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Research on Modelling of Aviation Piston Engine for the Hardware-in-the-loop Simulation

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Abstract. In order to build the aero piston engine model which is real-time and accurate enough to operating conditions of the real engine for hardware in the loop simulation, the mean value model is studied. Firstly, the air-inlet model, the fuel model and the power-output model are established separately. Then, these sub models are combined and verified in MATLAB/SIMULINK. The results show that the model could reflect the steady-state and dynamic performance of aero engine, the errors between the simulation results and the bench test data are within the acceptable range. The model could be applied to verify the logic performance and control strategy of controller in the hardware-in-the-loop (HIL) simulation.

1. Introduction

Developing a controller for aircraft engine is a very long term work, which will cost a lot of manpower and material resources. In order to improve design efficiency and reduce the risk, the controller is usually applied to the HIL (hardware in the loop) platform before controlling the real engine [1]. Therefore, establishing a general HIL platform is important for an aircraft engine controller. In this article, a piston engine model for aircraft is built based on the mean value engine modelling approach. At the same time the built model was verified in MATLAB/SIMULINK, and which could provide a fast modelling approach for real-time engine model based on the code generation technology. Considering the control period of aero engine is generally less than 20ms, the complex aero engine model with a long computing period is difficult to satisfy the requirement of real time. [2-3] According to the demand of the HIL system, the engine model should meet the requirements as followings: (1) The engine model can reflect all operating conditions; (2) Its accuracy could meet the requirements on verifying the logic and performance of controller [4]; (3) Both steady-state simulation and dynamic simulation can be carried out [5]; (4) It has high universality and could be applied to the different engines after slight modification.

Engine dynamic model mainly includes mean value engine model (MVEM) and each cylinder respectively controlled engine model (CCEM) at present. Compared to each cylinder respectively controlled engine model, mean value engine model has the advantages of simple structure, lower

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computing iteration amount, the overall accuracy can meet the requirements of simulation, the model can describe the steady and dynamic characteristics of engine, and it could be applied to the electronic control system design and analysis of engine modelling [6]. Therefore, mean value engine modelling method is selected to establish aviation piston engine model in the article.

2. Introduction of MVEM model

MVEM model was first proposed by Rasmussen, however, its structure and general expression form were proposed by Elbert Hendricks [7]. MVEM model focuses on the dynamic characteristics of the engine, and ignores the difference of each cylinder working state in different crank shaft angle during a work cycle, and the difference of each cylinder is processed through the average value method [8-10]. According to the engine operating principles, the analysis and simulation of the working process of engine are started from the energy conversion and working medium flow. In the process of modelling, differential or algebraic equations are used to describe the simple and clear physical processes. Empirical formula is instead of those parts which are difficult to describe with mathematical models or complex physical processes. According to modular design method, the established model includes three sub-models of intake system, fuel system and power train system. The schematic diagram of the engine model is shown in figure 1. The main purpose of the hardware-in-the-loop simulation experiment is aimed at validating the electronic controller interface circuit and true-false of program logic, and in order to realize the tuning of system parameters, the engine model with fewer parameters and lower order is usually utilized to meet the requirements of the controller verifying [11-12].



Figure 1. Schematic diagram of the engine model

3. Establishment of air intake system model

3.1. The throttle air mass flow model

Throttle plays an important role in adjusting the air flow into the cylinder, so it is significant to design a model of air mass flow at throttle reflecting actual physical process for predicting the state of the air inside the intake manifold and measuring the actual air quantity entering into the cylinder each cycle.

This article adopts the model of air mass flow at throttle proposed by Hendricks, the model divides the air flow at throttle disc into two parallel master-slave isentropic and master-slave air flows, and which converge in the back of the throttle body [13-14]. The expressions of the model are as follows:

m

$$\mu_{at} = \frac{p_{amb}}{\sqrt{T_{amb}}} \beta_1(\alpha) \cdot \beta_2(p_r)$$
⁽¹⁾

$$\beta_1(\alpha) = 1 - \varphi_1 \cos(\alpha) + \varphi_2 \cos^2(\alpha)$$
⁽²⁾

$$\beta_{2}(p_{r}) = \begin{cases} \sqrt{p_{r}^{p_{1}} - p_{r}^{p_{2}}} / p_{n}, \text{if } p_{r} \ge p_{c} \\ 1 & \text{, if } p_{r} < p_{c} \end{cases} \begin{pmatrix} p_{c} = \left(\frac{p_{1}}{p_{2}}\right)^{\frac{1}{p_{2} - p_{1}}} & \text{, } p_{n} = \sqrt{p_{c}^{p_{1}} - p_{c}^{p_{2}}} \end{pmatrix}$$
(3)

Where P_1 , P_2 , φ_1 , φ_1 , P_c and P_n are constants used in the simplified process of the throttle valve air mass flow model. These constants are independent of the specific throttle structure, therefore, Hendricks can obtain these common model parameters after fitting test data form different engine throttle bench:

$$\begin{cases} p_1 = 0.4404 & p_2 = 2.3143 \\ \varphi_1 = 1.4073 & \varphi_2 = 0.40877 \\ p_n = 0.7404 & p_c = 0.4125 \end{cases}$$
(4)

Where \dot{m}_{at} is air mass flow at throttle; P_{amb} and T_{amb} are the throttle inlet air pressure and temperature, respectively; $\beta_2(\alpha)$ is the throttle efficient coefficient of flow area; $\beta_2(P_r)$ is the inlet air corrected value depended on the state of air at throttle; α is the throttle opening degree; P_r is the ratio between the throttle inlet and outlet pressure, that is P_{ap}/P_{amb} ; P_{ap} is pressure inside the intake manifold.

3.2. Intake manifold pressure model

Assuming that the intake manifold is a control body, \dot{m}_{at} and \dot{m}_{ac} respectively are air flow into the intake manifold and air flow out of the intake manifold. According to the conservation law of mass, air flow \dot{m}_{ap} inside the intake manifold can be obtained as follows:

$$\dot{m}_{ap} = \dot{m}_{at} - \dot{m}_{ac} \tag{5}$$

The ideal gas state equation is $m = PV(RT)^{-1}$, and derivation on both sides of the equation:

$$\dot{m}_{ap} = \frac{V_{ap}}{RT_{ap}}\dot{p}_{ap} - \frac{p_{ap} - V_{ap}}{RT_{ap}^2}\dot{T}_{ap}$$
(6)

Since the gas temperature inside the intake manifold changes little, compared with the gas pressure change inside intake manifold, it can be neglected and $\dot{T}_{ap} \approx 0$ could be obtained. Substituting equation (5) into equation (6), an intake manifold pressure model expression can be deduced as follows:

$$\dot{P}_{ap} = \frac{RT_{ap}}{V_{ap}} (\dot{m}_{at} - \dot{m}_{ac})$$
(7)

Where T_{ap} , m_{ap} and P_{ap} are respectively air absolute temperature, mass and pressure inside the intake manifold; V_{ap} is the intake manifold volume; R is the air gas constant, which is generally taken 287 J/(kg • K).

3.3. The intake valve air mass flow model

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Air mass flow at intake valve has a direct influence on fuel quantity into the cylinder, thereby affecting the engine speed and torque, therefore, it is important to build an intake valve air flow model [15]. However, the model is a difficulty in the mean-value modelling, it is determined initially by experimental data identification and data regression analysis method. Although the model built by this method is applicable for a specific intake system, it can't be applied to other types of engine air intake system effectively. In order to construct an intake valve air flow model with good portability, and avoid mass collection of experimental data to identify and analysis for different engines, this article applies a generic air flow model of the intake valve, and utilizes the speed-density method to establish air mass flow model at intake valve for four-stroke engine. The expression is as follows:

$$\dot{m}_{ac} = \frac{NV_s P_{ap}}{120 R T_{ap}} \phi_v \tag{8}$$

Where N is the speed of the engine crankshaft; V_s is the engine displacement; ϕ_v is the engine volumetric efficiency.

Integration on equation (8), intake air mass of the engine single cylinder in each work cycle can be obtained:

$$n_{ac} = \int_{i_o}^{i_c} \dot{m}_{ap} dt \approx \frac{NV_s p_{ap} \phi_v}{120 R T_{ac}} \cdot \frac{30}{N} = \frac{V_s}{4 R T_{ac}} (s_i p_{ap} - y_i)$$
(9)

Where s_i and y_i respectively are the slope and intercept air temperature inside the intake manifold, because both s_i of y_i are nearly same with different the engine speeds, they could be considered as constants; i_o and i_c respectively are the moment to open and close intake valve; 30/N is intake time of the per cylinder each cycle.

4. Establishment of fuel system model

Fuel ejected into cylinders by injector is difficult to mix with air absolutely. Some fuels attach to wall surface of the intake manifold, intake or the back of intake valve, these fuels will usually form film. The film is evaporated by high temperature and forms fuel vapour entering into cylinders. This phenomenon is called the film wet wall.

In the actual engine operation, the fuel system working principle is as followings: part of the fuel ejected by injector is mixed with the air and goes into the cylinder directly, while the remaining are adsorbed on the wall surface in the form of film. Fuel vapour is generated continually by film evaporation during engine operation, mixed with air and goes into the cylinder. When the engine works in steady state, the amount of film increasing and evaporated is equal in each working cycle, and the total mass of the film is unchanged, it can be considered that all of the fuel is injected into the cylinder and combusts [16]. When the engine works in transient operating conditions, the amount of film increasing and evaporated is different, which results in the fuel amount ejected by injectors is unequal to the fuel entering into the cylinder. Transient conditions contain two situations. One is that when opening degree of throttle becomes larger suddenly, the fuel injection and the film amount is increasing with the increase of the intake air amount, however, the acceleration of film evaporation requires some time, which will result in amount of evaporation is less than the deposited amount, and air-fuel ratio is too large. The other is that when throttle opening degree becomes smaller suddenly, which is contrary to the above situation [17]. Therefore, when modelling the fuel system, the dynamic characteristics of fuel transfer must be considered.

Based on Aquino model, Elbert Hendricks and Thomas Vesterholm made a further research and proposed that applying one-order inertial to describe the fuel transfer dynamic characteristics [15], which is presented as follows:

$$\begin{cases} \dot{m}_{ff} = \frac{dm_{ff}}{dt} = -\frac{m_{ff}}{\tau_{ff}} + x \cdot \dot{m}_{fi} \\ \dot{m}_{fv} = (1-x)\dot{m}_{fi} \\ \dot{m}_{f} = \dot{m}_{fv} + \frac{m_{ff}}{\tau_{ff}} \end{cases}$$
(10)

Where m_{ff} is the mass of the film; \dot{m}_{fi} , \dot{m}_f and \dot{m}_{ff} respectively are the fuel mass that is ejected by injector, actually entering into the cylinder and formed by film evaporation; \dot{m}_{fv} is the fuel mass which is ejected by injector and goes into the cylinder directly; τ_{ff} is the time constant of the film evaporation, which is generally taken 0.25 ~ 0.4 s; x is the deposited fuel radio of the fuel injection, which is generally taken 0.5 ~ 0.8.

5. Establishment of dynamic system model

Engine power system operating state is modelled from perspective of flow of working fluid and energy transition. Engine output torque and power are computed according to the amount of air and fuel entering into the cylinders, and other important parameters (engine speed, the ignition advance angle, etc.). Mixture gas inside the cylinder combusts and swells quickly after ignited by sparks to promote the piston acting and torque is output through crankshaft. According to the conservation law of energy and Newton's second law, energy change rate pushing the piston movement is accelerating power of crankshaft rotation. Engine power model is built as follows [18-20]:

$$\dot{\omega} = \left[H_u \eta_i \dot{m}_f (t - \tau_d) / \omega - (T_f + T_p + T_b) \right] / J \tag{11}$$

Where ω is the angular velocity of crankshaft; J is rotational inertia of the engine; H_u is the fuel heat value; η_i is the engine indicated thermal efficiency; τ_d is the mean time delay of fuel feed; T_f , T_p and T_b respectively are resistance moment of frictional loss of the engine, resistance moment of pumping loss of the engine and load torque of the engine.

6. Validation of Engine Model

6.1. Validation of Inlet Flow and Inlet Pressure

Two groups of data are selected to validate inlet flow and inlet pressure. One is inlet flow and inlet pressure vary according to the throttle opening degree at the rotary speed is 2500r/min; the other is inlet flow and inlet pressure vary according to the throttle opening degree when the speed is 5000r/min.

For the rotary speed is at 2500r/min, as shown in figure 2, when the engine works in a state of heavy load and middle or low speed, the inlet pressure values measured in bench test is higher than simulation and both have large deviation; The inlet flow values measured in bench test is higher than simulation and both deviation is small. Maximum relative error of inlet pressure and inlet flow are respectively about 4% and 2% when the throttle opening degree is more than 60%. This is because the engine status is not stable and actual crankshaft speed fluctuation is large under the working condition, which results in intake noise and inlet pressure fluctuations are larger, so the values measured in bench test is higher than simulation. For intake flow, as the gas flow inertia in the air intake manifold and long response time of flowmeter measurement, which play a role as low-pass filter to inlet flow measurement, therefore, the deviation between bench test measurement values and simulation is small.

As shown in figure 3, the inlet flow values measured in bench test are lower than simulation in a state of small load and high speed. For example, maximum relative error of inlet flow is about 3% when the throttle opening is lower than 25%. That is because inlet flow rate is very high when the engine is in a state of high speed and small load. Actual intake flow loss increases, so the inlet flow value that measured by bench test is less than the simulation test. Figure 2 and figure 3 show that a deviation exists between bench test measurement values and simulation under the circumstances of low speed, heavy load and high speed, small load. For aspect of accuracy, the values of inlet flow and inlet pressure obtained by the engine model are consistent with values measured by bench test. The maximum error is less than 5% and is within the allowed error range. Air intake system model could accurately simulate the steady state parameters, such as inlet flow, inlet pressure and so on. Therefore, this model is utilized to compute fuel injection quantity when the engine is in steady state conditions.

6.2. Validation of Engine Output Torque and Rotational Speed

Performance data measured by the engine bench test is applied to further verify the engine model. Part of steady state conditions data measured by engine-dynamometer bench system is shown in table 1. The throttle opening range is $12\%\sim16\%$ and the crankshaft speed range is $2580r/min\sim5880r/min$ in the collected data. Engine simulation model is verified with data collected from a large scope of working condition.



Figure 2. Engine model simulation results at 2500r/min



Figure 3. Engine model simulation results at 5000r/min

TPS (%)	Tb (Nm)	N (r/min)
12	32	2580
15	32	3260
20	39.8	4150
30	52.9	5280
40	68.6	5560
50	73.4	5750
60	76	5880

Table 1. Part of steady state conditions data measured by engine-dynamometer bench system

The values of throttle opening and load torque are put into the input of the engine model, the output torque and rotational speed of the engine could be computed through the model. From the simulation results of figure 4 and figure 5, the torque and rotational speed computed from different working conditions of engine model are very consistent with the data from bench test, and the error is within acceptable range. AFR is the throttle opening degree. Figure 6 shows the simulation result of crankshaft speed computed by the engine model when the throttle opening degree changes from 12° to 15°. From figure 6, after the sudden change of throttle opening degree, dynamic changes of the crankshaft speed are similar to actual situation of engine. The simulation results after the engine model is stable are consistent with data measured from bench test.



Figure 4. Engine model torque simulation curves

Figure 5. Engine model speed simulation curves

Figure 6. Engine model speed simulation curves when the throttle opening abrupt change

From analysis of the verification results of the inlet flow rate, inlet pressure, engine output torque and rotational speed. The engine model can truly reflect operating characteristics of the real engine. The errors between the simulation results and the bench test data are within the acceptable range. Therefore, this engine model could be applied to validate control strategy and logic performance of electronic controller, it can avoid the risk that the electronic controller is utilized to bench test directly and reduce the actual workload. For another aspect, errors existing in some certain conditions show that the actual engine working process is very complicated. Apart from the external environmental factors, the characteristics of the engine under different conditions are also diverse.

7. Conclusions

Mean valve model of aviation piston engine is built with MATLAB/SIMULINK platform from the energy conversion and working medium flow in the article. The engine model has advantages of simple structure, lower computing iteration amount, the overall accuracy can meet the requirements of simulation, it can describe the steady and dynamic characteristics of engine, and it is applicable to the hardware-in-the-loop simulation system. The engine model can truly reflect the operating characteristics of actual engine and the errors between the simulation results and bench test data are in the acceptable range by analysing the verification results of the inlet flow rate, inlet pressure, engine

output torque and rotational speed. As the built model could be utilized as controlled plant of HIL system, it has great value to performance testing and logic validation of the electronic controller.

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