Study: Variable Valve Actuation for Internal Combustion Engines.

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***Abstract*- This paper provides an extensive overview of Variable Valve Actuation (VVA) systems in internal combustion engines, encompassing both cam-driven and camless technologies. The evolution of VVA systems, such as Variable Valve Timing (VVT), Variable Valve Duration (VVD), and cam-based VVA, is explored, highlighting their significance in enhancing engine efficiency and performance. Additionally, camless VVA systems, including electro-magnetic and electro-hydraulic approaches, are detailed, showcasing their potential for precise control over valve lift and duration. These advancements in VVA technology are vital for meeting the demands of improved fuel efficiency and reduced emissions in internal combustion engines, ensuring their continued relevance in the evolving automotive industry.**

***Keywords*- VVA, VVT, DVVL, CVVL, EMVVA, EPVVA.**

INTRODUCTION

Hybrid electric vehicles have become a significant segment of the automobile market due to their overall efficiency, but they still come with a notable cost increase. As a result, their market penetration remained modest at 3.2% in 2013 and 2.7% in 2018 in the United States, for instance [1]. Fuel cell vehicles offer the promise of minimal overall emissions, coupled with driving ranges and refueling times comparable to vehicles powered by internal combustion engines. However, the development of fuel cell vehicles is still in its early stages due to technological immaturity, cost issues, and performance challenges, with only a limited number of pilot vehicles in operation globally [2].

Internal combustion engines are expected to continue to play a major role in vehicle powertrains in the foreseeable future, either independently or as part of highly electrified powertrains, such as hybrid electric vehicles, plug-in hybrid vehicles, and range extender vehicles. This is likely to remain the case unless there is a major breakthrough in battery and/or fuel cell technology. Therefore, it is essential to continue progressing toward more efficient and less polluting internal combustion engines.

NEED FOR ELECTRONIC CONTROLS

In gasoline engines, the method of fuel injection has evolved over time. It has transitioned from a purely mechanical process, such as using a carburetor, to a more advanced electronically controlled process. This modern approach includes techniques like port fuel injection and the recently adopted direct injection (as shown in Figure 1). Given the gaseous state, low density, and resulting large volume, electronic control of air exchange has also seen a gradual evolution. This has progressed from variable valve timing (VVT) to more sophisticated systems like discrete variable valve lift (DVVL), continuous variable valve lift (CVVL), cam-based variable valve actuation (VVA), and even camless variable valve actuation (camless VVA), all of which are explored further in this article.

To enhance engine fuel efficiency, engine downsizing methods are commonly implemented, often in conjunction with turbochargers. When this approach is employed, systems like variable valve timing (VVT), variable valve lift (VVL), or variable valve actuation (VVA) play a crucial role in enhancing the transient responses of the engine system.

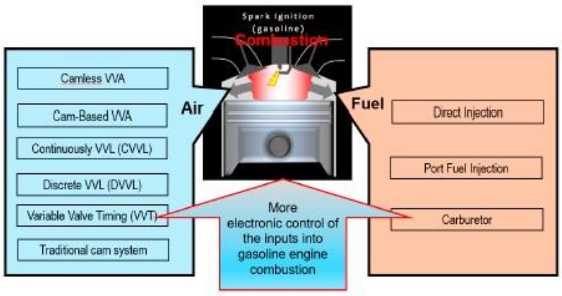

Figure 1: Electronic interaction with Internal Combustion Engine.

In the case of diesel engines, the evolution of fuel injection has seen a transition from purely mechanical pumping and injection systems to the adoption of common-rail fuel injection. This modern method involves electronically controlled fuel pressure and injectors. It's important to note that injection timing directly affects ignition, particularly in the context of compression ignition. Advanced air charge management is essential for more sophisticated combustion techniques like the Miller cycle and premixed charge compression ignition (PCCI). However, this review focuses exclusively on valve systems designed for gasoline engines.

Valve Actuation System Types

Valve actuation systems can be broadly categorized into two main groups: cam-driven and camless systems. In a cam-driven system, cam lobes are used to control valve lift, whereas camless systems do not rely on cam mechanisms and instead use hydraulic, electromagnetic, or pneumatic actuation to provide flexible control over valve lift.

Camless systems typically provide greater control flexibility and capability, but their implementation in production vehicles has been hindered by technical challenges and commercial considerations.

Variable Valve Timing (VVT) technology was introduced in production engines by Alfa Romeo in 1980 and has since become a standard feature in most modern engines worldwide. Initially, VVT systems were standalone mechanisms for controlling valve timing. Over time, they evolved and became integrated with variable lift mechanisms, forming a cam-based Variable Valve Actuation (VVA) system, which combines Variable Valve Lift (VVL) with VVT. This integrated system offers improved control and flexibility over both valve timing and lift. Following are the different types of VVTs used in Internal Combustion engines.

1. Hydraulic-driven VVT (HVVT)

The Hydraulic Variable Valve Timing (HVVT) system comprises a hydraulically actuated cam phaser or variator, which has evolved in design over the past four decades. The design of this system originated from a patented design (US Patent 4,231,330) created by Alfa Romeo engineer Giampaolo Garcea [3]. The cam phaser consists of a cylinder that houses a pressure chamber and a piston with helical splines. When oil pressure is applied through a solenoid valve, the piston rotates slightly due to the helical splines. This rotation advances the inlet valve timing by 25 degrees, increasing engine valve overlap. This adjustment typically occurs between 1500 and 2000 rpm and above 5000 rpm. At other engine speeds, the valve timing remains in its natural state.

The operation of hydraulic Variable Valve Timing (VVT) systems can be vulnerable to various factors, including oil pressure fluctuations, oil quality, viscosity, and contamination. Issues may arise in cases where the cam phaser doesn't receive sufficient oil due to wear-induced leaks in the lubrication system [4]. Additionally, at low temperatures, the system may experience longer response times because of the high oil viscosity. As a result, the hydraulic VVT system cannot be activated, and it has to remain in its default lock position. This can affect cold-start performance and emissions, preventing improvements in these areas [5].

2. Mechanically driven VVT (MVVT)

Porsche introduced a mechanical Variable Valve Timing (VVT) system called VarioCam, which was first utilized in the 1992 3.0 L engine of the Porsche 968 [6]. VarioCam operated by varying the timing of the intake valves through adjustments to the tension of the timing chain that connected the intake and exhaust camshafts.

However, in a later version known as VarioCam Plus, Porsche transitioned to a design that employs a rotary vane hydraulic phaser, similar to most Hydraulic VVT (HVVT) systems [7].

3. Electrically driven VVT (EVVT)

Toyota Variable Valve Timing - Intelligent Electric (VVT-iE) is an evolution of dual VVT-i technology, where the hydraulic cam phaser for intake camshaft timing is replaced with an electric cam phaser. However, the exhaust camshaft timing continues to be regulated using a hydraulic cam phaser. VVT-iE technology was initially introduced in the 2007 model year (MY) Lexus LS 460, which featured a 1UR engine [8]. This innovation leverages electric actuation for fine control of intake valve timing, enhancing the efficiency and performance of the engine.

In the VVT-iE system, the electric motor within the cam phaser is synchronized with the intake camshaft, rotating at the same speed to maintain the camshaft's timing. To adjust the camshaft timing, the actuator motor either slightly speeds up or slows down in comparison to the camshaft's speed. This speed difference between the actuator motor and the camshaft timing is utilized to control a mechanism that alters the camshaft timing as needed. This precise control allows for real-time adjustments to optimize engine performance and efficiency.

4. Variable Valve Duration (VVD) system

The basic concept was developed by Mitchell and it was published and patented back in 1973 [9]. 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.

It also involves the utilization of some pins and slots to create eccentric alignment. With the duration variation in accordance with 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% [10].

5. Discrete and associated VVA system

A discrete variable valve lift (DVVL) system consists of a mechanism that can switch between two or three different cam profiles or lobes to vary valve lift, and it becomes a cam-based variable valve actuation (VVA) system (or DVVL + VVT) when a variable valve timing (VVT) mechanism is added. Honda introduced the world's first commercial DVVL system in an automobile engine, called the Variable Valve Timing and Lift Electronic Control (VTEC) system, in their Integra model in 1989 [11,12]. In this system, the timing variation is linked to the cam profiles and is not independently adjustable from the lift variation.

In 1992, Mitsubishi introduced the world's first cam-based variable valve actuation (VVA) system, which is a discrete variable valve lift (DVVL) system with variable valve timing (VVT) known as the Mitsubishi Innovative Valve Timing Electronic Control System (MIVEC). This system includes both low-lift and high-lift cam profiles designed for low-speed and high-speed engine modes, respectively. These profiles are switched using a locking pin mechanism. Each intake valve is operated by a low-lift cam and rocker arm, while a T-lever between them engages the high-lift cam [13]. The VVT-i system from Toyota also incorporates a similar switching mechanism [14].

6. Continuous VVL (CVVL) and Associated VVA systems

In 2001, BMW introduced the world's first CVVL (Continuously Variable Valve Lift) system combined with a VVT (Variable Valve Timing) system, known as the Valvetronic system [15,16]. This innovative technology combines BMW's double VANOS variable cam timing system for both intake and exhaust valves with the CVVL system to control the lift of the intake valve, providing greater control and flexibility in engine performance.

In 2002, PSA Peugeot Citroën and BMW collaborated to develop an engine based on the Valvetronic concept, known as the Variable Valve Lift and Timing Injection (VTi) engine [17]. This technology incorporates variable valve lift and timing control, similar to the Valvetronic system, and offers advanced control over the engine's performance and fuel injection.

7. Opposed solenoid Electro-Magnetic VVA

The development of camless Variable Valve Actuation (VVA) systems primarily focused on Electromagnetic VVA (EMVVA), which is actuated by a pair of opposing electromagnets and balanced by compression springs. EMVVA systems offer variable valve timing and duration but with fixed lift operation. Valeo acquired related technologies from FEV, Sagem, and Johnson Control and further developed these technologies into a more mature system. This system was marketed as "smart valve actuation" (SVA) [18] and later as "e-Valve." [19,20].

8. **Electro-Hydraulic VVA system**

In EHVVA (Electro-Hydraulic Variable Valve Actuation) systems, the primary actuators are hydraulic actuators that typically use a piston-cylinder mechanism. These hydraulic actuators are controlled by electro-hydraulic valves. The hydraulic fluid used in these systems has a high bulk modulus, which is suitable for snubbing in the valve seating process. However, its viscosity can be highly sensitive to temperature, becoming too viscous for proper function at lower temperatures.

Efforts in the development of EHVVA systems aim to minimize the energy consumption by the VVA system itself. One approach involves using some form of a pendulum mechanism, similar to the compression spring pendulum used in EMVVA systems. These mechanisms are designed to optimize the efficiency and performance of the EHVVA system.

9. Electro-pneumatic VVA system

There were several studies and developments in electro-pneumatic VVA (EPVVA) systems [21,22]. Watson and Wakeman [23] 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 main control techniques used in the process include model reference adaptation and the MIT rule [24]. 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.

Adaptive peak lift control has been utilized in various variable valve actuation systems (EMVVA and EPVVA) to ensure proper repeatability of valve lift. Additionally, feedforward control techniques have been applied to manage valve timing and compensate for any delays in valve opening or closing. These control strategies help optimize the performance and reliability of EHVVA and EPVVA systems

The specific methods and studies mentioned in your message include those conducted by Levin et al. [25], Ma et al. [26], Liao et al. [27], and Ma et al. [28], each contributing to the development and refinement of control strategies for different types of variable valve actuation systems.

In addition, there were studies associated with the application of EMVVA systems in the combustion mode transition between SI and HCCI combustions [29], stratified lean combustion [30], and turbulent jet ignition [31].

10. Conclusion

In conclusion, the automotive industry is continuously evolving to meet the demands for greater efficiency and reduced emissions in internal combustion engines. The development and integration of advanced variable valve actuation systems, both cam-driven and camless, play a pivotal role in achieving these goals.

In this paper, different systems of Variable Valve Actuation (VVA) were discussed and the following system was explained.

- Variable Valve Timing (VVT).
- Variable Valve duration (VVD)
- Cam-based VVA system
- Camless variable valve actuation

These advancements in valve actuation technology contribute to the continuous improvement of internal combustion engines, making them more efficient, responsive, and environmentally friendly. As the automotive industry explores alternative power sources, internal combustion engines when equipped with these advanced technologies, continue to be a crucial part of the transition to cleaner and more efficient transportation. The future holds further innovations in this field, ensuring that internal combustion engines remain relevant in a changing automotive landscape.

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