

Numerical and Experimental Assessment of a Solenoid Common-Rail Injector Operation with Advanced Injection Strategies

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ABSTRACT

The selection and tuning of the Fuel Injection System (FIS) are among the most critical tasks for the automotive diesel engine design engineers. In fact, the injection strongly affects the combustion phenomena through which controlling a wide range of related issues such as pollutant emissions, combustion noise and fuel efficiency becomes feasible. In the scope of the engine design optimization, the simulation is an efficient tool in order to both predict the key performance parameters of the FIS, and to reduce the amount of experiments needed to reach the final product configuration.

In this work a complete characterization of a solenoid ballistic injector for a Light-Duty Common Rail system was therefore implemented in a commercially available one-dimensional computational software called GT-SUITE. The main phenomena governing the injector operation were simulated by means of three sub-models (electro-magnetic, hydraulic and mechanical).

The model was validated using experimental data obtained by a Zeuch's method injection analyzer. To this end, the experimental injection rate profiles and injected volumes along with rail pressure profiles were acquired in several multi-event injector operation strategies pertaining to different engine operating conditions, typical of the NEDC operation. The use of different Energizing Time (ET) and Dwell Time (DT) values allowed the evaluation of the injector potential in applying advanced actuation strategies and the assessment of the model capability to simulate the injection system operation in challenging operating conditions such as close injection events.

CITATION: Piano, A., Millo, F., Postrioti, L., Biscontini, G. et al., "Numerical and Experimental Assessment of a Solenoid Common-Rail Injector Operation with Advanced Injection Strategies," *SAE Int. J. Engines* 9(1):2016, doi:10.4271/2016-01-0563.

INTRODUCTION

The fuel injection apparatus is a key sub-system for direct-injected internal combustion engines as its operation controls to a large extent both the mixture formation and the combustion processes. In particular, in compression ignition engines the fuel metering accuracy, the required injection rate time-profile and the uniform fuel spray spreading in the combustion chamber are strictly governed by the injection system behavior. The achievement of these complex tasks is mandatory in order to fulfill the current automotive market design targets in terms of fuel conversion efficiency, combustion noise control and pollutant emissions level. [1], [2], [3], [4].

In the last years the injection systems design has been continuously developed in order to allow the application of complex, multi-event injection strategies so as to gain a better control of the fuel injection rate time-profile, which is the most effective approach to control the

combustion process development in Diesel engines. The application of injection strategies based on reduced dwell-time, multi events and/or on the modulation of the fuel discharge rate in the single event enabled significant improvements in the combustion control capabilities with respect to first-generation, common rail injection systems. The injection system ability to actuate complex strategies is largely based on an improved injector dynamic response, which in turn allows lower dwell-times; obviously, the injector dynamic characteristics are realistically exploitable only if the system shot-to-shot repeatability in terms of fuel metering and injection rate is preserved, along with the prescribed jet-to-jet evolution uniformity. [5].

In this scenario, the introduction of ballistic common-rail injectors, in which the needle lift is not limited by a mechanical stop but is determined by the system hydraulics and the needle inertia, is a

significant step in the development of fast-response systems. Given the improved capabilities of this last generation common-rail systems, the need of both experimental and numerical tools assisting the injection system tuning process is even higher than in the recent past. [6]. The huge amount of potentially interesting injection and combustion strategies requires validated and robust numerical tools simulating both the injection and combustion systems operation, possibly in a coupled numerical environment, in order to reduce the number of experimental tests at the hydraulic and engine test benches.

In the frame of a medium term research program aiming at the development of a comprehensive numerical tool to simulate both the injection system and the engine operation, a numerical 1-D model of a solenoid, ballistic injector was built and validated in the GT-SUITE environment. The injector model was validated by means of experimental data acquired by a Zeuch's Method-based Injection Analyzer. [7], [8], [9].

As the present research final goal is developing a design tool for the Fuel Injection System (FIS) operating in part load conditions typical of the NEDC cycle, the injection system 1-D model was developed and tuned focusing on complex injection strategies. As a matter of fact, although several papers are present in literature concerning the development of 1-D models for Diesel injectors, unfortunately only partial validations of such models are generally presented: the reported validations are often carried out for relatively long injection events, which are only moderately interesting for the implementation of advanced, multi-event injection strategies currently used for automotive applications.

The injection system was operated in several multi-injection strategies, at different rail pressure values. The results obtained at the hydraulic bench (injection rate profiles and rail pressure profiles) were used to tune the 1-D injector model, obtaining a satisfactory accuracy of the predicted injection rate profiles also with complex, reduced dwell-time actuation strategies.

EXPERIMENTAL FACILITIES

As it is described in the introduction section, the goal of this work is the model building and calibration of a commercial second generation solenoid common-rail injector and, then, the validation against the experimentally measured mass flow rate and total quantity injected data.

Since in order to validate the 1-D injector model, in addition to all the main geometric characteristics of the injector, experimental hydraulic data are required mainly in terms of rail pressure time history and solenoid current profile (inputs to the model) and injection rate curve (to be compared with the model main output). The experimental facilities which were exploited to this end will be described in detail in next paragraphs.

Internal Geometry

The detection of the internal geometry of the injector is needed to obtain a good geometric characterization. Nozzle, Z-hole and A-hole are the critical parts of the injector where cavitation can appear and, consequently, a precise detection has to be done. In literature, the

most used technique for the evaluation of geometric parameters, consists of the use of special silicone to obtain a mold of the physical part. Then, using a Scanning Electron Microscope, pictures are obtained and processed by means of CAD software. [10], [11], [12].

In this work a different methodology was adopted: more specifically, a 3D Computed Tomography (CT) of the injector was carried out. This technique is nowadays among the most advanced available in the industry; CT is a completely nondestructive and noncontact method for obtaining three-dimensional representation of the scanned object both externally and internally. A CT scanner consists of an x-ray emitting source, a positioning system, a detector and electronic and computational devices for data acquisition and elaboration. The principles are described below: radiographic images of the part are acquired from different angles; then, combining together all the acquired images, a virtual slice through the part is reconstructed. When different consecutive slices are computed, a 3D visualization is obtained. The reason why it was decided to use this technique is that it has many advantages with respect to traditional dimensional measuring systems, especially in terms of reduced measuring time, including scanning, reconstruction and analysis time. [13], [14]. An example of the images of the injector obtained through CT is reported in Figure 1.

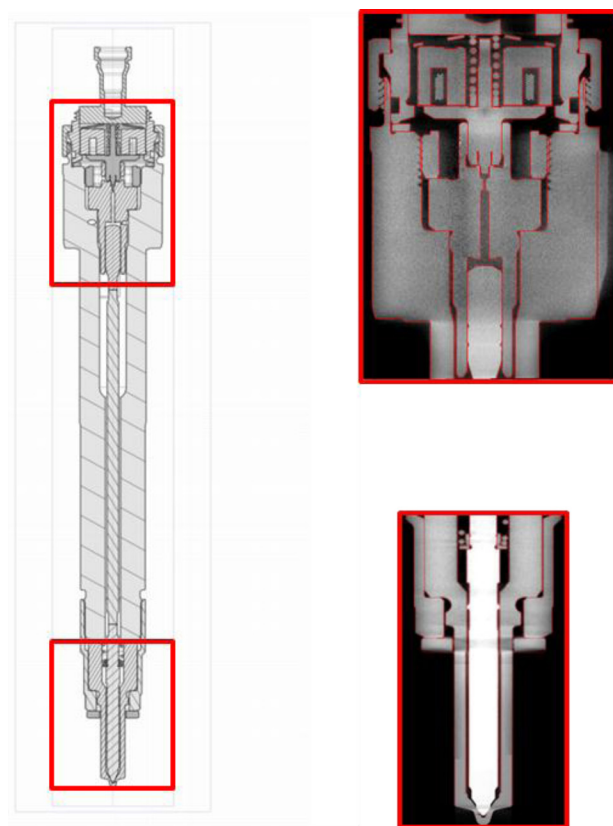


Figure 1. Computed Tomography of the injector: from scan to CAD 3D

Injection Analyzer

The experimental hydraulic data used to tune and validate the GT-SUITE 1-D model of the solenoid injector were obtained at Perugia University SprayLab by a proprietary SprayLab Injection Analyzer. This instrument is designed to simultaneously measure

both the global injected volume and the injection rate time history (along with other dynamic signals such as rail pressure, injector current, needle lift) in a given operating condition. The operating condition is defined by the rail pressure level and by the injector actuation strategy, based on $2n-1$ parameters (with n ET values and $n-1$ DT values); the instrument can vary any of the $2n-1$ parameters to analyze the system behavior. The mean injected volume and the dynamic signals are acquired in the same batch of consecutive injection events, allowing both the mean behavior and the shot-to-shot dispersion evaluation. In case of multi-injections strategy, the injected volume from the single injection events can also be derived.

The injection rate measurement by the STS Injection Analyzer is based on the Zeuch's Method, *i.e.* the injection in a closed, fixed-volume chamber filled with the same injected fluid. At the injection occurrence, the injected volume ΔV is forced to enter the measuring chamber, in which before the injection event the P_{base} level (50 bar in this campaign) is maintained, causing its pressure to rise according to Equation 1:

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

where k is the fluid Bulk Modulus and V is the measuring chamber volume. Differentiating Equation 1 allows the injection rate evaluation:

$$\dot{Q} = \frac{dV}{dt} = \frac{V}{k} \frac{dP}{dt} \quad (2)$$

The pressure history in the measuring chamber, along with the fluid temperature, is detected by a piezo-resistive sensor (Kistler 4075 A100). At the end of each injector actuation cycle, the globally injected volume is evacuated from the measurement chamber by a fast acting solenoid valve in order to re-set the P_{base} pressure level for the next injection cycle. The fluid escaping the Injection Analyzer 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) to measure the mean injected mass and the fuel density over an assigned set of injector actuation cycles. Further, the mass flow meter allows a continuous instrument calibration overcoming the difficulties in determining the fluid bulk modulus in the actual operating conditions. More details about the STS Injection Analyzer are reported in [15], [16], [17].

The rail supply was provided by a CPIH Bosch pump driven by an electric motor, with a transmission ratio set to simulate a 2100 engine rpm operation. A pickup on the pump shaft triggered the pulse train generation for the injection system, with an injection phasing to the pump TDC analogous to the engine operation. The rail pressure is set by a two-way, PWM-modulated inlet metering valve controlled by a self-developed PID strategy. In stand-by (no injection) conditions, a rail pressure ripple within the minimum between 2% of the set point and 10 bar was obtained. The rail was submerged in an oil-heated vessel so as to regulate the fuel temperature in the rail-injector pipe @40 $\pm$ 1 °C with all the injection pressure levels and injection strategies. The used fluid for the experimental test is a commercial,

ISO4113 compliant Diesel pump test fluid [18]. The same standard test fluid has been selected from the GT-Suite database for the numerical simulations.

COMPUTATIONAL INJECTOR MODEL DESCRIPTION

GT-SUITE is a simulation tool for design and analysis of engine and vehicle system and components [19]. It is capable of modeling the coupled behavior of hydraulic and mechanical components, and it is also able to study steady-state and transient response. GT-SUITE is based on one-dimensional, compressible, unsteady fluid dynamics and multi-body dynamics. Moreover, flow and heat transfer in the piping and volumes can be modeled, as well as mass dynamics. As it can be seen in the next sections, the flow solver includes models for cavitation, frequency dependent friction, species transport and non-equilibrium aeration everywhere in the system. [20].

Electromagnetic Valve

The solenoid model is built from electric and magnetic primitives representing the electromagnetic system: a current source, a coil, radial and axial magnetic components, and the air gap between the solenoid and armature. The main geometrical characteristics of the solenoid valve components are reported in Table 1.

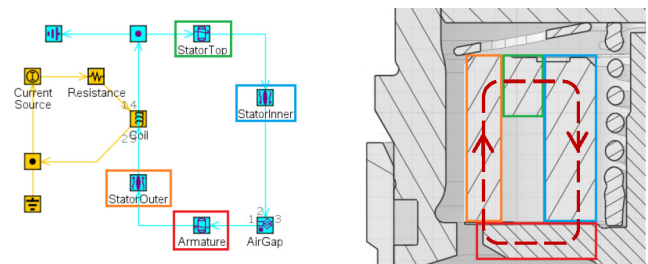


Figure 2. Electromagnetic valve model

Table 1. Geometrical and electrical parameters for electromagnetic valve

Element	Number of turns	Number of layers	Coil diameter
[-]	[-]	[-]	[mm]
Coil	40	4	0.25
Element	Length	Inner Diameter	Outer Diameter
[-]	[mm]	[mm]	[mm]
Stator top	2.84	9.68	13.80
Armature	1.65	4.76	15.50
Element	Length	Cross-sectional area	
[-]	[mm]	[mm ²]	
Stator inner	7.57	55.79	
Stator outer	7.57	135.15	
Element	Gap	Cross-sectional area	
[-]	[mm]	[mm ²]	
Air gap	0.03	31.82	

The model solves for the magnetic flux induced by current in the coil. This flux passes through the magnetic circuit, generating a force on the armature according to the flux and air gap, as shown in [Figure 2](#), where the flux is represented by a dashed red line.

Control Valve

The performance of a servo driven injector is mainly ruled by the control valve, typically a solenoid actuated valve. The fluid-structure interaction of the valve is modeled using the 1D mechanic library and some fluid-mechanical sub-models or templates (FMT). Starting from the Bosch CRI 2.5 model on, a new generation of valve called 'pressure-balanced' has been introduced. With the 'pressure-balanced' valve it is possible to increase rail pressure without increasing at the same time the spring's preload, the magnetic force and the static leakage [21]. Because of its layout, the pressure-balanced valves have a sealing seat-diameter three times higher than the standard ones. To get the same flow area of the standard valve these valves have a reduced stroke-end thereby improving the injection performances. The valve-seat region was modeled by two fluid mechanical templates with opposed pressure forces. Two different templates were used to model correctly the valve-seat region of the valve. More specifically, a "FluidPiston" template was used to model the interaction between flow and mechanical system, while a "FlapperValve" template was used to calculate the change in flow area as a function of the lift of the poppet, the pressure force on the poppet and the redistribution of the attached volumes. For the latter, a linear variation of the pressure acting in the flapper seat area was assumed. The net hydraulic force acting on the armature results from the difference between the flapper valve's diameter and the fluid piston's diameter. This difference of diameters generates a total force which is consistent with the values found in literature [21]. The flapper valve template also defines the flow area as a function of the armature's lift.

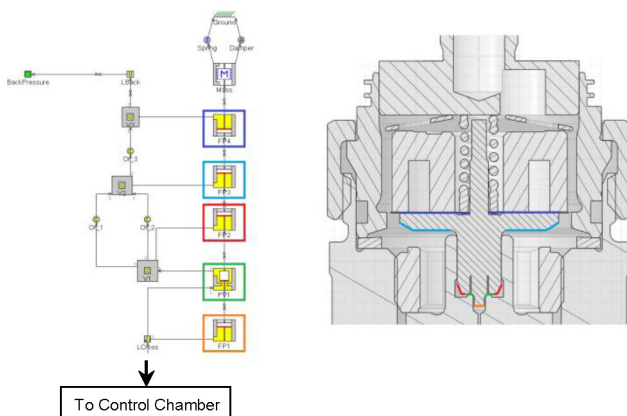


Figure 3. Control valve model

In order to model the armature's movement accurately it has been necessary to simulate both all the pressure surfaces of the armature and the fuel path across the pilot valve.

Control Chamber

As known, the needle motion results from an imbalance of the pressure forces acting on the needle. This imbalance results from a reduction of the pressure in the control chamber which is initiated by opening the control valve. When the control valve is opened, fuel drains from the high pressure at the inlet of the injector, through the inlet orifice into the control chamber, and through the outlet orifice to the low pressure downstream of the control valve. Once the control valve is fully open, the design of these orifices has a significant impact on the pressure in the control chamber and therefore the imbalance of forces on the needle. The large pressure drop across these orifices can cause cavitation so care is required to investigate the flow through them.

The geometry of the inlet and outlet holes strongly affects the dynamic behavior of the needle. As a result, the control volume orifice of the injector need to be hydraulically characterized. An example of a possible experimental setup for the characterization of the flow through these controlling orifices was proposed by Salvador et al. [9].

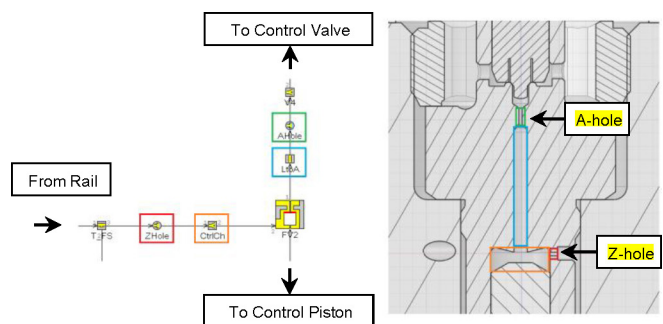


Figure 4. Control chamber model - Inlet and outlet holes

Z-Hole

The Computed Tomography of the injector shows a conical section of the orifice. In this case, the sub-model adopted to evaluate the discharge coefficient of the inlet orifice, does not consider the cavitation phenomenon. This hypothesis is consistent with hydraulic characterization made by Salvador et al., where the mass flow rate has a linear behavior with the square root of the pressure [10].

The value of the maximum discharge coefficient is related to the orifice geometry and it can be defined by the mass conservation equation:

$$C_d = \frac{\dot{m}_f}{A_0 \sqrt{2 \cdot \rho_f \cdot \Delta p}} \quad (3)$$

Where $\dot{m}_f$ is the fuel mass flow rate, A_0 is the geometric area of the orifice, ρ_f is the fuel density and Δp is the difference between upstream and downstream pressure.