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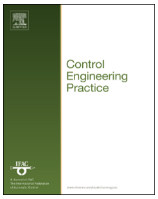

Dynamic surface control of a piezoelectric fuel injector during rate shaping

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ABSTRACT

Fuel injection rate shaping is a strategy to improve fuel efficiency and reduce harmful emissions in diesel engines. Due to their fast response, piezoelectric fuel injectors are capable of rate shaping operation. This paper describes a model-based closed-loop controller of injection flow rate for a piezoelectric fuel injector. This within-an-engine-cycle control strategy utilizes a dynamic surface control scheme and shows an injection flow rate tracking capability. Practical issues with LabVIEW FPGA control implementation are also addressed. The performance of the controller is verified with simulation and experimental results at different rail pressures and desired injection rates. The experiments show a maximum error of total fuel per one injection event of 2.5%. A stability analysis is also included.

1. Introduction

Compared with solenoid actuated fuel injectors, piezoelectrically actuated injectors have a higher bandwidth, which allows for the delivery of more complex injection rate profiles, examples including tightly spaced pulse trains and rate shaping. In prior efforts including one of the co-authors, a model-based engine-cycle-to-cycle control strategy for tightly spaced pulses was developed (Satkoski, Ruikar, Biggs, & Shaver, 2012). On the other hand, the effort outlined here is focused on within-an-engine-cycle control of rate shaping. Injection rate shaping reduces overall fuel consumption and improves the trade-off between NOx and particulate matter emissions (Kohketsu, Tanabe, & Mori, 2000; Rottmann, Menne, Pischinger, Luckhchoura, & Peters, 2009). A boot shape injection profile (Fig. 1), an example of rate shaping, includes a “toe” and a “shank”. Tanabe, Kohketsu, and Nakayama (2005) showed optimum injection rate shapes for each operating condition of a heavy duty DI diesel engine where boot shape injection rate is optimum at high load, medium speed. Rate shaping injection can be achieved using various techniques. Rajagopalan and Shinogle (2000) used a piezoelectric fuel injector with open-loop control to produce rate shaped injections. In Kohketsu et al. (2000), a system with two common rails was used to create rate shaped injection profiles. In Yan (2011), a position sensor was installed to estimate fueling rate for the purpose of closed-loop injection rate control and failure diagnosis. In Wu and Sun (2013), a novel injector design was outlined which can enable rate shaping by utilizing an internal feedback mechanism.

Among different rate shapes, a boot shape is most challenging since the injection rate is very sensitive to needle displacement during the toe portion of the profile (Le, Shen, Ruikar, & Shaver, 2014). As described in this paper, in order to deliver desired boot shape injection rate profiles, a model-based closed-loop control strategy was developed and experimentally validated. Specifically, this paper describes and experimentally demonstrates a dynamic surface control (DSC). While backstepping is a flexible strategy for controlling nonlinear systems, it suffers from the issue of “explosion of terms” due to the high relative degree of the model (Swaroop, Hedrick, Yip, & Gerdes, 2000). Instead of analytically calculating the virtual control derivatives as in backstepping, dynamic surface control uses first-order low-pass filters to approximate the derivatives numerically. As such, DSC requires less computational effort (Yip & Hedrick, 1998). In addition, DSC is capable of attenuating high frequency measurement noise as a result of the approximation of derivatives via low-pass filters (as will be demonstrated in Section 4 for the piezoelectric fuel injector). The strategy of numerical derivatives can use different forms of low-pass filters such as the linear and nonlinear second-order low-pass filters in Farrell, Polycarpou, Sharma, and Dong (2009) and Yoon, Kim, and Park (2012), respectively. Song, Hedrick, and Howell (2002) used convex optimization for selecting the controller gains. However, in this paper, the gains and the time constants of the linear first-order low-pass filters are tuned experimentally.

Novel contributions outlined in this paper include (i) the model-based development of an algorithm for “within-an-engine-cycle” control of fuel injection rate shaping with a piezoelectric fuel injector, (ii) a model-based stability analysis, (iii) validation in simulation, and (iv) experimental validation via algorithm implementation with an

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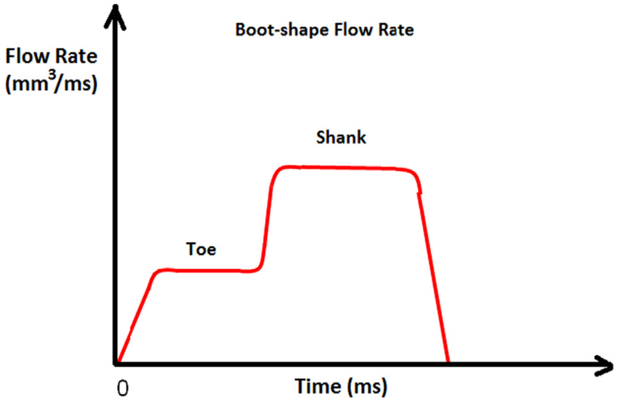

Fig. 1. Boot shape fuel injection flow rate.

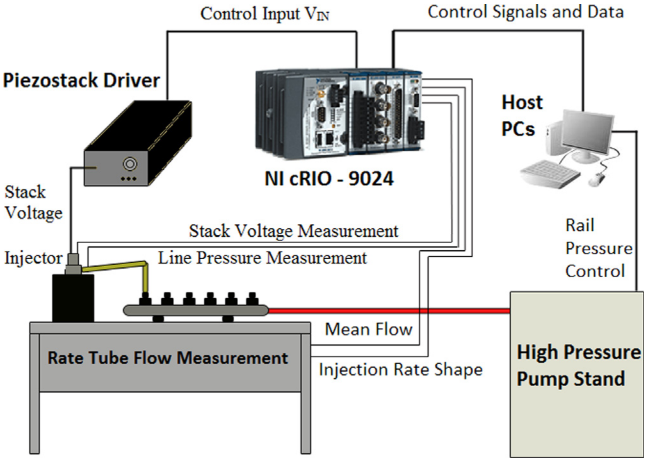

Fig. 2. Experimental setup.

FPGA. These contributions incorporate a dynamic nonlinear model and a real-time injection flow rate estimation strategy developed by several of the authors in prior efforts (Le et al., 2014; Shen et al., 2013).

2. Experimental setup

The experimental setup is shown in Fig. 2. A high pressure pump is used to provide pressurized fuel to the piezoelectric fuel injector. The host PCs are used for data logging and communication with the Engine Control Module to control rail pressure. Real-time data acquisition (DAQ) and control are implemented with an NI CompactRIO FPGA system. The NI CompactRIO sends a control signal to a QorTek piezostack driver, and receives measurements of line pressure, piezostack voltage, mean flow rate, and injection rate shape. The DAQ is run with a sampling frequency of 500 kHz and an analog 200 kHz anti-aliasing filter, while the driver has an update period of 10.24 µs. The injection flow rate measurement system (Fig. 3), described in detail in Satkoski et al. (2011), utilizes a Bosch (1966) rate-tube approach.

3. Reduced-order model of injector

3.1. Injector operating principle

Fig. 4 shows a schematic diagram of the piezoelectric fuel injector. When the driver applies a voltage across the piezostack, the stack expands and forces the shim and the plungers down. The trapped volume pressure is then increased, causing the needle to open and allow injection to occur. When the driver stops applying voltage, the piezostack, the shim, and the plungers retract under the pressure forces. Therefore, the trapped volume pressure is decreased, resulting in closing the nozzle and stopping the injection.

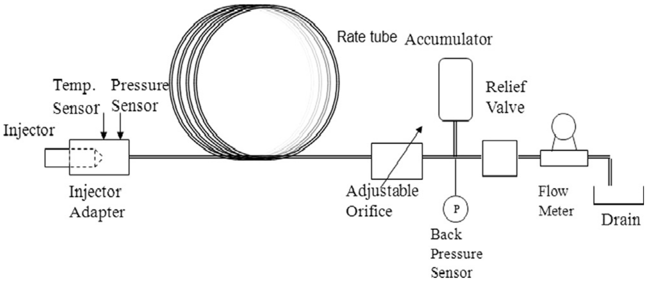

Fig. 3. Injection flow rate measurement setup.

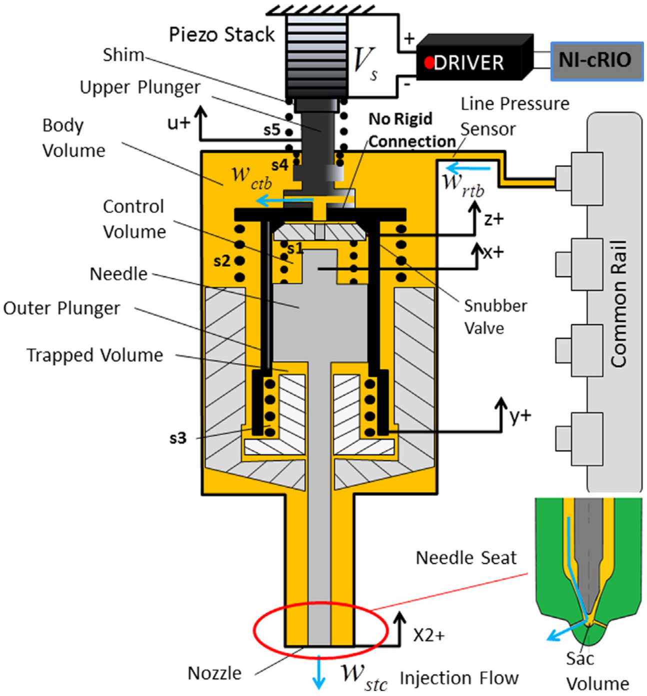

Fig. 4. Injector schematic.

The model briefly outlined below and used for control design and stability analysis in this paper is based on a reduced-order model described in Shen, Ruikar, Le, and Shaver (2013), which was simplified from more detailed "simulation model" originally outlined in Le et al. (2014).

3.2. Piezostack, shim, and plunger dynamics

The piezostack, shim, and plungers are lumped into a mass M with spring constant k as in the dynamic equation of motion:

$$M\ddot{y} = PL_{tot} - (k_{tot}+k)y - b_1\dot{y} + A_{bv}P_{bv} + A_{obot}P_{tv} - f(V_s) \tag{1}$$

where $y, PL_{tot}, k_{tot}, b_1, A, P_{tv}, f(V_s)$ are the displacement, total preload, total stiffness of the springs, damping ratio, areas of the injector parts, trapped volume pressure, piezostack force, respectively (descriptions of all the variables, subscripts, and parameters are summarized in Table A1 in the Appendix). Note that the control volume pressure, which acts on the outer plunger and the needle as illustrated in Fig. 4, is assumed to be equal to the