine waste-gate in different operating conditions can be researched by using this model. The results show that the power and the intake air pressure of the engine can be achieved to the design goal within an altitude of 10,000 meters. The regulating law of the turbine waste-gate is the basis for Turbine Control Unit, which is fairly important for the development of piston aircraft engine.

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Keywords: piston aircraft engine, two-stage turbocharger, regulating law of turbine waste-gate, GT-Power, TCU;

1. Introduction

The piston aircraft engine is widely applied on small plane due to the characteristic of light weight, small size, low cost, etc. In order to improve flight altitude and airworthiness, we usually use Turbo Technologies.

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In this paper a certain type of piston aircraft engine with one-stage turbo charger and electronic control of boost pressure was selected as a testing engine. The power of the engine will be dropped quickly after the altitude exceeds 5,000 meters. To ensure the power of the engine can be recovered to ground condition at an altitude of 10,000 meters, a two-stage turbo charger system was matched to the engine. Avoiding the boost pressure is more than the required structure strength for this piston aircraft engine matched two-stage turbocharger system, the exhaust gas by pass waste-gate should be regulate exactly.

2. Matching of Engine and Turbo Charger

2.1 Description of the Engine

According to the requirement of design, we selected a certain type of piston aircraft engine as a testing engine. This engine is 4-stroke, 4 cylinders horizontally opposed, spark ignition engine, equipped with one-stage turbo charger and electronic control of boost pressure and 2 constant depression carburetors. Performance data and Dimensions of this engine are shown in Table1 and Table 2.

Table 1. Performance data

| Power-Setting      | Engine speed [rpm] | Performance [kw] | Torque [Nm] | Throttle position[%] |
|--------------------|--------------------|------------------|-------------|----------------------|
| Take-off power     | 5800               | 84.5             | 139         | 115                  |
| Max. continuous power | 5500               | 73.5             | 128         | 100                  |

Table 2. Dimensions

| Bore [mm] | Stroke [mm] | Displacement [ml] | Compression ratio |
|-----------|-------------|-------------------|-------------------|
| 79.5      | 61          | 1211              | 9:1               |

2.2 Description of the Turbo Charger

To ensure the engine and the turbocharger can be matched well and meet requirement of the design, we should design a suitable turbocharger according to the total pressure ratio and air mass flow. According to the ambient pressure at altitude of 10 kilometres and the pressure that we wanted to achieve in air-box and consider losses of turbochargers and intercoolers, the total compression ratio can be confirmed by the formula below:

\[ P = \frac{P_b}{P_a\eta_e} \]  

Where \( P \) is the total pressure ratio, \( P_b \) is the pressure in the Air-box, \( P_a \) is the ambient pressure, \( \eta_e \) is the coefficient of efficiency.

Because the turbo charger system in this article is two-stage, we also should confirm compress ratios of each one. The distribution of compress ratios should be confirmed by experiments because it varies in different operating conditions [1].

The air mass flow can be confirmed by
\[ G_e = \frac{N_e g_e \alpha \eta_e}{3600} \]  

(2)

Where \( G_e \) is the air mass flow, \( N_e \) is the power, \( g_e \) is the fuel consumption, \( \alpha \) is the excessive air ratio, \( \eta_e \) is the volumetric efficiency, \( l_0 \) is the air-fuel ratio.

3. Two-stage Turbo Charger Model

A two-stage turbocharger model based on GT-Power software was built according to the parameters of the engine and turbocharger and boundary conditions. The flow model involves the solution of the Navier-Stokes equations, namely the conservation of continuity, momentum and energy equations. These equations are solved in one dimension, which means that all quantities are averages across the flow direction [2]; Combustion model in the cylinder is based on the burn rate, which can be calculated from the cylinder pressure which has been measured in the laboratory; Heat transfer model in the in-cylinder uses Woschni model [3] to calculate the heat transfer coefficients. The mechanical friction in the engine uses the Chen-Flynn model [4] to calculate engine friction using the following formula:

\[ FMEP = C + (PF \times Pmax) + (MPSF \times Speedmp) + (MPSSF \times Speedmp^2) \]  

(3)

Where FMEP is the Friction Mean Effective Pressure, Pmax is the Maximum Cylinder pressure, Speedmp is the Mean Piston Speed, C is the Constant part of FMEP, PF is the Peak Cylinder Pressure Factor, MPSF is the Mean Piston Speed Factor, MPSSF is the Mean Piston Speed Squared Factor.

The two-stage turbocharger model is equipped with two parallel turbines and two series compressors, making use of the energy in the exhaust gas for compression of the intake air (boost pressure) [5]. There are also two intercoolers, which are arranged behind each compressor. In actual engine, the boost pressure in the air box is controlled by means of an electronically controlled flap (waste gate) in the exhaust gas turbine and in this model it is achieved by a PID controller. The waste gate regulates the speed of the turbo charger and consequently the boost pressure in the air box. The required nominal boost pressure in the air box is determined by the throttle position sensor mounted on the carburetor. The sensor's transmitted position is linear from 0 to 115% corresponding to a throttle position from idle to full power.

4. Model Testing

We can demonstrate the model's effectiveness by means of comparing the simulation results with the experiments results. To achieve this goal, a model of the testing engine was built keeping partial of the two-stage turbocharger model from air intake system to the exhaust system unchanged. Fig.1 shows simulation results and the experiment results contrast diagram of speed characteristic at 100% throttle position. Fig.2 shows simulation results and experiment results contrast diagram of load characteristic at 5,500 RPM.
Form Fig.1 and Fig.2 above, we can see that the maximum power error is less than 3% and the maximum fuel consumption error is less than 5%. So we can draw a conclusion that the model is effectiveness.

5. Simulation Results of Two-stage Turbocharger Model

As the increase of altitude, the density and temperature of intake air are gradually reduced. In order to ensure the power of the engine can be recovered to the ground condition, the intake air should be boost but should not exceed the required nominal boost pressure in the air-box, which is controlled by the PID control system. Fig.3. shows engine power recovery curves in different altitudes at 5500 RPM, and Fig.4 is the corresponding fuel consumption.
Fig. 3 shows that the engine power can be recovered to the ground condition within 10 kilometres, so we can draw a conclusion the matching between engine and turbocharger satisfies the design purpose. From Fig.4, we can see that the fuel consumption accords to theory values and is lower than one-stage turbocharger engine compared with Fig.2. So the advantages of two-stage turbocharging engine not only in dynamic performance but also in the economic performance.

6. Regulation Law of Turbine Waste-gate

The design goal of this engine is to ensure the engine power can be recovered to ground condition at a certain altitude. However, if the regulating law is not correct, the boost pressure in the air box maybe will exceed the required strength of the engine, which is dangerous especially for aircraft engine. Fig.5 shows exhaust gas mass flow that through the waste-gate in different altitudes at 5500 RPM.

We can see that exhaust gas mass flow that through the waste-gate is gradually decrease with increase of the altitude, and the mass flow is not zero. This indicates the exhaust gas is sufficiently for turbine, so the design of the two-stage turbocharging engine is reasonable. Apparently, research on regulating law of turbine waste-gate has a profound significance on safety for aircraft airworthiness.
7. CONCLUSION

In this paper a study on turbine waste-gate was performed. Its main goal is to find the exact regulating law of turbine waste-gate, which is the fundamental data for TCU. At the same time, we can use this model to test and optimize the matching between turbocharger and engine, so that the turbocharger can be worked in high efficiency zone. In all, it provides a good way to research regulating law of turbine waste gate and some dangerous cases that are difficult to experiment in reality. It makes a certain meaning for aircraft’s development.

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