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HYDRAULIC VARIABLE VALVE SYSTEM FOR IMPROVING THE PERFORMANCE OF INTERNAL COMBUSTION ENGINE

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ЗАСТОСУВАННЯ ГІДРАВЛІЧНОЇ СИСТЕМИ РЕГУЛЬОВАНИХ КЛАПАНІВ ДЛЯ ПІДВИЩЕННЯ ПРОДУКТИВНОСТІ ДВИГУНІВ ВНУТРІШНЬОГО ЗГОРАННЯ

Purpose. The engines with variable valve system can achieve better performance for all engine speed compared to those with fixed valve timing and lift. In this article, a hydraulic variable valve system is proposed according to the requirements of the engine. Both intake and exhaust valves can all be regulated.

Methodology. We have built a valve movement test platform and tested the hydraulic variable valve system performance for valve regulation. Using the intake and exhaust valve curves regulated by hydraulic variable valve system, we have predicted the performance of engine by 1D simulation software AVL Boost.

Findings. The test results show that the valve timing and lift can be continuously varied according to the engine speed by hydraulic variable valve system. The simulation results show that the engine with various valve timing and lift has a certain improvement of volumetric efficiency, brake power, brake torque, brake specific fuel consumption and residual gas coefficient compared to base engine at different engine speed. The improvement is obvious especially in low and middle speed.

Originality. The construction and working principle of hydraulic variable valve system is new, and the regulation strategy of valve is different from others.

Practical value. The hydraulic variable valve system can be applied on engines for better performance and has advantages of simple structure, easy control and low cost.

Keywords: *variable valve system, valve timing, valve lift, engine performance*

Introduction. The reasonable variable valve system should consider intake process and exhaust process at the same time. In the intake process, too small intake valve opening advance angle (IVOAA) causes the increase of intake flow loss due to the lower cylinder pressure at the beginning of intake stroke, while too large IVOAA causes exhaust backflow. The proper IVOAA should be increased with the increase of engine speed. At high engine speed, a large intake valve closing retard angle (IVCRA) can make full use of the intake inertia and increase the volumetric efficiency, while at low engine speed, the IVCRA should be small in order to reduce intake backflow [1, 2].

In the exhaust process, the exhaust valve opening advance angle (EVOAA) affects the pumping loss and effective expansion work. A large EVOAA increases pumping loss, while a small EVOAA decreases effective expansion work, the proper EVOAA can make the sum of effective expansion work loss and pumping loss minimum. The research suggests that the EVOAA should be increased with the increase of engine speed. The exhaust valve closing retard angle (EVCRA) increased with the increase of engine speed can make full use of the exhaust inertia for reducing the residual gas coefficient [3,4].

Therefore, the intake and exhaust valve timing should be varied according to the engine speed, the IVOAA, IVCRA, EVOAA and EVCRA should be increased with the increase of engine speed. In addition, the valve lift also should be increased with the engine speed increasing [5].

Currently, the variable valve technologies are various. Variable camshaft timing technology used by Variable Valve Timing (VVT) of Toyota is the most applied technology, the IVCRA can be changed according to the engine speed, which helps increase volumetric efficiency, but it cannot change the opening duration and the lift of valve as per engine demand. Cam changing has been used by Variable Valve Timing and Valve Lift Electronic Control System (VTEC) of Honda, Variable Valve Timing &Lift Intelligent (VVTL-I) of Toyota, Audi valve-lift system (AVS) and Mitsubishi Innovative Valve Timing Electronic Control System (MIVEC), it only has two cam profiles for different intake valve timing and lift, which cannot meet the requirements for all engine speed. Valvetronic combined with Vanos system of BMW to achieve variation in valve timing and lift can better meet the demands of engine, but its structure is complex and high priced. Fiat has developed a 3D cam mechanism that can change the contact position between the cam and the follower, so as to regulate the valve timing and lift. The mechanism is easy to cause serious wear and tear because of the point contact and the manufacturing is complex. This technology is not used to the car up to now. An electric hydraulic variable valve system is developed by Lotus, it can easily control valve open or closed. But every valve should be individually controlled and the demand for actuation response rate is too high, so the system is complex and high cost [6–8].

A hydraulic variable valve system (HVVS) is proposed in this paper. The valve timing and lift can be continuously varied according to the engine speed by HVVS which has the advantages of simple structure, easy control and low cost. The construction and working principle of HVVS, valve regulation testing and engine performance prediction have been discussed in the subsequent paragraphs.

Construction and working principle of HVVS. As shown in Fig. 1, the hydraulic variable valve system is composed of a cam mechanism, a valve assembly, a regulator, a seating sunbber and hydraulic components. The limit device inside regulator can control the left dead center of regulator plunger movement. The plunger is also at rightmost of cylinder by the regulator spring preload when the cam tappet is on the cam base circle. When the cam tappet is driven upwardly by cam, the oil pressure is increased and the oil will only flow into regulator cylinder until the regulator plunger is against by the limit device since the regulator spring force is less than the valve spring preload. As camshaft continues to rotate, the oil pressure rises to overcome the valve spring preload and pressured oil begins to flow into valve cylinder, then the valve is opened and until reached to maximum lift. When the cam tappet is driven downwardly, the valve is moved back to valve seat firstly and has a smooth seating by the seating sunbber, then the regulator plunger is moved to the initial position. In this process, the advance angle, retard angle and lift of valve are all reduced. Obviously, the valve timing and lift can be continuously varied by regulating the left dead center of regulator plunger. In addition, more intake valves can be regulated in a HVVS by parallel connection with the hydraulic circuit, and the same as exhaust valves, so an engine only needs a double HVVS for all intake and exhaust valves, which makes structure simple.

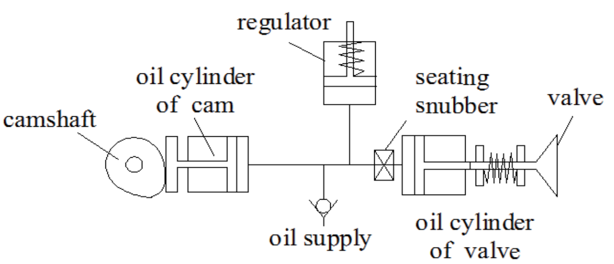
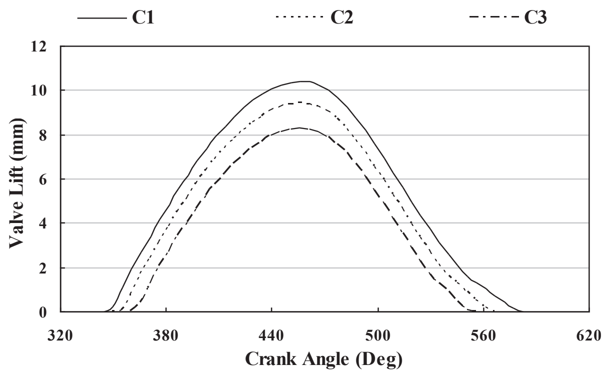


Fig. 1. Schematic diagram of hydraulic variable valve timing and lift system

Test of HVVS. Fig. 2 shows the test platform of HV-VS. The camshaft is driven by an inverter motor which can simulate the rotation of engine. The test of HVVS were based on the different engine speed and regulating quantity. The test platform has angular displacement sensor, pressure sensor and displacement sensor which can mea-sure cam phase, system oil pressure and valve lift, all of the signals were acquired and transferred to the computer. The following will be the discussion of the HVVS test results.

As shown in Fig. 3, the lift and opening duration of valve without regulating are smaller than cam tappet because of the oil compressibility. The oil pressure curve shows the system has certain pressure fluctuations, when the oil pressure is lower than the initial pressure, oil source will automatically fill oil, the valve cannot sit down, and it will seriously affect the normal work of HVVS. As a result, the oil compressibility and pressure fluctuations must be considered in the design of HVVS.



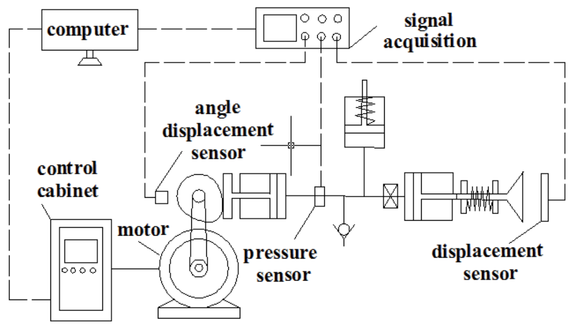


Fig. 2. Schematic diagram of HVVS test platform

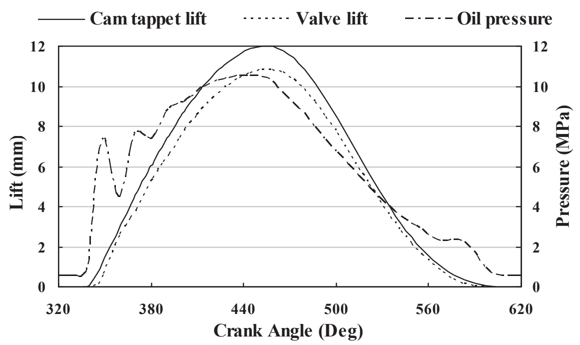


Fig. 3. The curves of cam tappet lift, valve lift and oil pressure at 2000rpm without regulating

C1, C2 and C3 are the corresponding valve lift cur-ves with the regulating quantity gradually increased, as shown in Fig, 4. It can be seen that the advance angle, retard angle and lift of valve were gradually reduced. In addition, the regulating ratio of advance angle to retard angle can be adjusted by changing the cam profile.

Fig. 5 shows that under the same regulation quantity the higher the speed, the higher the valve lift, and the same to the valve duration, which is due to greater kinetic energy. However, this trend is in accordance with the requirements of the engine for high speed, the increment can also be controlled by regulator. In addition, the valve at all different speed did not appear obvious rebound phenomenon after seating, which indicates that the snubber assembly can effectively control the valve seating velocity.

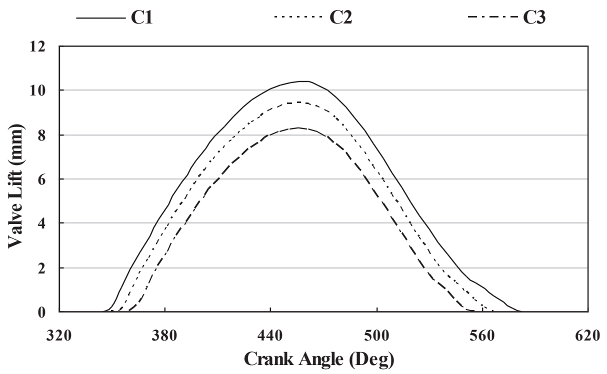


Fig. 4. The valve lift curves of different regulating quantity at 2000rpm

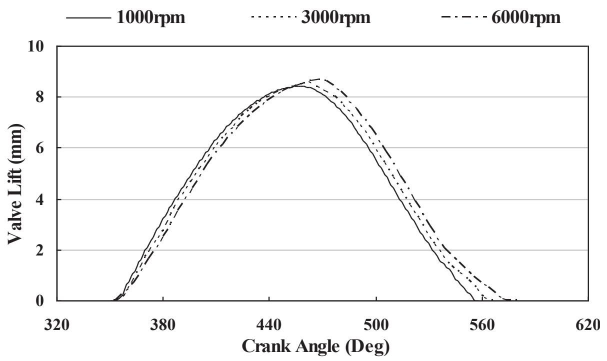


Fig. 5. The Valve lift curves with different speed under the same regulating quantity

As shown in Fig. 6, the regulated valve lift curves for different speed are variable, so the continuously variable of valve advance angle, retard angle and lift according to the engine speed can be achieved by HVVS.

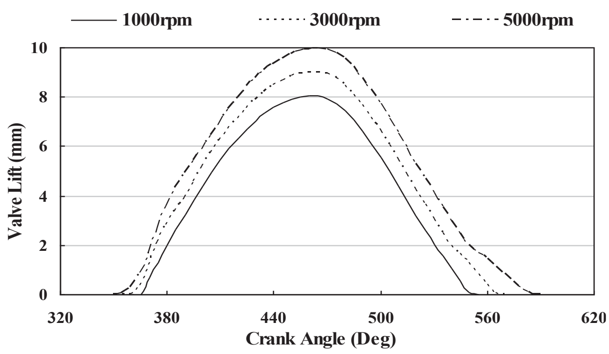


Fig. 6. The regulated valve lift curves for different speed

Through the above analysis, it can be seen that the continuously variable of valve advance angle, retard angle and lift according to the engine speed can be achieved by HVVS. The effect of rotational speed on valve lift curve is controllable. The snubber assembly can achieve stable valve seating. Therefore, under the consideration of the oil compressibility and pressure wave, the valve timing and lift can meet the requirements of engine at different speed by reasonably cam design and regulation.

Performance prediction of engine with HVVS. Using the detailed specification simulation of base engine was done in 1D Simulation software AVL Boost to obtain the performance of engine at various valve timing and lift regulated by FVVS. The specification of the engine is shown in Table 1 and the simulation model is shown in Fig.7.

Table 1

Engine specification

Engine specification		
No	Parameter	Description
1	No of cylinders	4
2	Capacity (L)	1.604
3	Bore (mm)	82
4	Stroke	76
5	Compression ration	10.5
6	Rated Torque	151 N·m @ 5000 rpm
7	Rated Power	86 Kw @ 6000 rpm
8	IVO(degree of CA)	365 @ 1mm lift
9	IVC(degree of CA)	570 @ 1mm lift
10	Intake valve lift	9.5 mm
11	EVO(degree of CA)	154 @ 1mm lift
12	EVC(degree of CA)	356 @ 1mm lift
13	Exhaust valve lift	8 mm
14	Number of valves	8 Intake / 8 Exhaust
15	Camshaft type	DOHC

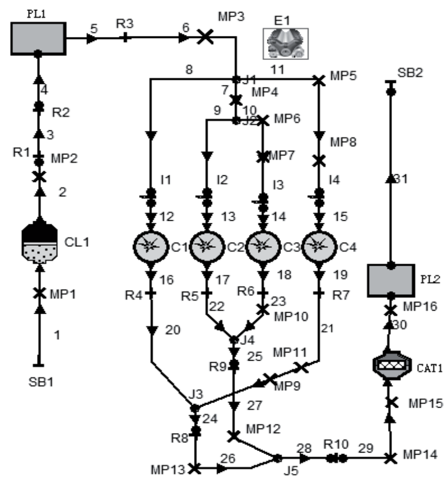


Fig.7. Simulation model for engine performance

The optimization of HVVS has been done on the test platform according to the requirements of different engine speed based on the engine simulation. Fig. 8 shows the intake valve and exhaust valve lift test curves regulated by optimized HVVS, the detailed parameters are shown in Table 2. It can be seen that with the increase of engine speed, the advance angle, retard angle and lift of intake valve were increased, and the same to exhaust valve. When the engine speed is below 4000rpm, the advance angle, retard angle and lift of valves are all less than base engine with fixed valve timing and lift.

Fig. 9 shows the effect of HVVS to improve the volumetric efficiency of engine. It is clear that overall volumetric efficiency is increased throughout the speed range, especially at the low and middle speed. Because the engine can reduce backflow loss at low and medium speed due to the regulating of intake valve by HVVS. There is an average improvement of 10.97% in the volumetric efficiency of engine with maximum improvement of 24.25% at 1000rpm of engine compared to base engine.

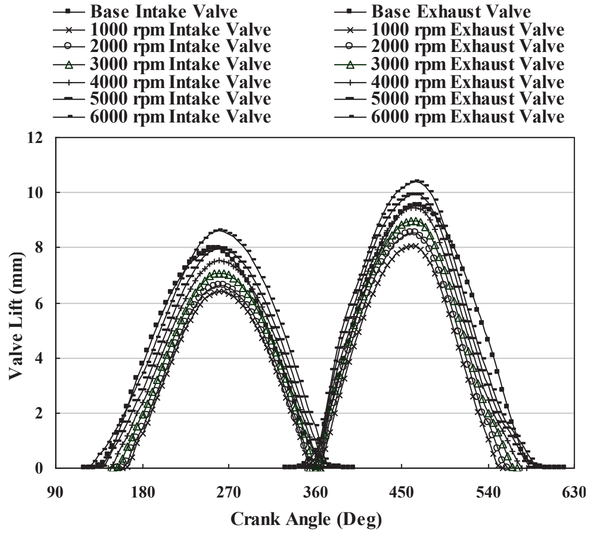


Fig. 8. Valve lift curves of HVVS and base engine

Table 2

Valve lift curves detailed parameters of HVVS and base Engine

	Intake Valve			Exhaust Valve		
	IVO (Deg) @ 1mm lift	IVC (Deg) @ 1mm lift	Lift (mm)	EVO (Deg) @ 1mm lift	EVC (Deg) @ 1mm lift	Lift (mm)
Base	365	570	9.5	154	357	8
1000rpm	373	540	8	176	346	6.4
2000rpm	370	547	8.6	173	348	6.6
3000rpm	368	553	9	168	352	7
4000rpm	366	560	9.45	162	356	7.5
5000rpm	365	566	9.9	155	360	8
6000rpm	363	574	10.3	146	364	8.6

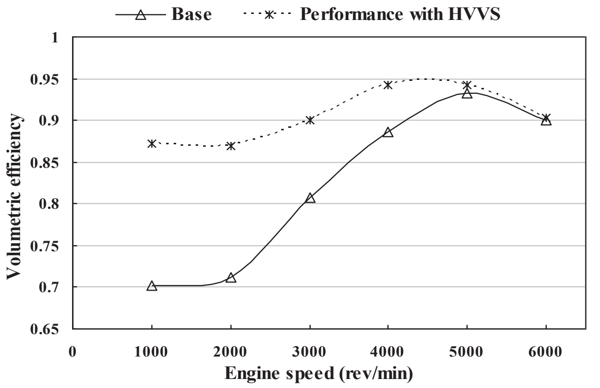


Fig. 9. Volumetric efficiency versus engine speed of HVVS and base engine

Fig. 10 and 11 shows that the engine regulated by HVVS has an overall uplifted performance of brake power and brake torque throughout the speed range compared to base engine. The improvement of performance here is due to the increase of volumetric efficiency.

There is an average improvement of 12.58% in the brake power and brake torque of engine with maximum improvement of 27.35% at 1000rpm of engine compared to base engine.

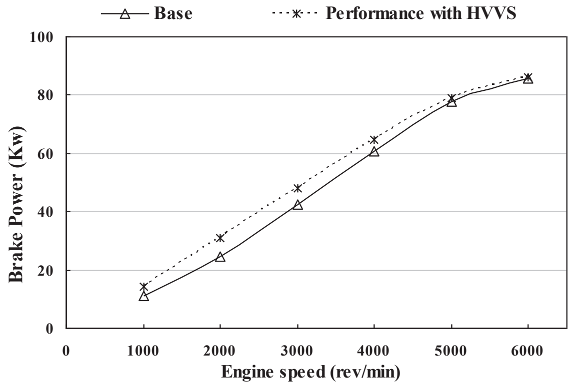


Fig. 10. Brake Power versus engine speed of HVVS and base engine

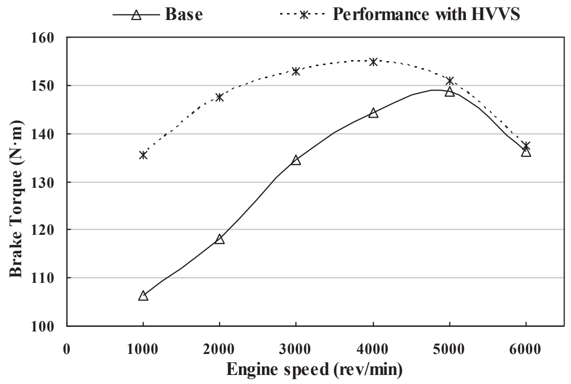


Fig. 11. Brake Torque versus engine speed of HVVS and base engine

Fig. 12 shows the engine has an average reduction of 1.71% in the BSFC with HVVS. The effect of BSFC is due to the volumetric efficiency improvement and intake loss reduction by intake valve regulating. Moreover, the regulating of exhaust valve, especially the regulating of the EVOAA makes effective expansion work loss and pumping loss minimum.

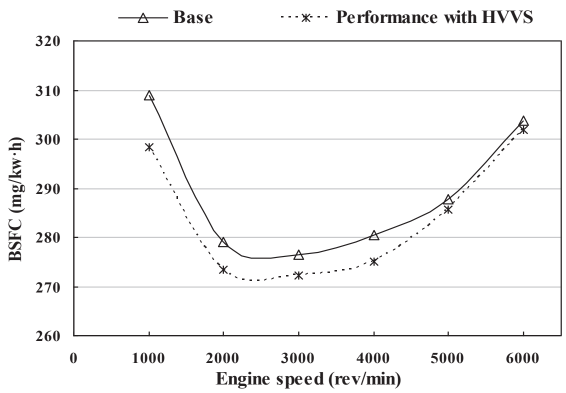


Fig. 12. BSFC versus engine speed of HVVS and base engine

Fig. 13 shows the engine has an average reduction of 27.89% in the residual gas coefficient with HVVS since the regulating of the EVCRA can control the quantity of exhaust gases that flow back into the combustion chamber in low and middle speed.

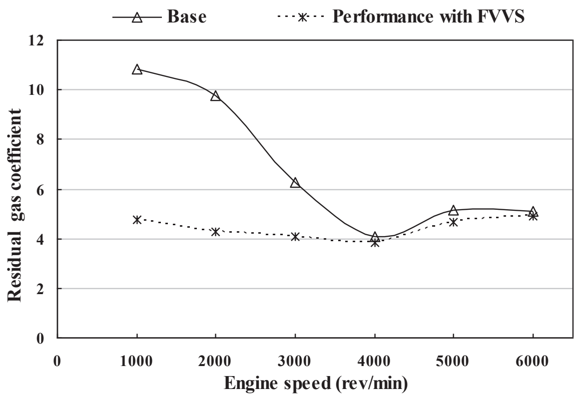


Fig. 13. Residual gas coefficient versus engine speed of HVVS and base engine

In a word, the engine with FVVS has a certain improvement of volumetric efficiency, brake power, brake torque, brake specific fuel consumption and residual gas coefficient compared to base engine, and the effect is obvious especially in low and middle speed.

Conclusion. In order to improve engine performance, the IVOAA, IVCRA, EVOAA, EVCRA and valve lift should be increased with the increase of engine speed. To meet hese requirements, a hydraulic variable valve system HVVS is proposed in this article. The performance of HVVS has been tested and the results show that the effect of engine speed on valve lift curve is controllable. The valve can achieve a smooth landing. The IVOAA, IVCRA, EVOAA, EVCRA and valve lift can be continuously varied according to engine speed. The intake and exhaust valves of an engine can all be regulated by HVVS.

The performance of engine with various valve timing and lift regulated by HVVS has been predicted by 1D Simulation software AVL Boost. The simulation results show an improvement of volumetric efficiency by an average of 12.58%, brake torque and power by an average improvement of 12.58%, an average reduction of 1.71% in BSFC and a reduction of residual gas coefficient by an average of 27.89% compared to base engine. And the improvement is obvious especially in low and middle speed. On the whole it concludes that HVVS can be applied on engines for better performance.

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References / Список літератури

1. Liu Fushui,Shang Yong,Wang Li, et al.(2013), "Influence of Intake Closing Timing on Gas Exchange Process in Internal Combustion Engine",*Chinese Internal Combusion Engine Engineering*, vol.34, no.6, pp.51–57.

2. Shang Yong, Liu Fushui, Lu Ying (2015), "Influence of Valve Overlap on Air Exchange Process in Internal Combustion Engine",*Chinese Internal Combustion Engine Engineering*, vol.36, no.4, pp.104–111.

3. Shang Yong, Liu Fushui, Wang Yali (2015), "Influence of Exhaust Valve Opening Timing on Gas Exchange Process in Internal Combustion engine",*Chinese Internal Combustion Engine Engineering*, vol. 34, no. 2, pp.7–12.

4. Verhelst, S., Demuynck, J.,Sierens, R., Huyskens, P. (2010), "Impact of variable valve timing on power, emissions and backfire of a bi-fuel hydrogen/gasoline engine", *International Journal of Hydrogen Energy*, vol. 35, no. 9, pp. 4399–4408.

5. Hu Zhilong, Gui Yong, Min Xu, et al. (2015),"Design of a variable valve hydraulic lift system for diesel engine", *Journal of Mechanical Science and Technology,* vol. 29, no. 4, pp. 1799–1807.

6. Tomoda, T., Ogawa,T., Ohki, H., et al. (2010), "Improvement of diesel engine performance by variable valve train system", *International Journal of Engine Research*, vol. 11, no. 5, pp. 331–44.

7. Okazaki, A. (2011), "Development of highly efficient engine with Electromagnetic variable valve lift", *Nippon Institute of Technology*, vol. 41, no. 2, pp. 9–10.

8. Haas, Michael. (2010), " Electro-hydraulic fully variable valve train system", *AutoTechnology*, vol. 10, no. 2, pp. 38–43.

Мета. Двигуни з системою управління клапанами газорозподілу володіють кращою продуктивністю в порівнянні з двигунами, в яких зафіксовані моменти відкриття та закриття, а також висота підйому клапанів. У роботі запропонована гідравлічна система управління клапанами газорозподілу, що відповідна вимогам двигуна. Вона дозволяє регулювати обидва клапани: впускний та випускний.

Методика. Створено випробувальний стенд руху клапанів і протестована ефективність регуляції клапанів системи управління клапанами газорозподілу. На основі графіків показників впускного та випускного клапанів, регульованих системою, за допомогою програмного забезпечення для 1D-моделирования AVL Boost були спрогнозовані робочі показники двигуна.

Результати. Тести показали, що моменти відкриття та закриття клапанів можуть постійно змінюватися системою відповідно до обертів двигуна. Результати моделювання двигуна з регульованими клапанами демонструють поліпшення показників потужності на одиницю робочого об'єму двигуна, потужності гальмування, гальмівного моменту, питомої витрати палива на гальмівному стенді, коефіцієнта залишкових газів на різних обертах двигуна в порівнянні з вихідним двигуном. Покращення особливо помітні на низьких і середніх обертах.

Наукова новизна. Запропоновані нова конструкція та принцип дії гідравлічної системи управління клапанами газорозподілу, стратегія регулювання клапанів, що відрізняються від відомих.

Практична значимість. Запропонована гідравлічна система управління клапанами газорозподілу може використовуватися у двигунах для покращення їх робочих характеристик, відрізняється простотою конструкції та контролю, низькою собівартістю.

Ключові слова: *система регулювання клапанів, фаза газорозподілу, висота підйому клапана, характеристика двигуна*

Цель. Двигатели с системой управления клапанами газораспределения обладают лучшей производительностью по сравнению с двигателями, у которых зафиксированы моменты открытия и закрытия, а также высота подъёма клапанов. В работе предложена гидравлическая система управления клапанами газораспределения, соответствующая требованиям двигателя. Она позволяет регулировать оба клапана: впускной и выпускной.

Методика. Создан испытательный стенд движения клапанов и протестирована эффективность регуляции клапанов системы управления клапанами газораспределения. На основе графиков показателей впускного и выпускного клапанов, регулируемых системой, с помощью программного обеспечения для 1D-моделирования AVL Boost были спрогнозированы рабочие показатели двигателя.

Результаты. Тесты показали, что моменты открытия и закрытия клапанов могут постоянно изменяться системой в соответствии с оборотами двигателя. Результаты моделирования двигателя с регулируемыми клапанами демонстрируют улучшение показателей мощности на единицу рабочего объёма двигателя, мощности торможения, тормозного момента, удельного расхода топлива на тормозном стенде, коэффициента остаточных газов на разных оборотах двигателя по сравнению с исходным двигателем. Улучшения особенно заметны на низких и средних оборотах.

Научная новизна. Предложены новые конструкция и принцип действия гидравлической системы управления клапанами газораспределения, стратегия регулирования клапанов, отличающиеся от известных.

Практическая значимость. Предложенная гидравлическая система управления клапанами газораспределения может использоваться в двигателях для улучшения их рабочих характеристик, отличается простотой конструкции и контроля, низкой себестоимостью.

Ключевые слова: *система регулирования клапанов, фаза газораспределения, высота подъёма клапана, характеристика двигателя*

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EXPERIMENTAL DETERMINATION OF THE FRICTIONAL PROPERTIES OF THE FLEXIBLE BODY SLIDING OVER A BLOCK

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ЕКСПЕРИМЕНТАЛЬНЕ ВИЗНАЧЕННЯ ФРИКЦІЙНИХ ВЛАСТИВОСТЕЙ ГНУЧКОГО ТІЛА ПРИ КОВЗАННІ ПО БЛОКУ

Purpose. Experimental determination of the dependence of the force and the coefficient of friction of the flexible body on the normal reaction between bodies while sliding over the fixed block.

Methodology. The frictional properties of the friction pair "flexible body–block" was determined by means of the test bench with different forces applied to the ends of the flexible body. Then, according to Euler's Solution, the experimental dependence of the force and the friction coefficient on the normal reaction between the bodies was developed and compared with the accumulated data of the theory and practice.

Findings. Experimental dependence of the force and the coefficient of friction of the flexible body on the normal reaction between bodies while sliding over the fixed block was established.

Originality. For the first time, the two-parameter linear dependence of the friction force and inversely proportional dependence of the coefficient of friction of the flexible body on the normal reaction between bodies while sliding over the fixed block were obtained experimentally. This corresponds to Coulomb's law of friction between two solid bodies, new solution of Euler's classical problem of flexible body sliding over the fixed block, and practice data.

Practical value. Research results can be used in mechanical engineering while designing and operating transport vehicles with a flexible traction body as well as in research and education.

Keywords: *law of friction, flexible body, thread, sliding, block, tensile force, frictional properties, friction force, coefficient of friction, normal reaction*

Objectives. The purpose of the article is to define experimentally dependence of the strength and the coefficient of friction of the flexible body on the normal reaction between the bodies sliding over the fixed block.

Previously, the normal reaction between the flexible body and block the has never been defined with the direct method since according to Euler's solution it was determined with the indirect method and depended on the frictional properties of the flexible body – the coefficient of friction.