

Modeling Fresh Air Charge and Residual Gas Fraction on a Dual Independent Variable Valve Timing SI Engine

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ABSTRACT

We propose a model of in-cylinder air mass and residual gas fraction of a turbocharged SI engine with Variable Valve Timing (VVT) actuators. VVT devices are used to produce internal exhaust gas recirculation at part load, providing beneficial effects in terms of fuel consumption and pollutant emissions. At full load, VVT actuators permit to push back knock limit by scavenging fresh air to the exhaust pipes. Modeling in-cylinder composition is an essential task for control purpose. Actually, VVT actuators affect in-cylinder fresh air charge. This has an impact on engine torque output (leading to driveability problems), and on Fuel/Air Ratio (leading to pollution peaks). In this paper, we present a model of in-cylinder air mass and residual gas fraction using only commercial-line sensors (engine speed, intake manifold pressure and VVT actuators positions). It is designed for real-time control purpose. The model does not necessitate a lot of calibration time. The proposed method consists in modeling the quantity of fresh air going through the intake valve. The model is composed of three terms. All these terms have their own physical meaning: first term gives in-cylinder total mass, second term gives the gas mass that goes through both valves during the valve overlap (either backflow of burned gas, or scavenging of fresh air), and last term models the residual gas mass staying in the cylinder from one cycle to the next one.

INTRODUCTION AND MOTIVATIONS

Lately, downsizing (engine size reduction) has appeared as a major way to reduce fuel consumption of Spark Ignition (SI) engines. Downsizing lowers pumping losses under partial load and, thus, saves energy [7]. Turbochargers are used to compensate the induced power losses. To take advantage of all the potentialities of direct injection and turbocharging, engine can be equipped with Variable Valve Timing (VVT) devices.

VVT systems use electro-hydraulic mechanisms which rotate the camshaft relating to the crankshaft in order to modify the engine breathing. There are four VVT strategies for Double Over-Head Camshaft engines (DOHC) [8]. This paper focuses on the most efficient VVT strategy, i.e. the phasing of the exhaust and the intake independently (dual independent, Figure 1). These devices permit some air and burned gas decanting between engine intake and exhaust. On the one hand, under atmospheric conditions, an appropriate control of VVT actuators positions permits an Internal Exhaust Gas Recirculation (IEGR). This significantly reduces fuel consumption. Moreover, it can have an important impact on Nitrogen Oxides (NO_x) and Carbon Monoxides (CO) emissions reduction. On the other hand, under turbocharging conditions, load increase imposes a knock control. Yet, knock is strongly linked to in-cylinder burned gases. Then, large overlap is used to take advantage of the positive difference between intake and exhaust pressure, to improve cylinder flushing and decrease residual burned gas concentration.

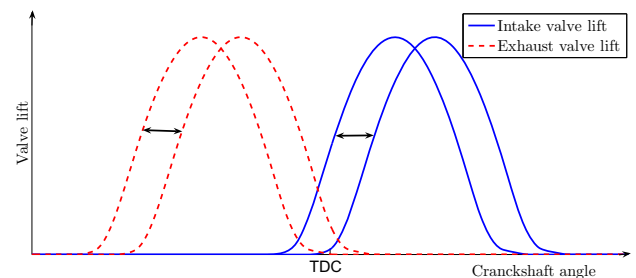


Figure 1: Dual independent variable valve timing. Valve timing actuators can move separately.

One basic task in engine control consists in managing engine torque output according to driver's requests, while limiting pollutant emissions. On SI engines, torque control is achieved by managing the in-cylinder air mass, while keeping the Fuel/Air Ratio to the stoichiometric value in order to minimize exhaust emissions (treated in a three way catalytic converter). To reach

these two control objectives, knowledge of in-cylinder air mass is necessary [9]. As no sensor is available in the cylinder to give such an information, models are used to compute the in-cylinder air mass. On conventional (fixed-valve timing) engines, a reference in-cylinder air mass is directly computed from the intake manifold pressure through a quasi-static relation depending on the volumetric efficiency [4]. On engines equipped with VVT actuators, the in-cylinder air mass is also affected by VVT actuators positions. Actually, under atmospheric conditions, IEGR decreases inducted fresh air charge, whereas under turbocharging conditions, air scavenging increases in-cylinder fresh air charge. As VVT actuators affect the in-cylinder air mass, their positions have to be taken into account to model the in-cylinder air mass.

Another task, in engines equipped with VVT actuators, is to control the IEGR. Actually, the in-cylinder residual gas fraction plays a role on combustion stability as well as on pollutant emissions. Modeling the in-cylinder burned gas quantity is then of considerable interest.

We propose a model of the in-cylinder fresh air and residual gas masses. The model uses only commercial-line sensors: engine speed, intake manifold pressure and VVT actuators positions. It is calibrated off-line on experimental test bench data and runs in real-time for engine control application.

This paper is organized as follows. First, we expose the experimental setup. The following two parts present the effects of the VVT actuators on the engine under atmospheric and turbocharging conditions. After presenting existing models of the literature, we propose a model of in-cylinder air and burned gas masses and evaluate its performances relating to test bench data. Then, we discuss some model results for VVT actuators positions variations. Finally, we conclude and give future directions.

EXPERIMENTAL SETUP

The considered engine is a 1,8L four-cylinder SI engine using direct injection technology and homogeneous combustion. The airpath consists of a turbocharger with monoscroll turbine controlled by a waste-gate, an intake throttle and a downstream-compressor heat exchanger allowing intake air temperature regulation. To take advantage of direct injection and turbocharging, the engine is equipped with two variable valve timing devices, one at the intake and one at the exhaust. The engine architecture is presented on Figure 2 and Table 1.

VVT actuators positions define Intake Valve Opening (IVO) and Exhaust Valve Closing (EVC). IVO is in crankshaft angle degree Before Top Dead Center ($^{\circ}$ BTDC) and EVC is in crankshaft angle degree After Top Dead Center ($^{\circ}$ ATDC). We define the valve overlap (in $^{\circ}$ CA) as the sum of IVO and EVC.

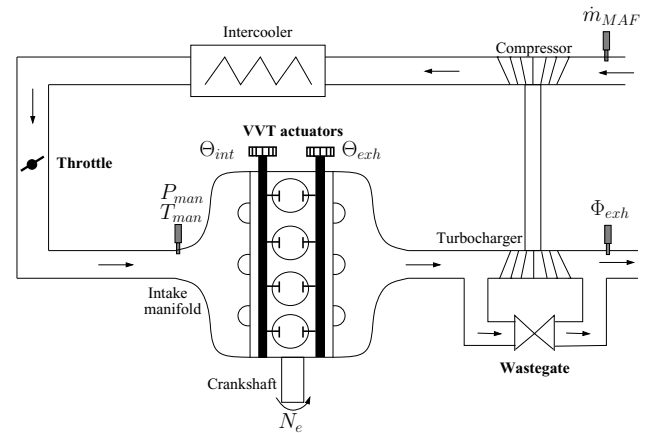


Figure 2: Engine scheme. Intake Mass Air Flow (MAF), $\dot{m}_{MAF}$, intake manifold pressure and temperature, P_{man} and T_{man} , engine speed, N_e , and Fuel/Air ratio, Φ_{exh} , are measured by sensors. Θ_{int} and Θ_{exh} are the VVT actuators positions.

Engine type	Renault F5P
Number of cylinders	4
Bore $\times$ Stroke	82.7 $\times$ 83.0 mm
Compression ratio	10.5:1
Engine Displacement	1.8 Liters
Turbocharger type	Mono-scroll
IVO	30 / -10 $^{\circ}$ BTDC
EVO	-29 / 11 $^{\circ}$ ATDC

Table 1: Experimental setup

IMPACT OF VVT DEVICES ON THE ENGINE UNDER ATMOSPHERIC CONDITIONS

At part load, when the intake manifold pressure is lower than the exhaust manifold pressure, IEGR may occur in the cylinder (Figure 3). On VVT engines, this phenomenon is strengthened because the valve overlap (instant when both intake and exhaust valves are open simultaneously) can be very large.

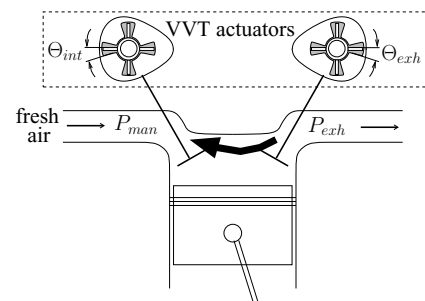


Figure 3: Under atmospheric conditions ($P_{man} < P_{exh}$), back flow of exhaust burned gases may occur during the intake stroke.

On a SI engine, deterioration of the cylinder filling at part load enables to increase the intake pressure at constant air mass flow. If this deterioration is made without any additional pressure losses between the intake manifold and the combustion chamber, it leads to a reduction of the pumping losses. An appropri-

ate control of the VVT actuators allows to handle the cylinder filling through two effects:

- An increase of the burned gas fraction (obtained by crossing the valves), permits an exhaust gases back flow towards the intake. It reduces the available volume for fresh air.
- Modifying the intake valve phasing in relation to the piston course modifies the effective cylinder capacity, and so the admissible air volume.

Figure 4 presents simulated mass flow rates for a 0.4 bar intake manifold pressure and a 1.1 bar exhaust manifold pressure. The model under consideration is given in [6]. Overlap entails negative intake mass flow rate and lowers exhaust mass flow rate. Thus, exhaust gases flow back to the intake, a large part of it comes from the exhaust manifold.

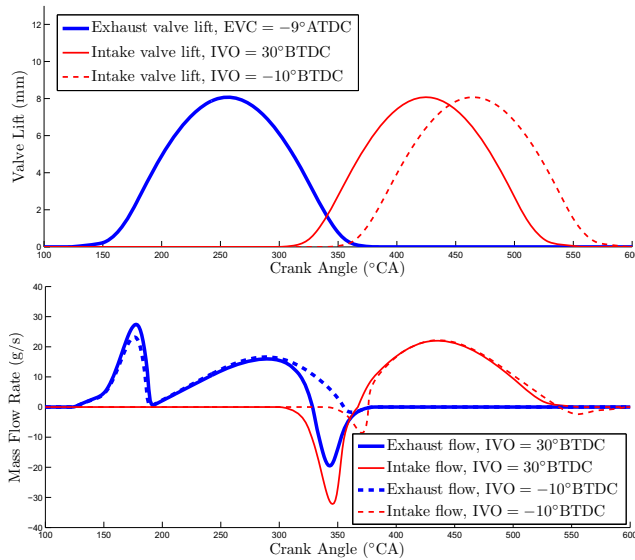


Figure 4: Flows through intake and exhaust valves for two different valve overlaps at part load ($P_{man} = 0.4$ bar).

Now, we present the effects of VVT actuators on combustion, pollutant emissions and fresh air charge.

EFFECTS ON COMBUSTION Residual burned gases increase the in-cylinder mixture temperature. It accelerates fuel vaporization and improves charge homogenization before ignition. On SI engine, we look for limiting Fuel/Air ratio dispersions in the combustion chamber because rich zones burn with lower efficiency. Fuel is only partially oxidized and the part of the CO in the combustion products increases. Yet, formation of CO provides less energy than the one of CO₂. Thus, residual burned gases permit a diminution of fuel consumption by improving mixture preparation.

Limit of the IEGR is governed by combustion stability. Indeed, mixture including too much residual gases burns with difficulty. Water and CO₂ molecules contained in the burned gases slow down the flame propagation (they possess a higher specific heat than air and absorb more easily the combustion heat release). Flame temperature is then lower and propagation is less efficient. Figure 5 shows the effects of the IEGR on the combustion

process.

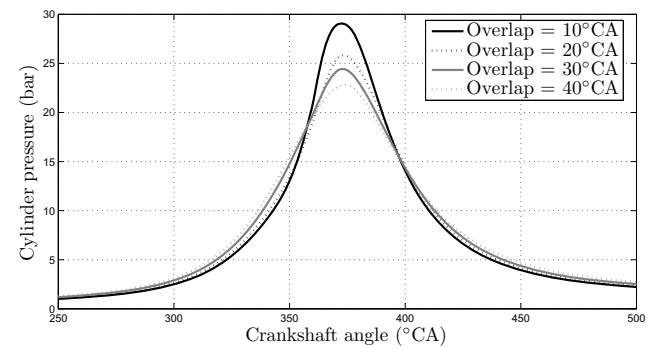


Figure 5: Cylinder pressures for a variation of valve overlap at constant engine speed (1000 rpm) and constant BMEP (4 bar).

EFFECTS ON POLLUTANT EMISSIONS Figure 6 shows the effects of IEGR on NO_x emissions and on intake manifold pressure at constant part load. The higher the valve overlap is, the higher the residual gas quantity is. Decrease of NO_x emissions comes from a cooler combustion temperature thanks to residual gases in the chamber. Increase of the intake pressure is necessary to stay at same engine torque output. Thus, it leads to a reduction of the pumping losses, and then a decrease of fuel consumption.

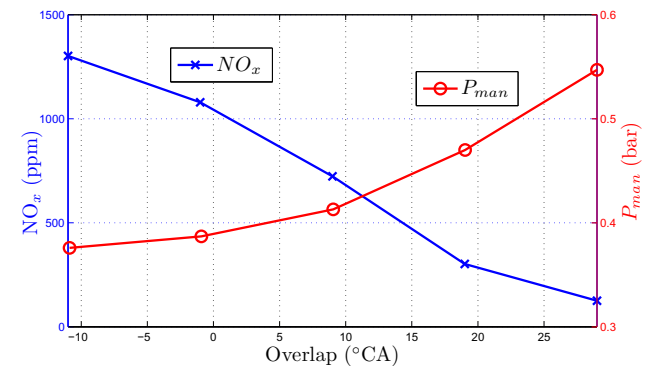


Figure 6: Effects of variation of valve overlap on intake manifold pressure and NO_x emissions at constant engine speed (1500 rpm) and constant torque (30 Nm).

EFFECTS ON FRESH AIR CHARGE On classical SI engines, considering accurate spark and Fuel/Air ratio control, engine torque response is determined by the quantity of fresh air in the cylinders. Generally, the mass air flow through the intake valve, $\dot{m}_{air}^{iv}$, is directly derived from the engine speed, N_e , and intake manifold pressure, P_{man} , through a quasi-static relation depending on volumetric efficiency, η_{vol} ,

$$\dot{m}_{air}^{iv} = \eta_{vol}(N_e, P_{man}) \rho_{man} V_d \frac{N_e}{120} \quad (1)$$

where ρ_{man} is the intake manifold air density and V_d is the displaced volume of all cylinders [4].

On engine with internal EGR, volumetric efficiency is affected