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Fractional-Order Modeling of High-Pressure Fluid-Dynamic Flows: An Automotive Application

Paolo Lino * **Guido Maione** * **Fabrizio Saponaro** *

* *Dipartimento di Ingegneria Elettrica e dell'Informazione, Politecnico di Bari, Bari, 70125 Italy (e-mail: {paolo.lino,guido.maione}@poliba.it, saponaro.fab@gmail.com)*

Abstract: Performance of internal combustion engines is strictly affected by the metering of the air/fuel mixture. Achieving accuracy in metering is difficult due to the complex fluid-dynamics of the fuel injection process. However, injection control can benefit from appropriate models describing the process dynamics. To this aim, this work develops a mathematical model of the common rail diesel electro-injector. Fractional-order modeling of pressure wave propagation in the pipes is investigated with respect to the integer order modeling approach. A comparison between simulation and experimental results validates the fractional-order model, that also shows better prediction capabilities than an integer-order model. Then the proposed model is suitable for mechanical optimization of the injector and for deriving fuel rate shaping strategies.

Keywords: Fractional-order modeling, fractional-order partial differential equations, diesel engines, injection systems, fuel injection control, irrational operators, automotive control.

1. INTRODUCTION

The automotive industry has financed, analyzed, and built new vehicles and engine systems to cope with severe requirements posed by international regulations to decrease the environmental pollution. Electric, hybrid, or gas-powered vehicles allow reducing the consumption of traditionally employed fuel (diesel or gasoline) and the emission of polluting gases (CO, NOx, HC, particulate matter). Moreover, conventional diesel engines were improved by advancements of the common rail (CR) technology to increase efficiency of the combustion process and of the engine, then to decrease pollutant emissions. In this context, electro-injectors can be designed and realized to improve the injection process and its model-based control. To this aim, an accurate representation is necessary for the nonlinear fuel dynamics and for the mechanical deformation of relevant parts of electro-injectors. The model should be accurate enough to identify faults, analyze different configurations and functional layouts, but also it should allow easy implementation of control algorithms.

However, the dynamic performance of the engine must be satisfactory. Then, a trade-off between the conflicting objectives of efficiency and performance must be reached. To this aim, current trend is to accurately meter the air/fuel stoichiometric ratio (Stumpp and Ricco, 1996). In particular, two strategies exist for CR injection systems: first, the injection timing is accurately controlled by operating on the opening time intervals of electro-injectors; second, the CR pressure is maintained uniform and constant at required operation levels (Lino and Maione, 2013b,a, 2014). In both cases an electronic control unit (ECU) determines the levels of reference rail pressure and opening time intervals of the injectors.

Given the previous considerations, this work proposes new results in modeling electro-injectors by fractional-order partial differential equations. The area of fractional calculus is older than three centuries, but applications in control systems engineering only grew up in the last decades. Differentiation and integration of non-integer order allowed to better represent processes with long-range dependencies, power laws, long-term memory effects (Oldham and Spanier, 1974; Samko et al., 1993; Podlubny, 1999a; Mainardi, 2010; Monje et al., 2010; Tenreiro Machado et al., Mar. 2011). One popular application is the analysis and prediction of diffusion process in semi-infinite media and thermal systems (Oldham and Spanier, 1974; Mainardi, 1996; Battaglia et al., 2001; Gabano and Poinot, 2011a,b). In control systems, the first inspiring results were achieved by early and seminal works (Bode, 1945; Tustin, 1958; Manabe, 1961). More recently, different approaches to non-integer (fractional) order modeling and control were proposed (Oustaloup, 1991; Podlubny, 1999b; Chen, 2006; Chen et al., 2009; Monje et al., 2010; Caponetto et al., 2010; Luo and Chen, 2012). Basically, fractional operators can be beneficial for many control loops that take advantage of important properties for robustness and dynamic performance. Namely, many control design procedures based on the frequency response allow us to easily achieve a nearly flat phase diagram in a sufficiently wide frequency range around the gain crossover frequency, which indicates a robust behavior to parameter variations.

There also exist some applications to combustion engines (Moze et al., 2010; Colin et al., 2011; Lino and Maione, 2013b,a, 2014) but accurate fractional-order models have not yet been developed for fluid-dynamic phenomena in injection systems, but for an initial study (Saponaro et al., 2014b). Then, this paper investigates fractional-

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order modeling of pressure wave propagation in the common rail and pipes of diesel injection systems.

Section 2 describes the CR injection system under investigation, by specifying the system configuration with the main components, the operation and control problem, and the electro-injector. Section 3 gives a mathematical model of the electro-injector. Section 4 explains how a fractional-order model can be obtained to describe the propagation of fuel wave pressure. Section 5 presents simulation results to validate the model by comparison with real data. Finally, some remarks are given in Section 6.

2. THE COMMON RAIL INJECTION SYSTEM

A classical CR diesel injection system includes a low pressure circuit and a high pressure circuit. A scheme is shown in Fig. 1. In the low pressure circuit, a pump draws fuel from the tank to feed it to the high pressure circuit. In this last circuit, a high pressure pump sends the fuel through a discharge valve to the common rail (CR), which is an accumulation volume directly connected to the electro-injectors. An electronic controlled solenoid valve is placed on the CR to regulate its pressure by drawing an appropriate amount of fuel towards the low pressure circuit. The electro-injectors ultimately control the amount of fuel injected into the combustion chamber. The main purpose is to provide a proper shape of the injected flow rate for the fuel metering.

2.1 The electro-injector

The electro-injector consists of a control circuit and a feeding circuit (see Fig. 1). The first includes a control chamber, which is fed by the CR through the Z-hole, and sends the fuel to a low pressure circuit through the A-hole, whose section can be changed by an electro-hydraulic valve. The feeding circuit includes a constant accumulation volume, that receives fuel from the CR through an annular pipe, and feeds a small SAC (from French ‘cul-de-sac’, i.e. dead-end) volume at the end of the flow path, where the injector nozzles are symmetrically located.

A plunger-needle element lies between the control and feeding circuits to regulate the injection flow. If the needle moves up (to the right in low part of Fig. 1), the accumulation volume is connected to the SAC and the fuel outflows through nozzles. Since the plunger-needle lift depends on the difference between pressures in the control chamber and in the accumulation volume, it is possible to open (close) the injector by properly reducing (increasing) the first pressure. This can be done by acting on the electro-hydraulic valve that regulates the flow section between the control chamber and low-pressure circuit: if the valve is closed, the pressure on the top face of the plunger is almost equal to the rail pressure, and the needle-plunger element is pushed down; if the valve opens, the pressure in the control chamber diminishes and the needle-plunger element is pushed up.

3. MATHEMATICAL MODEL OF THE ELECTRO-INJECTOR

Modeling is achieved by dividing the electro-injector into different control volumes. The continuity equation, the momentum equation, and the Newton’s second law of motion are employed to build each subsystem model, resulting in lumped or distributed parameters representations. In the former case, each control volume has a uniform, time-varying, pressure distribution, described by a set of ordinary differential equations (ODEs). Moreover, the fluid dynamic phenomena due to the propagation of pressure waves are neglected. In the latter case, a time-varying and nonuniform pressure distribution in the control volume yields a set of partial differential equations, where pressure wave propagation is properly represented. Since a constant fuel temperature is assumed in the whole system, the dynamics is completely defined by the pressure variations in each volume. The model inputs are the boundary conditions and the valve driving signals, while outputs are the displacements of moving parts, the pressures in control volumes, the instantaneous volumetric flow rates.

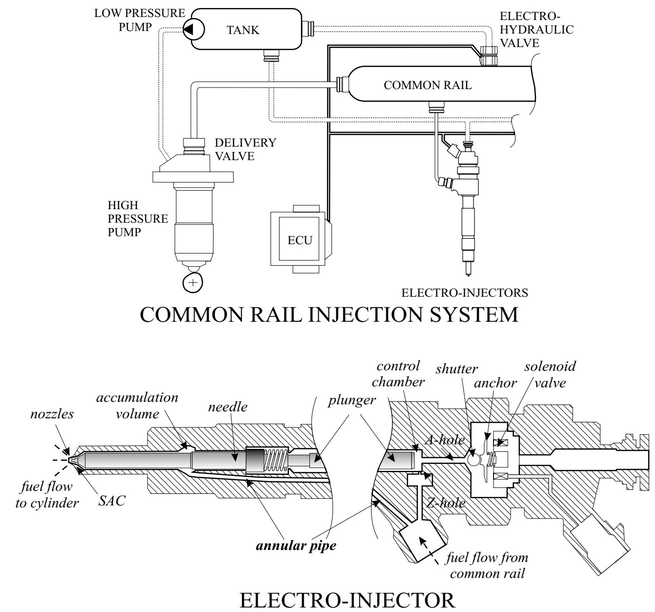

Fig. 1. The electro-injector in a CR injection system

3.1 Lumped parameters hydraulic model

As for large accumulation volumes, a lumped parameters representation is used (see (Saponaro et al., 2014a) for details). The continuity law, the conservation of momentum equations, and the Newton’s second law provide a set of ODEs to describe the fuel pressure dynamics inside each control volume. The fuel is assumed compressible with a Bulk modulus $K_f = 1.2 \cdot 10^4 \cdot [1 + P \cdot 10^{-3}]$, with P being the chamber instantaneous fuel pressure ($K_f = 12.000$ bar in standard operating conditions) (Lino et al., 2005).

For a generic control volume, it holds:

$$\frac{dP}{dt} = -\frac{K_f}{V}\left(\frac{dV}{dt} - Q_{leak} + \sum_i Q_i\right) \tag{1}$$

where the algebraic sum of intake and outtake flow rates is considered and fluid volume V changes also because mechanical elements move. Then the pressure in each control volume is computed by using the given flow rates, instantaneous volumes, and initial conditions. In particular, flow rates derive from the momentum equation (Lino et al., 2005):