

Experimental and Numerical Assessment of Multi-Event Injection Strategies in a Solenoid Common-Rail Injector

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ABSTRACT

Nowadays, injection rate shaping and multi-pilot events can help to improve fuel efficiency, combustion noise and pollutant emissions in diesel engine, providing high flexibility in the shape of the injection that allows combustion process control. Different strategies can be used in order to obtain the required flexibility in the rate, such as very close pilot injections with almost zero Dwell Time or boot shaped injections with optional pilot injections. Modern Common-Rail Fuel Injection Systems (FIS) should be able to provide these innovative patterns to control the combustion phases intensity for optimal tradeoff between fuel consumption and emission levels.

In this work, a 1D-CFD model in GT-SUITE of a solenoid ballistic Common-Rail injector was firstly refined respect to the previous work [1] and then it was validated against an extensive experimental dataset of single injections, standard double pilot and multi-pilot injection patterns (up to 4 pilot events) with almost zero dwell time between two consecutive injection events. The experimental hydraulic test data used to validate the one-dimensional model were obtained by means of the UniPG Injection Analyzer based on the Zeuch's method.

The comparison between the experimental and simulated volumetric injection rates showed a more than satisfactory accuracy of the model in predicting the actual behavior of the ballistic injector for all the injection patterns tested, even for relatively complex injector command strategies, characterized by reduced Dwell Time values between consecutive injection events.

CITATION: Piano, A., Boccardo, G., Millo, F., Cavicchi, A. et al., "Experimental and Numerical Assessment of Multi-Event Injection Strategies in a Solenoid Common-Rail Injector," *SAE Int. J. Engines* 10(4):2017, doi:10.4271/2017-24-0012.

INTRODUCTION

In Compression Ignition Direct Injection (CIDI) engines the Fuel Injection System (FIS), and in particular the injector itself, plays a key role in the optimization of the combustion process, in order to maximize the power output and reduce fuel consumption and pollutant emissions. The NO_x and soot emissions represent the major concern for the modern Diesel Common-Rail (CR) engine both for the current legislation, i.e. Euro6 with NEDC (New European Driving Cycle) and WLTC (Worldwide harmonized Light duty Test Cycle) cycles, and for the future required standards such as RDE (Real Driving Emissions) [2].

Multi-injection strategies, i.e. more than one actuation of the injector during the engine cycle, were studied since the introduction of the CR technology with electro-actuated injectors. Such a system, thanks to the capability to decouple the injection pressure and injection timing

from the engine speed, supported by the high dynamic response of CR injectors has allowed splitting the fuel quantity in multiple injection events [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16].

The effectiveness of the pilot injection in reducing the combustion noise and the NO_x production was demonstrated in several studies [3, 4, 5]. The pilot injection shortens the ignition delay of the following fuel injection and thus reduces the quantity of premixed combustion phase. The result is a smoother cylinder pressure rise and lower peak temperatures, reducing noise and NO_x. In addition, a well-calibrated pilot injection improves the soot-NO_x trade-off [6].

The first generation of CR injectors was limited to two injections per cycle and the minimum allowed Dwell Time (DT) was very long (about 1800 μs) [7]. The introduction of the second generation of solenoid injectors led to an improved dynamic response, in fact

pressure levels and more precise fuel delivery [8, 9, 10]. In particular, the improved dynamics of the new injectors allowed overcoming the pilot+main strategy toward more complex patterns.

A three-injection pattern was proved to reduce the smoke by oxidizing the previously produced soot by means of an after injection, without increasing the NO_x formation [11].

A further development of the multi-injection was splitting the main injection in three close events (pre, main, after), maintaining the possibility of managing pilot and post injections, for an injection pattern up to five pulses [12,13]. The pre injection is useful to modulate the ROHR (Rate Of Heat Release) and control the cylinder pressure, while the after injection lengthens the combustion in order to oxidize the soot and the post injections are used during the particulate filter regeneration [14].

Even more advanced strategies consist in the injection rate shaping, i.e. modulating the instantaneous flow rate in order to obtain the optimum profile for the better consumption-emission trade-off [15,16]. This rate modulation, although is very promising in terms of emission control, is very difficult to obtain with traditional solenoid injectors, while can be performed with direct actuation piezo-injectors that permit the direct control of the needle lift. The piezo injectors are characterized by very high performances in terms of dynamic response (from 0.4 to 0.1 ms of delay between electric and hydraulic start of injection) [17,18]; however, they are very expensive and the solenoid injector still represents the most spread solution for Diesel CR engines.

The development of the CR injectors is nowadays oriented to improved dynamic response, lower minimum DTs, reduced static leakage, and increased injection pressure [19,20].

A significant development is represented by the pressure balanced pilot valve, characterized by a smaller leakage area and shorter anchor lift [21]. Thanks to these features, it ensures a very limited static leakage and an improved dynamic response, with the capability to be actuated with DT shorter than 0.3 ms.

Operating the engine with multi-injection strategies represents an exponential growth in terms of parameters to calibrate in order to optimize the engine output. Each single injection parameter, Energizing Time (ET) and DT, has to be calibrated in order to fully exploit the multi-injection potential. In this scenario the numerical approach is very useful in the aim of reducing the number of the experiments. Once a model is validated, it can be used in a predictive way to explore different operation strategies for the injector model, reducing time and costs related.

In this paper, a 1D-CFD numerical model in a commercially available software GT-SUITE, of a pressure-balanced CR injector is proposed as a validation extension of a previous work reported in [1]. In the

first work a basic validation was proposed, particularly focused on single injections. Since the results showed a good agreement with the experimental reference values, the model was tested with advanced multi-injection strategies, up to 5 consecutive events, and with very short DTs. The numerical results were validated with experimental injection rate curves acquired at the Perugia University proprietary test bench. The tested multi-injection patterns are very challenging for the model in terms of capability to capture the injector dynamic behavior. Although, the results are satisfactory and show a good response even in very close injections. After that, the potential of the Genetic Algorithm (GA) in the GT-SUITE optimizer was evaluated in order to calibrate a 1D-CFD injector model.

EXPERIMENTAL TEST

Injection Analyzer

The data set used to validate the numerical model was acquired at the Perugia University SprayLab by means of a proprietary injection rate meter. This device, working according to the Zeuch method [22], measures the injection rate by detecting the pressure rise in a closed volume determined by the injection event. The pressure increment ΔP in the measuring chamber is proportional to the injected volume ΔV according to equation (1). By time deriving the (1), the injection rate IR can be evaluated from (2).

$$\Delta P = \frac{k}{V_0} \Delta V \quad (1)$$

$$IR = \frac{dV}{dt} = \frac{V_0}{k} \frac{dP}{dt} \quad (2)$$

While the chamber volume V_0 is constant, the fuel bulk modulus k varies with temperature and pressure. In order to calibrate the instrument over different operating conditions, the fuel volume discharged from the chamber (base pressure = 50 bar) after each injection event flows through a Coriolis mass flow meter (Siemens Sitrans CF 2100, accuracy $\pm 0.5\%$ of the actual reading in the range 0.1-4 kg/h). The mean injected mass was measured and the instrument constant (V/k) adjusted in such a way that the injection rate time-integral equals the mean injected mass. In a multi-injection pattern, the injection rate meter is able to detect each injection event and evaluate the partial contribute to the total injected mass and the relative shot-to-shot dispersion [23].

The analyzed injector, mounted on the injection rate meter, is fed by a complete FIS composed by an automotive high pressure pump, driven by an electric motor (equivalent engine speed = 2100 rpm), the piping and the CR, reproducing the actual engine lay-out. The injection is phased with respect to the pump TDC (Top Dead Center) like in engine operation. The rail pressure is regulated by means of a metering valve modulating the pump inlet, controlled in PWM

strategy by a PID regulator. The rail temperature is set at $40 \pm 1^\circ \text{C}$ by a self-developed heat exchanger where the rail is placed into a chamber filled with thermo-regulated oil.

For each tested condition, determined by the rail pressure level and the injection command parameters (n ET values and $n-1$ DT values) the injector, after a proper warm-up, is operated for 300 consecutive shots and the dynamic quantities (injector driving current, injector pipe pressure and injection rate) are acquired at 100 kHz. The signals are then filtered, except the current, with an 8 kHz low-pass Bessel filter and averaged, computing the shot-to-shot dispersion. Back-leak pressure and temperature, fuel temperature upstream the injector and measuring chamber temperature are measured as average value during the 300 shots. These measured parameters, were used as input of the numerical model in order to accurately reproduce the experimental settings.

Dataset

The experimental activity was carried out in order to investigate the solenoid injector behavior with unconventional driving strategies for obtaining the injection rate shape. This analysis was performed by means of the STS injection analyzer measuring the instantaneous injection rate and the total injected volume, needed for the validation of a 1D-CFD model.

The experimental campaign was carried out at 2 different rail pressure values (400 bar and 1000 bar) for selected injected volumes for each injection event. The operating conditions in [Figure 1](#) were used to assess the injection system hydraulic behavior with ISO 4113 test fluid. For each of the predefined operating conditions, the following quantities were measured:

- Mean and individual injected volumes, enabling the shot-to-shot dispersion analysis, mean system temperatures, pressures and the current V/k ;
- Mean and individual time-histories of injector current, injector inlet pressure and injection rate.

In this software configuration, the Injection Analyzer could operate with up to 5 injection events, with the injection strategy defined by 9 parameters (5 ETs and 4 DTs). The Injection Analyzer operates according to the following global procedure: firstly, the system is warmed-up until the target temperature and pressure levels are reached; then, for each of the operating conditions, the injection strategy is set and executed for a given number of cycle (in this analysis 250 cycles). After a local warm-up (50 cycles), for a given number of consecutive cycles the previous quantities are acquired and recorded.

The injector operation was investigated with the injection control strategies shown in [Figure 1](#).

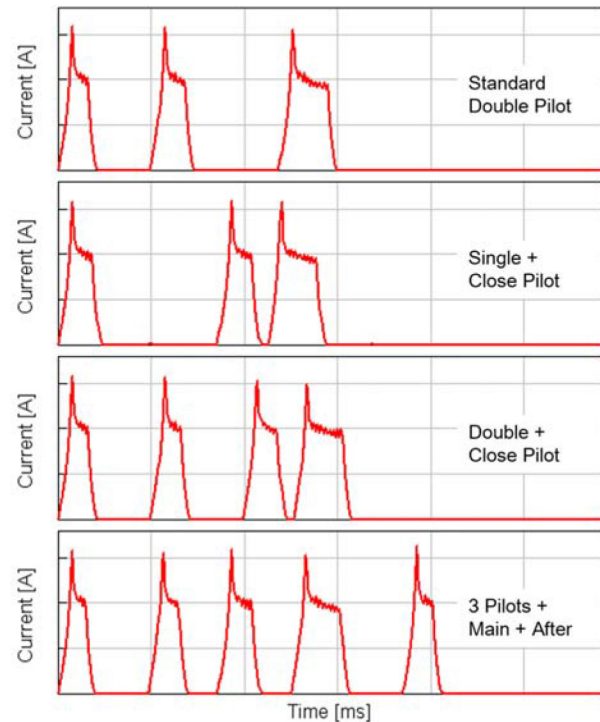


Figure 1. Current injection operation investigated.

INJECTOR MODEL VALIDATION

The model built in [1] was validated against an extensive experimental dataset of close double pilot and multi-pilot injection patterns (up to 4 pilot events) with almost zero dwell time between two consecutive injection events. In the next paragraphs, the results will be shown.

[Figure 2](#) and [Figure 3](#) show the results in terms of comparison between experimental and simulated injection rate for standard double pilot strategy. The accuracy with which the model predicts the injection rate confirms that the injector dynamic is fully captured. The model is able to predict the correct timing and to capture the pulse to pulse interaction at 2 different rail pressure levels.

[Figure 4](#), [5](#), [6](#), and [7](#) show the close pilot effect with single or double pilot injection results. As in the previous case, the accuracy in the prediction of the injection profile is more than satisfactory for both the rail pressure levels (400 bar and 1000 bar).

Also for the multi-pilot patterns ([Figure 8](#) and [Figure 9](#)) the comparison between the experimental and simulated volumetric injection rates shows a more the satisfactory accuracy of the model in predicting the actual behavior of the ballistic injector even with injection strategies characterized by reduced DT values between consecutive events.

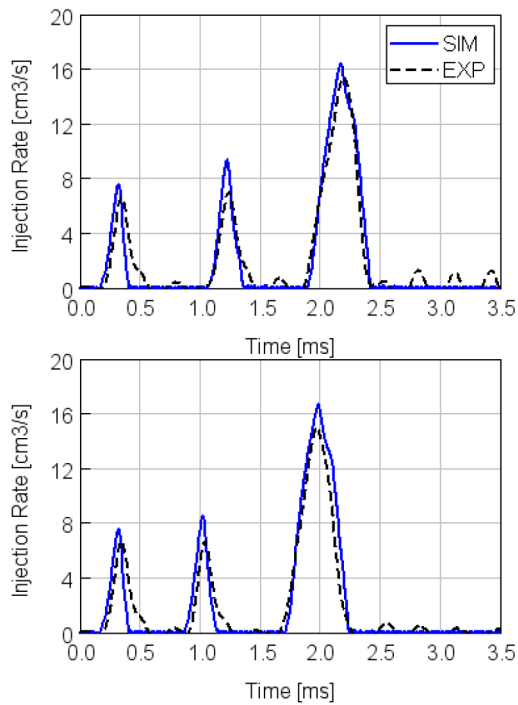
Standard Double Pilot Strategy**Rail Pressure = 400 bar**

Figure 2. Experimental (black dashed) and simulated (blue solid) injection rates for standard double pilot strategy at rail pressure equal to 400 bar

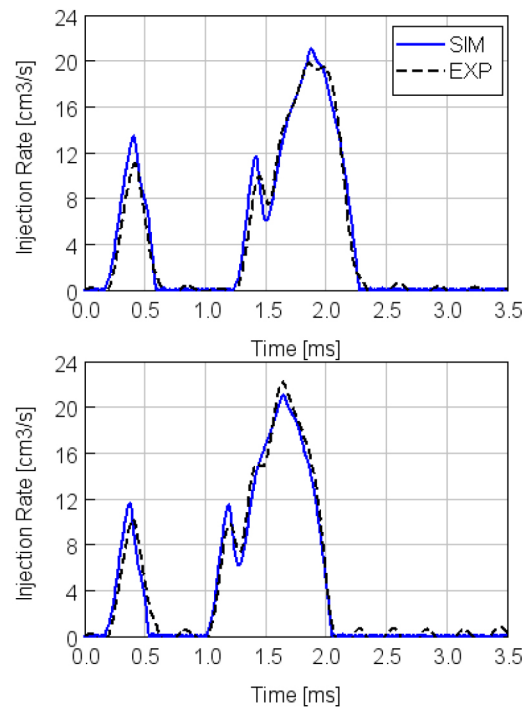
Single + Close Pilot Strategy**Rail Pressure = 400 bar**

Figure 4. Experimental (black dashed) and simulated (blue solid) injection rates for single + close pilot strategy at rail pressure equal to 400 bar

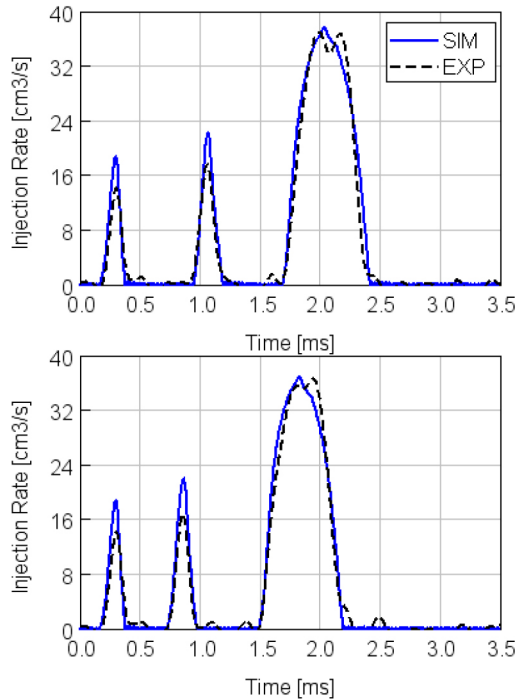
Rail Pressure = 1000 bar

Figure 3. Experimental (black dashed) and simulated (blue solid) injection rates for standard double pilot strategy at rail pressure equal to 1000 bar

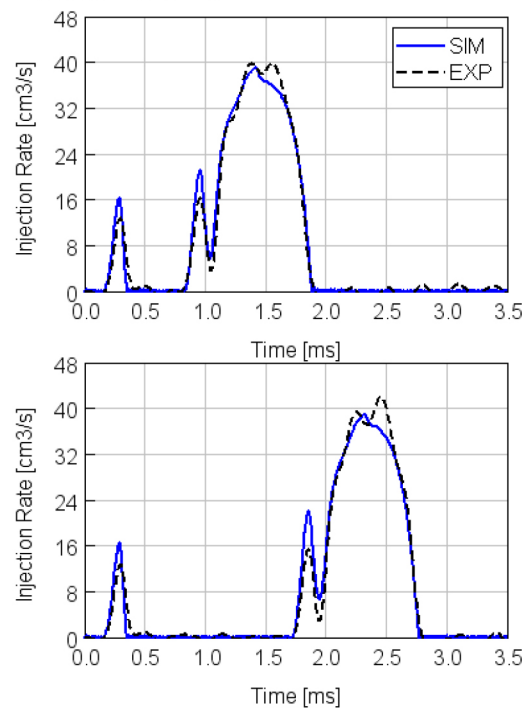
Rail Pressure = 1000 bar

Figure 5. Experimental (black dashed) and simulated (blue solid) injection rates for single + close pilot strategy at rail pressure equal to 1000 bar