Diagnosis of Stuck Valves in IC Engines with VVA Systems

[1]Vrinda P Menon, [2]Chethana K, [3]Karan Shah

[1]Student, [2]Associate Professor, [3]Technical Architect
[1]Department of Electronics and Communication Engineering,
[1,2]Dayananda Sagar College of Engineering
Bengaluru, India

Abstract: **The increasing global concern for environmental conservation has led to stringent emission standards and a need for reducing fuel consumption. The automotive industry is thus in constant search for technological solutions for improved fuel economy and reduced emissions. The variable valve system meets these requirements by providing control over the engine valve profiles. Obtaining the desired efficiency and emission standards, with an engine employing the variable valve system, depends on the proper functioning of the valves is essential. The introduction of electronic control in the automotive sector has made it convenient for automotive manufacturers to provide and maintain highly efficient vehicles. This paper focuses on the diagnosis of a stuck valve in an IC engine with variable valve system, governed by an engine management ECU. The various variable valve actuation methods are discussed. The diagnosis of stuck valves for an electro-hydraulic VVA system is validated in this research, by implementing the function on an engine management ECU, and the simulation results for the same are provided.**

Index Terms**: VVA, electro-hydraulic valve, stuck valve, diagnostic, ECU, IC engine, VVL, VVT**

I. Introduction

The increasing levels of pollution and concerns of energy usage have led to research and production of electric vehicles. However, IC engines continue to be the dominant source of power for vehicles due to their affordability and robustness. It is thus necessary to utilize advancements in technology to meet the stringent requirements of reduced emissions and improved efficiencies. Variable valve actuation system is one such technology that helps improve engine efficiency while reducing emissions.

In conventional engines, the in-cylinder air flow is controlled by the rotation of the camshaft through a mechanical actuation and a throttle. This results in wastage of energy and a non-optimal metering of the air mass trapped in the cylinders according to the rapid changes of the driving conditions. Variable valve actuation (VVA) systems vary the timing, duration, and lift of the engine valve to provide improved engine efficiency while meeting emission standards. The variable valve timing (VVT) is a powertrain technology that allows control of transient phases for opening/closing of the intake valves. Whereas, variable valve lift (VVL) is a technology that varies the height to which an engine valve opens. VVA systems combine the VVT and VVL technologies. It can add functionalities such as in-cylinder charge motion control, improved combustion, improved stability, selective cylinder deactivation, exhaust gas recirculation, improved low-end torque, and a good volumetric efficiency across the entire speed range, to an engine. It also reduces pumping losses. Over the years many different VVA methods have been proposed and implemented. Some of these have been discussed in section II of this paper. These systems continue to be areas of interest for research as emission standards become more stringent.

In the EHVVA system, the dynamics of the engine's intake valves is decoupled from the cam profile by introducing a high-pressure oil volume and a fast-acting solenoid switching valve, which is controlled by an electronic engine control unit (ECU). The timings and lifts of the intake valves can be controlled independently, cylinder by cylinder and stroke by stroke, by acting on the solenoid valve. This possibility involves several actuation strategies to improve the performance in terms of fuel consumption, emissions and available power.

The main contribution of this paper is the diagnosis of stuck valves in engines employing VVA systems. It is organized as follows. Section II discusses the various

VVA systems and their benefits. Section III discusses the stuck diagnosis function and its dependence on profile tracking. Section IV gives the simulation results for the diagnostic function. Section V summarizes the paper.

II. VARIABLE VALVE ACTUATION SYSTEMS

The four basic control objectives for variable valve actuation systems are - valve lift control, valve timing control, profile area control, and soft-seating. The leading VVA technologies include the electro-pneumatic VVA (EPVVA), electro-hydraulic VVA (EHVVA), and electromagnetic VVA (EMVVA).

The electromagnetic variable valve actuation system uses electromagnetically controlled valves, which can operate optimally at all engine speeds, torque levels, and temperatures. These systems employ a hybrid of two methods – commanded holding and commanded acceleration, which are complementary [1]. The commanded holding method uses stored mechanical potential energy converted to kinetic energy for transition of valves and then stores the kinetic energy as mechanical potential energy to hold the valve in position until the next transition is desired.

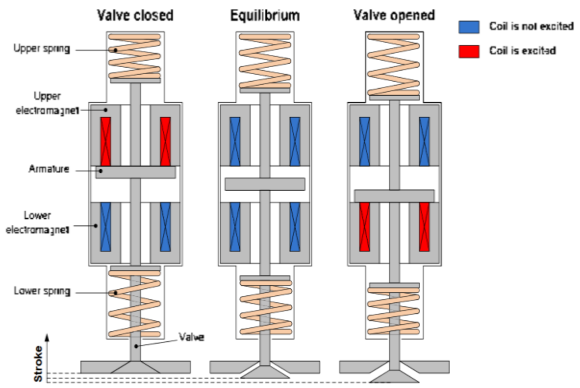

Fig 1 Principle of operation of EMVVA as in [2]

An electro-pneumatic VVA system actuates a piston-cylinder arrangement using air-pressure, which in turn actuates the poppet valves. Control valves (spool valves) are used to regulate movement of pressurized air in and out of the piston-cylinder arrangement. The spool valves are controlled by a solenoid. In order to reduce the energy consumption, EPVVA uses a hydraulic latch, allowing the actuator to extract the full expansion work out of the air that is drawn into the cylinder.

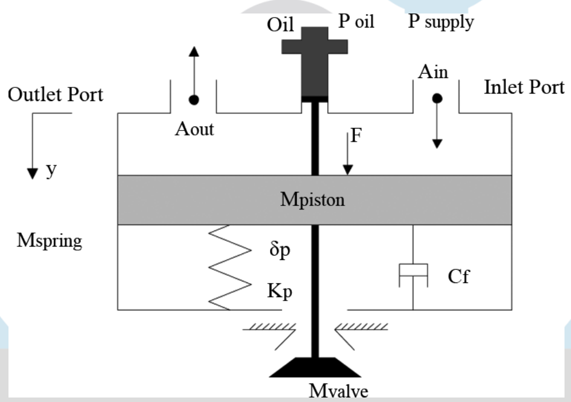

Fig. 2 EPVVA piston model as in [4]

The EPVVA consists of two control solenoids, an actuator cylinder, two port valves, two spool valves, an actuator piston, and a hydraulic latch-damper system [4]. Fig 2 shows the piston model for an EPVVA system. The cylinder can be single or double acting. In single acting cylinder, the valve is opened using pressurized air and is closed using a return spring. Whereas, in double acting cylinder, the valve is opened and closed using pressurized air. To open the valve, the upper chamber of the cylinder is allowed to be filled by the pressurized air, while the lower chamber is exposed to the atmosphere [5]. The difference in pressure across the pneumatic piston, moves the poppet valve downwards. The control valves are then closed to hold the valves in the desired position. To close the valve in a double acting cylinder, the air and oil chambers are depressurized and the control valves are opened.

The EHVVA system consists of an electro-hydraulic actuator, which is driven by a camshaft, with integrated fast-switching hydraulic valves. The EHVVA systems use a defined volume of oil, controlled by solenoid driven valves, to change the valve lift height and timing as desired. The position of the cylinder head in engines employing EHVVA can be chosen freely since the valves and cam are connected by a hydraulic interface [6].

III. STUCK DIAGNOSIS FOR EHVVA SYSTEMS

The solenoid valves are of central importance for controlling the EHVVA system as they are the control elements of the engine valves. The valve control module software controls the solenoid valves, individually. The software stored in the engine management ECU is used to implement the requested lift modes with defined angles for opening and closing of the engine valves. To find the correct actuation points and timing, the software considers various factors that affect the system behavior.

The control module faces various challenges to meet the control objectives. The following are the major challenges for the control module: Precise valve motion, operational environment uncertainties, and the valve timing strategies to be applied [7].

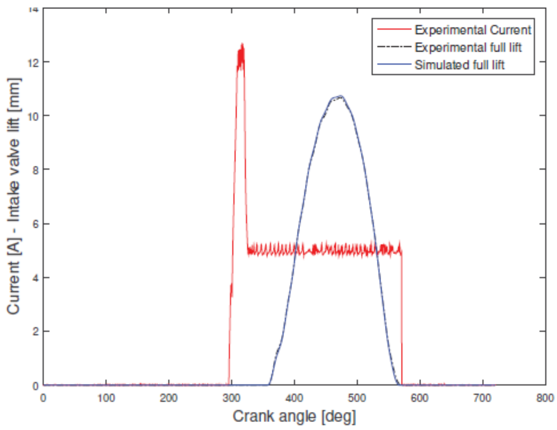

Fig 3 Current profile and lift curve for full-lift [10]

The detectability of the current curve over the complete temperature range poses an additional challenge in EHVVA systems. Hence, profile tracking controller is required to obtain desired engine performance. Various profile tracking controllers have been proposed in the past [8] [9]. Fig. 3 shows the current profile for the solenoid valves, in case of full lift, as given in [10]. The current curve obtained, for each cylinder, during the solenoid valve switching must be monitored and adjusted depending on the operating conditions. A stuck valve creates distortion in the current profile. A distortion of the current curve (Fig 3) in the transition region from peak current to hold current indicates that the valve is either stuck open or stuck mid-lift. A distortion in the tail current indicates a valve stuck close. An optimal profile tracking controller would detect any such distortion in the current profile. Based on inputs from the monitoring function, a flag is raised to indicate a temporary fault. The temporary fault is then debounced to confirm the fault which can then be entered in a fault code memory.

The fault diagnosis function discussed in this paper, consists of a diagnostic counter which monitors the fault flag for temporary fault occurrence and its healing. Once the fault is confirmed to be permanent, an error bit it set and the fault is reported. This in turn lights the malfunction indication lamp (MIL) of the vehicle. The fault code recorded by the system can be read at service stations and appropriate measures can be taken to fix the valves. Fig 4 describes the diagnostic counter.

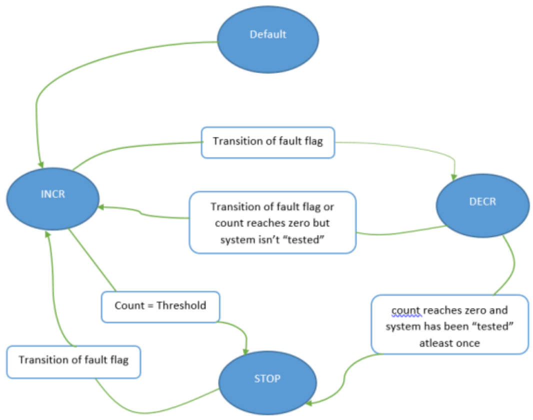

Fig 4 Diagnostic counter

An event based diagnosis technique is used here to detect the fault in the system, which internally uses an up-down counter. The counter starts counting up as soon as the system is active, and electrical signal readings are confirmed to be valid. In case of a fault-free drive cycle, once the count reaches an ascertained threshold, the system is reported to be "tested". In case a fault occurs, the counter resets and starts counting up, until the fault threshold is reached. Once the fault threshold is reached, the fault is confirmed to be permanent and is recorded by the system as a fault code. If the fault is temporary, the fault flag goes low and the counter starts counting down. Once the count reaches zero, the fault is said to be healed, in which case the fault isn't recorded. The fault codes reported also indicate specifically, which position the valve is stuck at – open, close, or mid-lift.

IV. SIMULATION RESULTS

The diagnostic function was designed on a model-based development software and its operating frequency was kept at 10ms, which is the fastest operating frequency supported by the ECU. The simulation results for the implemented function are analyzed in this section.

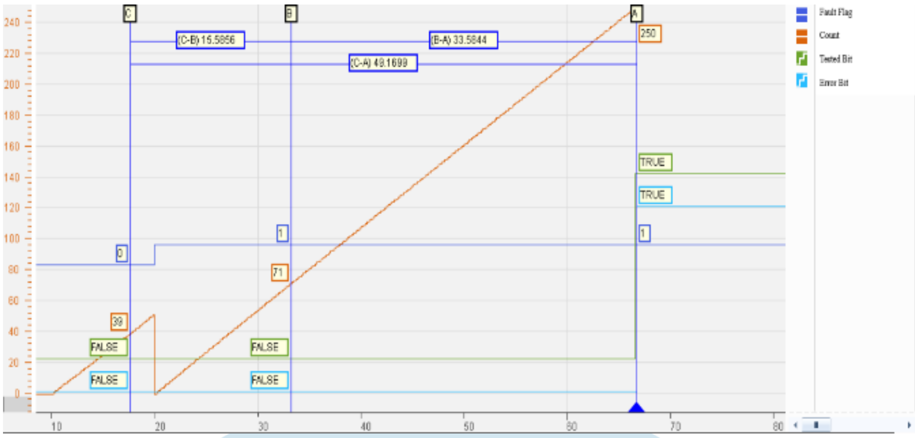

Fig 5 Fault confirmed to be permanent

Fig 5 shows the simulation result for when a fault occurs and is confirmed to be permanent. The fault occurs at 20s. At this point, the counter resets and starts counting up again. It counts up to the fault threshold, which can be decided by the OEMs. Here, the threshold is kept at 250. Once the count reaches 250, the fault is confirmed and the tested bit and error bit are set to TRUE.

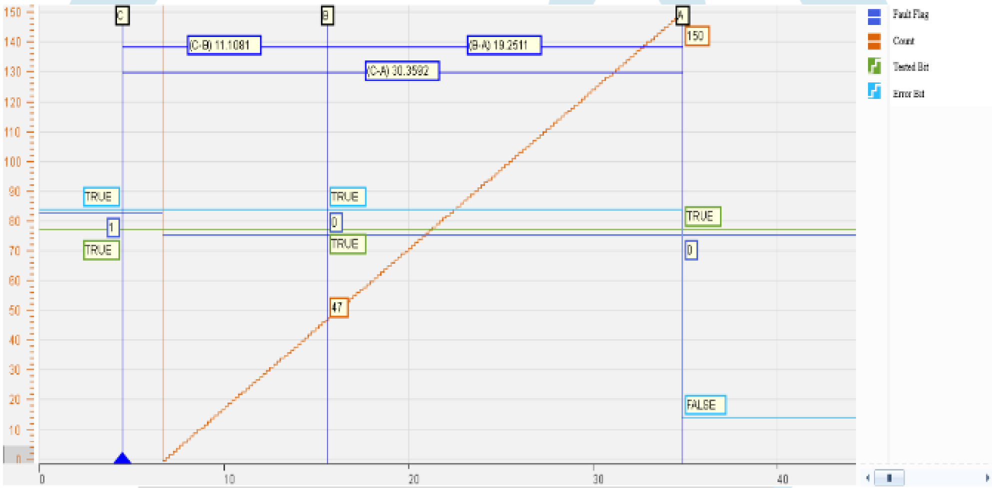

Fig 6 Fault healing confirmed

Fig 6 shows the simulation result for when a fault that was earlier confirmed as permanent and reported, heals. In this scenario, the counter is reset, and counts up. If the count reaches a pre-determined healing threshold (150 here), the error bit is pulled low to indicate that the fault is healed. If instead, a fault occurs again and interrupts the healing, the counter would count down.

V. CONCLUSION

This paper discusses the existing variable valve actuation technologies, the various methods of variable valve actuation and how these systems operate. These systems help improve the engine's performance and also helps decrease emissions to meet the increasingly stringent emission standards of the modern world. Hence, the need for diagnosing a stuck engine valve in such systems is discussed and a diagnostic function for detecting and reporting a stuck valve is designed and the simulation results for the same are presented. The implemented function detects a stuck valve based on the actuation current curve and reports a fault by turning on the Malfunction Indication Lamp (MIL) of the vehicle.

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