

Fault Diagnosis of Fully Variable Valve Actuators on a Four Cylinder Camless Engine

Ipek Saraç and Karsten Mischker

Robert Bosch GmbH

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ABSTRACT

Fully Variable Valve Actuation (FVVA) systems enable to employ a wide range of combustion strategies by providing the actuation of a gas exchange valve at an arbitrary point in time, with variable lift and adjustable ramps for opening and closing. Making such a system ready for the market requires appropriate fault-diagnostic functionality. Here, we focus on diagnosis possibilities by using air intake system sensors such as Manifold Absolute Pressure (MAP) sensors. Results obtained on a 4-cylinder test bench engine are presented for the early intake opening strategy under different loads, and at medium range rotational speeds on steady-state conditions. It is shown that detection and identification of the different critical faults on each actuator is possible by using a Fourier series signal model of the MAP sensor.

INTRODUCTION

Variable Valve Actuation (VVA) improves fuel consumption, torque characteristics, and emissions of combustion engines by enabling the realization of different combustion strategies [2, 3] (e.g., HCCI, Early Intake Valve Closing, 2/4 Stroke Switching). Fully Variable Valve Actuation (FVVA) makes it possible to apply a wider range of strategies by providing the actuation of a gas exchange valve at an arbitrary point in time, with variable lift and adjustable ramps for opening and closing. The Electro-Hydraulic Valve System (EHVS) consists of hydraulic (fully variable) actuators on both engine intake and exhaust sides, a hydraulic cycle including a high-pressure pump as a part of the engine oil cycle, and a control unit [12].

Making EHVS ready for the market requires providing the system with appropriate fault diagnosis functionality. Diagnosis of EHVS actuators can be achieved by introducing position sensors for each actuator. This approach increases, however, the cost of the system undesirably. Thus, it is necessary to explore alternative methods by redefining the system (EHVS including the engine), and making indirect use of other sensors which are already present and used for other purposes.

Since the valve actuators are parts of the air intake system, their faults have direct effect on the air intake sensors, such as the Mass Air Flow (MAF) and Manifold Absolute Pressure (MAP) sensors. The effects on the other sensors (e.g., crank-angle, lambda) would require additional information about other engine actuators and their states (e.g., fuel, ignition), so a model which uses the air intake sensors as its inputs reduces the complexity of the Fault Detection and Isolation (FDI). For instance, a fault of one cylinder's intake valve may cause misfire, but a misfire is not necessarily caused by a fault of a valve actuator. Thus, in this case fault identification needs more time and information on other engine components to find the most likely fault candidate if it is not coupled with an air intake diagnosis function. Furthermore, using active diagnosis which manipulates the engine in a way that the possible faults are revealed, may lead to choose suboptimal control schemes for accommodating the diagnosis requirements [11]. Hence, the aim of this paper is to explore the possibilities of FDI without relying on active diagnosis.

The first section presents how the engine operating points are chosen for the early intake valve closing strategy under different loads and at medium range rotational speeds. This analysis is based on minimizing specific fuel consumption, maintaining drivability, and reducing emissions. The section aims to fill the gap between the engine operating points and valve timings to enable analysis of the diagnosis possibilities for a range of operating points. The second section gives an overview of the possible valve actuator faults and their effects on emissions on the chosen valve timings. In the next section the possibility of using a MAF sensor with a model of the in-cylinder air charge for steady or quasi-static states is discussed. The last section deals with a possible FDI approach using a signal model of the manifold pressure for steady-state conditions for the chosen valve timings. The results of such an effort on a 4-cylinder Audi EA 113 test bench will be analyzed for different fault cases. The signal model uses few harmonics of the Fourier series and, contrary to existing efforts to detect cam profile switching faults [14], it works in the time domain and makes use of the information about occurrence times to identify faults between the intake and the exhaust actuator.

OPERATING POINT IDENTIFICATION

The operating point for an engine is defined by its rotational speed (n) and load (M). Criteria to identify operating points for the SI operation mode are defined to minimize specific fuel consumption and maintain drivability. The drivability (or combustion quality) constraint is defined in terms of the Coefficient of Variation of Indicated Mean Effective Pressure (COV_{IMEP}). Let σ_{IMEP} be the standard deviation of Indicated Mean Effective Pressure (IMEP) and μ_{IMEP} its mean value, then the drivability constraint is as follows:

$$COV_{IMEP} = \frac{\sigma_{IMEP}}{\mu_{IMEP}} \cdot 100 \leq 4\% \quad (1)$$

This criterion must hold for each cylinder individually as well as for the sum of all cylinders. IMEP is calculated individually for each cylinder based on data provided by the in-cylinder pressure sensors available for each cylinder on the test bench. The definition of IMEP is given in the literature [6].

The specific fuel consumption (sfc) is defined as fuel flow rate per unit power [6]. Let $\dot{m}_f$ be the mass fuel flow for unit time and P the power output, sfc can be defined as:

$$sfc = \frac{\dot{m}_f}{P} \quad (2)$$

The quantity of sfc is minimized to minimize the pumping loss and to find efficient operating points in terms of the fuel supplied to produce work. The unit used in this context is g/kWh.

The other important criteria for operating point identification are the emissions. NOx and HC concentrations are taken into account during the decision process for both operation mode and points. The HC value constraint is set to be below 5000 ppm, whereas the NOx values are required to be minimized for different loads and engine speeds.

The measurements are taken on a slightly throttled basis. Let P_{env} indicate the environmental pressure and P_{man} be the pressure in the manifold, then the throttle valve is adjusted such that:

$$P_{man} = 0.98 \cdot P_{env} \quad (3)$$

The throttle opening angle α_t for the condition presented in (3) can be seen in Figure 1 for 2500 rpm. It is found to be a linear function of the engine speed n and IMEP in the range between $n=2000$ and 3000 rpm.

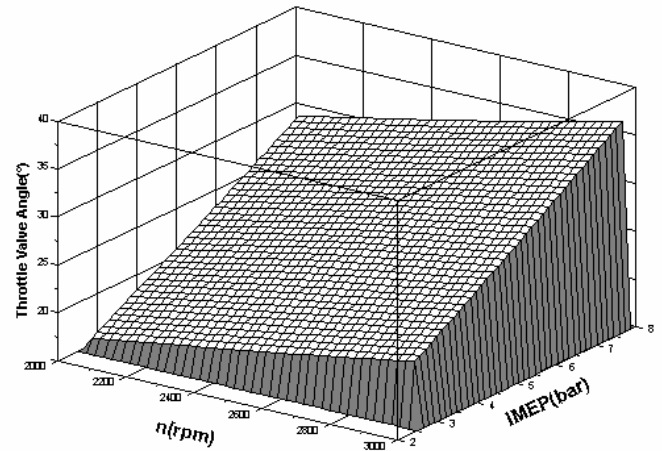


Figure 1: Throttle Valve Angle satisfying (3) for different IMEP and n . The data is taken from Audi EA113 4-Cylinder Test bench engine.

Although the main purpose of slight throttling is to avoid acoustical noise, on the Audi EA113 4-Cylinder test bench data it is also observed that drivability (COV_{IMEP}) is improved by the amount up to 0.2% for the measured range of operating points. Another positive effect of slight throttling can be seen for manifold pressure dynamics, namely less disturbances acting on the air intake sensors. For the slightly throttled case, Hot Film Mass (HFM) sensors are observed to measure with 2% less error as compared to the wide-open throttle case.

The measurements are carried out keeping the IMEP constant for different valve times. This suggests having a demand map of engine speed n and torque M for each operating point. Here, the points for low and medium engine loads are analyzed at steady state for engine speeds between 2000 and 3000 rpm.

The degrees of freedom of the FVVA system can be seen in Figure 2. In this study, the slopes of both intake and exhaust valves are fixed for the sake of reducing complexity. The hydraulic pressure in the system [12] is 100 bars for all measurements although it is capable of delivering up to 200 bars (steeper slope, faster opening time).

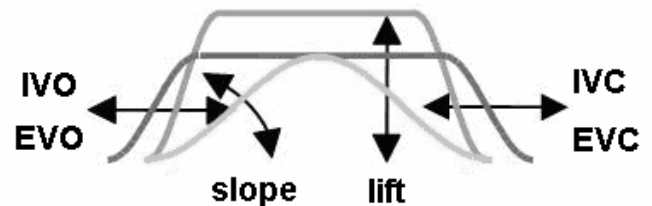


Figure 2: Representation of degrees of freedom for FVVA

VALVE TIMING STRATEGY

For gasoline engines operating in Standard Injection (SI) mode, various valve timing strategies are studied. An overview of these can be found in [8]. The right strategy has to be chosen to meet different requirements such as maximizing torque or minimizing pumping loss and sfc. The latter is chosen to be the aim of this paper.

Some authors [9, 10] conclude that the air being pushed back to the manifold during “Late Intake Valve Closing” (LIVC) causes the volumetric efficiency to decrease at low speeds. The “Early Intake Valve Opening” (EIVO) strategy is reported to reduce pumping loss when combined with “Early Intake Valve Closing” (EIVC) [8]. An alternative to that method would be “Late Exhaust Valve Closing” (LEVC), which is another way of taking the burned gasses to the manifold. This backflow enables an internal EGR mechanism and reduces unburned gasses, i.e. NO_x. The “Early Intake Valve Opening” (EIVO) strategy is proven to be more efficient in terms of reducing HC [7]. Sample valve curves for EIVO are presented in Figure 3.

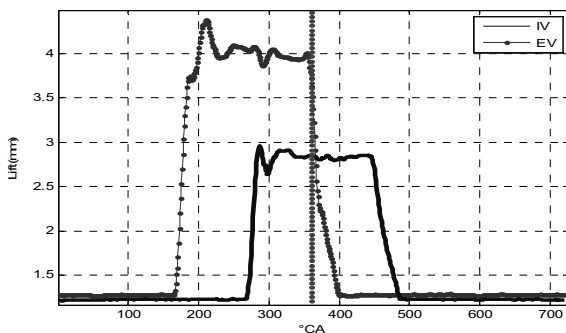


Figure 3: Sample IV and EV Lift curves for Early Intake Valve Opening and Early Intake Valve Closing combined at 2000 rpm. The TDC of the cylinder (360°CA) is shown with a straight line between IV and EV.

The exhaust valve opening (EVO) parameter is taken to be at 167 °CA (13°CA before BDC). For stable early intake valve opening intake valve timings, various experiments with different exhaust valve lift (EVL) and exhaust valve closing (EVC) parameters are carried out. It is observed that EVC later than 30°CA after TDC renders the corresponding engine unstable and, thus, contradicts the drivability criterion. Optimum EVC in accordance with the criteria presented in (1) and (2) for 2000 rpm and 2.5 bars IMEP is found to be 380 °CA (20 °CA after TDC) with a lift of 4 mm. These values are fixed throughout the intake valve measurements.

Here, the intake valve close (IVC) parameter is determined by the air charge requirement. The intake valve open (IVO) and intake valve lift (IVL) parameters are optimized in terms of sfc, COV_{IMEP}, and emissions criteria for IMEP between 2.5 to 5 bars for different engine speeds. For IMEP exceeding 6 bars, it is observed that valve profiles with less overlap perform better than early intake valve closing (EIVC). Hence, the engine operation mode should be switched to profiles

with less overlap between the intake and the exhaust valves while going to higher loads. The case of high-load operation has to be studied further and is not included in the scope of this paper.

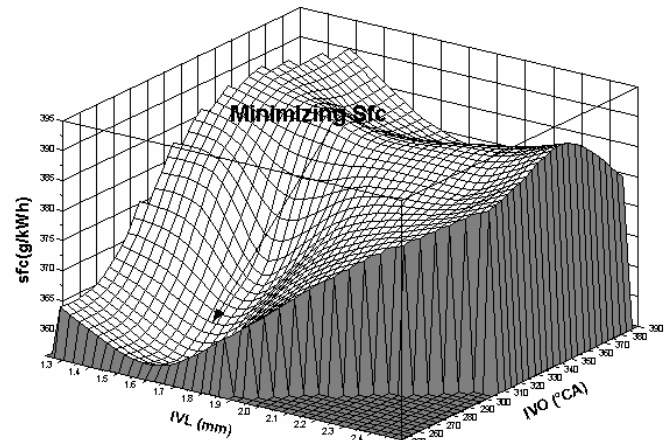


Figure 4: IVL and IVO points taken for 2000 rpm, 2.5 bars IMEP show optimum points in terms of sfc minimization. The data is taken from Audi EA113 4-Cylinder Test bench engine.

The effect of early intake valve opening (EIVO) on sfc can clearly be seen in Figure 4 for the case of low speed and low load. The minimum for this case occurs at around 260 °CA (100°CA before TDC), and is well below the sfc values that can be reached by normal and late intake valve openings. On the other hand, the minimum point in Figure 4 does not satisfy the drivability constraint shown in Figure 5 fully. The reason for this is that the minimum point is located close to a steep unstable combustion transition caused by excessive burned gas in the cylinder. This means that a small disturbance or malfunctioning of the intake valve may lead the engine to an unstable condition. To compensate this property of the minimum sfc point, a near by operating point with a higher drivability value in terms of COV_{IMEP} is chosen, i.e. for 2000 rpm and IMEP of 2.5 bar, the intake valve parameters are intake valve opening (IVO) at 270 °CA (90 °CA before TDC) with 1.6 mm lift.

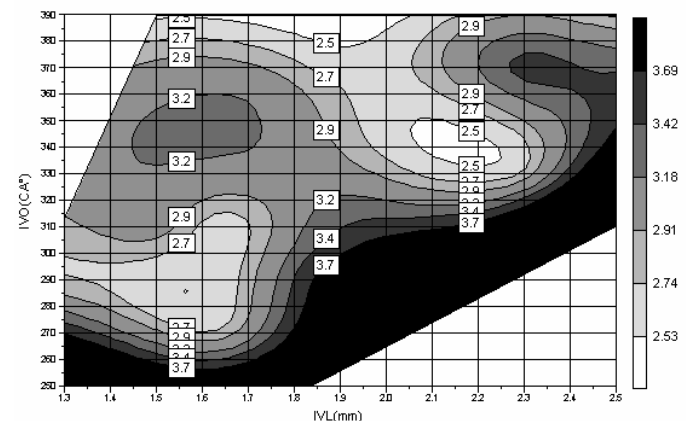


Figure 5: IVL and IVO points taken for 2000 rpm, 2.5 bars IMEP show combustion stability in terms of COV_{IMEP} (%). TDC is at 360°CA. The data is taken from Audi EA113 4-Cylinder Test bench engine.