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Improved Intake System Design for FSAE Engines

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Abstract

The traditional approach to limiting the maximum output power of a FSAE car's engine is to install a single circular restrictor at the engine. However, restrictor installation would adversely lower the air flow speed and fuel burning rate, which further result in the declining of the pressure in the intake pipe. In this paper, we first analyze the influence of intake restrictor on engine power, intake pipe's pressure, inflatable efficiency and fuel consumption in the case of a typical four-stroke engine of FSAE cars. One-dimensional engine cycles are simulated by using the AVL BOOST. Intake quantity correction is then designed based on the characteristics of EFI system and the analysis results. The control unit is further designed by both means of hardware circuit and software design. According to pulse width of driving signal for injecting fuel, the performance of FSAE car's engine is improved by intake quantity correction of the control unit. Other direct improvement includes lowered fuel consumption hence more economical efficiency.

Keywords: *FSAE, Fuel Economic, Restrictor, Control Unit, Pulse width*

1. Introduction

Due to security considerations, FSAE event requires that a single round restrictor must be installed between the throttle in air intake system and engine and all the intake air must be through the restriction so as to limit the engine maximum output power. [1] At present, many researchers focused on how to increase the intake air amount of engine and reduce the pressure loss in the intake pipe caused by restrictor. Hiroshi Enomoto and Hiroyuki Motoi [2] improved the inlet pressure by use of vortex supercharger, thus improving the engine torque. Jianmin Xu and Jinwu Liu [3] analyzed the change of engine power due to the installed location of the restrictor and made use of the CFD software analysis results to improve the design of the air intake system. Dan Cordon and Charles Dean studied the process of one-dimensional CFD engine simulation using WAVE analysis software and analyzed the restrictor influence on engine performance and optimized the air intake system [4]. Mark Claywell and Donald Orkheimer improved the air intake system design through 1D & 3D coupling analysis method [5]. Dalhousie University carried on the related research by using Venturi tube connecting the inlet pipe and engines.The central part of Venturi tube was the circular intake restrictor. So the circular structure reduced the pressure loss caused by the restrictor to some extent. However, most studies did not consider restrictor effect on the car's fuel consumption, especially to the FSAE car using EFI system. In fact the intake pipe pressure loss caused by restrictor reduced the intake air amount measurement accuracy of the EFI system for engine, and then destroyed control accuracy of the fuel injection and air-fuel ratio, and finally made the actual fuel consumption more higher, which reduced competence in fuel economy and durability of competitiveness. However, fuel economy is an important index on the SAE Formula

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event. Thus reducing the fuel consumption has become a necessary research subject on FSAE engine.

2. Simulation Analysis on Restrictor Effect on Engine Cycle

The pressure loss inside the intake air pipe caused by restrictor made the intake air amount measurement accuracy of EFI system decline, which affected the injection and air-fuel ratio control accuracy. By using the AVL BOOST software, one-dimensional cycle simulation model of the FSAE engine was finished; the influence of the restrictor on the engine performance was analyzed, which provided the basis for establishing the intake air amount correction scheme.

2.1. Working Process of BOOST Cylinder

The working process of the internal combustion engine cylinders is very complex. It includes comprehensive processes such as physical, chemical, flow, heat transfer *etc*. [6] In order to describe the state of the cylinders, BOOST cylinder was viewed as a heat transfer system. The boundary of the system was composed of the piston head, cylinder head and the wall of cylinder liner. Within system, the state of working medium was determined by the three basic parameters such as the pressure P and temperature T, quality m. In order to more accurate and convenient simulation in cylinder heat exchange process, some assumptions were made as follows [7].
(1) At the beginning of the combustion, gas mixture is uniform;
(2) During combustion, air-fuel ratio is a constant value;
(3) Although not flammable and flammable air composition is different, they have the same pressure and temperature.

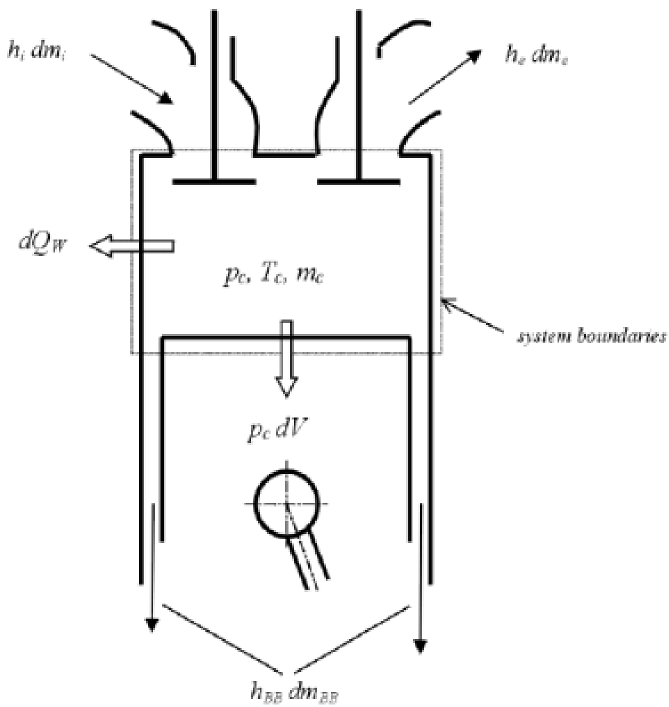

Figure 1. Energy Balance in the Cylinder

Based on the above assumptions, the basic parameters of status of the gas (p, T, m) can be connected with each other by using the conservation of energy and the conservation of mass and state equation. Finally we can solve the basic state parameters by using the three equations. [8-10] Energy balance in the cylinder diagram was shown as in Figure 1.

2.2. The Working Process of the Pipe Inside

The working process of engine is intermittent and periodic. Gas in the intake and exhaust system is unsteady. In one-dimensional model, the time effect of pressure wave transferring along the length direction was considered. Not only pressure wave transmission in pipe changes with time, but also at the same time the pressure fluctuation at different locations along the length direction is different. That is to say: the gas pressure P in the tube is a function of both time and position. [12] In order to make the more accurate and simple simulation calculation of the pipe internal flow, the following assumptions were made by the BOOST simulation:

(1) Because the pipeline axial geometry size is much bigger than the radial geometry size, the pipe axial flow effect is much bigger than the transverse flow effect. Thus ignoring the radial gas flow effect and assuming that the pipe flow is one-dimensional, each flow parameter was viewed as on the average of the flow parameter in the corresponding pipeline interface.

(2) Inner flow was unsteady. Each flow parameter is a function of horizontal coordinates and time. At the cross-sectional area of the pipes, the gas flow changes slowly and the pipe wall is rigid.

(3) Considering the friction and heat transfer of tube wall, we use the one-dimensional flow model in order to simplify the model, but the flow process is isentropic and the gas in the pipeline is completely gas and no gravity.

2.3. Analysis Model of the Engine

The FSAE engine is a single-cylinder and water-cooled and four-stroke and gasoline engine. Its diameter is 94 mm. Distance of travel is 85 mm. The compression ratio is 9.7:1.The displacement is 589.9 cm^3.

The engine BOOST cycle simulation model for car is shown in Figure 2. The engine intakes the air from the surrounding atmosphere SB1.The air enters into the air filter CL1 through the tube 1. Pipeline 2 and 3 were connected by the air cleaner and nozzle. The pipeline 13 is restrictor, which was connected with the intake pipe 4.The diameter of the resrtictor is 20mm.The pipe 6 was connected with the exhaust pipe 5 and three catalytic converters. The muffler was made up of three airflow rotating cavity PL1 and PL2 PL3 and pipeline 8, 9, 11.At the last, pipe 10 which was located at the system boundary SB2 discharges waste gas.

Fuel combustion in cylinder is a complex chemical process. It is affected by many parameters. The BOOST describes the combustion cylinder by weber function. The semi-empirical formula of single weber model was used. Weber function describes the combustion in cylinder by some parameters, such as the starting angle of burning, the shape parameter, the combustion duration and degree of combustion.

2.4. The Analysis on Simulation Results

2.4.1. Restrictor Effects on Engine Power Output

Through analyzing the simulation results, we can find that after installing the restrictor in the inlet pipe, engine performance is affected by the large, and this effect is more obvious with the increase of engine speed. The engine power changes with velocity before and after installing restrictor, which can be shown in Figure3. Under the condition that the rotational speed is low (less than 3000 RPM), engine power which is effected by the restrictor is not very obvious, which is similarity to the change of the engine power before installing the restrictor, but when the engine speed is over 3000 RPM, the engine's power which is influenced by restrictor is gradually obvious, and the engine’s power is most influenced by the speed at 3500 RPM. The most engine power was reduced by 21% than that before installing restrictor.

The engine output torque is influenced by the restrictor, which is the same as engine power. When the engine speed is at 5000 RPM, within a cycle, the peak torque falls nearly 20%. When the engine speed is 5000 RPM, the torque varies with crank angle, which can be shown in figure4.

2.4.2. Intake Air Pressure Loss and the Change of the Inflate Efficiency

Through observing the pressure changes in intake pressure sensor of intake pipe before and after installing restrictor, we can find that after installing restrictor, the gas pressure in the sensor when the engine velocity is less than of 3000 RPM, basically agree with that before installing restrictor. However, with the increase of rotational speed, they changes gradually slow (as shown in Figure 5), and the pressure value is higher than that before installing restrictor. The difference is also with the increase of rotational speed.

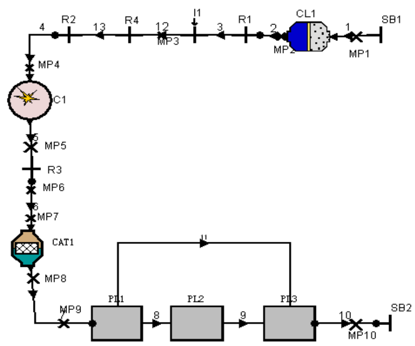

Figure 2. FSAE Car Engine Cycle Simulation Model in BOOST

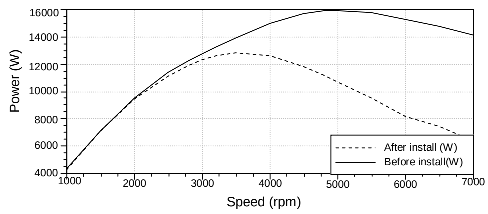

Figure 3. Power - Speed Curve

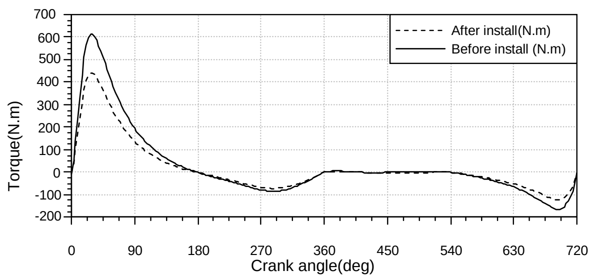

Figure 4. Torque Changes at the Maximum Speed of 5000 RPM

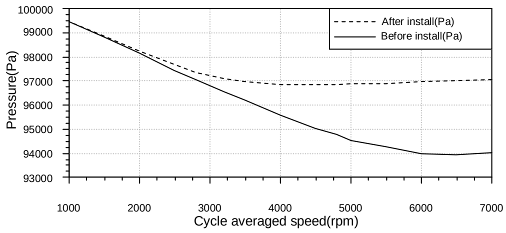

Figure 5. The Changes of Pressure in Intake Pressure Sensor with Engine Speed

The change of mixed gas pressure in inlet valve has a close relationship with the intake quantity in each cycle. The inlet valve pressure changes with engine speed before and after installing restrictor, which can be shown in Figure 6. From Figure 6, the mixed air pressure of the inlet valve is similarity to the value of pressure sensor which shows before installing restrictor. After installing restrictor, the pressure of the inlet valve reduces in a certain extent. The pressure difference between before installing restrictor and after installing restrictor increases with increasing rotate speed. The maximum is around 5800pa when the rotate speed is 7000RPM.

Inflatable efficiency is to measure the performance of engine power and an important indicator of air intake process. Due to the restrictor installed at the intake pipe, the area of the place is smaller, and the cross section changed largely, which caused great flow losses, thus leading to a fall in engine inflatable efficiency. Inflatable efficiency curve is shown as Figure 7.The maximum inflatable efficiency fell by nearly 30% than that not installing restrictor. The engine performance influenced severely.

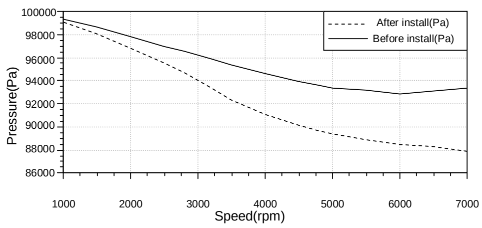

Figure 6. Inlet Pressure Curve

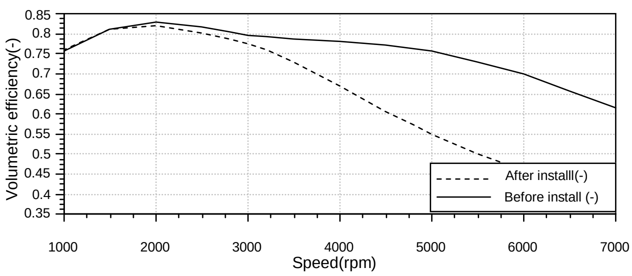

Figure 7. Inflatable Efficiency Curves

2.4.3. Restrictor Impact on Fuel Consumption

Because the inflatable efficiency drops, after installing the restrictor, quality of engine combustion per unit time dropped. Under a certain air-fuel ratio, decrease of air quality also lead to the fall of fuel combustion per unit, which can be shown as in Figure 8 and in Figure 9.

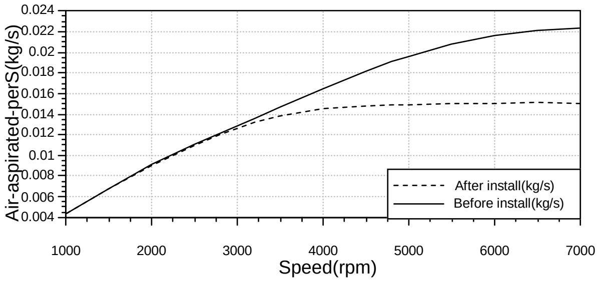

Figure 8. Air Combustion Quality Change per Unit Time

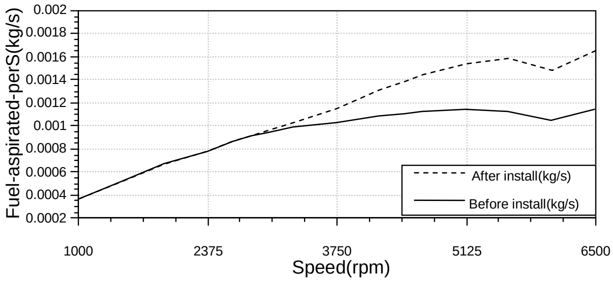

Figure 9. Quality of Fuel Combustion Per Unit Time

After installing restrictor, fuel combustion quality per unit time drops, but through the detection of the injection pulse width, the actual injection quantity increases slightly, thus effective engine combustion efficiency increases. The effective fuel consumption before and after installing the restrictor is shown in Figure 10.

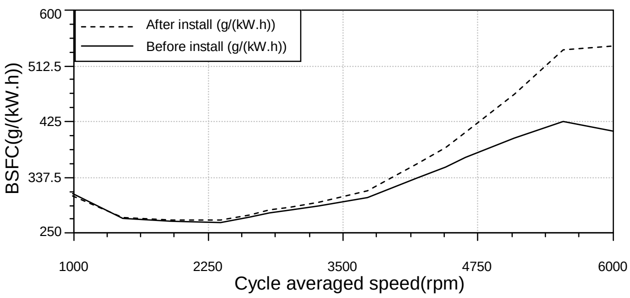

Figure 10. The Change of the Effective Fuel Consumption

From figure 10, after installing restrictor, the effective engine fuel consumption rate increases, but the fuel economy declines. One reason is that intake quantity reduces so that the fuel combustion is not sufficient. Another reason is that the pressure of pressure sensor which was located in front of the restrictor increases, and the pressure of the system is on the basis of the intake volume calculation, so that the calculation value of the volume is higher than the actual air inflow.Because the certain air-fuel ratio was required, fuel injection is "excessive" and the decline of fuel economy is aggravated.

3. Injector Drive Signal Analysis

3.1. Injection Control Signals

After the actual injection time is determined, electronic control unit (ECU) produces injection signals at the fuel injection time. And then the fuel injector works and completes a fuel injection under engine cycle. There are four work schedules in the engine: intake stroke, compression stroke, power stroke and exhaust stroke. The electronic control unit control the fuel injection by adjusting the effective level width and cycle of control signals. Fuel injection control signal is shown in Figure 11.

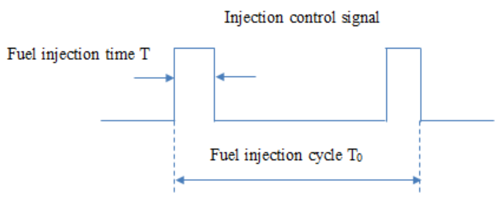

Figure 11. ECU Fuel Injection Control Signals

Under the different load and speed, injection cycle T_0 is different from fuel injection time T , in order to meet the conditions of air-fuel ratio control requirements. Injection cycle gradually shortened with the increase of rotational speed, and the injection pulse width T directly reflects the change of engine fuel injection quantity of each cycle.

3.2. Injection Pulse Width and Fuel Consumption

By the characteristics of injector, fuel injection quantity of the specific model of injector is only proportional to the open time. Therefore, for FSAE single-point injection system, the quality Q of the engine fuel consumption under any condition can be expressed in formulas (1):

$$Q = K \cdot \sum_{j=1}^{N} T_j \tag{1}$$

From the equation (1), the injection pulse width directly reflects the change of the engine fuel consumption. Detection of fuel injection pulse-width is also a method of rapid detection of fuel consumption at present.

4. Measurement on FSAE Air Intake EFI System

Engine air inflow is the main basis on the control of engine EFI system fuel injection amount according to the working condition of engine. The car EFI system uses the speed - density method to measure the volume of the fuel injection. The volume computation formula is as follows: [11]

$$\dot{m}_a = \frac{V_d p_m}{RT} \cdot \eta_v \cdot \frac{n}{120} \tag{2}$$

Where:

$\dot{m}_a$ --- the engine intake air amount per cycle; V_d ---the engine exhaust; n--- the engine speed; η_v ---the charging efficiency of engines (associated with inlet pressure and rotational speed); p_m ---the intake pipeline absolute pressure; T ---inlet gas temperature; R---gas constant.

Using speed - density measurement, the engine air inflow accuracy is higher, which can adapt to the change of the load due to a variety of causes, because if the load changes, inlet pressure will change [12]. But the car engine intake pipe is small in size and inlet pressure fluctuation is very big. Although the EFI system has special software to process, so as to guarantee the stability of inlet pressure, the restrictor was installed in the inlet pipe, which result in intake pipe pressure loss before and after the restrictor, so that the measurement errors of the EFI system is increased.

5. The Accomplishment of the Control Unit and the Establishment of the Intake Air Correction Scheme

5.1. The Engine EFI System Adjustment

For FSAE engine EFI system, the measured air intake amount is higher than that of the actual air inflow, which resulted in a certain degree of injection "excess" problem. This article aims to make some appropriate adjustment to the EFI system inlet measuring, so as to modify the volume measurement. The ways of EFI system adjustment mainly have the following three aspects:
(1) The modification of electronic control unit (ECU) through the archived program chip;
(2) The use of external adjustable control unit;
(3) The use of professional electronic control unit.

5.2. The Volume Correction Scheme

This paper uses the modified intake temperature sensor signal, to achieve the goal of correcting air inflow. The air intake temperature sensor reflects the density of air intake. The sensing element is a negative temperature coefficient resistance. The appropriate change of resistance value can realize the purpose of correct measurement for air inflow.

The range of air intake temperature sensor temperature is from 40℃ to 120℃, and the resistance value range of is from 0KΩ to 20KΩ.When the temperature is 20℃, the typical resistance is at 3.52KΩ.The event is usually held in June.We can set the inlet temperature as 27.85℃ when the FSAE engine is working. At that time the inlet sensor temperature is 2500Ω. The value of resistance is set as the basis of volume correction. Because the air intake pressure sensor should reflect the change of the inlet valve pressure, we can use the curve of pressure of inlet valve as air inflow compensation reference curve. Under different rotation speed, air intake pressure sensor pressure and the pressure loss in inlet valve and temperature correction value can be shown as Table 1.

Air intake temperature sensor is a resistive sensor. We can change its signal resistance value through an external circuit so as to achieve the correct temperature resistance. The temperature compensation sensor resistance can be acquired by non-linear interpolation. Because the air intake temperature sensor has negative temperature coefficient characteristics, through paralleling different resistance potentiometer resistance under different rotational speed, the resistance value can be realized. The corresponding air intake temperature sensor resistance and the revised resistance under different rotational speed can be shown as the Table 2.

5.3. The Diagram on the Air Intake Correction Control Unit

For real-time modification on air inflow of FSAE engine EFI system, we need to design the electronic control unit which can match with the existing system. Control unit hardware circuit requires high reliability, and shall not affect the normal original system work. The software design requires enough control precision, and has certain anti-interference ability.

Table 1. The Pressure Loss and Revised Temperature under Different Rotational Speed

Rotational speed（rpm）	Pressure sensor（bar）	Pressure inlet valve（bar）	Pressure loss（%）	Revised temperature（%）
1500	0.988	0.981	0.71	0.71
2000	0.982	0.964	1.83	1.87
2500	0.977	0.946	3.17	3.28
3000	0.972	0.942	3.09	3.18
3500	0.971	0.924	4.84	5.09
4000	0.969	0.906	6.50	6.95
4500	0.969	0.901	7.02	7.55
5000	0.969	0.888	8.36	9.12
5500	0.969	0.885	8.67	9.49
6000	0.971	0.882	9.17	10.09
6500	0.971	0.882	9.17	10.09
7000	0.971	0.881	9.27	10.22

Table 2. Temperature Compensation Resistance Value

Rotational speed（rpm）	Sensor resistance（Ω）	Revised resistance（Ω）	Rotational speed（rpm）	Sensor resistance（Ω）	Revised resistance（Ω）
1500	2208	18904	4500	973	1593
2000	2055	11545	5000	812	1203
2500	1760	5946	5500	780	1134
3000	1500	3750	6000	750	1071
3500	1318	2788	6500	720	1011
4000	1120	2029	7000	700	972

The hardware circuit of control unit includes circuit design on microcontroller system, design on speed signal acquisition circuit, and design on drive circuit. The determined overall scheme of the hardware circuit and the control system can be shown as Figure 12.

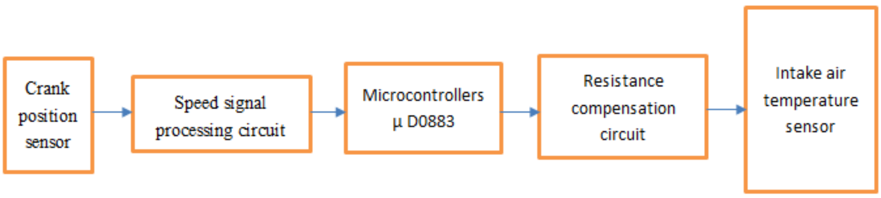

Figure 12. The Intake Air Correction Diagram of the Control Unit

6. Experiment and Test

6.1. Test Equipment

In order to verify whether the intake air correction control unit can meet with the design requirements, this paper deals with the engine test. The test equipments include FSAE car electronic fuel injection engine (as shown Figure 13), the volume correction control unit (as shown Figure 14) and Taike TDS1002 oscilloscope.

6.2. The Test Results

For single point injection system, fuel injection control signal pulse width directly reflects the change of fuel consumption, thus the change of fuel consumption can be measured by detecting injection pulse width.

In the experiment, the output signal of volume correction control unit paralleled with the system temperature sensor signal lines. During the trial, the volume correction control units with the original electric control system can work stable. The injection pulse width measurement can be shown as Table 3.

Figure 13. Engine Installed In FSAE

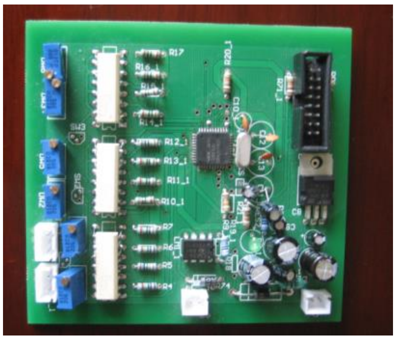

Figure 14. The Intake Air Correction Control Unit

Where:
pw_1---- the injection pulse width not installed restrictor;
pw_2----not corrected injection pulse width with installed restrictor;
pw_3---compensated injection pulse width with installed restrictor.

Table 3. Injection Signal Test Results

Rotational speed （r/min）	Fuel injection cycle(ms)	Pulse width of injection(ms)		
		pw_1	pw_2	pw_3
1500	80	4.8	4.8	4.8
1800	69	4.4	4.4	4.4
2100	53	4.15	4.15	4.15
2900	42	4.2	4.3	4.1
4000	32	4.8	4.96	4.6
4200	28	4.9	5.08	4.7
5000	24	5.2	5.3	5.1
6000	21	5.5	5.5	5.2
6800	19	5.2	5.2	5.0

From the Table 3, through the correction of air inflow, the car engine fuel injection control signal pulse width has been effectively reduced. The volume correction control unit reduces the fuel consumption and improves the fuel economy of the car to a certain extent.

7. Conclusion

The formula SAE gets more and more attention of the universities and the global auto industry, but the domestic is still in its infancy to participate in the competition. The car production levels or competitive ability of drivers is still a gap with foreign universities. Combining with the FSAE car research subject and competition rules, by using BOOST engine cycle simulation theory, the one-dimensional FSAE car engine cycle simulation analysis model was established. And then the influence of the restrictor on the engine was analyzed. According to the results of the simulation analysis, combining the characteristics of the car EFI system, the air intake correction scheme was established by changing the temperature sensor signal. Through analysis of engine electronic control fuel injection system, the hardware and software of control unit design are completed. At last through the engine matching test, the compensation scheme of the fuel injection signal is feasible by detecting injection signal.

Acknowledgment

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