

Iterative Learning Control for a Fully Flexible Valve Actuation in a Test Cell

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ABSTRACT

An iterative learning control (ILC) algorithm has been developed for a test cell electro-hydraulic, fully flexible valve actuation system to track valve lift profile under steady-state and transient operation. A dynamic model of the plant was obtained from experimental data to design and verify the ILC algorithm. The ILC is implemented in a prototype controller. The learned control input for two different lift profiles can be used for engine transient tests. Simulation and bench test are conducted to verify the effectiveness and robustness of this approach. The simple structure of the ILC in implementation and low cost in computation are other crucial factors to recommend the ILC. It does not totally depend on the system model during the design procedure. Therefore, it has relatively higher robustness to perturbation and modeling errors than other control methods for repetitive tasks.

CITATION: Wu, H., Chen, J., Li, M., Durrett, R. et al., "Iterative Learning Control for a Fully Flexible Valve Actuation in a Test Cell," *SAE Int. J. Passeng. Cars - Electron. Electr. Syst.* 5(1):2012, doi:10.4271/2012-01-0162.

INTRODUCTION

Fully flexible valve actuation (FFVA) is a key technology of next generation internal combustion engines. It is beneficial to fuel economy, emission control and drivability over the fixed geometry of a camshaft. It can also simplify engine structure by eliminating the throttle and enable advanced combustion auto-ignited (CAI) engines. Mechanical, electro-mechanical and electro-hydraulic systems have been introduced to achieve fully flexible valve actuation. BMW VALVETRONIC, for example, is a mechanical fully variable valve control system which was introduced to BMW's range of spark-ignition (SI) engines [1]. It controls the load from idle to full load instead of using a throttle. Besides improvement of fuel consumption and emission, it improves power output, engine speed capability, response, and economy. The cost, complexity, and durability of mechanical VVA, however, are not favorable. Electro-mechanical variable valve systems, such as the GM R&D electromagnetic valve actuators [2], FEV [3], Siemens [4], and Aura [5] are implemented by electromagnetic mechanism with relatively low cost. Their simple 'catch and hold'

structure introduces the difficulties in seating speed control because of the nonlinearity. The electro-hydraulic systems, such as the Ford 'camless' system [6], the Sturman system [7] and the Lotus system [8] also provide fully flexible valve event control. The electro-hydraulic systems can achieve higher lift control accuracy; but their drawback is the energy consumption and structure complexity. A new VVA system using a stiff hydro-mechanical internal-feedback mechanism is proposed in [9]. A built-in physical feedback is designed, which is activated and deactivated by two on/off valves. The concise structure can reduce the cost and it was claimed to be feasible for a mass production engine. In this paper, an FFVA system for a test cell is the focus. The main purpose of this system is to achieve accurate and repeatable valve lift for both steady-state and transients. An electro-hydraulic structure is adopted to guarantee the accuracy and repeatability.

VVA control design has become a very active research area in the past few years for the development of both laboratory systems [10, 11, 12, 13] and production engine systems [5, 8, 14, 15, 16]. From the frequency point of view,

perfect tracking requires the system to have a wide bandwidth corresponding to the spectrum of desired lift, and the bandwidth must be traded off with the noise and disturbance rejection capability. Because of the nonlinearity, non-minimum phase and time delay characteristic of practical electro-mechanical and fluid systems, system inverse-based tracking control is not applicable and generic PID control cannot meet the design criteria [17]. Usually, a feedback controller is designed to stabilize the system, and then a feed-forward compensator is designed to improve the tracking performance. Model reference control [18], repetitive control [17, 19] and iterative learning control [20] are employed to utilize input information and the engine cyclic characteristics to achieve better tracking performance. Among them, repetitive control has been extensively investigated for laboratory VVA system [17]. With a periodic signal generator, it can asymptotically track a periodic reference signal with high accuracy based on the internal model principle. Perfect tracking is reported from experimental data. But repetitive control is a model based method. The controller structure and computation cost limits its robustness to modeling error and need powerful controller.

In this research, a new iterative learning control algorithm is proposed for FFVA control. The objective is to loosen the constraints to reference signal so that we can apply it to a wide range of engine speed and transient situation. The robustness and performance are investigated with simulation and hardware-in-loop test.

SYSTEM DESIGN

System Design Requirements

The FFVA controller is required to accurately track lift profiles. The operation covers engine speed from idle up to 3000 rpm. Considering the valve wear and noise, the seating speed needs to be limited to a given level. Valve opening and closing timing is controlled because of its importance in combustion investigation. Safety functions, such as collision avoidance between valves and piston, and emergency stop when tracking error exceeds tolerance limits also need to be implemented.

The valve actuation system consists of electro-hydraulic servo valves, cylinders and two intake and two exhaust valves. The actuator system moves the intake and exhaust valves from initial closed position to final closed position. The valve periodically follows the reference signal in duration and height based on crank angle. The lifting profile is the same for every intake and exhaust strokes at steady engine operating points. A typical valve lift profiles is shown in [Figure 1](#). During load transient, the valve lifting profile changes according to combustion requirement.

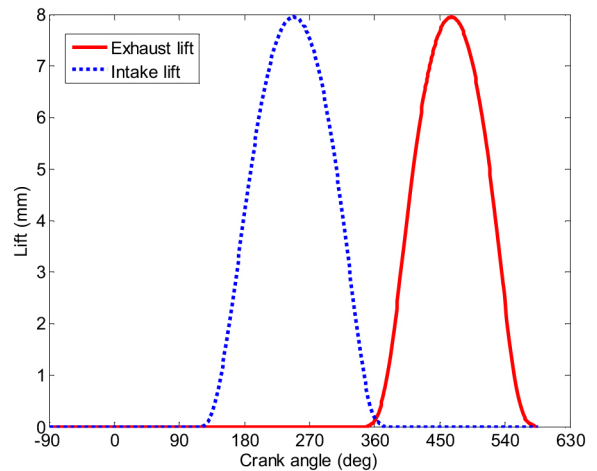


Figure 1. Typical lift profiles of intake and exhaust valve

Test Bench Setup

A test bench is set up for the FFVA system analysis, control design and verification purpose. The structure of the FFVA is summarized in [Figure 2](#). The system consists of hydraulic components, actuator components and an electronic controller, which is implemented in a dSPACE DS1103 control board. A servo current amplifier drives the torque motor of a two-stage servo valve to regulate the fluid flow, which is proportional to spool displacement. The pressure difference between the two sides of the actuator cylinder output force movement of the piston of the hydraulic actuator against the valve spring to accomplish valve lift according to the command profile. The piston rod of the actuator is separate from valve stem. It has a linear variable displacement transducer (LVDT) mounted on the other end. The low voltage conditioner (LVC) provides low distortion sine wave excitation for the LVDT and employs a synchronous demodulator to convert the LVDT's AC output signal to a DC signal proportional to core position. This position signal is fed back to the amplifier and system controller to be compared with the command profile. Meanwhile, the engine encoder generates crank angle signal to synchronize the valve lift with movement of the engine cylinder piston. During the operation, the hydraulic actuator pushes the valve downward against valve the spring to open the valve. The energy is stored in spring and later used to push the valve back just like the situation in a mechanical cam. The actuator needs to control the seating speed to avoid damage and reduce the wear and noise. Once the valve is seated, the piston rod and valve stem can be separated to ensure the valve closure. The impact between actuators and valves stem should be also considered. The system has an internal position feedback loop closed at the servo amplifier to stabilize the system, minimize the initial condition difference and sensitivity to different mechanical offsets, which are the necessary conditions to utilize the ILC.

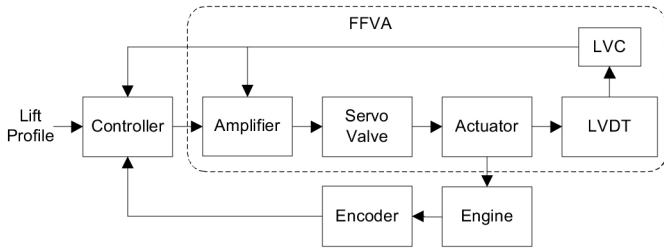


Figure 2. Schematics of FFVA system of test bench

System Modeling

To obtain the system model of the FFVA, the frequency response is measured using a swept sine signal. The system Bode diagram is plotted in Figure 3. The frequency response shows jittering behavior of the system beyond 500 Hz (3140 rad/s). The beginning of the fluctuation in both the magnitude and phase diagram is from the spring resonance, as the spring has its lowest resonance frequency around 280 - 460 Hz (1750 - 2900 rad/s). The following jump part may be from the separation between valve stem and actuator rod.

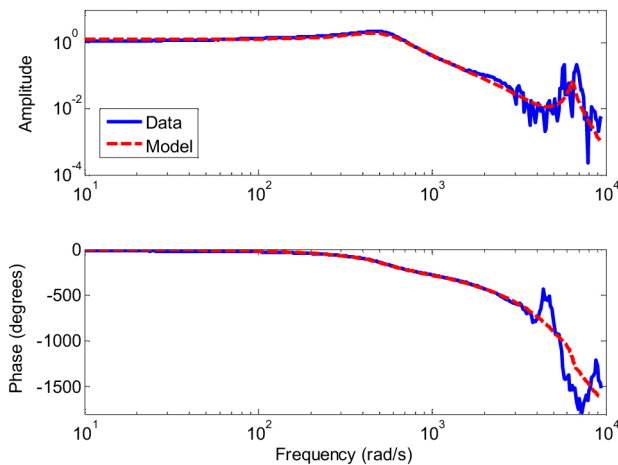


Figure 3. FFVA system frequency response

System identification is carried out with an autoregressive moving average (ARX) model

$$A(q)y(t) = B(q)u(t) + e(t) \quad (1)$$

where q is the standard shift operator. A system order of five, with a pure time delay of six samples was chosen at a sampling rate of the 3000 Hz, which is chosen to have 30 samples during system rising time of 0.01s. The system parameters are listed in Equations (2) and (3). The corresponding discrete transfer function model is given in Equation (4) and has a good fit with the original frequency response measurement data, as shown in Figure 3.

$$A(q) = 1 - 1.045q^{-1} + 0.06679q^{-2} - 0.7335q^{-3} + 0.9325q^{-4} - 0.1535q^{-5} \quad (2)$$

$$B(q) = 0.004518q^{-6} + 0.01286q^{-7} + 0.01531q^{-8} + 0.03261q^{-9} + 0.02156q^{-10} \quad (3)$$

$$\frac{y(z)}{u(z)} = z^{-6} \frac{0.004518z^4 + 0.01286z^3 + 0.01531z^2 + 0.03261z + 0.02156}{z^5 - 1.045z^4 + 0.06679z^3 - 0.7335z^2 + 0.9325z - 0.1535} \quad (4)$$

From the zeros and poles location indicated in Figure 4, the FFVA system is a non-minimum phase system with a delay of 6 samples times.

Iterative Learning Control for the FFVA

An iterative learning control (ILC) is chosen for FFVA tracking because the system is required to repeat the same operation over a finite time interval (crank angle duration). For every individual cycle, the valve starts from the same initial position, which is the closed condition and ends with the closed condition, again. The same exact sequence of lift height and opening/closing time must be followed on each cycle during engine steady-state operation. In both laboratory and production engines, steady-state operation dominates the operating condition, accompanying certain transients between two different conditions

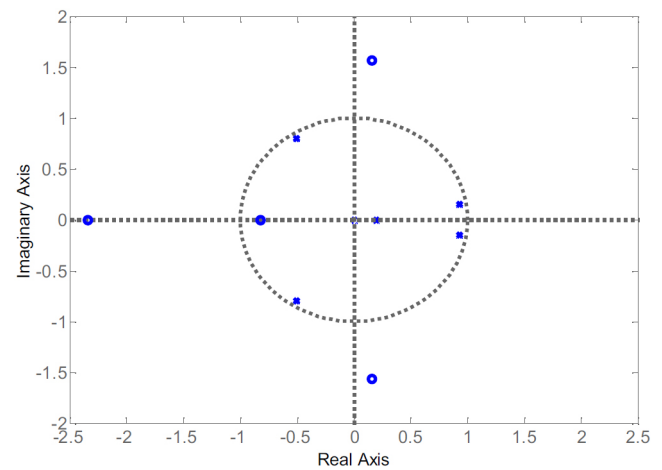


Figure 4. Pole-zero plot of FFVA

The learning and memory capability of the ILC can be utilized to improve the tracking performance while running. After a single execution of the lift control is completed (off-line or online during calibration), the input control action and output response produced are available to update the control input for the next cycle and thereby sequentially improve the tracking performance. Once the satisfied control sequences are learned, they can be stored for later recall under the same condition. Two different lift profiles can be used later for fast transient control.

The simple structure of ILC in implementation and low cost in computation are other crucial factors to recommend the ILC. It does not totally depend on the system model during design procedure. Therefore, it has relatively higher robustness to perturbation in signal and modeling errors than