applied sciences

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Review

Review of Advancement in Variable Valve Actuation of Internal Combustion Engines

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Received: 16 December 2019; Accepted: 22 January 2020; Published: 11 February 2020

Abstract: The increasing concerns of air pollution and energy usage led to the electrification of the vehicle powertrain system in recent years. On the other hand, internal combustion engines were the dominant vehicle power source for more than a century, and they will continue to be used in most vehicles for decades to come; thus, it is necessary to employ advanced technologies to replace traditional mechanical systems with mechatronic systems to meet the ever-increasing demand of continuously improving engine efficiency with reduced emissions, where engine intake and the exhaust valve system represent key subsystems that affect the engine combustion efficiency and emissions. This paper reviews variable engine valve systems, including hydraulic and electrical variable valve timing systems, hydraulic multistep lift systems, continuously variable lift and timing valve systems, lost-motion systems, and electro-magnetic, electro-hydraulic, and electro-pneumatic variable valve actuation systems.

Keywords: engine valve systems; continuously variable valve systems; engine valve system control; combustion optimization

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1. Introduction

With growing concerns on energy security and global warming, there are global efforts to develop more efficient vehicles with lower regulated emissions, including hybrid electrical vehicles, electrical vehicles, and fuel cell vehicles. Hybrid electrical vehicles became a significant part of vehicle production because of their overall efficiency, and they still pose a significant cost penalty, resulting in a stagnant market penetration of 3.2% and 2.7% in 2013 and 2018, respectively, in the United States (US), for example [1]. Electrical vehicles reached a market penetration of 1.3% in the US in 2018 [1], still limited by high cost and concerns on well-to-wheel CO_2 emissions, charging speed, driving range, battery safety, and battery recycling issues. Fuel cell vehicles offer truly low overall emissions with driving range and fueling time comparable to vehicles powered by internal combustion engines. Hydrogen [2], the favorable fuel for fuel cells, can be generated from diverse sources, including natural gas, nuclear, coal, and renewable sources such as solar, wind, biomass, hydro, and geothermal sources. The development of fuel cell vehicles [3] is still in its infancy because of issues in technology maturity, cost, and performance, with only a few thousands of pilot vehicles on the road worldwide.

Internal combustion engines are believed to remain as a major part of vehicle powertrains in the foreseeable future, either standing alone or being part of highly electrified powertrains such as hybrid electrical vehicles, plug-in hybrid vehicles, and range extender vehicles, unless there is a major technology breakthrough in battery and/or fuel cell technology. For these reasons, it is imperative to continue advancement in more efficient and less polluting internal combustion engines.

1.1. Combustion and Need for Electronic Control of Gas Exchange

The combustion in an internal combustion engine involves three key components: in-cylinder fuel, air, and ignition. In gasoline engines, the fuel injection process evolved from a pure mechanical process such as via a carburetor to an electronically controlled process such as via port fuel injection or the recently adopted direction injection (see Figure 1). Spark ignition via a spark plug is completely electronically controlled for spark energy and timing. With its gaseous state, low density, and, thus, large volume, the electronic control of air exchange was a slow evolution process, from variable valve time (VVT) to more sophisticated systems such as discrete variable valve lift (DVVL), continuous variable valve lift (CVVL), cam-based variable valve actuation (VVA), and camless VVA, which are reviewed later in this article. There were also efforts to develop camless VVA to have complete electronic control of the air exchange process, which is a major enabler for advanced combustion such as homogeneous charge compression ignition (HCCI) to improve engine fuel economy and reduce emissions [4–7]. To improve engine fuel economy, engine downsizing techniques are widely used with the help of turbochargers. In this case, the VVT, VVL, or VVA system is able to improve engine system transient responses.

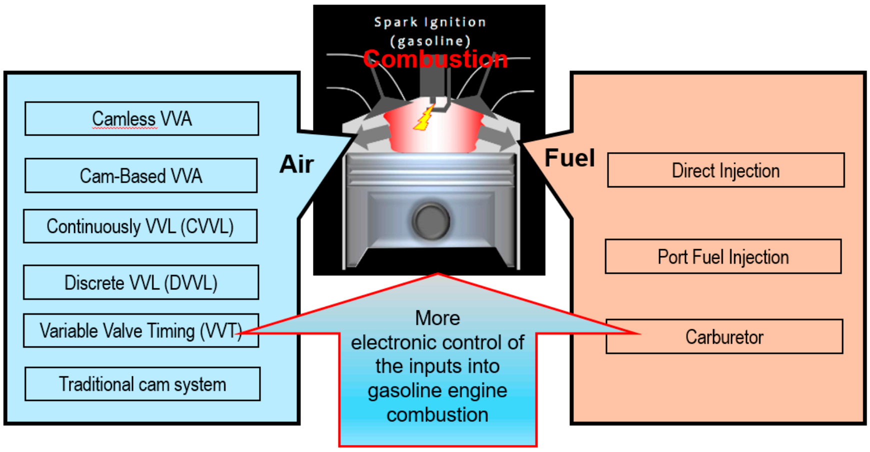

Figure 1. More electronic control of inputs into gasoline engine combustion.

In diesel engines, fuel injection evolved from pure mechanical pumping and injection systems to common-rail fuel injection via electronically controlled fuel pressure and injectors. Note that injection timing directly controls the ignition because of the compression ignition. There is less demand or development on controlling gas exchange in traditional diesel engines because of its compression ignition and lean combustion process. More sophisticate air charge management is needed for more advanced combustions such as the Miller cycle and PCCI. However, this review is limited to valve systems for gasoline engines.

1.2. Valve Lift, Valve Timing, and Valve Duration

The main function of an engine valve actuation system is to control the gas exchange into and out of a combustion chamber via intake and exhaust valves, respectively. The associated valve lift or travel is typically illustrated in a valve timing diagram (see Figure 2 for an example), where valve timing, valve lift, and valve duration are defined. A valve lift profile describes the valve lift as a function of camshaft angle between its opening and closing. The opening and closing points define the valve timing in the crank angle domain and, thus, the relationship between the lift profile and the rest of the engine components and events such as the piston movement and ignition. Valve lift is often optimized for minimal pumping loss. Often, intake and exhaust valve lifts are the same, but the diameter of the intake valve is larger than the exhaust one to ensure that fresh air can be easily charged into the cylinder. Note that variable valve lift has the potential of throttling the cylinder by reducing the intake valve lift to reduce the pumping losses associated with the conventional throttle. However, this requires very close control of lift to match changes in engine speed and load conditions, which is yet to be fully proven. The overlap between the intake valve opening and the exhaust valve closing is an important secondary parameter that has a major impact on combustion efficiency. The area under a lift profile represents the capacity for gas exchange. For the purpose of classifying valve actuation systems, the following definitions are provided:

- Valve lift refers to the amplitude, especially the peak value, of the valve lift profile.
- Valve timing refers to the phase shift in crank angle domain of the valve lift profile, especially the valve opening and closing events, such as EO, EC, IO, and IC.
- Valve duration refers to the duration when the valve is kept open, i.e., the span between the valve opening and closing events.

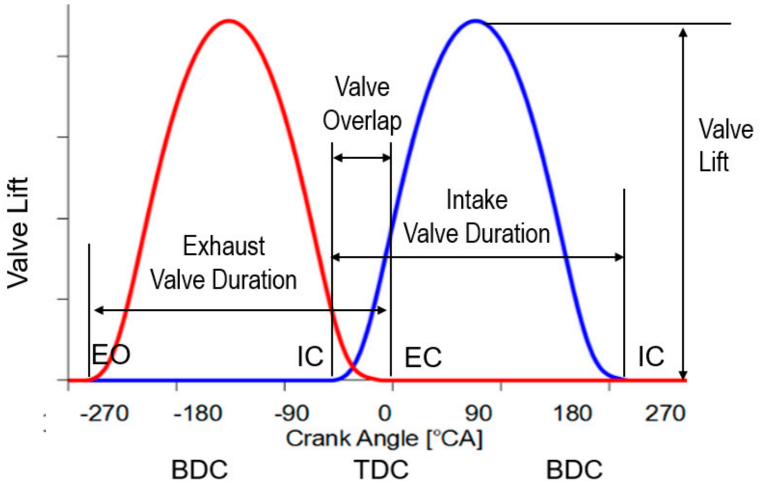

Figure 2. Regular valve timing diagram for naturally aspirated engines, defining valve lift, timing, and duration.

Modern engines are often equipped with multiple intake and exhaust valves, for example, two intake and two exhaust valves. The valve lift, timing, and duration can be optimized for each individual valve (for example, using VVA technology) to optimize in-cylinder mixing.

1.3. *Classification of Valve Actuation Systems*

Valve actuation systems are firstly classified into two large groups: cam-driven and camless systems. A cam-driven system utilizes cam lobes to actuate the valve lift, while a camless system does not include any cam mechanism and varies the valve lift using hydraulic, electro-magnetic, or pneumatic actuation to provide flexibility in control. Valve actuation systems are further classified based on the valve parameters being controlled.

Camless systems generally offer more control flexibility and capability, but they are yet to be implemented in production because of technical difficulties and commercial issues. For this reason, this review covers commercialized cam-based systems and only some development work in camless systems.

1.3.1. Cam-Based Valve Actuation Systems

A cam-based valvetrain system is based upon the traditional cam-system to drive the engine intake and exhaust valves with limited control over valve timing and/or lift, and it is now widely adopted in many new production engines. Cam-based systems include the following:

- **Variable valve timing:** Only the valve timing is independently controlled while the valve lift and duration remain the same. The VVT systems are also called cam (or camshaft) phasers. VVT systems are further classified into hydraulic (HVVT), mechanical (MVVT), and electrical (EVVT) types based on their respective cam phasing actuator designs. Many production VVT systems are HVVTs, using a device known as a variator that allows continuous adjustment of the cam timing, and EVVTs are getting popular for improving system response time at low temperature or engine start-up. However, the duration and lift cannot be adjusted.

- **Variable valve duration (VVD):** Only the valve duration is independently controlled.
- **Variable valve lift (VVL):** Only the valve lift is independently controlled. VVL systems further include discrete VVL (DVVL) and continuous VVL (CVVL) designs. A DVVL system includes a cam profile switching mechanism to activate one of two or three cam profiles or lobes, and a CVVL system includes a mechanism capable of continuous variation of the life profiles. In most, if not all, VVL systems, the lobes and mechanisms are designed such that the valve duration increases with the valve lift, which is a fixed relationship and not an independent control of the valve duration, although it serves the needs of a normal combustion. These VVL systems by themselves are, therefore, not classified as VVT, VVD, or VVA systems.
- **Cam-Based Variable Valve Actuation (VVA):** Cam-based VVA systems include (1) the VVL + VVT type, which is a combination of VVL (either DVVL or CVVL) and VVT, and (2) the lost-motion type (LMVVA).

Major cam-based valve actuation systems in production engines are listed in Table 1. Some of them are discussed in more detail in the later sections.

Table 1. Major cam-based valve actuation systems in production engines.

Classification	Company	System	Ind. Timing	Ind. Lift	Ind. Duration	Introd. Year, Comments & Refs
HVVT	Nissan	VTC/NVCS	2-stage			1987
HVVT	Toyota	VVT-i	Cont, Int			1996
HVVT	Mazda	S-VT	Variable, Int			1998
HVVT	Ford	Ti-VCT	2-stage, Both			2011
HVVT	Alfa Romeo	VCT	2-stage, Int			1980, 1st VVT, piston, [8]
HVVT	BMW	Single VANOS	2-stage & Cont, Int			1992, [9]
HVVT	BMW	Double VANOS	Cont, Both			1996, [9]
HVVT	Ford	VCT	2-stage, Int			
HVVT	GM	DCVCP	Cont, Both			
HVVT	Hyundai	CVVT	Cont, Both			
HVVT	Hyundai	VTVT	Variable, Both			
HVVT	Daihatsu	DVVT	Cont, Int			
HVVT	Ducati	DVT	Cont, Both			
HVVT	Nissan	CVVTCS/CVTC	Cont			
HVVT	Subaru	AVCS	VVT			
HVVT	Toyota	Dual VVT-i	Cont, Both			
HVVT	Toyota	VVT	2-stage			
MVVT	Porsche	VarioCam	Cont, Int			1992, 1st Cont VVT, [7,9]
EVVT	Toyota	VVT-iE	Cont, Both			2007, electric Int, hydraulic Exh
VVD	MG Rover	VVC			Cont, Int	1993, eccentric mechanism
VVD	Hyundai	CVVD			Cont, Int	2019, eccentric mechanism
DVVL	Honda	VTEC		2- & 3-lobe, Int		1989, [10]

Table 1. *Cont.*

Classification	Company	System	Ind. Timing	Ind. Lift	Ind. Duration	Introd. Year, Comments & Refs
DVVL	Audi	AVS		2-lobe, Both		2006, [11]
DVVL	Subaru	i-AVLS		2-lobe		2007, [12]
DVVL	Proton	CPS		2-lobe, Int		2016, [13]
DVVL	Yamaha	VVA		2-lobe		2017, motor cycle appl, [14]
DVVL + VVT	Mitsubishi	MIVEC	VVT, Both	2-lobe, Int		1992, [15]
DVVL + VVT	Nissan	VVL/VVL + VVT	VVT	2-lobe, Both		1997, [16]
DVVL + VVT	Porsche	VarioCam Plus	VVT	2-lobe, Int		1999, [4,17]
DVVL + VVT	Toyota	VVTL-i/VVT-iL	Cont	2-lobe		1999, [18]
DVVL + VVT	Honda	i-VTEC	Cont, Int	2-lobe, Int		2001, [19]
DVVL + VVT	Audi	AVS	Cont, Int	2-lobe, Int		2006, [11]
CVVL	Hyundai	CVVL		CVVL		2012, [20]
CVVL + VVT	Great Wall	CVVL + VVT	Cont, Both	CVVL		2018, [21]
CVVL + VVT	BMW	Valvetronic	Cont, Both	CVVL, Int		2001, [22]
CVVL + VVT	BMW and PSA	VTi	Cont, Ink	CVVL, Int		2002, [23]
CVVL + VVT	Nissan	VVEL + CVTC	Cont	CVVL		2007, [24,25]
CVVL + VVT	Toyota	Valvematic	Cont, Int	CVVL		2014, [26]
LMVVL	FCA	MultiAir	Cont	Cont		2009, [27,28]

Notes: Int = intake, Exh = exhaust, Both = both intake and exhaust, Cont = continuous.

1.3.2. Camless Valve Actuation Systems

Without the constraint from the cam mechanism, a camless system is capable of adjusting valve timing, duration, and lift independently to achieve more desired target levels that can be varied cycle-by-cycle. It also provides independent control of engine valves for each cylinder. For example, it is able to provide asymmetric opening for two intake valves for one cylinder, resulting in improved charge air and fuel mixing. It can also perform cylinder deactivation under low load conditions. It, thus, offers more control with greater benefits than conventional cam-based valve system. Camless systems include the following:

- Opposed solenoid electro-magnetic (or electromechanical) camless VVA (EMVVA) [29–34];
- Electro-hydraulic camless VVA (EHVVA) [35–37];
- Electro-pneumatic camless VVA (EPVVA) [38,39];
- Rotary motor EMVVA, also called intelligent valve actuation (IVA) system by Camcon [33,34].

Camless systems are a key technical enabler for other advanced engine technologies, such as air hybrid vehicles [40], HCCI [41], and high-efficiency diesel engines [42].

In the subsequent sections, various valve actuation systems are grouped and reviewed based on the valve actuation control parameters and structures.

2. Variable Valve Timing (VVT) System

The VVT technology was first applied to production engines by Alfa Romeo in 1980, and they are now widely used in most modern engines worldwide as shown in Table 1.

VVT systems were initially stand-alone systems for timing control, and gradually they were integrated with variable lift mechanisms to become part of a cam-based VVA system, i.e., VVL + VVT. They are often applied to intake valves only. Their control evolved from two-stage, i.e., two discrete positions, in the early days to continuous control ("Cont" in Table 1) in more recent engines.

2.1. Hydraulic VVT (HVVT)

An HVVT system includes a hydraulically actuated cam phaser or variator, the design of which evolved over the last 40 years.

The 1980 Alfa Romeo Spider 2.0 L had the first VVT system, which was an HVVT on the inlet camshaft. The design comes from a patented design (US Patent 4,231,330) by Alfa Romeo engineer Giampaolo Garcea [43]. The cam phaser is a cylinder containing a pressure chamber and a piston with helical splines. Alfa Romeo calls it mechanical VVT because of the helical splines, and it is classified as hydraulic VVT because of the hydraulic piston. Under oil pressure via a solenoid valve, the piston rotates slightly due to the helical splines and advances the inlet valve timing by 25° to increase engine valve overlap, which happens between 1500 and 2000 rpm and over 5000 rpm. Otherwise, the valve timing remains in its natural state.

Most phasers of the later HVVT systems use a rotary vane hydraulic motor, which is actuated by pressurized oil controlled by a solenoid valve. The cam phaser is operated either in two settings or, as in most of the more recent systems, continuously.

The BMW single VANOS system, when first introduced in 1992 on the BMW M50 engine, controlled the timing of the intake camshaft to one of two discrete positions. In 1998, infinitely variable single VANOS was introduced on the BMW M62 V8 engine. The double VANOS system, which appeared on the S50B32 engine in 1996, continuously adjusts the timing of the intake and exhaust camshafts [44]. The maximum range of phase timing relative to the sprocket is typically 60° [45].

In operation, the hydraulic VVT system can be vulnerable because of oil pressure fluctuation, oil quality, viscosity, and contamination. There is also a case where the phaser does not get enough oil because of a wear-induced leakage in the lubrication system [46]. At low temperatures, the system may not have adequate response time because of high oil viscosity, and the hydraulic VVT system cannot be activated and has to remain at its default lock position such that the cold-start performance and emissions cannot be improved [47]. For example, the camshaft phasing speed of the hydraulic VVT drops to about half of that of the electrical VVT and almost to zero when the operating temperature drops from 90 °C to 40 °C and −10 °C, respectively. For an engine cold start at −7 °C, the HC emissions are reduced by about one-third when replacing a hydraulic VVT with an electrical VVT.

2.2. Mechanical VVT (MVVT)

Porsche developed VarioCam, a mechanical VVT first used on the 1992 3.0 L engine in the Porsche 968 [1,8] It varies the timing of intake valves by adjusting the tension on the timing chain connecting the intake and exhaust camshafts. This mechanical design was not kept in a later version of VarioCam Plus, which uses a rotary vane hydraulic phaser as most HVVT systems do [1,4].

2.3. Electrical VVT (EVVT)

The issues associated with HVVT systems discussed above led to the development of EVVT systems, which was also made possible by recent advances in permanent magnetic motor technology and dramatically reduced motor drive cost. Toyota variable valve timing—intelligent electric (VVT-iE), for example, is a variation of dual VVT-i, by replacing the hydraulic cam phaser with an electric cam phaser for the intake camshaft timing [47]. The exhaust camshaft timing is still controlled using a hydraulic cam phaser. This technology was first introduced on the 2007MY Lexus LS 460 as a 1UR engine [18]. In operation, the electric motor in the cam phaser spins with the intake camshaft, running at the same speed to maintain camshaft timing. To advance or retard the camshaft timing, the actuator motor rotates slightly faster or slower, respectively, than the camshaft speed. The speed difference between the actuator motor and camshaft timing is used to operate a mechanism that varies the camshaft timing.

The performance of an EVVT is less dependent on engine oil temperature and pressure [47], thus providing better control precision and improving engine performance over a wider operational range. The control accuracy and fast response of a VVT system is more critical for advanced combustion such as HCCI, especially for the combustion mode transition control between spark ignition (SI) and HCCI combustion, where the engine cam timing needs to follow a desired trajectory to accurately control the engine charge and recompression process, as articulated by Ren and Zhu [48].

3. Variable Valve Duration (VVD) System

In 1993, MG Rover developed a 1.4 L K-series engine with a variable valve control (VVC) system, which was the first production continuous VVD (CVVD) system. It is based on an eccentric rotating disc to drive the inlet valves of every two cylinders. Since eccentric shape creates nonlinear rotation, the opening period of the valves can be varied by controlling the eccentric position of the disc. The basic concept was developed by Mitchell and it was published and patented back in 1973 [49]. In this design, the control is purely to vary the valve duration, with the valve lift fixed, thus differing from various DVVL or CVVL designs.

In 2019, Hyundai Motor Group announced that it developed CVVD technology to be in the Smartstream G1.6 T-GDi for future Hyundai and Kia vehicles [50–52]. Their design is based on a concept disclosed by Kim et al. [53]. It also involves utilization of some pins and slots to create eccentric alignment. With the duration variation in accordance to driving conditions, it is able to deliver a 4% increase in performance along with a 5% boost in fuel efficiency. The CVVD technology also helps reduce tailpipe emissions by 12% [50].

4. Discrete VVL (DVVL) and Associated VVA Systems

A discrete VVL (DVVL) system includes a cam profile switching mechanism to activate one of two or three cam profiles or lobes, and it becomes a cam-based VVA (or DVVL + VVT) system when a VVT mechanism is further incorporated. The applications of DVVL and DVVL + VVT systems include, but are not limited to, Honda, Audi, Subaru, Proton, Yamaha, Mitsubishi, Nissan, Porsche, Toyota, Honda, and Audi, as shown in Table 1.

In 1989, Honda launched, in Integra, the world's first commercial DVVL system in a motor vehicle engine called the variable valve timing and lift electronic control (VTEC) system [10,19,54]. VTEC uses two (or occasionally three) intake camshaft profiles, switched via hydraulically actuated rocker arm locking pins. In the system, the timing variation is fixed in the cam profiles and not independent of the lift variation. Honda then launched, in 2001, a cam-based VVA system called intelligent VTEC (i-VTEC) in high-output DOHC four-cylinder engines by adding continuous intake cam phasing (timing) to the traditional VTEC. VTEC controls are still limited to distinct low- and high-RPM profiles, but the intake camshaft is now capable of advancing between 25° and 50°, depending upon engine configuration [55].

In 1992, Mitsubishi launched the world's first cam-based VVA system, a DVVL + VVT system called the Mitsubishi innovative valve timing electronic control system (MIVEC). It has low-lift and high-lift cam profiles for low-speed and high-speed engine modes, respectively, which are switched via a locking pin mechanism. The low-lift cams and rocker arms, used to drive separate intake valves, are situated on two sides of a centrally located high-lift cam. Each intake valve is operated by a low-lift cam and rocker arm, while a T-lever between them engages the high-lift cam [15]. The VVT-i system from Toyota has a similar switching mechanism [18].

In 1999, Toyota launched the variable valve timing and lift intelligent system (VVTL-i or VVT-iL). The Toyota VVTL-i concept, including its a lift variation system via rocker arm locking pins, is similar to the Honda i-VTEC concept. Each cam has two lobes, one designed for lower-speed operation and another designed for high-speed operation, with higher lift and longer duration.

In 1999, Porsche launched its VarioCam Plus, a DVVL + VVT system on the intake side. The two-lobe valve-lift function is performed by electro-hydraulically controlled switchable tappets. Each of these 12 tappets consists of concentric lifters which can be locked together by a pin. The inner lifter and the outer ring element are actuated by a small cam lobe and a pair of larger-profile lobes, respectively. The timing of each valve is seamlessly varied by an electro-hydraulic rotary vane cam phaser [1,4]

In 2006, Audi launched, in the 1.8 L TFSI engine, the Audi valve lift system (AVS) [11]. It uses sliding electro-magnetic sleeves on the camshaft to vary the lift of the valves in two stages depending on load and engine speed. The system, thus, increases torque while also reducing fuel consumption. Two versions of the AVS system are available: (1) in the V6 engines in which AVS is used, it acts on the intake valves, regulating the amount of intake air so that the throttle can remain wide open for free breathing even at part load, thus reducing throttle losses and improving efficiency; (2) in the latest-generation 2.0 TFSI, the AVS varies the lift of the exhaust valves, thus reducing flushing losses in the combustion chamber and ensuring the optimal flow of the exhaust gas to the turbocharger.

5. Continuous VVL (CVVL) and Associated VVA Systems

A continuous VVL (CVVL) system includes a mechanism capable of changing the lift profile continuously, and it becomes a cam-based VVA (or CVVL + VVT) system when a VVT mechanism is further incorporated. The applications of the CVVL and CVVL + VVT systems include, but are not limited to, those by BMW, PSA, Hyundai, Nissan, and Toyota, as shown in Table 1.

In 2001, BMW launched the world's first CVVL + VVT system, as well as the first CVVL system called the Valvetronic system [45,56]. The Valvetronic system combines its double VANOS variable cam timing system for intake and exhaust valves with their CVVL system for lift control of the intake valve. The CVVL system includes an eccentric shaft moved by an electric stepper motor and the camshaft, with the camshaft being driven by the VANOS phaser. The valve lift can be varied from 0.18 mm to 9.9 mm. Later, in 2002, PSA Peugeot Citroën and BMW jointly developed a variable valve lift and timing injection (VTi) engine based on the Valvetronic concept [23].

In 2007, Toyota launched, in the Noah, the Valvematic system, which is essentially a combination of VVT-i and a continuously variable valve lift (CVVL) mechanism for the intake valve. This system is functionally similar to and structurally simpler and more compact than BMW Valvetronic. It varies intake valve lift in the range 0.9 mm to 10.9 mm, with a corresponding or coupled valve opening duration range of 106° to 260° in crank angle [26].

In 2007, Nissan launched a cam-based VVA system by combining its continuous variable valve timing control (CVTC) and variable valve event and lift (VVEL) systems, which are VVT and CVVL mechanisms, respectively [24,25]. It performs similarly to BMW's Valvetronic system but with desmodromic control of the output cam, allowing VVEL to operate at higher engine speeds. The Nissan VVEL system includes a rocker arm and two types of links that open the intake valves by transferring the rotational movement of a drive shaft with an eccentric cam to the output cam. The movement of the output cam is varied by rotating the control shaft with a direct current (DC) stepper motor and changing the fulcrums of the links.

In 2012, Hyundai launched a CVVL system [20] characterized by its compactness, i.e., no increase in engine height, using a unique six-linkage mechanism. In 2018, Great Wall became of the first Chinese OEMs launching a CVVL + VVT system [21].

6. Lost-Motion VVA (LMVVA)

Various lost-motion systems were disclosed in many patents, for example, US 4671221, US 5193494, US 5839400, US 6053136, US 6553950, US 6918364, US 681476, US 7819100, US 8578901, US 8820276, US 8776738, and US 9625050.

Fiat Powertrain Technologies and Schaeffler Group developed the only mass production systems branded as MultiAir and UniAir, respectively, which were first launched at the 2009 Geneva Motor

Show in the Alfa Romeo MiTo and were licensed in 2017 to Jaguar Land Rover for its Ingenium engine family.

In the MultiAir system, a solenoid valve controls the hydraulic pressure in a passageway connecting the intake valves and the camshaft [27]. The solenoid valve regulates the amount of oil that is pumped by the cam action either to the valve or a bypass reservoir. When pressurized, the hydraulic line behaves like a solid body and transmits the lift schedule imparted by intake cam directly to the intake valve in the full valve lift mode for max power. When the solenoid is disengaged, a spring takes over valve actuation, losing solid transmission of the motion from the cam in other three modes, which are the early intake valve closing mode, the late intake valve opening mode, and the multi-lift mode, thus leading to the name lost motion. This electro-hydraulic link allows independent operation of the two components, resulting in certain control over the valve lift profiles. A closed solenoid keeps the hydraulic fluid pressurized, transmitting the intake cam profile to the valve in the normal fashion, while an open solenoid breaks the effective link between cam and valve, decoupling their profiles [27].

This system is not a full VVA system because the valve timing and duration are not independent of the lift in each of the three lost-motion modes although one has a choice to choose three different dependencies, i.e., variability or control flexibility, among these three modes. The intake valve opening event cannot be shifted ahead or left of that at maximum power, which may be necessary for certain EGR operations. Also, the intake valve closing event cannot be extended beyond or right of that at maximum power, which may be necessary for certain Miller cycles.

Jacobs Vehicle Systems Inc. also developed its own version of the lost-motion VVA system, with emphasis on diesel engine efficiency and after-treatment optimization [57]. It includes the capability of on-off control of secondary events for IEGR and engine braking, high load capacity for early exhaust opening and engine braking, and inherent protection against valve-to-piston contact.

More recently, there were efforts by Gongda Power [58] and Shandong University [59] to replace solenoid valves for individual actuators with motor-driven rotary valves common to a group of actuators, to achieve more stable and faster time response at low temperature and/or to devise an alternative hardware, but at the cost of losing independent controllability for individual actuators within a group. The Gongda Power system [58] uses two motor-driven rotary valves, instead of just one valve by Shandong University [59], to add control flexibility to achieve the Miller cycle by enabling much later intake valve closing to reduce pumping loss and lower air temperature. It can also incorporate a special cam lobe to achieve earlier exhaust valve opening and, thus, compression brake function for a diesel engine.

7. Electro-Magnetic VVA (EMVVA) Systems

7.1. Opposed Solenoid EMVVA

Most effort in camless VVA system development was devoted to EMVVA, actuated by a pair of opposed electromagnets and balanced by a pair of compression springs. It is capable of generating variable valve timing and duration, but with fixed lift operation.

The developers of this technology include Valeo [19,60–62], FEV [30,31,63–65], GM [29], Ford [66], Visteon [32], BMW [45], TRW [67], Siemens [68], MIT [69], Ibaraki University [70], LGD Technology [71], Instituto Motori of National Research Council of Italy [72], and Aura System [31].

Valeo acquired the related technologies from FEV, Sagem, and Johnson Control and developed them to a more mature system, which was marketed as smart valve actuation (SVA) [73] and later as e-Valve [60,62]. e-Valve claims to have reached the required maturity level for mass production [60].

The key issues and challenges, some of which may remain unresolved at this point, for EMVVAs in general include the following:

- Seating instability and the resulting noise and valve durability issues due to the highly nonlinear nature of the electro-magnetic latching force unique to the opposed solenoid design.

Chang et al. [69] incorporated a nonlinear spring or nonlinear mechanical transformer for better soft seating and/or low holding current.

- Need for an accurate, robust, and durable position sensor for each actuator [62].
- Limited or no capability to achieve a variable lift or low lift profile, necessary for some advanced combustions. Lou [71] proposed incorporating a hydraulic mechanism for enhanced capability.
- High incremental cost, which is a challenge for camless VVAs. A four-cylinder engine with electronic actuation on only the intake valves is expected to cost about €300 more to build [62].
- Electrical power consumption. Okada et al. [70] proposed a bias permanent magnet to reduce energy consumption and a seesaw architecture to improve performance and the fitness.

7.2. Rotary Motor EMVVA

Camcon Technology [33] is developing a camless engine for passenger vehicles based on their proprietary IVA system, which allows valve lift, timing, and duration to be independently and continuously controllable.

Different from earlier EMVVA systems using opposed solenoids, IVA employs a four-phase rotary actuator, i.e., a rotary motor, using a rotor which is extended to provide a separate camshaft for each individual poppet valve [34]. A desmodromic linkage connects this camshaft to the entirely conventional valve. The actuator is electronically synchronized with the crankshaft and drives the rotor through the required angular trajectory in order to provide the selected valve event, which is enabled via a non-contact absolute rotary encoder to determine the rotor position for each actuator.

Camcon collaborated with Jaguar Land Rover to fit the intake valve IVA onto an Ingenium 2.01 four-cylinder gasoline engine, with favorable test results in power consumption, lift repeatability, noise level, durability, and fuel economy [34,74].

Further development work is being carried out to achieve capability for higher engine speed and exhaust valve actuation [34]. Brunel University London is using a single-cylinder version of IVA technology called single-cylinder intelligent valve technology (SCI) to study future powertrain concepts and speed up OEM and tier 1 engine development [75]

7.3. Other EMVVAs

There are other kinds of EMVVAs. LaunchPoint Technologies, for example, developed a linear motor EMVVA, which includes a voice coil actuator, a position sensor, and a nonlinear energy storage mechanism [76]. The energy storage mechanism can both recover the valve's kinetic energy, thus reducing the system energy consumption, and help soft seating at the open and close. The low-power actuator is used only to catch and release the valve at the beginning or the end of the stroke. It is able to maintain repeatable performance with 1.63–3.82 ms switch times, 0.01–0.07 m/s seating velocity, and 1.33–3.15 J energy consumption per switch. No further report is available on the development since a news post in 2014 [76]. The need of a position sensor for its normal function may present cost and reliability issues in application.

8. Electro-Hydraulic VVA (EHVVA) Systems

In EHVVA systems, primary actuators are hydraulic actuators, such as a piston-cylinder mechanism, controlled by electro-hydraulic valves. Compared with an EMVVA, an EHVVA generally has higher power density but lower efficiency. The hydraulic fluid has high bulk modulus suitable for snubbing in the valve seating process, and its viscosity is highly sensitive to temperature, becoming too viscous for proper function at lower temperature. Some major EHVVA systems are listed below, which are also listed in Table 2 for comparison.

- Sturman Industries developed the hydraulic valve actuation (HVA) system. It includes two digital two-way pilot valves, a proportional valve, a hydraulic actuator with boost and drive pistons, and a position sensor necessary for closed-loop lift control [35,77]. The actuator is returned either hydraulically or by a return spring. It offers full control in valve timing, duration, and lift, and it was used in an experimental 15 L natural gas engine and as universal research modules for various research programs [78]. Its necessary use of a position sensor may incur high cost and reliability concerns for mass production.

- Lotus and Eaton jointly developed the active valve train (AVT) system. It includes one digital three-way pilot valve, one servo valve, one return spring, and a hydraulic actuator integrated with a position sensor needed for closed-loop lift control [79]. Like Sturman's HVA, the AVT system offers full control in valve timing, duration, and lift. It may also have cost and reliability issues associated with the position sensor.
- AVL and Bosch developed the electro-hydraulic valvetrain system (EHVS) system [80]. It includes two digital main valves, a hydraulic actuator with a two-stage differential piston drive, a pilot-controlled variable snubber for seating control, and no return spring. It uses an open-loop control and, thus, has no need for a position sensor, which offers substantial cost and reliability benefits but presents concerns in lift calibration and accuracy.
- Gongda Power developed the Gongda-VVA-2 (GD-VVA-2). It includes one digital three-way pilot valve, one digital three-way main valve, an actuator with one lift-control sleeve, two-step seating control, open-loop two-step lift control, and no position sensor [81–84]. The two-step lift control provides robust and accurate position control, which is delineated mechanically by the lift-control sleeve, without the need for an expensive and unreliable position sensor. It also has a two-level hydraulic damping mechanism for effective valve seating speed control over a wider temperature range. The two-step lift control does present certain functional compromise, which can be compensated for by its infinitely variable timing capability inherent in this and other EHVVAs. One GD-VV-2 prototype system passed 1000 h of durability testing on a test bench. There is also a proposal to incorporate some CVVL mechanisms into the base GD-VV-2 design, resulting in a full VVA system, still without the need for a position sensor for each engine valve [85].

Table 2. Some major electro-hydraulic VVA (EHVVA) systems.

Company	System	Design Features	Pros	Cons
Sturman	Hydraulic Valve Actuation (HVA)	Two digital 2-way pilot valves, a proportional valve, a return spring, and closed-loop control with a position sensor.	Full lift variability	High sensor cost and reliability concern
Lotus-Eaton	Active Valve Train (AVT)	One digital 3-way pilot valve, one servo valve, one return spring, and a hydraulic actuator integrated with a position sensor.	Full lift variability	High sensor cost and reliability concern
AVL-Bosch	Electro-hydraulic Valvetrain System (EHVS)	Two digital main valves, a hydraulic actuator with a two-stage differential piston drive and a pilot controlled variable snubber for seating control, no return spring, open-loop control without a position sensor	Full lift variability and low cost	Lift accuracy concern
Gongda Power	Gongda VVA-2 (GD-VVA-2)	One digital 3-way pilot valve, one digital 3-way main valve, an actuator with one lift-control-sleeve, 2-step seating control, open-loop 2-step lift control without position sensor.	Accurate lift and low cost	2-step lift

There are many other studies on EHVVA systems. One major effort is to minimize the energy consumption by the VVA system itself by using some kind of pendulum mechanism, similar to the compression spring pendulum used in the EMVVA system. Some examples are as follows:

- Ford developed an EHVVA system that has a unique hydraulic pendulum design, i.e., some fluid spring pendulum [7,86], which tries to convert the kinetic energy into hydraulic pressure or potential energy during both the opening and the closing stroke. The system includes a high-pressure and a lower-pressure switch valve and a couple of check valves, and it requires close monitoring and feedback on the engine valve position. However, the fluid spring may be difficult to manage because of the high bulk modulus of a typical hydraulic fluid. Additionally, the fluid bulk modulus is highly variable under the influence of the entrapped air.
- Gongda Power developed the LGD-VVA-1 system that consists of a two-spring actuation, a bypass passage, and an electro-hydraulic latch-release mechanism [36,37]. The two-spring pendulum system is used to provide efficient conversion between the moving mass kinetic energy and the spring potential energy for reduced energy consumption. Its latch-release mechanism can also compensate for the lost frictional energy during the pendulum motion. Prototypes of the system were bench- and engine-tested. This system, at least with its limited prototype design, presents some challenge in packaging because of its total height, considering adding two springs to the necessary hydraulic mechanism.
- DaimlerChrysler developed various designs using a two-spring pendulum with a hydraulic latching (US Patent Nos. 4930464, 5595148, 5765515, 5809950, 6167853, 6491007, and 6601552). However, the designs do not have an effective latching mechanism that can add energy to the pendulum to compensate for the frictional loss and cylinder air pressure, and there is no mechanism to change valve lift.

9. Electro-Pneumatic VVA (EPVVA) Systems

There were several studies and developments in electro-pneumatic VVA (EPVVA) systems [38,39,87–89]. As a work medium, air in an electro-pneumatic system is better than hydraulic fluid in an electro-hydraulic system in terms of the insensitivity of its viscosity to the system temperature. Air leakage also does not impose pollution problem. However, Watson and Wakeman [88] found the following issues with the pneumatic actuator:

- Noise issues associated with air exhaust, choking, and hard valve seating associated with a pure pneumatic actuator design.
- Repeatability issues in lift control because of air flexibility.
- Sizing issues, at least for their particular design, due to the peak air pressure limit.

The most serious development of an EPVVA system was carried out by the Swedish company Freevalve AB, formerly Cargine and a sister company to Koenigsegg Automotive AB, which developed an EPVVA system branded as Freevalve on an existing SAAB car engine [89,90]. The Freevalve technology also appeared in the Qoros 1.6 L four-cylinder engine [89,91]. The Freevalve system includes pneumatic valve actuators for opening, springs for valve closing, and position sensors for feedback control. An oil damping mechanism must be incorporated, as shown in Reference [38], to help resolve the seating issue, and the technology is, therefore, also called an electro-hydraulic-pneumatic actuator [89]. The claimed benefits include up to a 30% increase in horsepower and torque, up to a 30% improvement in fuel economy, and a 50% reduction in overall emissions, based on a report [90] in 2013.

Ma et al. [38] proposed an adaptive lift control scheme for an early version of the Freevalve technology to improve the intake valve lift repeatability. A control-oriented electro-pneumatic valve model was developed and used for adaptive parameter identification, and a closed-loop control scheme of valve lift was developed, utilizing the identified parameters in real-time. The main control techniques used in the process include model reference adaptation and the MIT rule [92]. The resulting maximum steady-state lift errors were less than 0.4 mm at high valve lift and less than 1.3 mm at low valve lift, which is still not accurate enough for commercial application.

10. Valve Profile Tracking of Camless VVA Systems

In an engine without a camshaft, the accuracy and fidelity of the electronic control of valve profile are critical to achieve the desired engine performance. The valve profile tracking includes the following basic control objectives for most camless applications [81]:

1) Valve timing control for optimum combustion phase and valve collision avoidance.
2) Valve lift control.
3) Profile area (integration of valve lift profile over time or crank angle) control for accurate air exchange.
4) Engine valve soft seating for noise control and extending durability.

As noted by Li et al. [81], the overall valve duration control and the valve transition response (rising and falling slopes) control studied in literature can be classified into valve timing control and profile area control, respectively. For traditional cam-based engine valves, the above four properties are guaranteed by proper design of the cam profile. For camless VVAs, these control objectives can be achieved either partially or simultaneously, depending on the specific VVA system design and its application.

Adaptive peak lift control was employed by Levin et al. [93] for an EMVVA and by Ma et al. [94] for an EPVVA to achieve proper valve lift repeatability.

Feedforward control was used for valve timing control to compensate for the valve-opening or valve-closing delays for EHVVA and EPVVA by Liao et al. [95] and Ma et al. [38], respectively.

Soft seating control is a challenge for the EMVVA because of nonlinear magnetic force, and it is one of the most studied subjects in the field. Peterson et al. [96] studied guaranteed valve response using extreme seeking control. Tai and Tsao [97] used a combination of a feedforward linear–quadratic regulator and repetitive learning control to reduce cycle-to-cycle variations. These control designs [96,97] were intended for single or multiple control objectives. Others dealt with the overall valve profile control as a single tracking problem. Wang and Tsao [98], for example, applied a combination of model reference control and repetitive control to achieve asymptotic profile tracking. Eyabi and Washington [99] applied the sliding mode control to achieve repeatable tracking performance with guaranteed seating velocity. In addition, there were studies associated with the application of EMVVA systems in the combustion mode transition between SI and HCCI combustions [63], stratified lean combustion [69], and turbulent jet ignition [64].

For an EHVVA system, Sun and Kuo [100] and Gillella et al. [101] proved the effectiveness of robust repetitive control and time-varying internal-model-based control, respectively, in tracking the desired valve profile under both steady-state and transient engine operations.

For the EHVVA system by Lou et al. [84], Li et al. [81] studied the profile tracking problem without the need for complicated control scheme because of the inherent robust nature of its lift control and seating-velocity control. However, the valve timing and profile area controls are still challenging because of the nonlinear and time-varying nature of the hydraulic system, including nonlinear flow dynamics and temperature-sensitive fluid viscosity [83,102]. A receding horizon linear–quadratic tracking (LQT) controller was designed along with a Kalman optimal state estimation, which was proven to be effective through both steady-state and transient validations.

11. Summary

As a summary, the engine valve system with active control can be mainly divided into three groups: variable valve timing (VVT), variable valve lift (VVL), and camless valve system. The authors believe that each valve system has its own application domain. For the variable valve timing system, the trend is to move to electrical VVT systems motivated by reducing engine cold-start emissions and significant cost reduction of electrical drive systems. VVA systems may be used for engines with advanced combustion modes such as spark-controlled compression ignition (SpCCI). Among VVA systems and compared with the combined VVT and VVL systems, the camless systems have higher cost and less maturity but have the ultimate control flexibility, which is needed as an enabler for more advanced combustion modes such as HCCI to further improve the engine performance with reduced emissions. The benefit of different valve technologies with respect to engine fuel economy is not readily discernable or available because a new engine is typically incorporated with multiple new technologies; some of them are summarized in Table 3 below, where the baseline is the conventional cam-based valve system.

Table 3. Fuel economy benefits.

Valve System Type	System and Fuel Economy and Other Key Benefits	Reference
HVVT	General: 3%–5% better FE	
HVVT	BMW double Vanos: up to 10% better FE	[9]
EVVT	General: 3%–5% better FE, especially with cold-start tailpipe emission reduction	
DVVL	Audi AVS system: up to 7% better FE	[103]
DVVL	GM intake valve lift control (IVLC): up to 4% better FE	[104]
DVVL + VVT	Honda i-VTEC: 13% better FE	[105]
CVVL + VVT	BMW Valvetronic: 10% better FE	[103]
CVVL + VVT	Toyota Valvematic: 6% better FE	[106]
LMVVA	Fiat MultiAir: 10% better FE	[107]
VVL + EVVT	General: enabling HCCI and 20% better FE	[108]
Camless VVA	General: enabling HCCI and 25% better FE	[108]

Author Contributions: Conceptualization, Z.L. and G.Z.; methodology, Z.L.; software, N.A.; validation, N.A.; formal analysis, N.A.; investigation, Z.L. and G.Z.; resources, Z.L. and G.Z.; data curation, N.A.; writing— Z.L. and G.Z.; writing—review and editing, Z.L. and G.Z.; visualization, Z.L.; supervision, Z.L.; project administration, N.A.; funding acquisition, N.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

AVCS	Active valve control system
AVLS	Active valve lift system
AVS	Audi valve lift system
AVT	Lotus-Eaton active valve train
BMW	Bayerische Motoren Werke automotive group
CA	Crank angle
CPS	Cam profile switching system
CVTC	Nissan continuous variable valve timing control
CVVD	Continuous VVD
CVVL	Continuous VVL
CVVT	Continuous VVT
CVVTCS	Continuously variable valve timing control system
DCVCP	Double continuous variable cam phasing
DOHC	double overhead camshaft
DVT	Discrete valve timing
DVVL	Discrete VVL
DVVT	Discrete VVT
EC	Exhaust closing
EHVS	AVL-Bosch electro-hydraulic valvetrain system
EHVVA	Electro-hydraulic VVA
EC	Exhaust closing
EGR	Exhaust gas recirculation
EO	Exhaust opening
EPVVA	Electro-pneumatic VVA
EVVT	Electrical VVT
FCA	Fiat Chrysler Automobiles

FE	Fuel economy
FEV	Forschungsgesellschaft für Energietechnik und Verbrennungsmotoren
GD-VVA-2	Gongda VVA-2
GM	General Motors
HC	Hydrocarbon
HCCI	Homogenous charge compression ignition
HVVT	Hydraulic VVT
IC	Intake closing
IEGR	Internal exhaust gas recirculation
IO	Intake opening
IVA	Camcon intelligent valve actuation
i-VTEC	Honda intelligent VTEC
LMVVA	Lost-motion VVA
MG	Morris Garages
MIT	Massachusetts Institute of Technology
MIVEC	Mitsubishi innovative valve timing electronic control
MVVT	Mechanical VVT
NVCS	Nissan valve control system
OEM	Original equipment manufacture
PCCI	Premixed charge compression ignition
PSA	Peugeot Société Anonyme
SpCCI	Spark-controlled compression ignition
SVA	Valeo smart valve actuation, also e-Valve
TFSI	Turbo fuel stratified injection
TRW	Thompson Ramo Wooldridge
VANOS	German words for variable camshaft timing
VTC	Valve timing control
VTEC	Honda variable valve timing and lift electronic control
VTVT	Variable timing valve train
VVA	Variable valve actuation
VVC	Variable valve control
VVD	Variable valve duration
VVEL	Variable valve event and lift
VVL	Variable valve lift
VVT	Variable valve time
VVT-iE	Toyota variable valve timing intelligent electric
VVTL-i or VVT-iL	Toyota variable valve timing and lift intelligent

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