

Improved Fuel Metering for Port Fuel Injection by Controlled Valve Operation

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ABSTRACT

Engine management systems combined with fuel injectors allow a precise fuel metering for a robust combustion process. Stricter emission legislations increase the requirements for these port fuel injection systems (PFI), whereas the price is still the main driver in the emerging low cost 2-wheeler market. Therefore, a holistic mechatronic approach is developed by Bosch, which allows an improved fuel metering over life time and furthermore provides new possibilities for diagnosis without changing the injector itself.

This example of an intelligent software solution provides the possibility to further improve the accuracy of the fuel metering of an injector. By use of the information contained in the actuation voltage and current, the opening and closing times of the injector are derivable. The present paper illustrates how these features can be used to extend the dynamic flow range of injectors (minimum amount of fuel compared to the maximum amount of fuel) and how the deviations from injector to injector can be reduced. In order to improve the robustness of the system regarding varying operating conditions (battery voltage, pressure, temperature...), an adaptation algorithm is introduced. This adaptation algorithm reduces air fuel ratio deviations in dynamics and by that the emissions, which cannot be directly reduced by an oxygen sensor. Besides the possible reduction of emissions, cylinder imbalances can be compensated and thereby the engine smoothness especially in idling is improved. In addition to the potential analysis, new possibilities for upcoming system trends are discussed.

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INTRODUCTION

Gasoline port fuel injection is still the most widely used powertrain system for gasoline engines in the world and the preferred solution especially for small engines. One of the most important system components is the fuel injector. It is responsible for the correct targeting and spray in order to provide a good fuel-mixture preparation. Although the development of the injectors is already very sophisticated, there are still requests for further improvements. These provoking requirements lead to a necessary tradeoff between performance and costs. Constructional changes of single components are very complex and expensive. Therefore system solutions are developed by Bosch. These solutions are based on overall system analyses and optimizations instead of exclusive improvements of single components. An example for a system solution is CVO (Controlled Valve Operation). CVO identifies the actual opening duration of the injector and compares it with the requested value. In case of a deviation, an adjustment function sets in to minimize fuel metering tolerances. Thereby the influence of varying operating conditions, aging effects and the spread of standard factory models can be compensated. The result is a more precise fuel metering especially for small amounts of fuel.

For direct injection gasoline engines (DI) CVO is already a standard-production application. It is the enabler for increasing pressure demands even with small loads and multiple injections. These help to avoid soot generation which is caused by wall and piston wetting. The necessary short injection times and the minimized metering tolerances over the vehicle's lifetime are very challenging and CVO is one possible solution. More details on CVO for DI can be found in [1]. Whereas quite a number of DI engines is already equipped with CVO, no reference was found that any PFI series project makes use of this technology. The contribution of this paper is an overview on the development of CVO for PFI engines. Whereas the main idea is the same as for DI, the challenges regarding the different disturbing influences on the opening duration are very much different. Although the achievable benefits for PFI are not as significant as for DI engines, CVO still retains a great amount of potential to further improve the performance of PFI engines.

The paper starts with an overview on low pressure fuel injection and an introduction of a hardware in the loop test bench for system development. After illustrating the determination of the opening and closing delays and the fuel metering adaptation function, the possible benefits are discussed based on experimental results. The paper will end up with a discussion on new possibilities for upcoming system trends.

CVO (CONTROLLED VALVE OPERATION) FOR PFI

CVO is a holistic mechatronic approach. It is not only important to know the characteristics of the injector, but also the interaction of the injector with the overall fuel system, the power electronics and the control unit. Therefore a system test bench was built-up and simulation models are used in order to gain as much system understanding as possible. In the following the fuel injector, the system test bench and the simulation model are introduced.

Experimental Setup

Low Pressure Fuel Injector

The fuel injector is an electromagnetic valve, which injects the pressurized fuel into the manifold. The main requirements are a precise fuel metering, a defined targeting and a good mixture preparation. The spraying is realized via a spray-orifice plate, which has at least four spray holes. Due to the high precision of the spray holes a high consistency of the flow rate is ensured. The spray pattern of the injected fuel is defined by the arrangement and the number of spray holes.

Construction

Figure 1 shows the Bosch injector EV14.

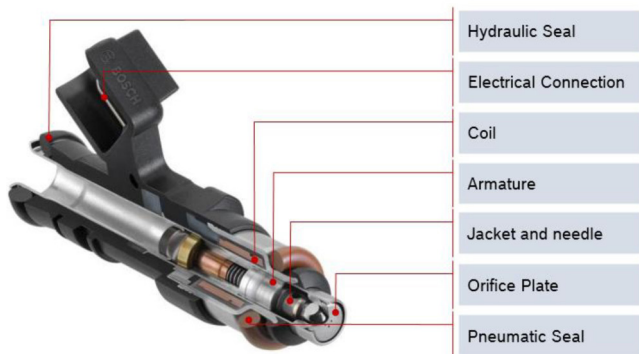


Figure 1. Bosch injector EV14

Mode of Operation

The injector is actuated from the EMS (Engine Management System) via an integrated low-side power switch with a Zener diode in parallel (figure 2). The Zener diode protects the circuit from the overvoltage due to the self-induction, which occurs when the energization of the injector coil is stopped.

In power-off mode (currentless coil) the needle is pressed into the cone-shaped valve seat by the spring and the resulting force of the fuel pressure. Like that the fuel supply system is sealed against the manifold. In power-on mode the coil is energized and an electromagnetic field arises, which pulls the armature back. Thereby the needle is lifted and the fuel is injected. A deactivation of the

energizing current again leads to the closing of the injector. Figure 3 shows the relationship between actuation pulse, current, needle lift and amount of injected fuel.

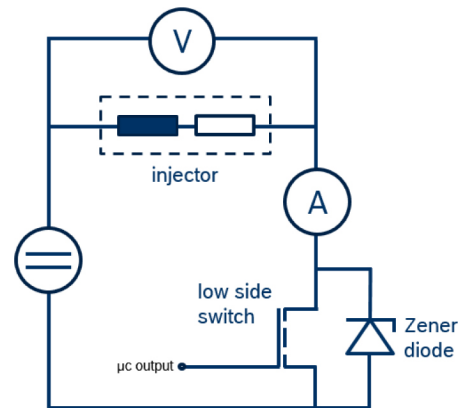


Figure 2. Power electronics for injector actuation

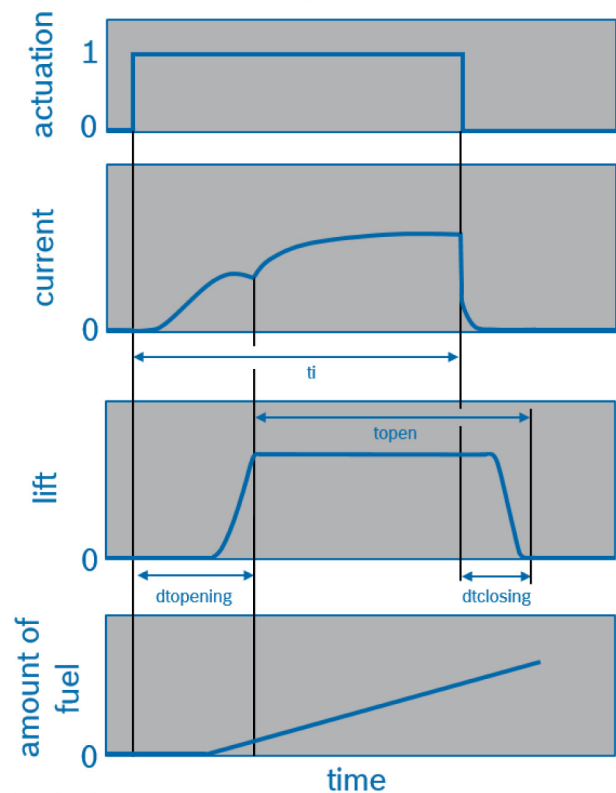


Figure 3. Actuation of injector, current, lift and approximate amount of fuel [2]

Each injector has a certain dynamic. After the beginning of actuation it takes some time until the needle reaches the full lift. The occurring delay time $dt_{opening}$ depends on plenty of disturbing variables: Actuation voltage, fuel pressure, manifold pressure, temperature and injector to injector variations like e.g. the spring force. For injector closing there is a similar effect. The electromagnetic field needs some time to dissipate, so a dead time occurs. Dead time plus flight time of

the needle lead to the delay dtclosing, which elapses until the injector is completely closed. For full-lift spring compression the injected amount of fuel is proportional to the opening duration (topen). The nonlinearities due to the flight times need to be compensated via the overall opening duration (topen) or for small actuation times (ti) by additional calibration.

System Test Bench

The system test bench is a hardware in the loop test bench. In order to represent the behavior of the target system as good as possible, four injectors are directly actuated by use of an off-the-shelf Bosch ECU. [Figure 4](#) gives an overview of the complete setup. The test bench is controlled by a Labview application. It is possible to adjust the fuel pressure and temperature automatically. A data acquisition system from National Instruments is used to measure the needle lift (laser vibrometer), voltage and current signals with 2MHz as well as pressure of the fuel. Furthermore the fuel flow can be measured by means of Coriolis measurement devices.

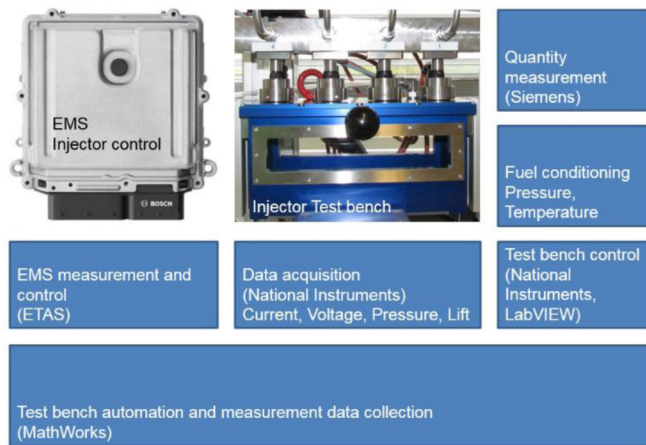


Figure 4. Overview of system test bench

Thanks to the high precision measurement instrumentation and the high level of automation the system test bench provides a very good development environment. It is used to gain a deep understanding of the component package, which includes the injector, the EMS and the software. Furthermore all our functions are pre-calibrated and validated on the test bench.

Simulation Model

The simulation model of our injector is composed of a hydraulic part and an electromagnetic part. It is possible to analyze influences on the magnetic behavior, while getting the resulting theoretical change in fuel metering accuracy simultaneously. [Figure 5](#) gives an overview of the model.

The model allows a fast sensitivity analysis regarding parameter variations and it helps to gain a very good physical understanding of our injectors. Thanks to the model e.g. the magnetic force, which is not measurable on the component, can be analyzed in detail. As a result the model is a very important tool for hardware as well as for functional (software) development.

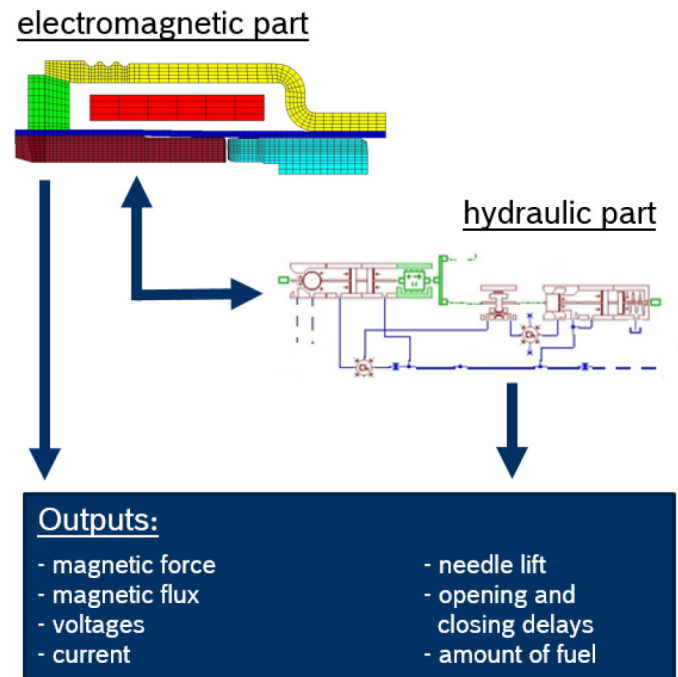


Figure 5. Structure of simulation model

Functions for Controlled Valve Operation (CVO)

CVO for advanced fuel metering is based on an adjustment of the opening duration (topen) of the injector. Hence the first step is the determination of topen, which is defined as following:

$$topen = ti - dtopening + dtclosing \quad (1)$$

The definition of the different time periods can be found in [figure 3](#). Since the actuation time ti is known, the opening and closing delays dtopening and dtclosing need to be identified.

CVO Features for Opening and Closing Delays

The introduced fuel injector is a direct current solenoid with linear armature movement. According to [3] and [4] the dynamic behavior of such a dc solenoid with a mechanical degree of freedom x can be described by the following set of differential equations:

$$u = iR + \frac{d\psi(i, x)}{dt} \quad (2)$$

$$m\ddot{x} + (k\dot{x} + F_{fric} \text{sign}(\dot{x})) + (c_{spring}x + F_{spring0}) = F_{mag}(x, i) \quad (3)$$

$$F_{mag}(x, i) = \frac{\partial}{\partial x} \int_0^i \psi(x, i) di \quad (4)$$