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Iterative learning control of a fully flexible valve actuation system for non-throttled engine load control

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ABSTRACT

This paper presents the application of a fully flexible valve actuation system for non-throttled load control of an internal combustion engine. A novel camless valve actuation system with a unique hydro-mechanical internal feedback mechanism which simplifies the external control design is first introduced. All the critical parameters describing the engine valve event, i.e., lift, timing, duration and seating velocity, can be continuously varied by controlling the triggering timings of three two-state valves. Initial testing of a prototype experimental setup reveals that the performance of the system (transient tracking and steady-state variability) is influenced purely by the state of the system when the internal feedback mechanism is activated. This feature motivates the development of a cycle-to-cycle learning-based external control for activating the internal feedback mechanism based on the desired valve profile characteristics and the system state. To verify the proposed control methodology, it is implemented on the experimental system to track reference trajectories for the various valve event parameters corresponding to the non-throttled load control of an engine during the U.S. Federal Test Procedure (FTP) urban driving cycle. Vehicle load demand analysis is used to compute the desired engine speed and torque requirements. Detailed dynamic valve flow simulations assuming full flexibility of the engine valve event parameters help to calculate the required trajectory of all these parameters to satisfy the speed and torque requirements without the use of a throttle. The experimental results show that the proposed framework, i.e., the valve actuation system and the external control methodology, is able to provide excellent performance even during the most aggressive transient operating conditions.

1. Introduction

Internal combustion engines (ICEs) are the preferred power source for many applications, including automobiles, locomotives, ships, and electric generators, due to their power density and the high energy density of the hydrocarbon fuels they typically burn. Concerns associated with ICEs include greenhouse gas emissions, chemical and particulate pollutant emissions, and the dwindling supply of fossil fuels. Thus, there is a strong motivation to increase the efficiency of the ICE.

One main source of efficiency loss in the spark-ignition (SI) ICE is pumping loss, caused by how its load (energy output) is typically controlled. An SI engine usually must operate near chemically correct (stoichiometric) air–fuel ratios due to combustion stability and emissions requirements. Decreasing the energy output of an SI engine requires decreasing the amount of fuel introduced into the cylinder for each engine cycle, and thus requires decreasing the amount of air introduced into the cylinder as well (to maintain near-stoichiometric operation). In the vast majority of such engines, this is accomplished by the use of a throttle valve, which decreases the pressure, and thus density, of the air delivered to the engine. This, in turn, causes pumping losses, because the engine must accept fresh charge at a low pressure and reject exhaust at a higher (near-atmospheric) pressure. This pumping loss is shown as the shaded area in the idealized pressure–volume indicator diagram, zoomed in to focus on the exhaust and intake strokes, presented in Fig. 1. Here, TDC and BDC refer to the piston's top- and bottom-dead center positions, respectively, p_e and p_i refer to the exhaust and intake pressures, respectively, and p_{atm} is atmospheric pressure. Note that p_i is significantly lower than p_{atm}.

Controlling the load of the engine without using the throttle valve could significantly reduce this pumping loss, as the intake pressure would be very nearly equal to atmospheric pressure. Reducing the pumping loss would lead to an increase in the engine's thermal efficiency (defined as the useful work output of the engine divided by the energy content of the fuel used to produce that work). This concept is referred to as non-throttled load control (NTLC). Several implementations of NTLC have been proposed, and will be briefly reviewed.

One way to reduce pumping losses is to relax the requirement that a stoichiometric air-fuel ratio be maintained. This would allow the intake of a full cylinder volume of air, adjusting the

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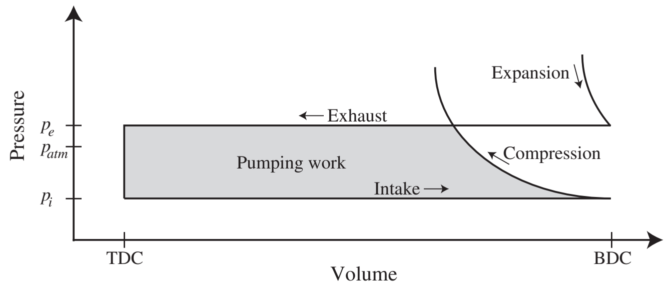

Fig. 1. Schematic indicator diagram showing pumping work (shaded).

amount of fuel introduced to the cylinder to control the load of the engine. Diesel (Stone, 1999), stratified-charge SI (Flierl & Klüting, 2000; Stone, 1999), homogeneous-charge compression ignition (HCCI) (Milovanovic, Chen, & Turner, 2004), and jet ignition (Boretti & Watson, 2009) are all methods for NTLC that work under this principal.

Another way to realize NTLC is to regulate the amount of air introduced to the cylinder by cutting off the intake completely at an appropriate point. This maintains a stoichiometric air–fuel ratio while maintaining the intake near atmospheric pressure. Several methods have been used to close off the intake. An additional rotary (Ueda, Sakai, Iso, & Sasaki, 1996) or poppet (Vogel, Roussopoulos, Guzzella, & Czekaj, 1996) valve can be installed in each intake runner and shut to cutoff intake air. The majority of intake-cutoff NTLC implementations, however, utilize variable valve actuation to control the intake valve to regulate the amount of air introduced into the cylinder, which fall into two main categories. In late intake-valve closing (LIVC) (Tuttle, 1980), the intake valve is kept open past BDC of the intake stroke. As the piston begins to return toward the TDC position, it will expel some fresh charge back into the intake manifold until the intake valve closes to trap an amount of fresh charge in the cylinder. In early intake-valve closing (EIVC) (Tuttle, 1982), the intake valve is closed before the piston reaches BDC of the intake stroke.

To implement EIVC or LIVC in a production engine, a mechanism for varying the intake valve timing is needed. NTLC has been implemented using cam-based variable-valve actuation mechanisms (Boretti, 2010; Flierl & Klüting, 2000; Flierl, Schmitt, & Hannibal, 2009). However, the use of the camshaft imposes limits on the range of variability of lift and phasing, and makes independent duration adjustment difficult. These systems also exhibit increasing mechanical complexity with increasing flexibility.

Fully flexible valve actuation (FFVA) or "camless" systems allow independent and continuous variation of the valve event parameters (lift, timing, and duration) over a wide range. Most FFVA implementations use either electro-mechanical (Flierl & Klüting, 2000), electro-pneumatic (Ma, Zhu, & Schock, 2011), or electro-hydraulic (Sun & Kuo, 2010) actuation. Ashhab, Stephanopoulou, Cook, and Levin (1998) presents simulation results demonstrating the use of a model-based controller to determine valve event parameters for non-throttled load control of a camless engine. In addition to NTLC, FFVA systems also facilitate additional benefits, such as cylinder deactivation (Fujiwara, Kumagai, Segawa, Sato, & Tamura, 2008), changing the engine's effective compression ratio via LIVC and EIVC strategies (Milovanovic et al., 2004; Picron, Postel, Nicot, & Durrieu, 2008), and the control of HCCI (Caton, Song, Kaahaaina, & Edwards, 2005; Milovanovic et al., 2004). A more rigorous discussion on the benefits of flexibility in valve actuation can be found in Flierl and Klüting (2000), Fujiwara et al. (2008), Picron et al. (2008), Turner, Bassett, Pearson, Pitcher, and Douglas (2004), Milovanovic et al. (2004) and Caton et al. (2005).

The removal of the mechanical linkage between the valves and the crankshaft demands reliable, real-time control of the valve position by the engine computer to ensure proper operation. Most previous FFVA implementations, for example Hoffmann, Peterson, and Stefanopoulou (2003), Sun and Kuo (2010), and Ma et al. (2011), are based on the use of complex feedback controllers to monitor the valve's position in real time and calculate the appropriate control action for the actuator. This approach demands accurate, low-noise position sensors and powerful microprocessors to enable low-latency, real-time calculation of the control effort. In addition, accurate and high-bandwidth actuators are needed to control the valve to the desired position at high engine speeds. As such, this strategy may be expensive and difficult to implement on a production engine.

A production-oriented camless FFVA system is required to operate with the same level of accuracy and repeatability when compared to existing cam-based systems to ensure proper engine operation and to avoid piston-valve interference (Picron et al., 2008; Sun, 2009). Such a system is also required to be relatively inexpensive to manufacture while having a sufficient bandwidth to allow high-speed engine operation. The control system to ensure accurate valve positioning, repeatability, and robustness to disturbances must be suited for mass production; i.e., it should use control algorithms capable of operating on the engine's control unit with a relatively low computational burden, low-cost sensors, and should require minimum calibration.

This paper presents the control design for a production-oriented FFVA system based on a hydro-mechanical internal feedback system (IFS) (Gillella & Sun, 2011; Sun, 2005, 2009). It was observed that, for a given physical design of the system, its trajectory and consequently the performance parameters corresponding to the engine valve event (lift, timing, duration and seating velocity) are dependent only on the initial state of the IFS, which can be modified in real time by adjusting the timing of simple two-state valves. However, the initial state of the IFS corresponding to the optimal performance varies with system operating conditions, thus making the use of a calibration-based open-loop controller intractable. This motivates the development of an iterative-learning-based controller capable of modifying the initial state by adjusting the timing of the activation/deactivation of the internal feedback loop to achieve the required performance objectives.

The system performance parameters need to be evaluated only once at the end of each cycle. This relaxes the demand for noise-free position sensors and also decreases the computational burden. The control inputs (time at which the IFS is engaged) need to be computed only once at the start of each engine cycle. The engine valves will be open for about one-fourth to one-third of the engine's 720-crank-angle-degree (CAD) cycle. This reduces the required real-time processing capability, as the actions for the next valve event can be calculated after the current event during the remaining time (approximately 360–480 CAD).

The rest of the paper is organized as follows. A brief description of the system design and operation is first presented. This helps identify some of the performance characteristics and the corresponding control challenges. It is followed by the development of a control strategy to address each of these challenges. Next, a framework is developed to go from a desired driving cycle to calculate the desired engine speed and load and intake valve lift and duration traces. The final section presents the implementation of the proposed controller on a prototype experimental non-firing setup to demonstrate its effectiveness in tracking the desired valve event parameters while maintaining acceptable seating velocity.

2. Electro-hydraulic valve actuation system with internal feedback

The concept of a new production-oriented FFVA system based on the internal feedback mechanism was first presented