

Progress in Camless Variable Valve Actuation with Two-Spring Pendulum and Electrohydraulic Latching

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ABSTRACT

Camless Variable Valve Actuation (VVA) technologies have been known for improving fuel economy, reducing emissions, and enhancing engine performance. VVA can be divided into electro-magnetic, electro-hydraulic, and electro-pneumatic actuation. A family of camless VVA designs (called LGD-VVA or Gongda-VVA) has been presented in an earlier SAE publication (SAE 2007-01-1295) that consists of a two-spring actuation, a bypass passage, and an electrohydraulic latch-release mechanism. The two-spring pendulum system is used to provide efficient conversion between the moving mass kinetic energy and the spring potential energy for reduced energy consumption and to be more robust to the operational temperature than the conventional electrohydraulic actuation; and the electrohydraulic mechanism is intended for latch-release function, energy compensation and seating velocity control. This paper presents the prototype design of a variable valve-time and two-lift LGD-VVA with bench and engine test results. The designed actuator is able to achieve 3 ms opening and closing response time with satisfactory valve seating velocity and low energy consumption. This is all achieved with a cost-effective design and open-loop control.

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INTRODUCTION

For traditional internal combustion engines, engine intake and exhaust valves operate with a fixed lift and timing and some valve systems are capable of dual-lift and variable valve timing [1, 2, 3]. Engines with Variable Valve Actuation (VVA) systems are capable of continuously variable lift and timing at any given operational condition to minimize the engine pumping loss with optimized combustion to improve engine performances in fuel economy, emissions, and torque delivery [4, 5, 6].

Engine valvetrain systems can be generally grouped into cam-based and camless. A cam-based valvetrain system is based upon the traditional cam-system to drive the engine intake and exhaust valves with limited control over valve timing and/or lift [7]. A camless system drives individual engine valve directly with electromagnetic [8, 9, 10, 11], electro-pneumatic [12-13], or electrohydraulic [14] VVA systems. Without the restriction of the cam system, a camless

system can control both valve lift and timing to achieve any desired target level that can be varied cycle-by-cycle. In addition, it provides control variations among engine valves and among engine cylinders. For example, it is able to provide asymmetric opening for two intake valves for a single cylinder, resulting in better air/fuel mixing. It can selectively deactivate one or more cylinders under low load conditions. Camless systems thus offer more control freedom and greater performance benefits.

Camless systems are the key technical enabler for 2/4-stroke-switch gasoline engine technology and air hybrid vehicles [15]. They are cost-effective with significant improvement of fuel-economy. Air hybrid vehicles have many advantages over electric hybrid vehicles. Also, a camless VVA system alone and combined with a direct injection fuel system is capable of extending the operation range of Homogenous Charge Compression Ignition (HCCI) [16]. Even high efficient diesel engines can benefit from

camless technologies in emission reduction as well as fuel economy [17].

A family of VVA systems, called LGD-VVA, was designed by LGD Technology, LLC. They consist of a two-spring actuation, a bypass passage, and an electrohydraulic latch-release mechanism. The two-spring pendulum system provides efficient conversion between the moving mass kinetic energy and the spring potential energy, and its resulting force-displacement curve is in agreement with an ideal curve needed for a sinusoidal motion. The springs, for example, are able to absorb most of the kinetic energy right before the engine valve being seated so that the snubber does not have to accommodate as much energy as in a traditional electrohydraulic VVA system. Most of the actuation energy comes from the two-spring system, which is more robust than traditional hydraulic actuation, especially under a wide range of temperatures [18]. The electrohydraulic mechanism in the LGD-VVA system is used primarily for latch-release function, and it is also flexible enough in its design to offer different levels of energy input to overcome engine cylinder pressure variations, which indicates that the LGD-VVA system can be used for actuating exhaust valves. In addition, LGD-VVA does not rely on a position sensor to perform engine valve seating control, thus reducing the cost and improving reliability.

The LGD-VVA designs include three types of lift-control: fixed-lift, two-lift, and continuously-variable-lift. The engine valve release and actuation is triggered by one switch action of a four-way directional valve, and the engine valve completes the rest of the stroke, including seating, without active control [18]. The combination of the two-spring pendulum and bypass design is able to reduce fluid flow during most of the engine valve travel, thus achieving actuator power consumption comparable to that of a conventional cam system. For instance, with 8.0 mm valve lift, up to 64% of the kinetic energy is converted to the spring potential energy before the snubber is engaged, and the energy conversion continues even after the snubber is engaged. This combination makes it possible to achieve a “short-tailed” seating without the need for closed-loop control [18].

In an earlier study described in [18], a numerical model of the LGD-VVA designs was developed and validated in simulations to demonstrate the benefits of the LGD-VVA design principle. This paper presents the prototype results of the LGD-VVA system with both bench and dynamometer tests results. And this paper mainly focuses on the two-step LGD-VVA design.

LGd-VVA DESIGNS

Basic Design Philosophy

As reported earlier in [18], LGD-VVA design is based upon a two-spring pendulum structure, widely used in electromagnetic VVA (EMVVA) technologies [10-11], with an electrohydraulic latch-release mechanism. With the help of

the two-spring pendulum actuation, the springs provide most of the actuation and efficient conversion between the potential and kinetic energy. Since the mechanical system is stable, the spring operation provides good displacement repeatability. Similar to the electromagnetic system, the LGD-VVA system reduces electrical-power consumption with the help of its electrohydraulic latch-release mechanism and stroke control mechanism; and it also provides robust valve-seating control due to its favorable force-displacement characteristics of the two-spring pendulum system. At last, the LGD-VVA system benefits from the effective energy conversion offered by its two-spring pendulum mechanism and the limited required hydraulic energy during the snubbing process, resulting in short seating duration and low seating velocity.

Two-Lift Design

The LGD-VVA family includes fixed-lift, two-lift, and continuously-variable-lift designs [18]. In the continuously-variable-lift design, the longitudinal position of the bottom of the actuator cylinder is controlled according to the target lift while the flow distribution is accomplished through a more elaborate flow port-and-circuit design to maintain proper pendulum actuation and flow bypass functions. This paper presents the two-lift design (as shown in [Figure 1](#)) and its experimental validation results. The details of its operation principle have been reported earlier in [18] through the system modeling and simulations. Briefly, the actuator consists of a piston, associated top and bottom piston rods, a hydraulic cylinder with a bypass and flow distribution mechanism that blocks external fluid flow during most of the stroke, and top and bottom springs that, together with all the moving mass, form a spring-mass pendulum driving mechanism for efficient energy conservation and consistency. The flow distribution mechanism also control fluid flow between the top of the cylinder and top port (Pt), and fluid flow between the bottom of the cylinder and the bottom port (Pb).

The actuator further includes top and bottom snubbers, each of which consists of an orifice, a check valve, and an optional relief valve. The top and bottom snubbers are designed to control the engine valve seating velocity and the opening terminal velocity, respectively. Fluid supply to the top and bottom ports are controlled by a fast-actuating main valve, a two-position four-way switch valve (not shown in [Figure 1](#)), that is in turn actuated by a pilot valve (a two-position three-way switch valve, not shown in [Figure 1](#)). Both main and pilot valves are on-off valve. Since they are neither a proportional nor a servo valve, the cost of the VVA system can be reduced significantly. One set of pilot and main valves can be used to control either one VVA actuator for one engine valve or two VVA actuators for either two intake or two exhaust valves of the same combustion cylinder. The disadvantage of using one set of pilot and main valves to control two intake or two exhaust valves is that these two valves would have to be operated in the same pattern.

The actuator also includes a spring controller, connected to the spring control port P_s , which is supplied by a spring controller switch valve (not shown in [Figure 1](#)). Depending on the system architecture or control strategy, one spring controller switch valve may control a whole bank of VVA actuators. Under no or low pressure, the top and bottom springs are under lightly compressed state, thus the moving mass is in the neutral position. The moving mass includes the piston, piston rods and the engine valve assembly; see [Figure 1](#) with the engine valve being closed. The switch action of the actuation valve (the pilot and main valves) causes the actuator to perform low-lift open and close actions; see [18] for details. Under high pressure, the top and bottom springs are under highly compressed state, thus the neutral position of the moving mass is such that the engine valve is half-way between the open and close positions. The switch action of the actuation valve causes the actuator to perform full-lift open and close actions; see [18] for details.

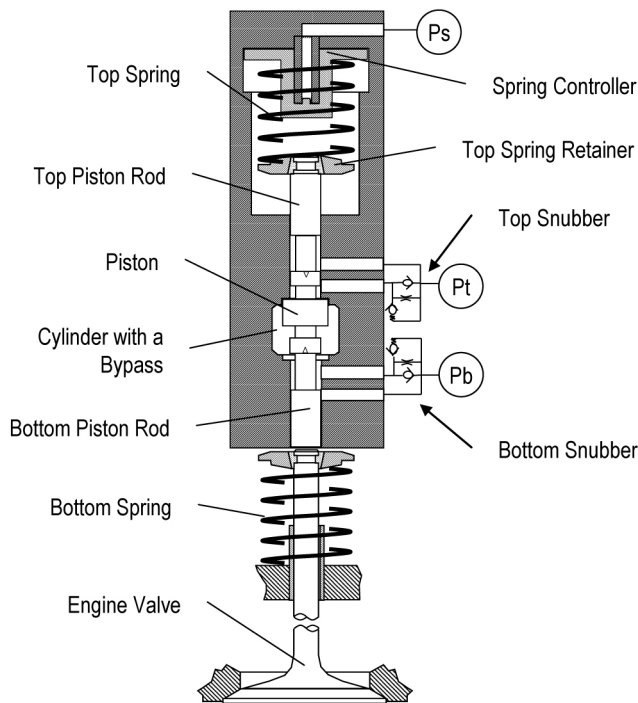


Figure 1. A Schematic of the Two-lift Design [19, 20, 21, 22]

Four generations of prototype actuators have been designed and tested, and the last two designs are noted as VS3 (as shown in [Figure 2](#)) and VS4. All of them are intended for intake valve application. One of the key differences between VS3 and VS4 is the placement of the top spring and associated spring controller. For VS4, they are placed at the top of the actuator as illustrated in [Figure 1](#). However, they were placed at the bottom of the actuator between the bottom piston rod and the bottom spring; see [18]. The key design parameters of the VS3 and VS4 are listed in [Table 1](#). To be more specific, VS3 and VS4 have a peak stroke of 10 mm and 8 mm, respectively, which is by

choice only. Each design is capable of lower or higher peak stroke value.

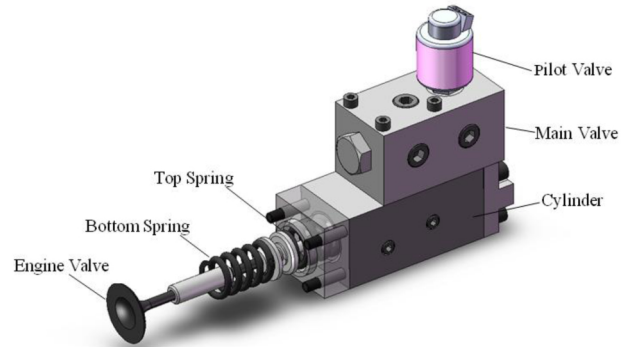


Figure 2. 3D View of the VS3 prototype

Table 1. Design Parameters

	VS3	VS4
Actuation piston diameter	11.55 mm	11.55 mm
Piston rod diameter	8 mm	8 mm
Engine valve mass	40 g	40 g
Piston and rods	33 g	26 g
Total moving mass (including spring dynamic mass)	126 g	115 g
Total effective spring stiffness	86 N/mm	76 N/mm
Natural frequency	131.5 Hz	129.4 Hz
Stroke	10 mm	8 mm

BENCH TEST RESULTS AND ANALYSIS

The bench test results described in this section were obtained on a VVA bench test system shown in [Figure 3](#), which includes a test bench with associated hydraulic fluid supply system, a clamping fixture, a set of control and data acquisition system, and a laser displacement sensor.

The engine valve displacement is measured by a Laser triangulation displacement measuring device (LTC-050-20-SA) from MTI Instruments Inc. It has a linearity of $\pm 5 \mu\text{m}$, a resolution of $\pm 2.5 \mu\text{m}$, a frequency response of 20 kHz and a sampling frequency of 40 kHz. The valve velocity and acceleration are derived from the displacement data through differentiation.

The fluid supply system is capable of regulating hydraulic fluid to a tank temperature between 0°C and 100°C . On the other hand, the test fixture is directly exposed to the room