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A New Hydraulic Variable Valve Timing and Lift System for Spark Ignition Engine

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A continuous variable valve timing and lift system by hydraulic volume adjustable (CVVTL) for both intake and exhaust valves of Spark Ignition (SI) engine is introduced in this paper. Unlike existing hydraulic variable valve systems, the CVVTL does not use the electro-hydraulic valves. A four-cylinder CVVTL prototype of engine cylinder head was built, and the valve movement laws of the prototype were tested. The experimental results show that the CVVTL can achieve fully variable valve timing and lift adjustment according to the engine speeds. An AVL Boost simulation model is built to simulate the performances of baseline engine and CVVTL engine. The simulation results show that the CVVTL engine has uplifted improvement in the power, torque, volumetric efficiency and brake specific fuel consumption (BSFC) compared to the baseline engine at different engine speeds, particularly at the low and medium speeds. Experimental and simulation results show that the CVVTL has the potential to eliminate the traditional throttle valve in the gasoline engines.

1. Introduction

In order to combat greenhouse gas emissions and scarcity of fossil fuels, the more stringent regulations of vehicles' fuel consumption and emissions are proposed in many countries. The variable valve technology is one of technologies to meet the increasingly stringent regulations. Its flexibility of adjustment the valve timing, duration, lift, or a combination of these could facilitate to improve the performance, fuel economy and emissions of the Spark Ignition (SI) engine(Turner et al., 2004). Therefore, numerous variable valve systems are proposed(Hu Z.L, et al,2015), and a few of them has been applied to the automobile engineering, such as Honda's VTEC, Toyota's VVT-i, BMW's Valvetronic which are the typical representative of camshaft-based mechanical variable valve actuation systems(Hosaka et al., 1991)(Flierl et al., 2000), and Fiat's Multiair that is the typical representative of electro-hydro-mechanical fully variable valve actuator(EHMFVVA) (Lucio et al., 2010). One fact that becomes evident is that the camshaft-based mechanical variable valve actuation systems have very limited flexibility, complicated mechanical structure and expensive with the increase in flexibility. Although the EHMFVVA has more flexibility(Gillella et al., 2011), but each valve is controlled by at least one high frequency servo valve, so the cost of EHMFVVA is expensive.

A continuous variable valve timing and lift system by hydraulic volume adjustable (CVVTL) is proposed in the paper. The CVVTL can realize the independent and continuous adjustment of valve timing and lift all working conditions, but it does not use the electro-hydraulic valves. A prototype was manufactured and the valve regulation was tested. The engine performance simulation model is established by AVL Boost software, and engine performance is simulated by the model with the experimental results of the valve regulation.

2. Structure and working principle of CVVTL

2.1 Structure of CVVTL

The structure of CVVTL is shown in figure 1. The CVVTL is composed of cam, cam cylinder, valve cylinder, valve assembly, phase regulator, lift regulator, seating buffer and oil supply system, and so on. The valve phase regulator and lift regulator mainly consists of cylinder, piston, spring, gag lever post, and adjusting device. The oil supply system consists of oil tank, oil pump, check valve, relief valve and pipeline.

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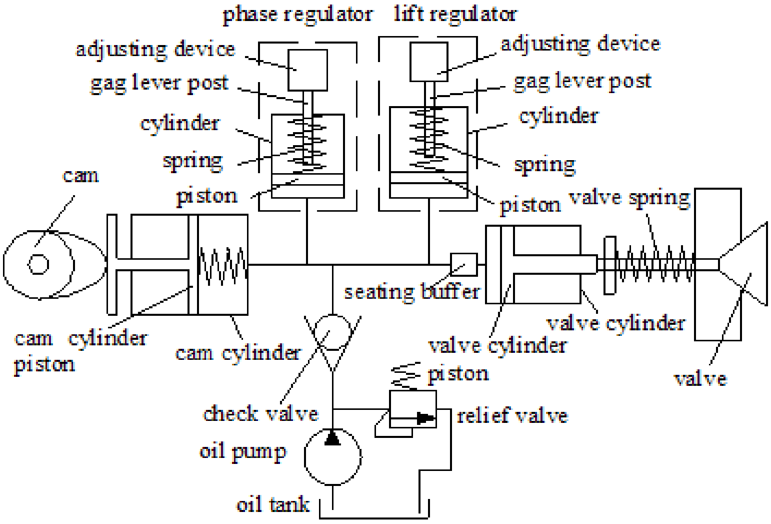


Figure 1: Schematic diagram of CVVTL

2.2 Working principle of CVVTL

The working principle of CVVTL as follow:

1) Valve timing adjustment. The phase regulator piston will be in the most front position of phase regulator cylinder under the effect of spring, while the cam working in the base circle segment for the gag lever post of phase regulator at any position in the adjustment range. When the valve timing needs to be adjusted, it only needs to vary the position of the gag lever post of phase regulator. The cam cylinder begins to pump oil when the cam lift is coming. Since the pre-tightening force of the phase regulator spring is less than that of valve spring, the oil pumped from the cam cylinder would firstly flows into the phase regulator cylinder until the regulator piston is stopped by the gag lever post. At this stage, the valve keeps still. Therefore, the valve is opened later than the adjustment of the gag lever post is zero. It is to say that the valve advance angle is decreased. While the cam continues rotating, the oil pressure of system gradually increases. When the valve cylinder can overcome the pre-tightening force of valve spring, the valve is opened and the opening of valve is gradually increased until the end of cam lift. The working process is opposite when the cam working in the cam's fall curve. Because of the valve spring force is bigger than the phase regulator spring force, the oil of valve cylinder will be the first to return back to the cam cylinder until the valve seated. While the valve seated, the cam continues rotating and the oil in the phase regulator also begin to return back to the cam cylinder under the effect of phase regulator spring until the cam returns to the base circle segment. Therefore, the valve is closed earlier than the adjustment of the gag lever post is zero. It is to say that the valve retard angle is decreased. From above, the system realizes the continuous adjustment of the valve advance angle, the valve retard angle and the valve duration angle by controlling the time that the oil flows into and flow out from the valve cylinder.

2) Valve lift adjustment. The lift regulator piston will be in the most front position of lift regulator cylinder under the effect of spring, while the cam working in the base circle segment for the gag lever post of lift regulator is at any position in the adjustment range. When the valve lift needs to be adjusted, it only needs to vary the position of the gag lever post of lift regulator. When cam working in its lift and the oil pressure of system has got to the point that can overcome the pre-tightening force of valve spring to open the valve, since the design value of pre-tightening force of the lift regulator spring is bigger than that of the valve spring, the lift regulator piston will be in idle state, and the oil pumped from the cam cylinder will only flow into the valve cylinder to open the valve. As the pressure of system continue to increase and get to the point that can overcome the pre-tightening force of lift regulator spring, the lift regulator piston moves under the effect of oil pressure. So the oil begins to flow into the lift regulator oil cylinder until the piston is stopped by the gag lever post of lift regulator. Therefore, the liquid volume flows into the valve cylinder will be decreased, and the valve lift also will be decreased. The working process is opposite when the cam working in the cam's fall curve. Because of the lift regulator is working in the opening of valve, the lift adjustment totally does not influence the valve timing. Obviously the system can realize the continuous adjustment of valve lift by controlling the liquid volume flow into the valve cylinder and lift regulator, which can control by fairly adjusting the position of gag lever post of lift regulator.

When the valve timing and lift need to be adjusted at the same time, the system can obtain the reasonable valve timing and lift by adjusting the phase regulator piston and lift regulator piston to their reasonable position according to the engine working conditions.

3. The movement law of valve

3.1 CVVTL prototype

A four-cylinder CVVTL prototype of engine cylinder head was built, shown in figure 2. In the prototype, the timing and lift of intake valve could be adjusted by the CVVTL, and exhaust valve only adjusts the timing. There is one cam cylinder, one phase regulator and one lift regulator for the intake valves of a cylinder, and one cam cylinder and one phase regulator for the exhaust valves of a cylinder. All intake cam cylinder pistons are driven by the intake cam and laid with each other 90°, also all exhaust cam cylinder pistons are driven by the exhaust cam and laid with each other 90°. The intake cam and exhaust cam are mounted on the same camshaft, the angle between intake cam and exhaust cam should be agreed with the requirement of engine gas distribution. The intake cam cylinders, exhaust cam cylinders, camshaft, intake phase regulators, intake lift regulators and exhaust phase regulators are integrated together in the driving assembly. The intake phase regulators and exhaust phase regulators are controlled by the phase adjusting device, and the intake lift regulators are controlled by the lift adjusting device. The intake valve cylinders are integrated in the intake valve cylinder assembly, and the exhaust valve cylinders are integrated in the exhaust valve cylinder assembly. The driving assembly connects the intake valve cylinder assembly and the exhaust valve cylinder assembly with the oil passage assembly. The camshaft is driven by the servo motor with the synchronous belt, and the transmission ratio is 1:1. The valve motion was measured by using the laser displacement sensor. In the experiment, both the phase adjusting device and lift adjusting device adjusted manually.

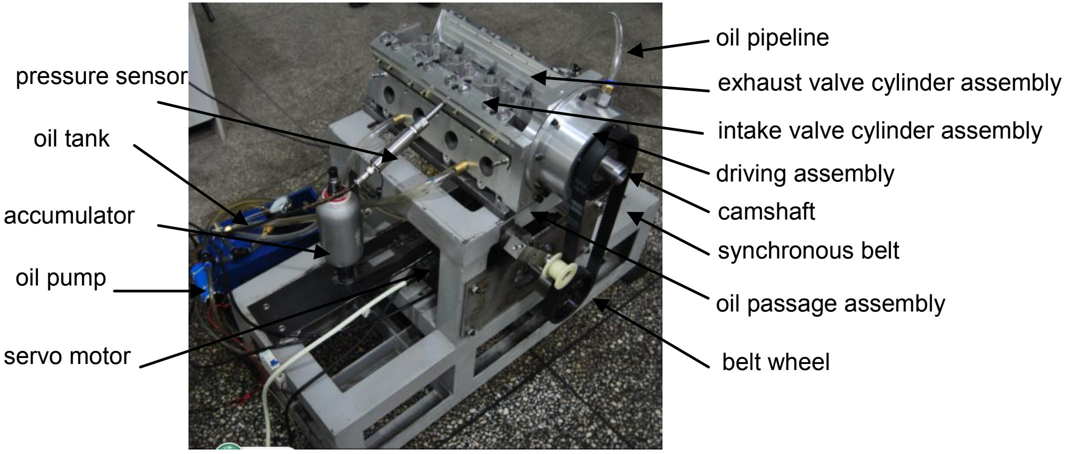


Figure 2: CVVTL prototype

3.2 The experimental results of valve movement law

Figure 3 shows the experimental results of exhaust valve timing adjustment at different engine speeds. These curves are obtained by adjusting the phase adjusting device to vary the regulation of phase regulator piston, the higher engine speed, the less regulation of phase regulator piston. It can be seen that the advance angle, retard angle, and duration angle can be varied at different engine speeds. As the speed is increased, the advance angle, retard angle, duration angle and lift are gradually increased, agreeing with the research result that the advance angle, retard angle should be increased with the increase of speed (Chen, 2014)(Shang et al., 2015). Although the valve lift is decreased with the increase of speed in the timing adjustment, but that is accord with the tendency of gas distribution requirement as engine speed is decreased.

Figure 4(a) shows the experimental results of intake valve lift adjustment at different engine speeds. These curves are obtained by adjusting the lift adjusting device to vary the regulation of intake lift regulator piston, the higher engine speed, the less regulation of intake lift regulator piston. It can be seen that the intake valve lift can be varied at different engine speeds and gradually increased as the engine speed is increased, but valve timing is not affected. Therefore, more air-fuel mixture can be drawn into the combustion chamber, and the engine volumetric efficiency would be increased (Wong and Mok, 2008).

Figure 4(b) shows the experimental results of intake valve timing and lift adjustment at different engine speeds. These curves are obtained by both adjusting the phase adjusting device and the lift adjusting device, the higher engine speed, the less regulation of intake phase regulator piston and less regulation of intake lift regulator piston. It can be seen that the timing and lift of intake valve can be varied by both adjusting intake phase regulator piston and intake lift regulator piston at different engine speeds. The advance angle, retard angle, duration angle and lift are gradually increased as the engine speed is increased. It is to say that the CVVTL allows more air-fuel mixture entering the cylinder at medium and high engine speeds, the CVVTL engine would achieve a higher volumetric efficiency at high engine speeds. Due to the CVVTL makes the valve to keep short open duration at low engine speed so as to prevent excessive valve overlap which reduces volumetric efficiency (Wong and Mok, 2008).

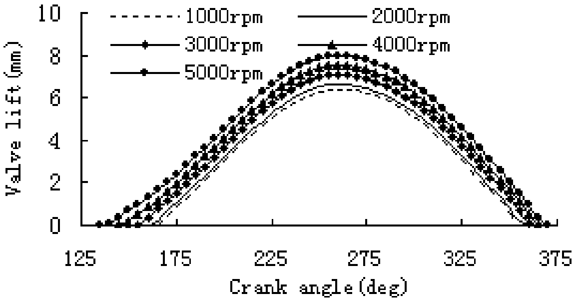
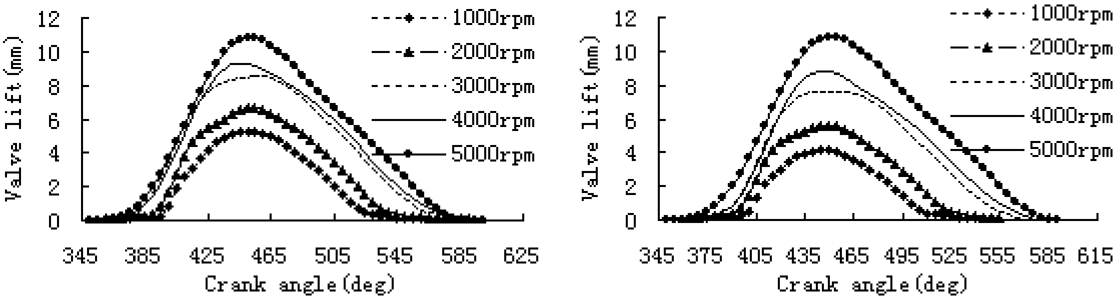


Figure 3: Valve lift curves of valve timing adjustment at different engine speeds



(a) Lift adjustment

(b) Timing and lift adjustment

Figure 4: Intake valve lift curves of different engine speeds

4. Performance of CVVTL engine

A simulation model of engine was established by AVL Boost software, shown in figure 5. The baseline engine specification is shown in table 1. Two case sets were setup, case set 1 was simulated the performance of baseline engine in the full load condition, the intake lift curve and exhaust lift curve of the baseline engine are inputted to the model. Case set 2 was simulated the performance of CVVTL engine in the full load condition, the experimental results of the exhaust valve timing adjustment (Figure 3) and the experimental results of both the timing and lift adjustment of intake valve(Figure 4(b)) are applied to the simulation.

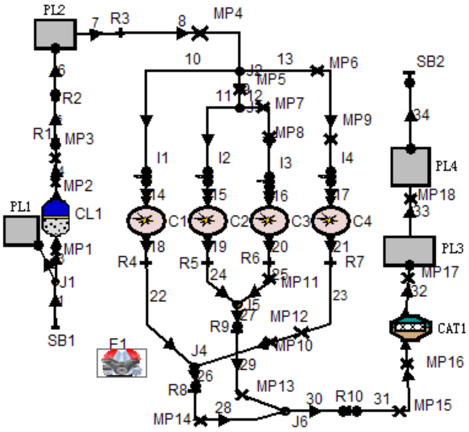


Figure 5: Simulation model of engine performance

Table 1: Engine specification

Parameter	Description	Parameter	Description
No of cylinders	4	IVC(degree of CA)	570@1mm lift
Capacity (L)	1.604	Intake valve lift	9.5 mm
Bore (mm) ×Stroke(mm)	82×76	EVO(degree of CA)	154@1mm lift
Compression ration	10.5	EVC(degree of CA)	356@1mm lift
Rated Torque	151N·m@5000rpm	Exhaust valve lift	8 mm
Rated Power	86Kw @ 6000rpm	Number of valves	8 Intake/8 Exhaust
IVO(degree of CA)	365 @ 1mm lift	Camshaft type	DOHC

Figure 6 shows the simulation results of volumetric efficiency. It is seen that overall volumetric efficiencies are increased under the engine speeds from 1000r/min to 5000r/min. Due to the exhaust valve timing, intake valve timing and intake valve lift are adjusted and suitable for the engine working conditions, so the volumetric efficiencies of CVVTL engine are all higher than that of the baseline engine under various engine speeds. The backflow of mixture is avoided for the low overlap duo to the exhaust retard angle and intake advance angle are adjusted by CVVTL at low and medium speeds, the volumetric efficiency is significantly improved, particularly at 2000r/min, the improvement reaches 15.7% compared to baseline engine. While at high speed, higher volumetric efficiency is achieved due to higher intake inertia and higher intake valve lift, because of the intake retard angle and intake valve lift are adjusted by CVVTL and those are more suitable for the high speed. The average improvement of volumetric efficiency is 7.74%.

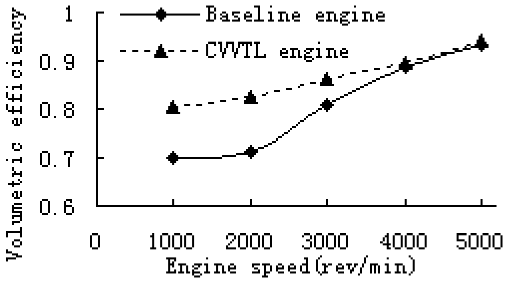
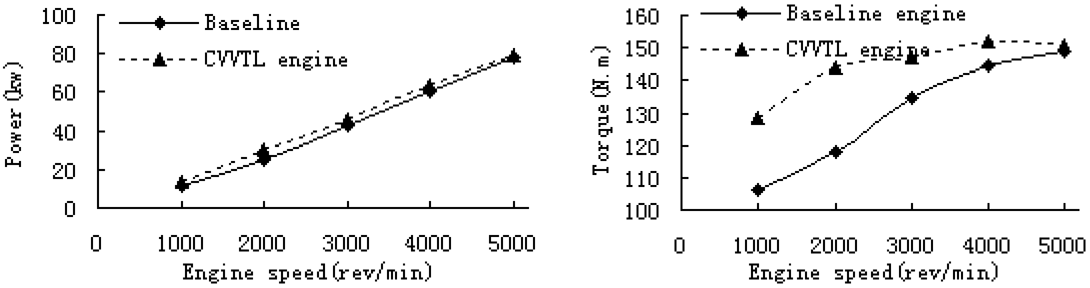


Figure 6: Volumetric efficiency versus for different engine speeds

The simulation results of power and torque are shown in figure 7. From the figure, we can know that the CVVTL engine has an overall uplifted performance of power and torque under the engine speeds from 1000r/min to 5000r/min compared to baseline engine, because of the increase of volumetric efficiency. The average improvement of power and the average improvement of torque are 11.67% and 11.76% respectively compared to baseline engine. The maximum improvement of power and the maximum improvement of torque are obtained at 2000r/min duo to the maximum improvement of volumetric efficiency is obtained at same engine speed. The values are 21.80% and 21.87% respectively.



(a) Power *(b) Torque*

Figure 7: Power and Torque versus for different engine speeds

Figure 8 shows the simulation result of BSFC. The BSFC of CVVTL engine is less than that of baseline engine, the average reduction of BSFC is 1.54% compare to the baseline engine, and the maximum is 2.6% obtained at 1000r/min. Because of the intake timing and lift, the exhaust timing can be varied according to the speeds in the CVVTL engine, the volumetric efficiency is increased compare to baseline engine. On the other hand, the cancel of throttle is beneficial to reduce the intake loss.

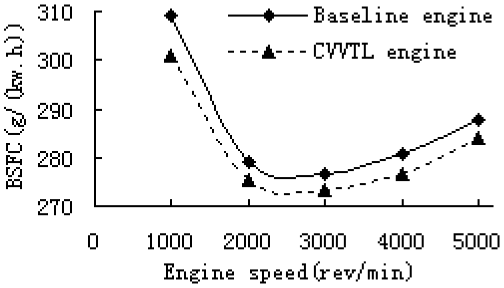


Figure 8: BSFC versus for different engine speed

5. Conclusions

A continuous variable valve timing and lift system by hydraulic volume (CVVTL) adjustable is proposed in the paper. The CVVTL consists of camshaft, cam cylinder, valve cylinder, valve assembly, phase regulator, lift regulator, seating buffer and oil supply system, and so on. The valve timing can be varied by adjusting the phase regulator, and the valve lift can be varied by adjusting the lift regulator. The structure of CVVTL is easy to integrate, and the control of this system also is simple. A four-cylinder CVVTL prototype of engine cylinder head was built, and the valve movement laws of the prototype are tested. The experimental results show that the CVVTL could realizes the valve timing continuously adjustment and the valve lift continuously adjustment. The valve timing adjustment affects the valve lift, but the valve timing is not affected by the valve lift adjustment. The intake advance angle, intake retard angle, exhaust advance angle, exhaust retard angle, duration angle, exhaust valve lift and intake valve lift of the CVVTL are increased as the increase engine speed by both adjusting the phase regulator and lift regulator, and the varying tendency satisfies the gas distribution requirements of various working conditions of engine very well. An AVL Boost simulation model of CVVTL engine is built, and the performance of CVVTL engine is simulated by the model. Comparing to the baseline engine, the CVVTL engine has great improvement in the power, torque, volumetric efficiency and BSFC and so on, particularly at the low and medium speeds, the maximums are 21.80%, 21.87%, 15.7% and 2.6% respectively, and the average values are 7.74%, 11.67%, 11.76% and 1.54% respectively.

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