International Journal of Engineering & Technology
CENTRE OF PROFESSIONAL RESEARCH PUBLICATIONS
ISSN 2049-3444

International Journal of Engineering and Technology Volume 2 No. 3, March, 2012

Optimization of Intake and Exhaust System for FSAE Car Based on Orthogonal Array Testing

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ABSTRACT

1-Dimensional software GT-Power was applied to simulate the engine performance. The simulation results were compared to the test results provided by the JH600 engine manufacturer with good agreement. The parameters including the sphere style plenum diameter, the intake runner diameter, exhaust runner lengths and the position of retractor were optimized via a combination of the 1-Dimensional simulation and an orthogonal L_9 (3^4) testing design. The optimal results can limit the effect of restrictor, and then improve the restricted engine's ability effectively in the high speed range (4000 to 7000rpm).

Keywords: *GT-Power*、*Orthogonal Array Testing*、*Restrictor*、*Plenum*

1. INTRODUCTION

Formula SAE is an international student design competition organized by the Society of Automotive Engineers (SAE). In this competition, student design teams design, build, and test a small Formula-style race car. The teams, acting as contractors for a fictional manufacturing company, are held to strict rules and design the car as if it were a production item. The cars are evaluated in a number of static and dynamic judging categories. The static events test the cars engineering design and cost as well as the teams' sales presentation. Dynamic events determine how well the car performs on track [1].

The intake system is one of the most important subsystems of the engine. It is the entrance point for air into the engine [2]. In order to increase the power output of the motor, the amount of air flowing into the engine must be maximized. However, the following rules for the FSAE competition are imposed on the race car's power train:

(1) The engine used must be 4 stroke spark ignition type having no more than 610 cm^3 in displacement

(2) The intake system must induct air solely through a single circular restriction located after the throttle and before the engine. The diameter of the restriction must be 20mm for cars fuelled by gasoline.

For the 2011 racing season, Xiamen University of Technology (XMUT) FSAE team uses a single cylinder 4 valve naturally aspirated JH600 engine which is made in China. The engine specification is summarized in Table 1. The purpose of this thesis was to develop an optimized intake and exhaust system design to be used on the 2011 XMUT FSAE racecar.

Table 1. Specification of JH600 engine

No. of Valves per cylinder	4
No. of Cylinders	1
Displacement /cm^3	589.9
Bore /mm	94
Stroke /mm	85
Compression Ratio	9.7:1
Maximum power	30 kW at 6000 rpm
Maximum torque	51 Nm at 4500 rpm
Cooling system	Water-cooled

2. INTAKE DYNAMIC PERFORMANCE

The air in the system is sloshing back and forth due to its inertia, bouncing against the resilience of the compressed gas in the resonant cavities; there are compression and expansion waves travelling through the gas, reflecting from closed and open ends, and from changes in cross section [3].

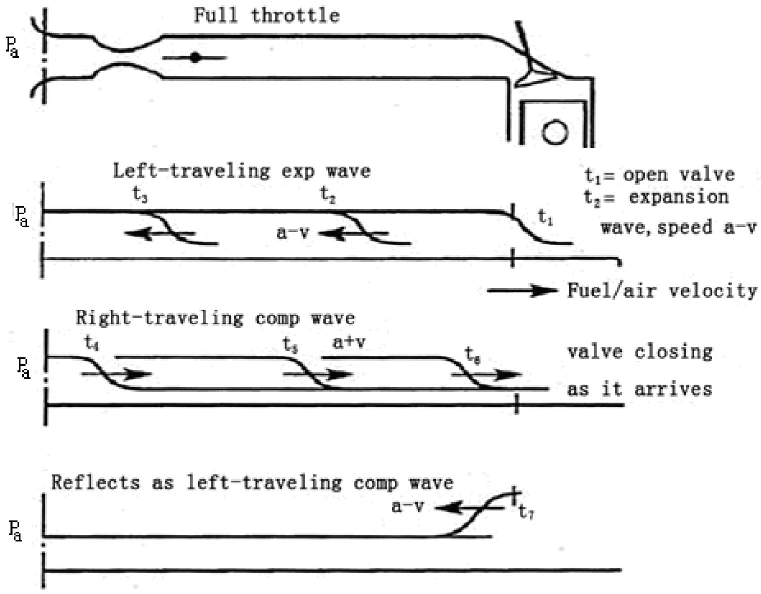

Fig 1. Intake dynamic performance

As can be seen in figure 1, at time t_1, while the piston is starting to drop the inlet valve opens and the air rushing in the cylinder pushes further the piston down. Then, the pressure in the cylinder drops by that movement relative to the pressure in the manifold and that leads to the creation of an expansion wave as a reduction of pressure is being displayed. This expansion wave of relative velocity a-v travels towards the open end of the manifold, which at time t_4 is reflected back as a compression wave of relative velocity a+v, as at open ends the incident waves are converted. At time t_6 the compression waves arrives just as the inlet valve is closing, being considered as a closed end boundary [4]. As a result, the transmitted compression wave will enter the cylinder with increased pressure, thus acting as a mild supercharging,

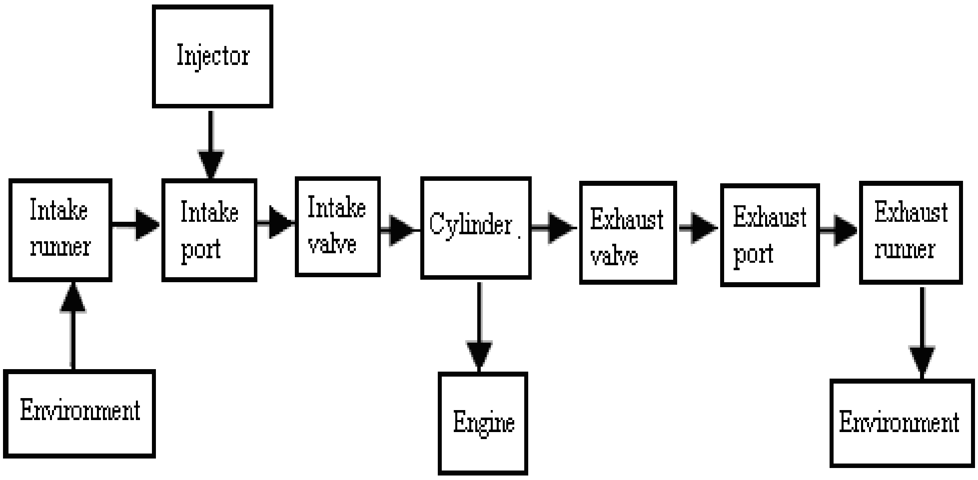

Fig 2. Schematic of engine model in GT-Power

3. ENGINE MODEL SETUP AND VALIDATION

3.1 The Engine Model in GT-Power

The JH600 engine model was built using the GT-Power platform, a one-dimensional gas dynamics code capable of representing flow and heat transfer in internal combustion engines. GT-POWER is the industry standard engine simulation tool, used by all leading engine and vehicle makers and their suppliers. Figure 2 illustrates the basic layout in GT-power of the engine model. Arrows show the flow of mass (both air and fuel) from environment through the engine and then exhausted to environment again. Many assumptions and simplifications were made to the system in order to complete the model. Firstly, the exhaust system was modeled as a straight pipe and did not consider the effect of silencer. Also, the pressure losses in these ports are included in the discharge coefficients calculated for the valves.

3.2 GT-Power Solution Theory

Engine performance can be studied by analyzing the mass and energy flows between individual engine components and the heat and work transfers within each component.

Simulation of 1-D flow involves the solution of the conservation equations: mass, energy and momentum, in the direction of the mean flow[5]. The governing equations are briefly given for reference:

Continuity

$$\frac{\partial \rho}{\partial t} + \rho \frac{\partial c}{\partial x} + c \frac{\partial \rho}{\partial x} + \frac{\rho c}{F} \frac{F}{dx} = 0 \quad (1)$$

Momentum

$$\frac{\partial c}{\partial t} + c \frac{\partial c}{\partial x} + \frac{1}{\rho} \frac{\partial p}{\partial x} + f \frac{c^2}{2} \frac{c}{|c|} \frac{4}{D} = 0 \quad (2)$$

Energy

$$\left(\frac{\partial p}{\partial t} + u \frac{\partial p}{\partial x}\right) - a^2 \left(\frac{\partial \rho}{\partial t} + \frac{\partial \rho}{\partial x}\right) - \rho(\kappa - 1)\left(q + cf \frac{c^2}{2} \frac{c}{|c|} \frac{4}{D}\right) = 0 \quad (3)$$

Where c is the Velocity, ρ is the density, p is the pressure, F is the area, f is wall friction coefficient, q is the heat transfer per unit mass and $D = \sqrt{\frac{4F}{\pi}}$

The combustion burn rate (X_b) using Wiebe function, can be expressed as Eq. (4):

$$X_b = 1 - \exp\left[-a\left(\frac{\theta - \theta_i}{\Delta \theta}\right)^{n+1}\right] \quad (4)$$

Where θ is the crank angle, θ_i is the angle where the start of combustion occurs, $\Delta \theta$ is the total combustion duration and a and n are adjustable parameters.

3.3 Model Validation

An engine model based on the JIALING JH600 motorcycle was made to verify the accuracy of simulation results. The dimensions and nature of the intake and exhaust flow networks were modeled by measuring the motorcycle.

Figure 3 shows the comparison of simulation results to measured dynamometer power results provided by China Jialing Industrial Co., Ltd. The simulation overestimates brake power when the engine speed greater than 5000rpm. And the simulation underrates brake power when the engine speed less than 5000rpm. Both curves show their respective peak power values at 6000rpm. The largest discrepancy is less than 10% over the entire speed range of the engine. The simulation model is suitable in terms of predicting the performance trends of the engine.

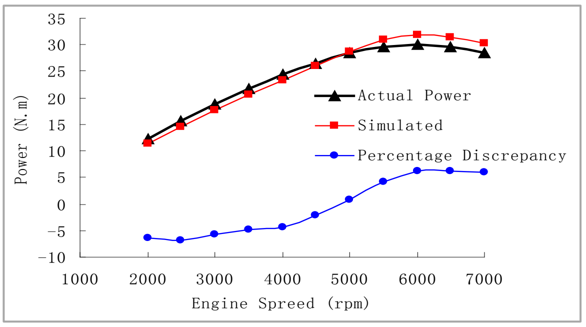

Fig 3: Comparison of simulated and measured power

4. INTAKE AND EXHAUST SYSTEM DESIGN

4.1 Restrictor Effect

As part of the FSAE competition rules, it is stated that an air restrictor of circular cross-section must be fitted downstream of the throttle and upstream of any compressor, no greater than 20mm for our engine. The air restrictor creates a major restriction on the engine airflow, and in turn restricts the power output [6]. Figure 4 shows the effect of restrictor on power. The restrictor plate reduces engine torque across the entire speed range with the greatest reduction occurring at higher speeds (5000 to 7,000rpm). The unrestricted model、restrictor plate and the restrictor body used for optimizing shown in Figure5.

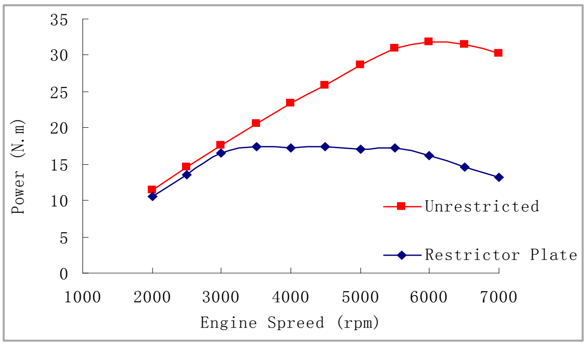

Fig 4. Effect of restrictor on power

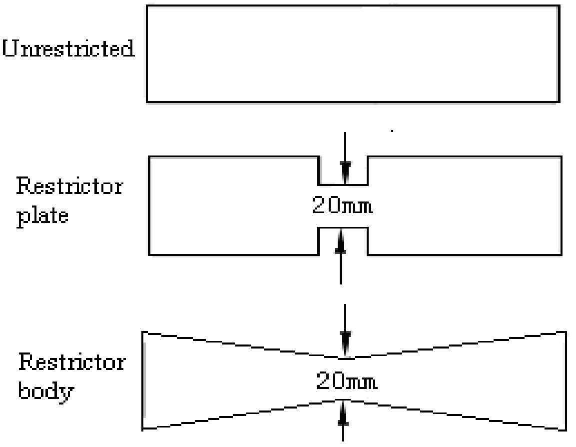

Fig 5. pipe configurations

4.2 Plenum Design

In order to limit the effects of the restrictor, the plenum designed by using Helmholtz theories was apply to decrease the pressure drop associated with the restrictor [7]. A sphere style plenum was chosen for the JH600 engine. The schematic of plenum can be seen in Figure 6. The Helmholtz resonator frequency can be expressed as following [8]:

$$f = \frac{c}{2\pi}\sqrt{\frac{F}{(L+L_k)V}} \quad (5)$$

Where f is the frequency, V is the volume of plenum, F is the cross-sectional flow area of branch pipe, L is the branch pipe, and $L_k = 0.8d$.

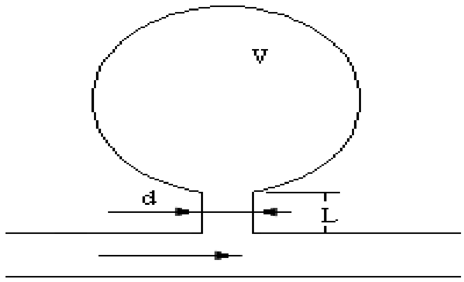

Fig 6. Schematic of plenum

4.3 Restricted Engine System for Optimizing

The intake and exhaust designs are dependent on each other in terms of overall engine performance so the two systems have to be designed together to achieve an optimal output [9]. It was decide to focus on four parameters for the intake and exhaust system: the sphere style plenum diameter、the intake runner diameter、the exhaust runner lengths and the position of restrictor. The restricted engine system used for optimizing was shown in figure 7.

5. ORTHOGONAL ARRAY TESTING

5.1 Orthogonal Array Testing Strategy

Orthogonal Array Testing Strategy (OATS) is a systematical, statistical way of testing pair-wise interactions by deriving suitable small set of test cases from a large number of scenarios. The testing strategy can be used to reduce the number of test combinations and provide maximum coverage with a minimum number of test cases. OATS utilizes an array of values representing variable factors that are combined pair-wise rather than representing all combinations of factors and levels [10]. The testing was conducted using an $L_9(3^4)$ orthogonal array optimize the Restricted engine system. The $L_9(3^4)$ orthogonal array used was shown in Table 2.

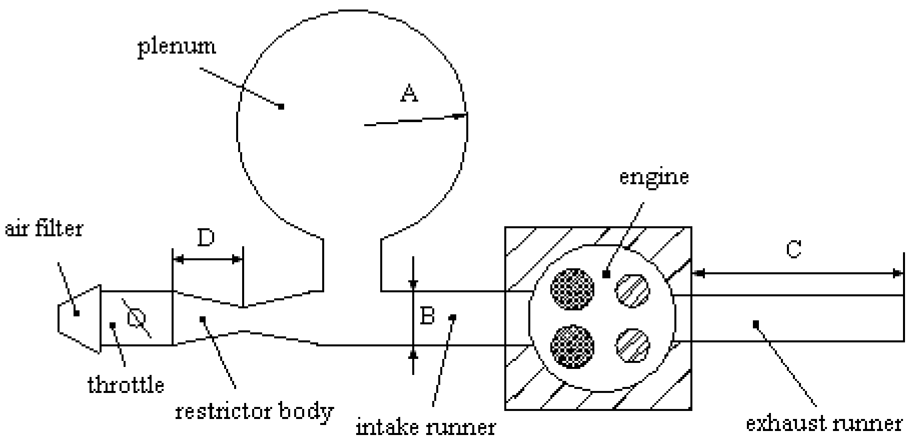

Fig 7. The restricted engine model

Table 2. Orthogonal test array

Test NO.	Factors							
	A (mm)		B (mm)		C (mm)		D (mm)	
1	A1	160	B1	40	C1	50	D1	900
2	A1	160	B2	45	C2	100	D2	1000
3	A1	160	B3	50	C3	150	D3	1100
4	A2	180	B1	40	C2	50	D3	1100
5	A2	180	B2	45	C3	100	D1	900

6	A2	180	B3	50	C1	150	D2	1000
7	A3	200	B1	40	C3	50	D2	1000
8	A3	200	B2	45	C1	100	D3	1100
9	A3	200	B3	50	C2	150	D1	900

Note: A-- the sphere style plenum diameter, B-- the intake runner diameter, C--the exhaust runner lengths, D--the position of restrictor

5.2 Results and Discussion

The overall effect was to maximize the power offered by the restricted engine. The factors were evaluated by extreme difference method to optimize horsepower 4,500 to 6,000rpm. The final values chosen were A = 200mm,B= 45mm, C=50mm and D=1000mm. Figure 8 shows the comparison of simulation results with the optimal intake and exhaust system to the unrestricted ones. The optimal results can offset the effect of restrictor, and improve the restricted engine's ability effectively in the high speed range (4000 to 7000rpm).

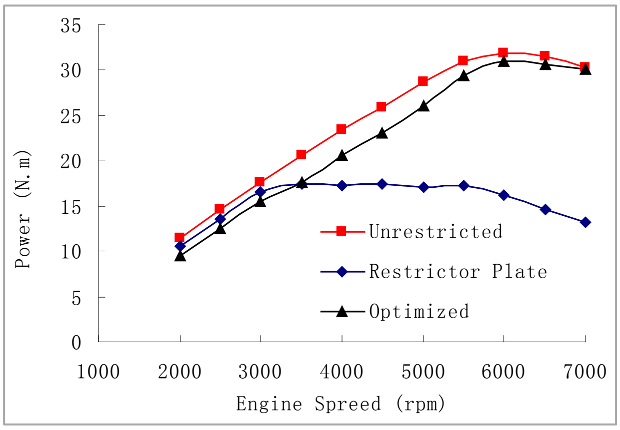

Fig. 8: Comparing the power of the engine with unrestricted model、restrictor plate and the optimized system

6. CONCLUSIONS

The study considered the performance characteristics of single cylinder restricted engine. The following conclusions are drawn:

(1) 1D software GT-Power can be use to an simulate the performance of single cylinder engine with a high degree of accuracy.

(2) The design of intake and exhaust system was determined by using Orthogonal Array Testing Strategy. The optimal results can offset the effect of restrictor, and improve the restricted engine's ability effectively in the high speed range.

(3) The cam timing should be studied together with the intake and exhaust system to tuning the restricted FSAE engine

REFERENCES

[1] 2011 Formula SAE Rules. http://students.sae.org/ competitions/ formulaseries/rules/

[2] Ryan Ilardo, Christopher B. Williams. Design and Manufacture of a Formula SAE Intake System Using Fused Deposition Modeling and Fiber-Reinforced Composite Rapid Prototyping Journal, Vol. 16 Iss: 3, pp.174 - 179

[3] Georgios V. Varsos. 1-D Simulation of the Intake Manifold of a Single-cylinder Engine[C]. Imperial College, London, UK, 2010.

[4] JL Lumley. Engines: an introduction. Cambridge University, 1999.

[5] Gamma Technologies, *GT-Power User's Manual*, GTSuiteVersion 6.1, 2004.

[6] James Correia. 1-Dimensional Simulation of a Restricted Engine For Formula SAE. University of Toronto, 2009.

[7] M.A. Ceviz. Intake plenum volume and its influence on the engineperformance, cyclic variability and emissions. Energy Conversion and Management 48 (2007) 961–966

[8] Tan Jianwei. Design of Automotive Helmholtz Intake Resonator Based on 1D /3D Models Coupling Simulation[J]. Automotive Engineering, 2007 (Vol. 29) No. 10.

[9] Nilufar Damji. Optimization of the Intake System for the 2008 Formula SAE Race Car[C]. University of Toronto, March 2008.

[10] Kia Bauer. Orthogonal Array Testing Strategy. www.tcqaa.org