

UDC 621.43
УДК 621.43

DOI:10.33744/0365-8171-2025-118.1-214-224

IMPROVING PERFORMANCE OF SPARK-IGNITION ENGINES
BY CHANGING THE VALVE TIMING AND LIFT

ПОЛІПШЕННЯ ПОКАЗНИКІВ ДВИГУНІВ З ІСКРОВИМ ЗАПАЛЮВАННЯМ
ЗМІНОЮ ФАЗ ГАЗОРОЗПОДІЛУ ТА ВИСОТИ ПІДЙОМУ КЛАПАНІВ



Korpach Anatolii O., Ph.D., Professor, Professor Department of Engines and Heating Engineering, National Transport University, Kyiv, Ukraine, e-mail: akorpach@ukr.net, tel. +380931203905.

<https://orcid.org/0000-0002-7070-7883>



Levkivskiy Oleksandr O., Ph.D., Technical Trainer, Limited Liability Company «Winner Imports Ukraine, LTD», Kyiv, Ukraine, e-mail: oleksandr.levkivskiy@gmail.com, tel. +38067797644.

<https://orcid.org/0000-0002-2951-2312>



Korpach Oleksii A., Ph.D., Associate Professor, Associate Professor Department of Automobiles, National Transport University, Kyiv, Ukraine, e-mail: korpach1988@gmail.com, tel. +380442804252.

<https://orcid.org/0000-0002-2496-4395>

Abstract. The article examines modern valve timing and lift adjustment systems used in spark-ignition automotive engines, which enhance power output and reduce harmful exhaust emissions.

The object of the study: Control systems for the intake valve timing mechanism.

The aim of the study: analysis of the main methods of regulating valve timing and lift and their impact on internal combustion engine performance.

Research method: Analytical.

The article explores the design and operating principles of variable valve timing (VVT) systems in spark-ignition engines. It has been established that modern engine manufacturers employ a unified approach to dynamic valve timing regulation, utilizing engine oil pressure to adjust the camshaft's angular position via a valve timing adjustment mechanism. Additionally, it has been determined that camshaft torque can be leveraged to enhance the efficiency of VVT systems.

Various types of variable valve lift (VVL) systems are analyzed. In general classification, VVL systems are divided into discrete variable valve lift (DVVL) systems and continuously variable valve lift (CVVL) systems. Discrete VVL systems operate by switching between different cam profiles and are widely adopted across manufacturers, with diverse implementations. In contrast, CVVL systems enable continuous

adjustment of intake valve lift, optimizing power and torque across all engine operating modes. CVVL systems regulate airflow into the cylinders, ensuring a smooth power output transition at any engine speed or load. It is also noted that CVVL systems can be either mechanically or hydraulically actuated.

The findings presented in this article can be used for further analysis and enhancement of existing valve timing and lift systems.

Keywords: internal combustion engine, valve timing, intake valve lift.

Introduction.

Problem Statement.

The conventional valve timing mechanism in spark-ignition engines operates with fixed valve timing, determined by the camshaft profile and its position relative to the crankshaft. However, a fixed valve timing and intake valve lift do not allow for optimal engine performance across the entire range of speeds and loads.

When the engine operates at maximum power (full throttle), high gas exchange speed improves cylinder filling by opening the intake valve before the top dead center and closing it after the bottom dead center, resulting in a significant valve overlap angle (when both intake and exhaust valves are open simultaneously). However, under low-load conditions (partial throttle opening), vacuum in the intake manifold and excessive valve overlap can cause exhaust gas backflow into the intake manifold, reducing cylinder filling efficiency [1].

In addition to valve timing, intake valve lift also influences fuel efficiency and engine power under various operating conditions. At low loads, reducing the intake valve lift increases the throttle opening degree, minimizing engine pumping losses. Conversely, under maximum load, increasing the intake valve lift improves cylinder filling, thereby enhancing power output [2].

Analysis of Current Research.

Traditionally, to ensure balanced engine performance across various operating conditions, engineers selected a compromise valve timing and intake valve lift height. However, this approach did not allow for optimal performance. Modern automotive engines incorporate systems that enable adjustments to both the valve timing and the intake valve lift [3].

The Aim of the Study.

Analysis of the primary methods of regulating valve timing and lift and their impact on internal combustion engine performance.

Main Content.

The principle of dynamic valve timing adjustment is universal across all modern automotive engines and is implemented via a variable valve timing (VVT) system. This system is an electro-hydraulic unit that can regulate either the intake valve timing alone or both intake and exhaust valve timing independently using two separate unit. Adjusting the opening moment of the intake valves and the closing moment of the exhaust valves relative to the camshaft position helps optimize engine performance, reducing fuel consumption and emissions of harmful substances in exhaust gases. This is achieved by modifying the valve overlap angle [4].

The position of each camshaft is monitored by the engine control module (ECM), which processes data from the camshaft and crankshaft position sensors. This information is used to control solenoid valves that regulate the supply of pressurized engine oil to different chambers of the VVT mechanism. When oil pressure is absent, the intake valve timing unit remains in the maximum retard position, while the exhaust valve timing unit is in the maximum advance position. These positions are locked by a locking mechanism, which is released when oil pressure is applied. In this state, the minimum valve overlap angle is maintained, ensuring stable engine startup.

During engine operation, when valve timing adjustments toward advance or retard are required, the solenoid valve directs pressurized oil to the appropriate chamber of the VVT mechanism (Fig. 1). The advance and retard adjustment chambers are located between two components of the VVT unit — one rigidly attached to the camshaft and the other connected to the timing gear. Under hydraulic pressure, the camshaft rotates relative to the timing gear, adjusting valve timing. Oil pressure can be supplied to the VVT mechanism at varying rates, allowing for independent and precise valve timing control.

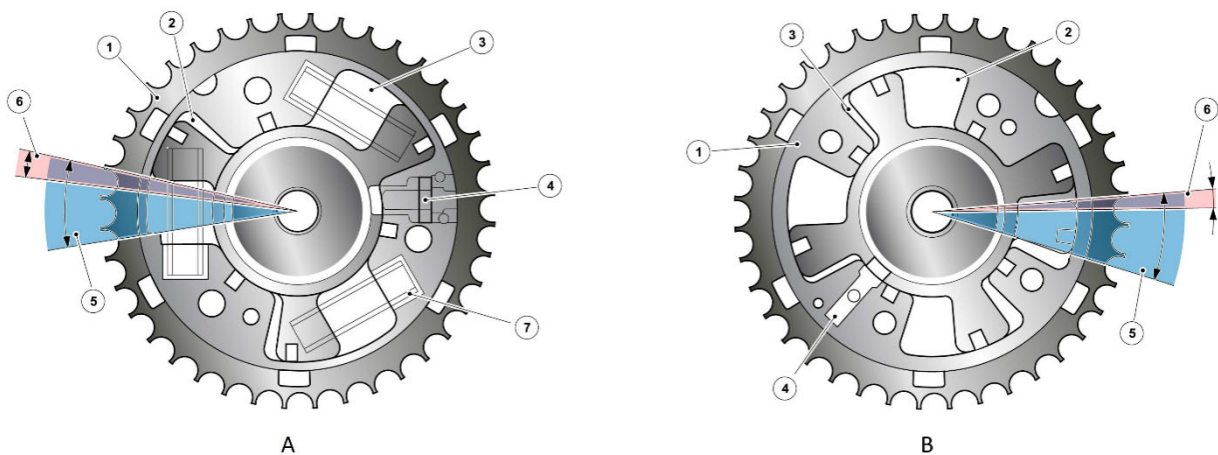


Figure 1 – A – Exhaust variable valve timing unit, B – Intake variable valve timing unit:
 1 – Body; 2 – Advance adjustment chamber; 3 – Retard adjustment chamber;
 4 – Locking pin; 5 – Adjustment angle; 6 – Free play (0.25-0.75 degrees); 7 – Return spring

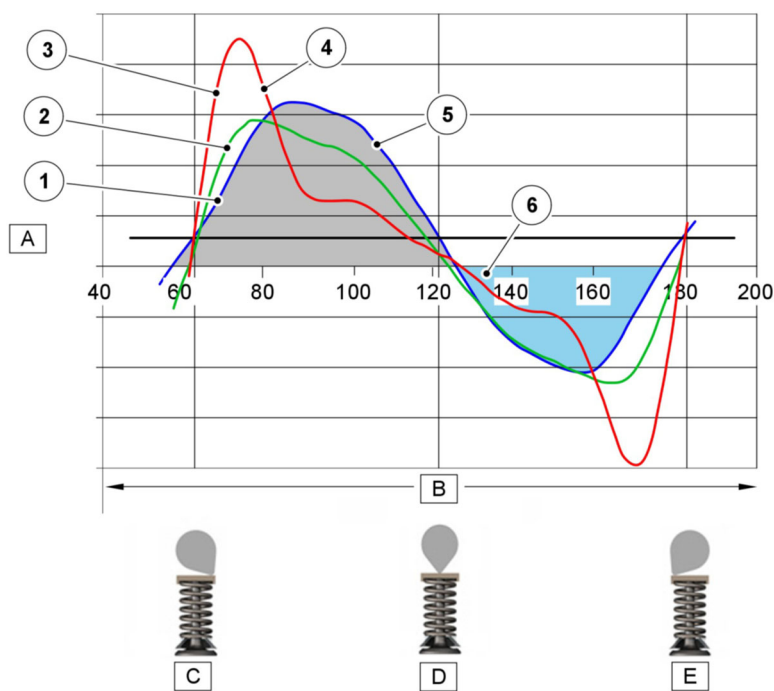


Figure 2 – A – Camshaft torque (Nm), B – Camshaft rotation (degrees), C – Valve opening, D – Valve peak lift, E – Valve closing: 1 – 1000 min⁻¹; 2 – 4000 min⁻¹; 3 – 7000 min⁻¹; 4 – Inertia effects from rotating mass; 5 – Force caused by valve spring; 6 – Bias torque from friction

Depending on the engine design, the variable valve timing unit has several pairs of advance/retard chambers (typically three to five). This design allows for an even distribution of forces on the camshaft to ensure precise adjustment of the valve timing advance or retard angle.

In recent years, a widely adopted valve timing adjustment technology has emerged, utilizing the torque generated on the camshaft for its rotation relative to the timing gear [5]. This torque arises due to the interaction of the camshaft lobes with valve springs and the inertia of the moving components in the valve mechanism (Fig. 2). Unlike systems that rely solely on pressure created by the oil pump, this approach primarily utilizes internal movement of engine oil between the chambers of the unit to regulate the camshaft's relative position (Fig. 3).

As a result of this approach, the operation of the variable valve timing system requires significantly less engine oil—approximately 15% less [5]. The reduction in oil consumption decreases the engine oil pump's workload, which in turn improves fuel efficiency and increases power output. Additionally, since this technology is less sensitive to fluctuations in engine oil pressure, it enhances response speed at low engine speeds and high temperatures, where oil pressure may be insufficient.

Beyond the variable valve timing mechanism, two types of variable valve lift systems are employed to enhance engine performance under different speed and load conditions: the discrete valve lift system (DVVL) and the continuously variable valve lift system (CVVL). The discrete valve lift system is based on the concept of switching between different camshaft profiles. During low-load engine operation, a lower cam profile is used, reducing fuel consumption by minimizing engine pumping losses, achieved by increasing the throttle opening angle. In high-power modes, a high cam profile is engaged, improving cylinder filling and thus increasing maximum power output (Fig. 4).

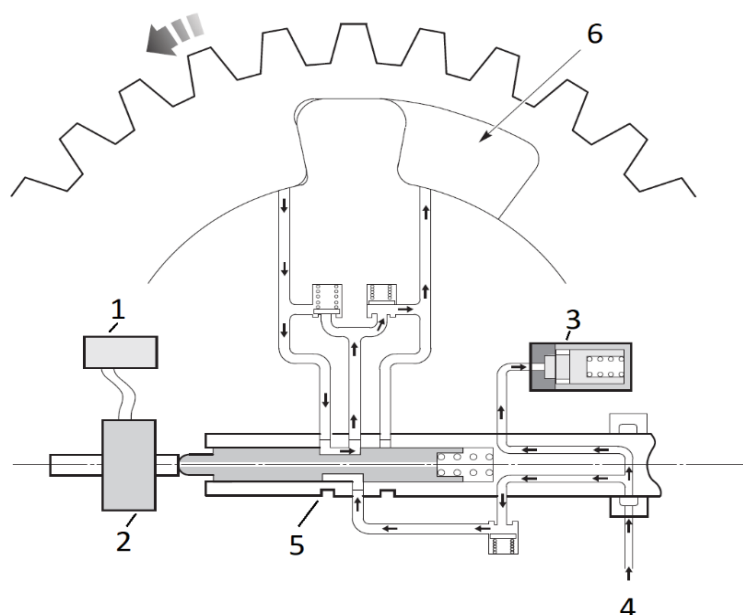


Figure 3 – Variable valve timing unit: 1 – Engine control unit; 2 – Solenoid valve; 3 – Locking mechanism; 4 – Engine oil supply; 5 – Spool valve; 6 – Retard chamber

Automakers adopt various approaches to controlling cam profile switching. Honda's i-VTEC (intelligent Variable Valve Timing and Lift Electronic Control) system consists of a camshaft with a central high-profile cam and external low-profile cams, along with corresponding roller rocker arms (Fig. 5). At low loads, valve actuation occurs through the external roller arms linked to the low-profile cams. As load increases, hydraulic oil pressure is used to engage a locking pin that connects the central roller arm to the external ones, allowing the intake valves to be actuated by the high-profile cam. Investigation completed on a 2.4L Honda engine have demonstrated torque and power increases of 3.67% and 9.33%, respectively, with the i-VTEC system [6].

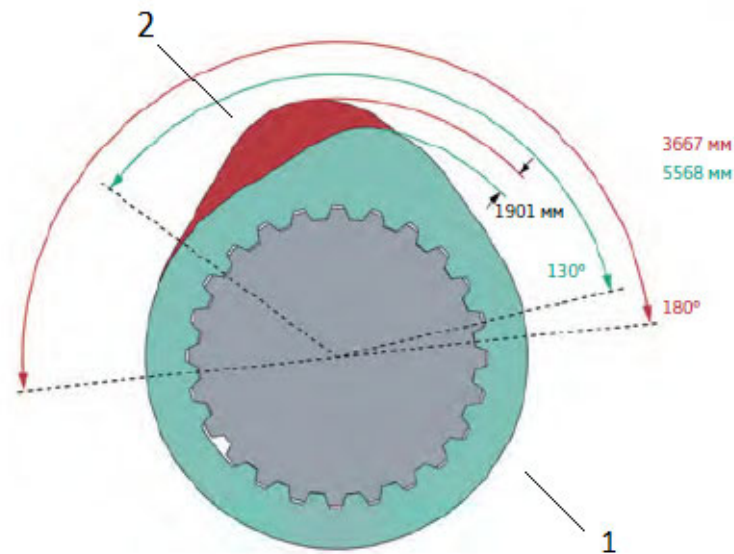


Figure 4 – Two cam profiles of the Audi EA839 engine with DVVL system:
1 – Low profile; 2 – High profile

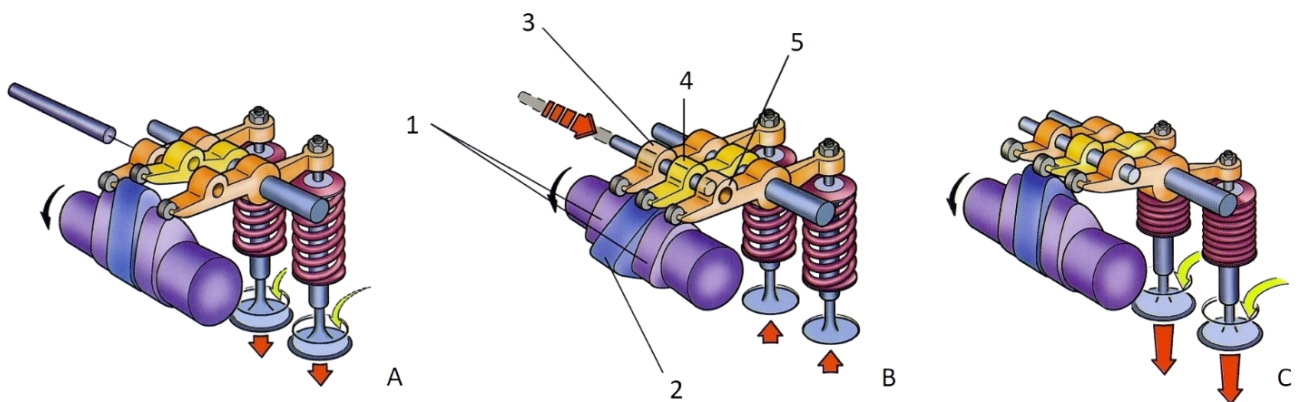


Figure 5 – Honda i-VTEC valve lift system: A – Low valve lift; B – Switching from low to high valve lift;
C – High valve lift; 1 – Low-profile cam; 2 – High-profile cam;
3 and 5 – Rocker arm for low-profile cam; 4 – Rocker arm for high-profile cam

Chevrolet's IVLC (Intake Valve Lift Control) system also switches between low and high cam profiles using a roller rocker arm. Similar to Honda's i-VTEC, this system engages or disengages two rocker arms via a hydraulic actuator from the lubrication system. However, in this case, a single high-profile and a single low-profile cam are used. Research conducted on a 2.5L Chevrolet EcoTec engine found that the IVLC system reduced fuel consumption by 4% [3].

A similar design is employed in the CPS (Camshaft Profile Switching) system used in Jaguar Land Rover AJ133 N/A engines. In this case, cam profile switching is performed via a hydraulic tappet (Fig. 6). In this system, at crankshaft speeds between 2,800 and 4,825 rpm (depending on load), the intake valve lift height is 5.5 mm (low profile), while in all other modes, the lift height increases to 10.53 mm (high profile) [5].

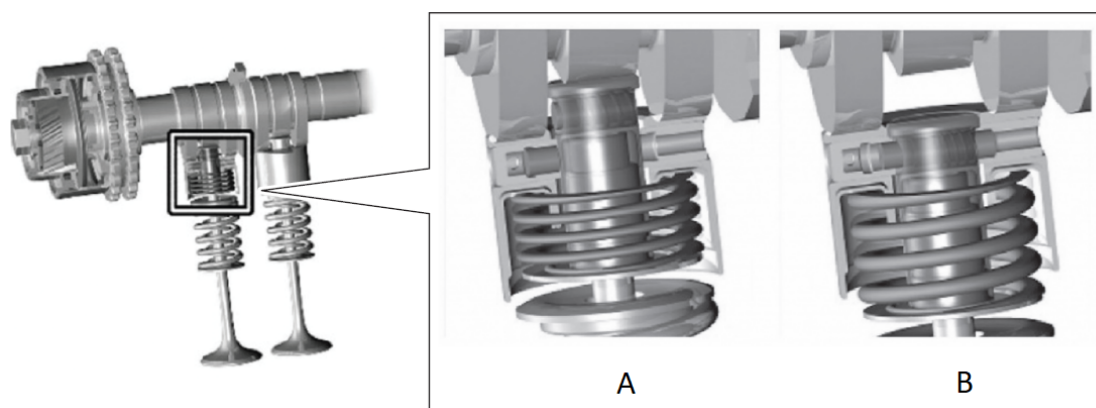


Figure 6 – Camshaft profile switching system of Jaguar Land Rover AJ133 N/A engine:
A – Low valve lift operation; B – High valve lift operation.

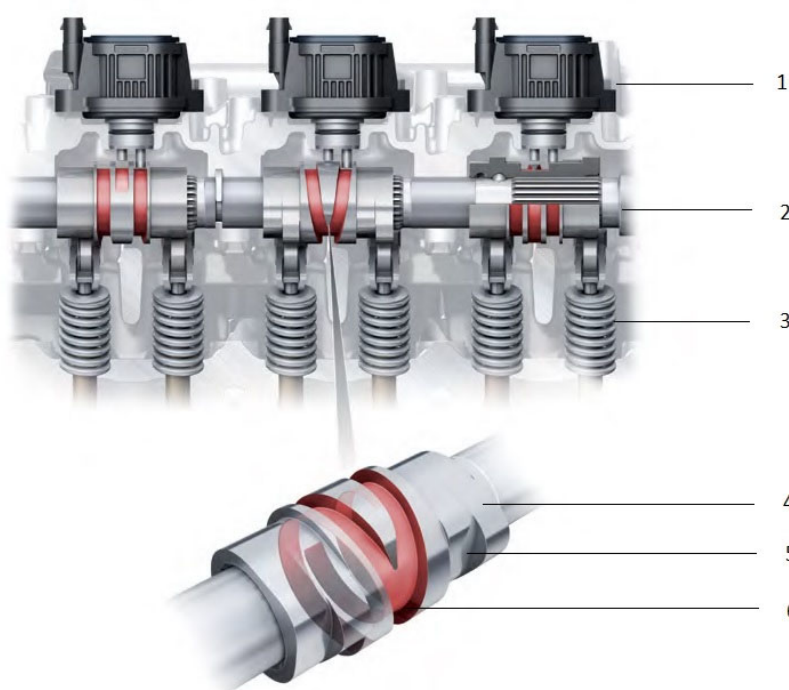


Figure 7 – Audi AVS: 1 – Electric actuator of the sliding module; 2 – Intake camshaft; 3 – Intake valves;
4 – High-profile cam; 5 – Low-profile cam; 6 – Spiral channel.

The Audi Valvelift System (AVS), which also employs camshafts with two different profiles, adjusts the valve lift height from 2 mm at low loads to 11 mm at high loads. The minimal valve lift height generates turbulence in the fresh charge, enhancing mixture formation at low loads. Two cams with low and high profiles for each of the two intake valves of a cylinder are mounted on a sliding module in such a way that the active cam can be switched depending on the longitudinal position of the sliding module on the camshaft (Fig. 7). Each sliding module has two spiral channels, into which a pin enters via an electric actuator to move the sliding module with the cams in the longitudinal direction. Another spiral channel and corresponding pin are used for switching the cam profiles in the opposite direction. The AVS system enables a fuel consumption reduction of up to 7% [7].

The Mercedes Camtronic system is similar to the Audi AVS system, except that it uses fewer sliding modules and, consequently, fewer pins with electric actuators. In the Mercedes system, a single sliding module serves multiple cylinders simultaneously.

Continuously variable valve lift (CVVL) systems allow optimal power and torque output across all engine operating modes. CVVL is used exclusively for intake valves and enables continuous regulation of the airflow into the cylinders, ensuring smooth power delivery at any engine speed or load. This system reduces valve lift when low torque is required and gradually increases lift as torque demand rises. By optimizing air intake, the CVVL system enhances engine dynamics and reduces fuel consumption.

The integration of CVVL with variable valve timing (VCT) is a key technology aimed at reducing fuel consumption and CO₂ emissions. Conventional engines with throttle-controlled power regulation experience energy losses due to air intake resistance. CVVL, in combination with VCT, directly regulates the required air volume via the intake valves for each engine operating condition. This is achieved through a flexible intake valve actuation process. The throttle is used to maintain proper intake manifold pressure under all operating conditions. Additionally, early intake valve closure reduces the amount of air entering the cylinder, decreasing the work required for compression. This results in lower temperatures, allowing the engine to generate more energy. The indicator diagram in Fig. 8 demonstrates reduced energy losses during cylinder filling when using CVVL combined with VCT.

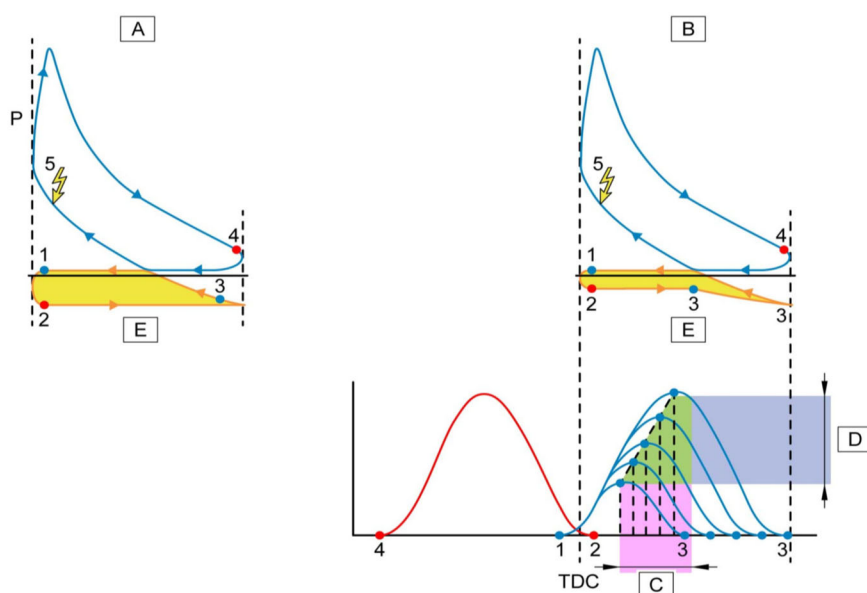


Figure 8 – A – Indicator diagram of an engine with a standard gas distribution mechanism, B – Indicator diagram of an engine with a CVVL system: 1 – Opening the intake valve; 2. – Closing the exhaust valve; 3 – Closing the intake valve; 4. – Opening the exhaust valve; 5 – Ignition; C – VCT control; D – CVVL control; E – Piston stroke; P – Pressure.

CVVL systems support multiple operating modes depending on the specific system design. For example, the CVVL system in Jaguar Land Rover Ingenium engines features the following modes:

- Full lift mode - The valves are fully opened and closed as during conventional control by the camshaft. The full lift mode is used at high engine speeds to obtain maximum engine power.

- Late intake valve opening (LIVO) mode - The opening of the intake valves are delayed when starting the engine and during idling. The valves open for a shorter period and at a lower lift providing precise control of the exact amount of air entering the cylinder. As a result fuel economy is improved during idling periods. During a cold start, only a small amount of cold air enters the cylinder, meaning the engine starts more easily.

- Early intake valve closing mode (EIVC) - Activated during low to medium engine speeds. The intake valves are closed hydraulically before the camshaft profile would normally allow. The mode reduces pumping losses, increases the engine output and prevents an undesirable backflow of the fuel mixture into the intake ports.

- Composite mode - is used at very low engine speeds and loads. It is a combination of LIVO and EIVC modes. Composite mode is used as it provides a stable combustion.

Continuously variable valve lift systems are classified into mechanical and electrohydraulic types. Mechanical systems include BMW Valvetronic and Toyota Valvematic. BMW Valvetronic was the first mechanical system for continuously variable valve timing, introduced in 2001 [3]. The primary goal of Valvetronic was to reduce fuel consumption by managing engine power through valve lift adjustments, thereby minimizing throttle losses and pumping losses. The latest generation of Valvetronic achieves a fuel consumption reduction of 10%.

In the Valvetronic system, a rocker arm is positioned between the camshaft and the roller finger follower. The position of the rocker arm is adjusted by an eccentric shaft driven by an electric motor via a worm gear (Fig. 9). Rotating the eccentric shaft changes the contact point of the rocker arm with the roller finger follower, thereby altering the valve lift height [3].

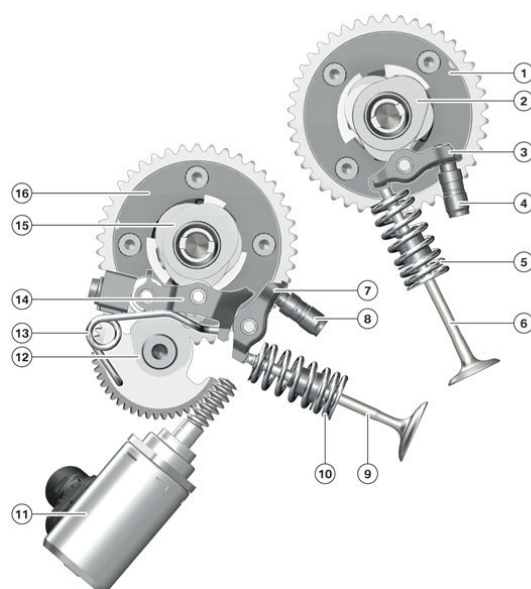


Figure 9 – BMW Valvetronic system:

1 – Exhaust variable valve timing unit; 2 – Exhaust camshaft; 3 – Roller cam follower; 4 – Hydraulic valve clearance compensator; 5 – Valve spring; 6 – Exhaust valve; 7 – Roller cam follower; 8 – Hydraulic valve clearance compensator; 9 – Intake valve; 10 – Valve spring; 11 – Valvetronic servomotor; 12 – Eccentric shaft; 13 – Spring; 14 – Intermediate lever; 15 – Intake camshaft; 16 – Intake valve timing unit.

In the Toyota Valvematic system, an intermediate shaft containing a roller and eccentric elements is positioned between the camshaft and the roller finger follower, which acts on the valve (Figure 10). The angular position of the shaft is adjusted via an electric motor. Increasing this angle increases the valve lift. Investigation completed on a 1.8-liter engine indicate that the Valvematic system improves fuel efficiency by 5% and increases power output by 6% [8].

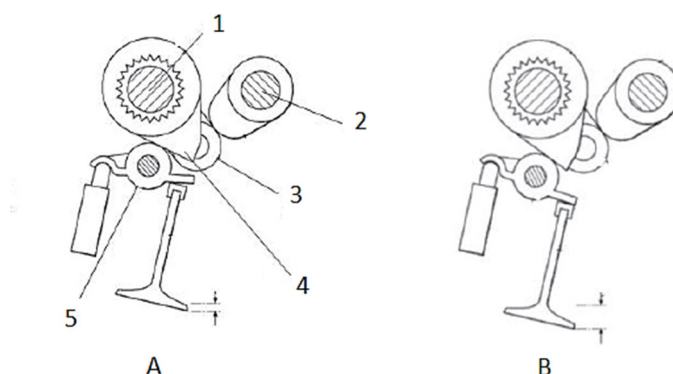


Figure 10 – Toyota Valvematic System: A – Low valve lift; B – High valve lift; 1 – Intermediate shaft; 2 – Intake camshaft; 3 – Intermediate roller; 4 – Eccentric; 5 – Roller rocker arm

Electrohydraulic systems include the CVVL system used in Jaguar Land Rover's Ingenium engines (Figure 11). In this system, there is no direct mechanical connection between the intake valves and the camshaft. Instead, the camshaft operates four small oil pumps that pressurize four hydraulic accumulators, which act as hydraulic buffers between the camshaft and the intake valves. If full valve lift is not required, oil is discharged from each accumulator via an electronically controlled solenoid valve, reducing the lift height provided by the camshaft. As the camshaft rotates, the action of the cam transforms into the movement of the pump piston, generating hydraulic pressure within the device. The high-pressure chamber serves as a hydraulic link between the pump, brake device, and solenoid valve. The hydraulic pressure can reach up to 150 bar. When the solenoid valve is closed, the hydraulic pressure of the engine oil opens the intake valve through the brake device. When the solenoid valve is open, part of the oil returns from the high-pressure chamber to the intermediate pump chamber, reducing valve lift. The brake device acts as a hydraulic valve lash adjuster and regulates valve closing speed in early intake valve closure mode. According to the manufacturer, CVVL improves fuel efficiency by 5% compared to the previous generation of engines.

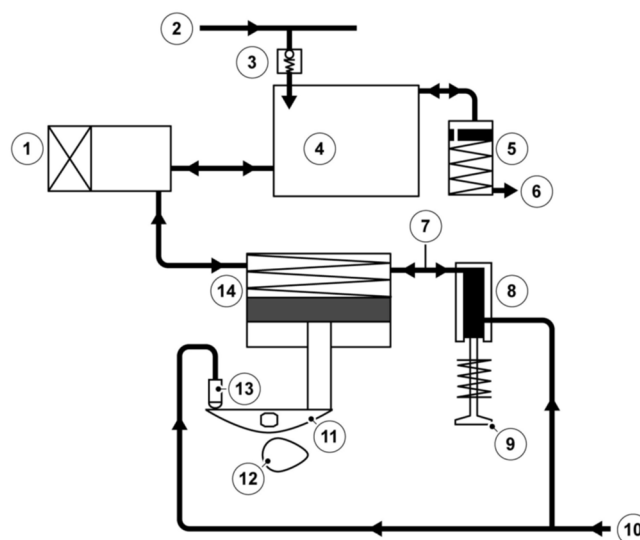


Figure 11 – Jaguar Land Rover CVVL system hydraulic circuit schematic: 1 – Solenoid valve; 2 – Engine oil supply; 3 – Check valve; 4 – Intermediate chamber; 5 – Pressure accumulator; 6 – Oil return line; 7 – Engine oil temperature sensor; 8 – Brake unit; 9 – Intake valve; 10 – Engine oil supply; 11 – Roller finger cam follower; 12 – Camshaft; 13 – Hydraulic tappet; 14 – Pump

A similar electrohydraulic continuously variable valve lift system, Multiair, is used in Fiat/Chrysler engines. The key difference is that it employs a single camshaft, which simultaneously operates the exhaust valves and drives hydraulic pumps for CVVL operation. According to the manufacturer, the Multiair system reduces fuel consumption by up to 10% and increases torque output by 15% at low engine speeds [3].

Conclusions.

The application of variable valve timing and variable valve lift systems enhances the power output of spark-ignition gasoline engines while reducing fuel consumption and, consequently, lowering exhaust emissions. Various system designs exist today, with the most efficient approach combining variable valve timing with continuously variable valve lift systems. This combination provides the most flexible control over the valvetrain, resulting in superior fuel economy across all engine operating conditions.

References

1. Heywood J. *Internal combustion engines fundamentals, 2nd edition*. New York: McGraw-Hill Education, 2018. 1056p. [in United States of America].
2. Gupta H.N. *Fundamentals of internal combustion engine, second edition*. Delhi: PHI Learning Private Limited, 2013. 658p. [in India].
3. *Cost, effectiveness, and deployment of fuel economy technologies for light-duty vehicles*. Washington: National academies press, 2015. 466p. [in United States of America].
4. *Bosch automotive handbook. 11th edition*. – Germany: Robert Bosch GmbH, 2022. 2044p. [in Germany].
5. *NP10-V8JLR: AJ133 5.0-Liter DFI V8 Engine*. Jaguar Land Rover North America LLC, 2009. 118p. [in United States of America].
6. Nitin Subhash, Sable Rahul, Krishnaji Bawane. *I-VTEC: Intelligent - Variable Valve Timing & Lift Electronic Control - A Review*. IJSRD - International Journal for Scientific Research & Development. 2017. №5. P. 594-596. [in India].
7. Robert Huber, Peter Klumpp, Heinz Ulbrich. *Dynamic analysis of the Audi valvelift system*. SAE International Journal of Engines. 2010. №3. P. 839-849. [in United States of America].
8. Hirohisa Kishi. *TNGA Powertrain*. Toyota Technical Review. 2018. №3. P. 4-9. [in Japan].

ПОЛІПШЕННЯ ПОКАЗНИКІВ ДВИГУНІВ З ІСКРОВИМ ЗАПАЛЮВАННЯМ ЗМІНОЮ ФАЗ ГАЗОРОЗПОДІЛУ ТА ВИСОТИ ПІДЙОМУ КЛАПАНІВ

Корпач Анатолій Олександрович, кандидат технічних наук, професор, професор кафедри двигунів і теплотехніки, Національний транспортний університет, м. Київ, Україна, e-mail: akorpach@ukr.net, тел. +380931203905, <https://orcid.org/0000-0002-7070-7883>

Левківський Олександр Олександрович, кандидат технічних наук, інструктор з технічного навчання, Товариство з обмеженою відповідальністю «Віннер Імпорте Україна, ЛТД», м. Київ, Україна, e-mail: oleksandr.levkivskyi@gmail.com, тел. +38067797644, <https://orcid.org/0000-0002-2951-2312>

Корпач Олексій Анатолійович, кандидат технічних наук, доцент, доцент кафедри автомобілів, Національний транспортний університет, м. Київ, Україна, e-mail: korpach1988@gmail.com, тел. +380442804252, <https://orcid.org/0000-0002-2496-4395>

Анотація. В статті розглянуто сучасні системи зміни фаз газорозподілу та висоти підйому клапанів, що використовуються в автомобільних двигунах з іскровим запалюванням та дозволяють підвищити потужність та знизити викиди шкідливих речовин з відпрацьованими газами.

Об'єкт дослідження – Системи керування газорозподільним механізмом впускних клапанів.

Мета роботи – Виконати аналіз основних методів регулювання фаз газорозподілу та висоти підйому клапанів та їх вплив на показники роботи двигуна внутрішнього згорання.

Метод дослідження – аналітичний.

Розглянуто будову та принципу роботи систем зміни фаз газорозподілу автомобільних двигунів з іскровим запалюванням, встановлено що виробники сучасних двигунів використовують єдиний підхід до динамічного регулювання фаз газорозподілу, який полягає у використанні тиску моторної оливи для зміни кутового положення розподільчого валу за допомогою механізму зміни фаз газорозподілу. Встановлено що для підвищення ефективності роботи системи зміни фаз газорозподілу можливо використовувати крутний момент, що виникає на розподільчому валі.

Розглянуто різні типи систем зміни висоти підйому впускних клапанів та визначено що в загальній класифікації виділяють дискретні систему зміни висоти підйому клапанів (DVVL) та безступінчасту систему зміни висоти підйому клапанів (CVVL). Дискретна системи зміни висоти підйому клапанів базується на концепції перемикання між різними профілями кулачків. Вони набули широкого розповсюдження та має різні варіанти виконання в залежності від виробника. Безступінчасті системи підйому клапанів дають змогу найбільш ефективно досягати максимальних значень потужності та крутного моменту в будь-якому робочому режимі двигуна. Системи CVVL дозволяють безперервно регулювати потік повітря, що подається в циліндри, в результаті чого забезпечується плавна зміна потужності за будь-якої частоти обертання або навантаження двигуна. Визначено що системи CVVL можуть мати як механічний так і гідравлічний привід.

Результати висвітлені в статті можуть бути використані для подальшого аналізу та вдосконалення існуючих систем зміни фаз газорозподілу та висоти підйому клапанів.

Ключові слова: двигун внутрішнього згоряння, фази газорозподілу, висота підйому впускних клапанів.

Перелік посилань

1. Heywood J. Internal combustion engines fundamentals, 2nd edition. New York: McGraw-Hill Education, 2018. 1056p.
2. Gupta H.N. Fundamentals of internal combustion engine, second edition. Delhi: PHI Learning Private Limited, 2013. 658p.
3. Cost, effectiveness, and deployment of fuel economy technologies for light-duty vehicles. Washington: National academies press, 2015. 466p.
4. Bosch automotive handbook. 11th edition. – Germany: Robert Bosch GmbH, 2022. 2044p.
5. NP10-V8JLR: AJ133 5.0-Liter DFI V8 Engine. Jaguar Land Rover North America LLC, 2009. 118p.
6. Nitin Subhash, Sable Rahul, Krishnaji Bawane. I-VTEC: Intelligent - Variable Valve Timing & Lift Electronic Control - A Review. IJSRD - International Journal for Scientific Research & Development. 2017. №5. P. 594-596.
7. Robert Huber, Peter Klumpp, Heinz Ulbrich. Dynamic analysis of the Audi valvelift system. SAE International Journal of Engines. 2010. №3. P. 839-849.
8. Hirohisa Kishi. TNGA Powertrain. Toyota Technical Review. 2018. №3. P. 4-9.