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# Improving energy efficiency and robustness of a novel variable valve actuation system for engines☆

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ABSTRACT

This study presents a new variable valve actuation (VVA) system, which is optimized to pursue the minimum energy consumption and the minimum sensitivity of the valve lift to cycle-to-cycle variations of engine pressure. Therefore, an experimentally verified mathematical model is proposed to calculate the objective function and constraints at each optimization step. Due to the complexity and constraints of the objective function along with the possible existence of local minima, a non-derivative optimization method i.e. a genetic algorithm (GA) is employed to find the optimum design parameters. The method of dynamic penalties is used to satisfy the optimization constraints. To remove the trade-off that exists between the system's power consumption and sensitivity, an energy recovery technique is proposed and implemented. The results show that the optimized system has a low variability of about 5% (0.5 mm) to cycle-to-cycle variations of 50% in the in-cylinder gas force. It is also observed that the optimized VVA with the proposed energy recovery system (ERS) consumes about 58% of the energy used in a conventional cam driven valvetrain.

## 1. Introduction

Cam based valvetrains offer reliable and repeatable operations. However, they are not efficient over a wide range of engine operating conditions because of the fixed opening duration, lift, and timings [1]. Previous research shows a remarkable improvement in the engine output power and emissions control through applying a variable valve timing or lift system [2,3]. Authors in [4,5] have shown that significant improvement in power density, volumetric efficiency, emission, and fuel consumption could be achieved by VVA systems. Different categories of variable valve actuation (VVA) systems used by more and more production engines is an evidence to such fact [6]. As a result, to address the two major challenges (i.e. fuel economy and exhaust emissions) in the transportation sector [7,8], designing a valvetrain with a higher flexibility & robustness and lower power consumption than conventional ones is one of the goals pursued by ICE manufacturers.

In general, VVA systems are either cam-based [9] or camless [10] systems. The former is directly driven by the engine crankshaft. Due to its high reliability, accuracy, and robustness, many of these systems have been already applied to vehicle engines. Among different cam-based VVA systems, cam-phasers and cam-profile–switchers (CPS) are two well-known technologies. A limited degree of flexibility is still a major disadvantage of cam-based valvetrains compared to the existing camless systems. In contrast to cam-based VVA, camless ones are completely disconnected from the engine crankshaft [11]. High levels of flexibility in valve timing and valve lift are the main advantage of these systems over others [12]. Electro-hydraulic, electro-mechanical, electro-pneumatic, and electro-magnetic valvetrains are all in this class [13,14]. Although these systems are highly flexible, some issues (e.g. the high cost, high power consumption, low robustness, and low reliability) deter manufacturers from their application. To address the aforementioned issues, a novel hydraulic VVA was designed, manufactured, and tested in our previous study [15]. The numerical and experimental results have shown its flexibility, reliability, and the repeatability is comparable with current camless valvetrains. To precisely control the engine valve timings, opening duration, and lift, the proposed VVA system has been equipped with linear and non-linear controllers.

Until now, all the works conducted on the designed VVA are limited to prove its feasibility, repeatability, and precision; however, for the sake of the real-world application, its robustness and power consumption should be viable or at least comparable to its counterparts. Therefore, design parameters of the proposed VVA should be optimized to pursue the maximum robustness with the minimum power consumption. Several techniques including non-gradient or gradient

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## Nomenclature

| | |
|---|---|
| $A_{HPSV}$ | HPSV port opening area [m$^2$] |
| $A_{LPSV}$ | LPSV port opening area [m$^2$] |
| $A_p$ | Hydraulic piston area [m$^2$] |
| $C$ | Hydraulic cylinder viscose coefficient [Ns/m] |
| $C_d$ | Rotary valves port discharge coefficient |
| $D_{tube}$ | Hydraulic tube diameter [m$^2$] |
| ERS | Energy recovery system |
| $F_{friction}$ | Coulomb friction force [N] |
| $F_{preload}$ | Engine valve return-spring preload [N] |
| GA | Genetic algorithm |
| HPSV | High pressure rotary spool valve |
| ICE | Internal combustion engine |
| $K$ | Engine valve return-spring stiffness [N/m] |
| $l$ | Rotary spool valve port length [m] |
| $L_f$ | Engine valve lift [m] |
| LPSV | Low pressure rotary pool valve |
| $L_{tube}$ | Hydraulic tube length [m] |
| $m$ | Engine valve moving mass [kg] |
| $n$ | Gas polytropic coefficient |
| $N_{engine}$ | Engine speed [rpm] |
| $N_{pump}$ | Hydraulic pump speed [rpm] |
| $P_{in}$ | Upstream pressure [pa] |
| $P_{out}$ | Downstream pressure [pa] |
| $P_1$ | Air accumulator pressure [pa] |
| $P_2$ | Hydraulic cylinder pressure [pa] |
| $Q_{HPSV}$ | Flow through HPSV [m$^3$/s] |
| $Q_{LPSV}$ | Flow through LPSV [m$^3$/s] |
| $Q_{leakage}$ | Leakage flow [m$^3$/s] |
| $Q_{pump}$ | Pump flowrate [m$^3$/s] |
| $r_c$ | Rotary spool valve casing radius [m] |
| $r_{pe}$ | Pump to engine speed ratio |
| $r_s$ | Rotary spool valve spool radius [m] |
| $Re$ | Reynold number |
| $t$ | Time |
| VVA | Variable valve actuation |
| $V_{disp}$ | Pump displacement volume [m$^3$/rev] |
| $V_1$ | Accumulator gas volume [m$^3$] |
| $V_2$ | Hydraulic cylinder volume [m$^3$] |
| $x$ | Engine valve displacement [m] |
| $\beta$ | Hydraulic fluid bulk modulus [pa] |
| $\varepsilon$ | Hydraulic tube surface roughness |
| $\vartheta$ | Spool angular position [rad] |
| $\mu$ | Oil dynamic viscosity [pa s] |
| $\rho$ | Oil density [kg/m$^3$] |
| $\varphi$ | Rotary spool valve port angle [rad] |
| $\omega$ | Spool rotary velocity [rad/s] |

methods can be employed to optimize the design parameters according to features of the optimization problems. For instance, some problems can be converted into the convex optimization problems and use the available solver for the optimal solution [16,17]. Compared to the gradient methods, non-gradient methods are more robust in locating the global optima especially when the problem is extremely complex and not convex [18,19]. Thus, GA is used in this paper. In addition, a simple mathematical model is built, validated experimentally, and used in the optimization process. Moreover, to further reduce the power consumption, a novel energy recovery system (ERS) is developed, which is used to capture the hydraulic energy otherwise wasted by regulating the downstream pressure of the whole system via an added secondary pump. Finally, the whole system is analyzed and compared to the conventional cam driven valvetrain.

The contributions of this study are as follows: This paper presents a novel variable valve actuation system for internal combustion engines. In addition, a simplified model is built to optimize the energy consumption by GA. Furthermore, a novel ERS is designed to save the

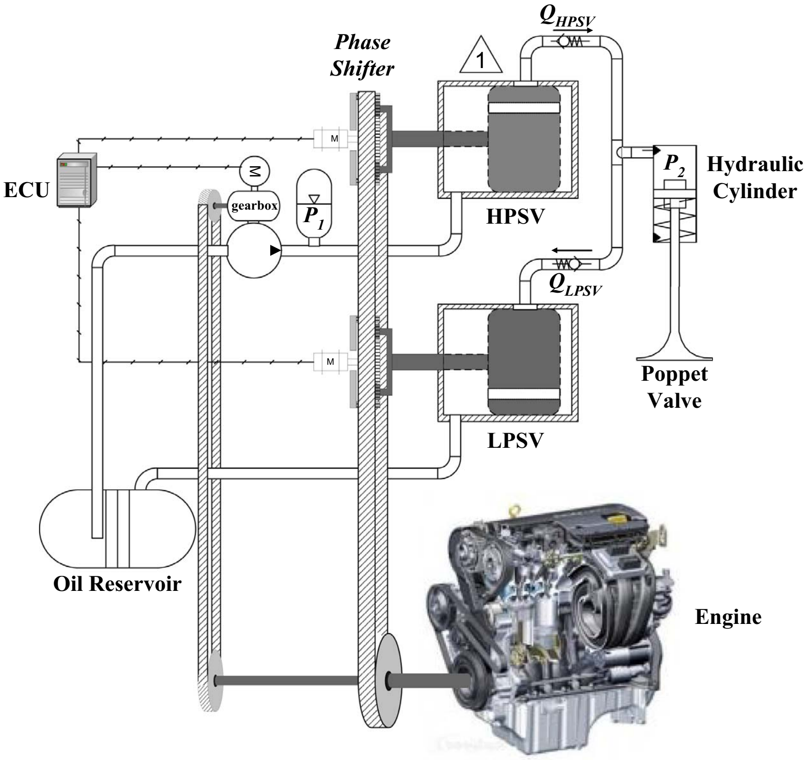

**Fig. 1.** Schematic of the proposed VVA.