

# Development of Continuously Variable Phase and Lift/Duration Mechanism for Widely Available Automobile Engines

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## ABSTRACT

The variable valve lift and duration (in the following: VVLD) devices, some have been mass-produced already in the world, are necessary to be assembled with the variable cam phaser (in the following: VCP) to optimize open and close valve timing. On the other hand, with the variable valve phase and lift (in the following: VVPL) mechanism, the valve event is advanced with decreasing the valve lift and duration. Hence, no additional VCP is required when using the VVPL for throttle-less operation.

A new VVPL has been developed as a mechanical, swing-cam actuation mechanism. The mechanisms of the conventional production VVLD devices are investigated and the functional analysis of the possible mechanisms is carried out to identify and design a simple mechanism for the new VVPL. The designed VVPL system is capable of continuously varying the valve lift from 0 mm to 10 mm, with the higher valve lift for any of the given duration.

CAE oriented study, conducted before the production of the prototype, predicted the unexpected problems of the system at the design stage. By the multi-body dynamic simulation, predicting the dynamic behavior of the system, the requirement for the design to obtain the stable operation in the entire operation range was clarified.

The trial manufactured VVPL was tested on the 4-cylinder test bench after the single cylinder test, and successfully operated up to 7000rpm of engine speed. The accuracy of the multi-body dynamic simulation was evaluated with the measured dynamic behavior. It was found that the high speed limitation of the system was sufficiently predicted by the multi-body simulation.

Following the functional test, the newly designed VVPL system was installed into the 4-cylinder gasoline engine and its effect on fuel efficiency was evaluated on the firing test bench. As a result, a large improvement in fuel efficiency was obtained with the developed VVPL system, as expected.

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## INTRODUCTION

A continuously variable valve lift/duration mechanism realizes throttle-less operation of gasoline engines, and improves fuel efficiency by reducing pumping loss. Especially in low load operation, improvement in the fuel

efficiency is remarkable<sup>(1)(2)(3)</sup>. Several continuous variable valve trains have been developed in the past<sup>(4)</sup>. However, the applications in engines for mass production vehicles that are equipped with such mechanisms have been limited. One reason for this is their complex mechanisms which forces the cost to be increased. Therefore, if a variable valve actuation

system can be developed at low cost, it would allow for widely available automobile engines to use this mechanism, and it would efficiently reduce the overall fuel consumption in the globe.

This paper describes the development process which includes identification of requirements, selection of the mechanism, a CAE oriented design process, and an experimental test with a prototype. Continuous variable valve lift systems without throttling enables to minimize the pumping loss for the required partial load (limited volumetric efficiency is required in the combustion chamber) via advanced timing of intake valve closing (IVC) before the piston reaches its bottom dead center. Thus, it is possible to increase the brake thermal efficiency (5).

Considering the phase of the intake valve lift events for reducing the pumping losses, intake valve opening time (IVO) should be fixed and IVC should be advanced, depending on the required lift/duration. In other words, it is desired to advance the valve lift event phase with decreasing required valve lift/duration. For that reason, VVLD mechanisms have usually been produced with VCP mechanism to enable optimal control of the intake valve event phase.

In such systems, during warm-up of the engine, it is possible to ensure stable combustion, even when the ignition timing is largely retarded to increase the exhaust temperature. It is achieved via offset intake valve lift timing for delayed opening and BDC closing. Thus the in-cylinder flow intensity is enhanced and the effective compression ratio becomes higher(5).

Furthermore, a VVPL mechanism has been developed as well. With the VVPL, because IVC is changed with the variation of valve lift/duration, throttle-less operation of the engine can be achieved without VCP. However, during the very low load region, due to the early closing of IVC, the effective compression ratio decreases and the combustion stability deteriorates. For that reason, an intake pressure has to be throttled even though the VVPL is used to obtain the required volumetric efficiency during very low load operation, in the practical usage. Here the pumping loss is inevitably increased but the combustion stability is ensured.

## SPECIAL FEATURE

In this study, while making the opening duration small with the advanced timing of the lift event, IVC is moved to very early timings and the IVO is slightly retarded, to eliminate the valve event overlap between the intake and exhaust valve. This measure could help, even in absence of a VCP, to achieve non-throttling stable combustion at very low load operation.

However, during an operation with high combustion stability, the potential of minimizing the pumping losses is sacrificed due to the elimination of valve event overlap duration by the slight IVO retard. In such a situation, by retarding the exhaust valve closing time (EVC) using the

VCP applied into the exhaust cam to provide an optimal valve overlap, the pumping losses can effectively decrease.

To investigate the effect of the valve event timing on pumping loss, a numerical simulation has been carried out using the commercial engine-cycle simulation tool GT-SUITE. A simulation model for a four cylinder 2.0 l engine was developed and simulation was carried out with an engine speed of 2000 rpm and fuel flow of 2.5kg/h (BMEP of about 200kPa).

Figure 1 shows the valve lift profiles of the four valve event configurations (spec. A-D) and a comparison of the P-V diagrams of the three configurations using continuous variable valve lift mechanisms (spec. B, C and D). In non-throttled operation with the delayed IVO configuration (spec. C), the in-cylinder flow intensity can be enhanced and the in-cylinder temperature could be increased compared with the non-throttled and simply advanced IVC configuration (spec. B). This is because the effect of its lower in-cylinder pressure during the intake process and the increased pumping loss. While there is the stable combustion margin, the pumping losses can be reduced by retarding the EVC (spec. D).

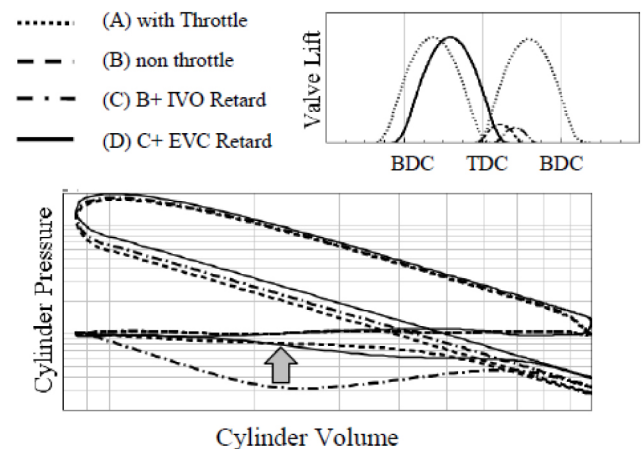


Fig.1. Low Load Pumping Loop Comparison for Variety of Valve Timings

The simulation results of fuel consumption rate and the in-cylinder temperatures of the four configurations can be seen in Table 1. The valve event configuration of spec D can recover the disadvantages in PMEP and BSFC of spec C. Also, an improvement in fuel efficiency from the spec B can be found. This is because a large amount of internal EGR could be obtained with the configuration of spec. D.

Table.1. Comparison of Fuel Consumption

| Spec.                                         | A     | B     | C     | D     |
|-----------------------------------------------|-------|-------|-------|-------|
| BMEP[kPa]                                     | 195   | 227   | 207   | 233   |
| PMEP [kPa]                                    | -68.3 | -44.8 | -61.7 | -40.6 |
| BSFC [g/kWh]                                  | 386   | 329   | 365   | 322   |
| In-Cylinder Gas Temp [K] @BTDC20deg           | 750   | 626   | 696   | 732   |
| In-Cylinder Residual Gas Fraction[mass%] @IVC | 11.6  | 9.5   | 9.5   | 20.3  |

From these results, the authors decided to develop the new VVPL system that is possible to be assembled without

VCP to achieve both the improvement in fuel economy and lower production cost. Furthermore, the special property of the variable valve train would be most suitably applied at the blow-down supercharge HCCI engine which has been examined at Chiba University and found to have a wide HCCI operating range (6).

## BASIC DESIGN

### Basic Configuration and Goal Setting

The following targets have been defined for an intake VVPL system for DOHC 4-valves gasoline engines requiring full load performance and part load fuel efficiency.

- (1). A maximum valve-lift of 10 mm, a minimum of 0 mm and a continuous variability.
- (2). A limit of the engine revolution speed is more than 7000rpm (for the 4~10 mm lift).
- (3). Appropriate phase advance (aiming at 25-50 CA) can be obtained with a decreases in the valve lift/duration.
- (4). Different valve lift/duration for each of 2 valves can be set for generating in-cylinder swirl flow.
- (5). The highest lift for any of given valve lift/duration among the VVA systems ever published can be achieved.

Hydraulic lash adjuster (in the following: HLA) and roller finger follower (in the following: RFF) are chosen as a basic configuration of the system because of their widely known advantage in the reduction of mechanical loss. For the actuation part of the system, the mechanical swing cam system has been chosen because of their advantages in terms of production cost, reliability and ease of actuation.

### Variable Mechanism for Swing Cam System

Figure 2 illustrates each type of ideal configuration of the swing cam system using RFF and HLA to understand how to obtain a simultaneous actuation of the lift/duration and phasing.

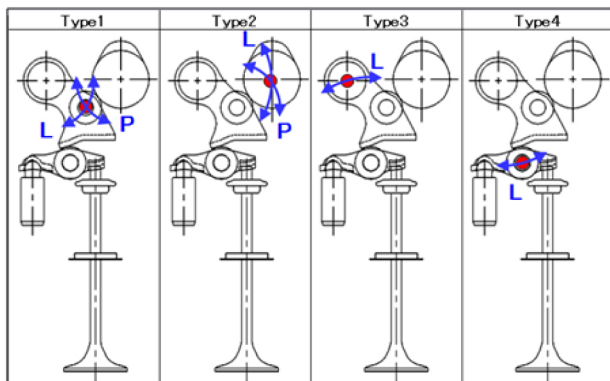


Fig.2. Variable Mechanism for Swing Cam

As for the type of actuation with a swing cam, four different methods are possible. Type 1 is a method of moving the swing arm roller where rotational cam force is applied, With a circumferential motion around the swing arm pivot, towards direction (P), the valve event phase is varied, and a circumferential motion around the rotational cam, towards direction (L), the valve lift/duration can be varied. Type 2 is a method of moving the position of the rotating cam, When the rotating cam moves around the swing arm roller in direction of (P), the valve event phase is varied, and motion around the swing arm pivot in direction of (L) varies the valve lift/duration. Type 3 is a method of relocating the pivot of the swing arm, in which the motion of (L) around the roller on the RFF changes the lift/duration. Although the phase will also be changed in the same motion, the amount of phase change is significantly small. Type 4 is a method of moving the roller on the RFF, in which motion of (L) around the pivot of the swing arm varies the lift/duration, but the phase will not be changed. The mechanisms of Type 1 and Type 2 have in common that lift/duration and phasing can both be controlled. Type 1 is considered as the best because type 2 requires the complex mechanism to move the heavy rotational cam.

### Actuation for the Variable Part

Several mechanisms are known for actuation, and some typical mechanisms are shown in Figure 3. The mechanism and their functionality are depicted, and combinations of them are possible as well. These mechanisms were evaluated for being applied to the Type1 mechanism, then the lever-type has been chosen, because of the small number of components and ease-of-mass production.

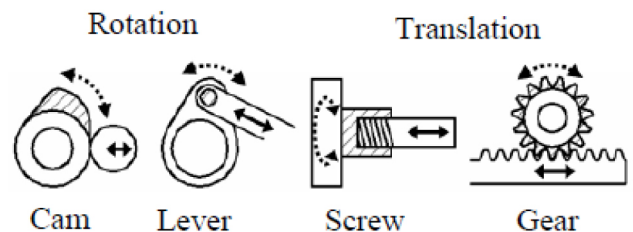


Fig.3. Acuator Function for Mechanical VVA

### Mechanism and Its Feature

The developed our VVPL, called “O(Ogino)VVPL”, is shown as a 3D sketch in Figure 4. While the rotating cam is acting on the swing arm through the control arm, and by the rocking motion of this swing arm, the valve opens/closes. Further, the pivot of the swing arm is supported by the outer surface of the adjust ring on the control shaft and the guide of the swing arm. Since the main parts of OVVPL can be mass-produced by pressing process, the manufacturing cost is expected to be held down