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Modeling and Simulation Study of Intake System Characteristics of Wankel Engine for UAV

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Abstract. Starting from the actual working process of Wankel engine, the intake system model of Wankel engine is constructed based on the mean value engine model. The parameters to be determined in the model are identified by the least-square method based on the engine test data. According to the nonlinear characteristics of the intake system, the structure of the model is improved by introducing the speed correction term, and the problem that the error of original throttle air mass flow model is larger under the larger throttle opening is solved. The results of simulation and steady-state test show that the maximum relative error between simulation and experimental values of throttle air mass flow is less than +3% and that between simulation and experiment values of intake pressure is less than +2%. The parameter identification and structure of the model have high precision, which can calculate the basic air intake flow of Wankel engine accurately and shorten the development cycle of the electric control system of Wankel engine.

1. Introduction

Compared with the traditional piston engine, Wankel engine has the advantages of small volume, low weight, high power density and low noise due to the elimination of crank-connecting rod mechanism and valve mechanism. In recent years, with the upsurge of unmanned aerial vehicle (UAV) research and development, Wankel engine, as a power device, has once again become the focus of the industry. In order to improve the power performance of Wankel engine, reduce the fuel consumption, and increase the cruising range of the engine, it is necessary to develop an electronic fuel injection system for Wankel engine of UAV.

The electronic fuel injection system can realize the real-time control of Wankel engine under different working conditions, thus greatly improving the environmental adaptability and working performance of Wankel engine [1]. Since the electronic fuel injection system requires accurate detection of the air mass flow per cycle to determine the injected fuel mass flow per cycle based on the stoichiometric air/fuel mass ratio, it is necessary to model and analyze the characteristics of the intake system of the Wankel engine based on the structure and actual working process of the engine.

Wankel engine is mainly composed of triangular rotor, cylinder block, eccentric shaft and various seals. The triangular rotor divides the internal space of the cylinder into three independent working chambers. When the engine is working, the triangular rotor in the cylinder rotates around the center of

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the main bearing and rotates around its own rotating center. The volume of each working chamber changes constantly, and each of them completes four strokes of intake, compression, work and exhaust respectively [2-4], as shown in figure 1. Because of this unique structure and movement mode of Wankel engine, the structure of the intake system is simple, and the direction of intake and exhaust is basically consistent with the direction of gas flow in the engine. Sufficient air intake flow can be provided for Wankel engine over the entire speed range of the engine.



Figure 1. Actual operation cycle of Wankel engine.

For the air/fuel ratio control of piston engine, scholars have been working to establish a control model with high control precision, few undetermined parameters, small amount of calculation, and strong system robustness. A type of simple mathematical engine model for spark ignition engines is the mean value engine model [5-7]. Based on this model, a number of authors have developed air-fuel ratio control strategies and intake air mass flow estimation algorithm for spark ignition engine [8-16]. However, there are few studies on the modeling of the intake characteristics of Wankel engine. In reference [17] and [18], the intake air mass flow model of Wankel engine is established, and the characteristic parameters of the engine intake system are calibrated according to the bench test results. Due to the saturation nonlinearity of air mass flow at throttle, the problem that the original model has a large error under large throttle opening has not been solved in references [17] and [18].

The purpose of this paper is to construct the intake characteristic model of Wankel engine by using the mean value model, and to determine the fixed parameters in the model using the steady test data. The validity of this model is validated by combining the simulation results of MATLAB/Simulink with the test data. Comparison results show that the model has simple structure and high accuracy. It can calculate the basic intake air mass flow of Wankel engine accurately and provide basic data for the development of the electronic controlled system of Wankel engine.

2. The intake system model of Wankel engine.

The mean value engine model is a commonly used control model. The average values of variables in several engine working cycles are used to describe the dynamic process of the engine [5]. A series of state differential equations are used to describe the corresponding system dynamics, so the expression of the model is simple. In addition, the model contains fewer fixed parameters to meet the needs of simulation and control and has a wide range of application. Figure 2 is a schematic diagram of the intake system of Wankel engine.



Figure 2. Schematic diagram of intake system of Wankel engine.

The intake pipe volume from the throttle to the intake port is regarded as the control body, as shown

in figure 3.



Figure 3. Schematic diagram of Intake manifold.

The air in this control body is regarded as an ideal gas [5]. According to the equation of state of the ideal gas, the air in the control body is given by the expression

$$m_i = \frac{p_i V_i}{R_a T_i} \tag{1}$$

where m_i is the total mass of air in the control body, p_i is the absolute pressure of the air in the control body, V_i is the total volume of the control body, R_a is the air gas constant, T_i is the absolute temperature of the air in the control body.

The derivation on both sides of the antithesis (1) has the form

$$\dot{m}_i = \frac{d}{dt} \left(\frac{p_i V_i}{R_a T_i} \right) = \frac{V_i}{R_a T_i} \dot{p}_i - \frac{V_i p_i}{R_a T_i^2} \dot{T}_i$$
(2)

According to literature [7], the change of the absolute pressure of the air in the control body relative to the time is much greater than that of the gas temperature in the control body relative to the time. Therefore, the item on the right side of equation (2) concerning the change of intake temperature can be neglected. In the control body, according to the law of conservation of mass

$$\dot{n}_i = \dot{m}_t - \dot{m}_p \tag{3}$$

where \dot{m}_t is throttle air mass flow, \dot{m}_p is port air mass flow, combined with equation (2), we can deduce

$$\dot{m}_i = \dot{m}_t - \dot{m}_p = \frac{V_i}{R_a T_i} \dot{p}_i \tag{4}$$

$$\dot{p}_i = \frac{R_a T_i}{V_i} \left(\dot{m}_t - \dot{m}_p \right) \tag{5}$$

The throttle air mass flow \dot{m}_t is regarded as the flow of a compressible fluid through a converging nozzle [5]

$$\dot{m}_t(\alpha, p_i) = C_{t1} \frac{P_{amb}}{\sqrt{T_{amb}}} \beta_1(\alpha) \beta_2(p_i) + C_{t2}$$
(6)

where C_{t1} and C_{t2} are fixed parameters to be calibrated by experiments, P_{amb} is the ambient atmospheric pressure, T_{amb} is the ambient temperature. Ignoring the throttling action of the air filter in the front of the intake pipe, the pressure and temperature upstream of the throttle can be approximately expressed by the ambient atmospheric pressure P_{amb} and the ambient temperature T_{amb} [5]. α is the throttle plate angle, $\beta_1(\alpha)$ is a function of throttle plate angle α , $\beta_2(p_i)$ is a function of the absolute pressure of air in the control body p_i . According to literature [5], functions $\beta_1(\alpha)$ and functions $\beta_2(p_i)$ have the following form

$$\beta_1(\alpha) = 1 - 1.4073\cos(\alpha) + 0.4087\cos^2(\alpha) \tag{7}$$

$$\beta_{2}(p_{i}) = \begin{cases} \frac{1}{0.7404} \sqrt{\left(\frac{p_{i}}{P_{amb}}\right)^{0.4404} - \left(\frac{p_{i}}{P_{amb}}\right)^{2.3143}} & , \frac{p_{i}}{P_{amb}} \ge 0.4125 \\ 1 & , \frac{p_{i}}{P_{amb}} < 0.412 \end{cases}$$
(8)

According to the speed-density equation, the port air mass flow \dot{m}_i has the form [7]

$$\dot{m}_p = \frac{nV_d p_i \eta_v}{60R_a T_i} \tag{9}$$

where *n* is the speed of the eccentric shaft of Wankel engine, V_d is engine displacement, η_v is engine volume efficiency, its form can be approximately expressed by literature [10]

$$\eta_{\nu} = C_{\nu 0} + C_{\nu 1} n + C_{\nu 2} n^2 + C_{\nu 3} p_i \tag{10}$$

where $C_{\nu 0}$, $C_{\nu 1}$, $C_{\nu 2}$, $C_{\nu 3}$ are all constants fitted by experiments.

Equation (5), (6) and equation (9) constitute a complete model of intake system of Wankel engine. The inputs of the model are throttle plate angle α and speed of the eccentric shaft of Wankel engine n, and the state variable of the model is the absolute pressure of the air in the control body p_i .

3. Identification of undetermined parameters and optimization of model structure

According to the intake system model of Wankel engine, the undetermined parameters in the model need to be identified. The research object of this paper is a single-rotor engine with circumferential intake, whose specific parameters are as shown in table 1. Aiming at the controlled engine, the steady-state bench test was carried out under different throttle opening and rotating speed. The engine test bench is shown in figure 4. In the course of the experiment, the signals such as throttle plate angle α , speed of the eccentric shaft, air mass flow rate \dot{m}_t and the absolute pressure of the air p_i are collected by data acquisition system.



Figure 4. Wankel engine test bench.

No	Engine Particulars	Value
1	Swept Volume/cm ³	294
2	Compression Ratio	9
3	Generating Radius/mm	69
4	Eccentricity/mm	11.6
5	Maximum Continuous Power/Kw	35.8
6	Maximum Continuous RPM/r/min	7100
7	Cooling	air and liquid cooling systems

Table 1. Main paramete	ers of Wankel engine.
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3.1 Parameters identification of throttle air mass flow model

The product of the three factors $P_{amb}/\sqrt{T_{amb}}$, function $\beta_1(\alpha)$ and function $\beta_2(p_i)$ in equation (5) is considered as a whole. The relationship between throttle air mass flow obtained from the steady-state test data of the engine and the product $P_{amb}\beta_1(\alpha)\beta_2(p_i)/\sqrt{T_{amb}}$ is shown in figure 5.



Figure 5. Relationship between throttle air mass flow and $\frac{P_{amb}}{\sqrt{T_{amb}}}\beta_1(\alpha)\beta_2(p_i)$.

According to formula (5), there is a linear relationship between the throttle air mass flow rate \dot{m}_t and the product term $P_{amb}\beta_1(\alpha)\beta_2(p_i)/\sqrt{T_{amb}}$. However, the measured values of the engine steadystate test show (as shown in figure 5) that a single linear relationship cannot completely cover the entire range of throttle opening and intake pressure p_i . When the engine speed is constant and the throttle opening is small, due to the obvious throttle effect of the throttle body, there is a good linear relationship between the throttle air mass flow rate \dot{m}_t and the product term $P_{amb}\beta_1(\alpha)\beta_2(p_i)/\sqrt{T_{amb}}$. When the throttle plate angle α increases to a certain large opening, the throttle effect of the throttle body is weakened, and the pressure drop before and after the throttle body will not change obviously. When the throttle air mass flow rate \dot{m}_t tends to be saturated, which is mainly affected by the rotor engine output shaft speed. As can be seen from figure 5, for different engine speeds, the inflection point of the curve is different, that is, when the engine is at different speeds, the value of larger throttle opening is not unique.

From the previous analysis, it can be seen that the error of the throttle air mass flow model is larger under the larger throttle opening, and the throttle air mass flow tends to be saturated with the increase of throttle opening, and it is related to the rotational speed of the engine output shaft. Therefore, the correction term of rotating speed needs to be introduced to improve the overall accuracy of the model:

$$\dot{m}_t(n) = C_{t3} \frac{P_{amb}}{\sqrt{T_{amb}}} \beta_3(n) + C_{t4}$$
(11)

where $\dot{m}_t(n)$ is the value of throttle air mass flow under larger throttle opening, which is determined according to the engine output shaft speed. C_{t3} and C_{t4} are the undetermined parameters of the model, $\beta_3(n)$ is the introduced correction term, which can be expressed as follows:

$$\beta_3(n) = \frac{n}{1000} \tag{12}$$

The throttle air mass flow data obtained from the engine steady state test are fitted to the fixed parameters C_{t1} , C_{t2} , C_{t3} and C_{t4} based on the least square method. The identification results are shown in table 2.

Undetermined Parameters	Value
C _{t1}	65
C_{t2}	6.5
C_{t3}	1
C_{t4}	8

Table 2. Undetermined parameters of throttle air mass flow model.

The throttle air mass flow may take the smaller of $\dot{m}_t(\alpha, p_i)$ and $\dot{m}_t(n)$

$$\dot{n}_t = \min(\dot{m}_t(\alpha, p_i), \dot{m}_t(n)) \tag{13}$$

The point in figure 6 is the throttle air mass flow measured by the experiments at different engine speeds and different throttle opening, and the thin solid line is the calculated value of the model whose structure is modified. Compared with the original model, the modified throttle air flow model still has higher precision under larger throttle opening, which solves the problem that the original model has larger error under larger throttle opening.



Figure 6. Comparison of measured values of steady-state test and calculated values of modified models.

3.2 Parameters identification of port air mass flow model

The port air mass flow \dot{m}_p can be derived from equations (9) and (10)

$$\dot{m}_{p} = \frac{nV_{d}p_{i}\eta_{v}}{60R_{a}T_{i}} = \frac{nV_{d}p_{i}}{60R_{a}T_{i}} * (C_{v0} + C_{v1}n + C_{v2}n^{2} + C_{v3}p_{i})$$
(14)

When the engine is working in a steady state, the filling and exhaust effect in the intake pipe is small, and the pressure change in the control body Δp_i is approximately 0. In this case, the port air mass flow \dot{m}_p is approximately equal to the throttle air mass flow \dot{m}_t . That is, the measured value of the steady air flow of the engine measured by the flowmeter installed in front of the throttle door. Therefore, the value of \dot{m}_p is the measured value of air mass flow of the engine measured by the flow meter installed in front of the throttle. In equation (14), $C_{\nu 0}$, $C_{\nu 1}$, $C_{\nu 2}$ and $C_{\nu 3}$ are the parameters of the model to be determined, which can be regarded as the characteristic parameters of the intake system of a specific engine. For Wankel engines with different intake forms and different rotor numbers, the intake system characteristic parameters need to be calibrated by the engine steady-state test.

In this paper, the single-rotor engine with the form of circumferential surface air intake is taken as the research object. The signals of air mass flow rate and rotational speed n are obtained through the

steady-state bench test of the engine, and the least squares method is used to identify the parameters. The identification results are shown in table 3.

Undetermined Parameters	Value
<i>C</i> _{v0}	-1.028×10^{2}
C_{v1}	4.339×10 ⁻²
C_{v2}	-3.537×10 ⁻⁶
C_{v3}	1.058

Table 3. Undetermined parameters of port air mass flow model.

4. Model simulation and experimental verification

According to equations (6), (11), (13), (14), Table 2 and Table 3, the simulation model of the intake characteristics of Wankel engine is built in MATLAB/Simulink, as shown in figure 7. The input of the model is the throttle plate angle α and the eccentric shaft rotating speed n, and the state variable of the model is the absolute air pressure in the control body p_i .



Figure 7. Block diagram of simulation for intake characteristics model of Wankel engine.

In this paper, the structure of the model and the accuracy of parameter identification are verified by a set of partial load tests and a set of full load tests. In the course of the test, the relevant signals are collected by the self-developed data acquisition system. The sequence of throttle plate angle α and eccentric shaft rotating speed n collected by the data acquisition system is taken as the input of the model. The throttle air mass flow value \dot{m}_t and the absolute air pressure p_i calculated by the model simulation are compared with the measured values, and the accuracy of the model is verified according to the comparison results.

For the partial load test, the engine is stably operated at the throttle opening of 10% and rotation speed at 3500 r/min by the dynamometer. We fixed the engine speed at 3500r/min and changed the throttle opening from 10% to 50% to verify the accuracy of the model at low and medium loads and low speeds. The comparison between the simulation results and the test data of throttle air mass flow is shown in figure 8, and the comparison between the simulation results and the test data of absolute air pressure in the control body is shown in figure 9.







Figure 9. Comparison between intake pressure model simulation and measured values with rotating speed 3500 r/min and throttle opening from 10% to 50%.

For the full load test, the engine is stably operated at the throttle opening of 100% and rotation speed at 5500 r/min by the dynamometer. We fixed the engine throttle opening at 100% and changed the rotation speed from 5500r/min to 7100r/min to verify the accuracy of the model under full load and high rotation speed. Figure 10 shows the comparison between simulation and measured values of throttle air mass flow, and the comparison between the simulation results and t measured values of absolute air pressure in the control body is shown in figure 11.



Figure 10. Comparison between throttle air mass flow model simulation and measured values with throttle wide open and rotating speed from 5000 to 7100 r/min.



Figure 11. Comparison between intake pressure model simulation and measured values with throttle wide open and rotating speed from 5000 to 7100 r/min.

The comparison between the model simulation and measured values of throttle air mass flow in figure 8 and figure 10 shows that under steady state conditions, the maximum relative error between the model simulation and the measured value does not exceed $\pm 3\%$. It can be seen from figure 8 that when the throttle opening is small, the throttle effect of throttle body is obvious, and there is an approximate linear relationship between the throttle air mass flow and the throttle plate angle. When the throttle opening increases to a certain large opening, the throttle air mass flow tends to be saturated. Combined with figure 10, it can be found that under the larger throttle opening, the throttle effect of the throttle effect of the throttle body is weakened, and the throttle air mass flow is mainly affected by the rotation speed.

Under steady-state operating conditions, the maximum relative error between the model simulation and measured values of intake manifold pressure of Wankel engine is no more than $\pm 2\%$, as shown in figure 9 and figure 11. Figure 9 shows that when the rotation speed is constant and throttle plate at a

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smaller angle, as the throttle opening increases, the intake pressure value increases significantly; when the throttle opening increases to a certain larger value, the intake pressure value increases slowly and tends to be stable. When the throttle opening is 100%, the comparison between the intake pressure model simulation and the measured value shows that intake pressure value decreases with the increase of the rotation speed, but compared with the itself, the variation range is not obvious.

Figure 8-figure 11 show that the comparison between simulation and measured values shows that the mean value model of intake system characteristics of Wankel engine established in this paper and the identification of undetermined parameters in the model have high accuracy. Based on this model, the basic intake air mass flow of Wankel engine can be calculated more accurately.

5. Conclusion

Based on the structure and characteristics of air intake system of Wankel engine, the model of Wankel engine intake system is constructed based on the mean value model. According to the engine test data, the least square method is used to identify the undetermined parameters in the model. Because the throttle air mass flow has the nonlinear characteristic, in order to solve this problem, the structure of the model is improved by introducing the speed correction term. The problem that the error of the original throttle air mass flow model is larger under the larger throttle opening is solved. The comparison between the model simulation and experimental values shows that the maximum relative error between the simulation and the measured values of throttle air mass flow does not exceed $\pm 3\%$, and the maximum relative error between the simulation and structure have high accuracy. The intake system model of Wankel engine constructed in this paper contains fewer parameters and has a simple structure and higher precision. Based on this model, the basic intake air mass flow of the engine can be calculated accurately, a lot of calibration work in the development of the engine electronic control system can be reduced, and the development cycle of the rotor engine electronic control system can be shortened.

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