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Precise lift control in a new variable valve actuation system using discrete-time sliding mode control

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ABSTRACT

Precise engine valve lift control is essential in improving the efficiency of internal combustion engines and avoiding unwanted engine valve closure or mechanical interference between the valve and engine piston at different operating conditions. In this paper, a recently proposed hydraulic variable valve actuation (VVA) system [1] is equipped with a novel lift control architecture. In this technique, the hydraulic supply pressure is controlled using a proportional bleed valve. A discrete sliding mode controller is designed using the average model of the system on the basis of a discrete Lyapunov function. The stability of the designed controller is proven and sufficient conditions of the controller gains to stabilize the system are given. The experimental results show an excellent tracking performance of the proposed lift controller during sudden changes in the reference final valve lift. The results also show that using the proposed valve lift controller, the maximum lift deviation from its reference value does not exceed 0.4 mm during transient operating condition.

1. Introduction

Owing to strict legislation on exhaust emission and fuel economy, combustion engine manufacturers are pushed toward development of new techniques to reduce exhaust gas emissions and improve fuel efficiency [2]. Variable engine valve actuation (VVA) is one of the most promising techniques for further improving the efficiency of the in-cylinder combustion (IC) engines [3]. Numerous studies have shown that appreciable improvement in engine power density, volumetric efficiency, emissions control and fuel economy could be achieved through precise control of the engine valve timing, duration and lift [4]. Hence, several cam-based and camless valvetrains have been developed by many researchers to flexibly change engine valve opening trajectory. Although camless valvetrains offer more flexibility in valve timing (crank angle degree at which the engine valve opens or closes) and lift (valve final displacement) compared to cam-based systems, they have lower degree of repeatability and robustness. A novel hydraulic fully flexible valve actuation system was recently proposed, prototyped and tested at University of Waterloo [1]. The system has shown a competitive degree of flexibility in comparison with camless systems while its repeatability and reliability are comparable with those in the conventional cam-driven valvetrain. A proportional-integral (PI) control was developed to precisely regulate the engine valve opening and closing events with respect to crankshaft angle. The developed control system was implemented in the test setup and its performance was evaluated. In addition to accurate valve timing, a precise and fast engine valve lift control is also crucial in hydraulic VVA systems where the engine valve lift is highly influenced by the upstream pressure, engine speed and other disturbances. Moreover, several advantages such as significant decrease in pumping losses through

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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_d Rotary valves port discharge coefficient
$C_{v,bleed}$ Bleed valve flow coefficient
e Engine valve lift tracking error [m]
E_{valve_system} Valve system energy consumption [Watt]
$F_{friction}$ Coulomb friction force [N]
$F_{preload}$ Engine valve return-spring preload [N]
F_{gas} Engine cylinder gas force [N]
$HPSV$ High pressure rotary spool valve
k engine cycle
K_{spring} Valve return-spring stiffness [N/m]
K_{fb} Feedback control law gain
L_f Engine valve lift [m]
$L_{f,ref}$ Reference engine valve lift [m]
$LPSV$ Low pressure rotary pool valve
m Engine valve moving mass [kg]
N_{engine} Engine speed [rpm]
N_{pump} Hydraulic pump speed [rpm]
P_1 Air accumulator pressure [pa]
P_2 Hydraulic cylinder pressure [pa]
$P_{reservoir}$ Oil reservoir pressure [pa]
Q_{bleed} Flow through the bleed valve [m^3/s]
Q_{HPSV} Flow through HPSV [m^3/s]
Q_{LPSV} Flow through LPSV [m^3/s]
Q_{pump} Pump flowrate [m^3/s]
r_{pe} Pump to engine speed ratio
S sliding mode
t time
T Engine cycle period [s]
u_{eq} Equivalent control law
u_{fb} Feedback control law
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]
β Hydraulic Fluid bulk modulus [pa]
$\eta_{volumetric}$ Pump volumetric efficiency
θ Crankshaft angle [deg]
$\theta_{opening}$ Engine valve opening angle [CA°]
$\theta_{closing}$ Engine valve closing angle [CA°]

throttle-less control of intake air and improve in the valvetrain power efficiency through reduction in final valve lift at lower engine speeds are gained by controlling the engine valve lift [5].

In electro-hydraulic camless valvetrain, control of the engine valve lift is usually achieved by precise control of the high pressure servo-valve within every engine cycle. Several studies have been conducted in designing a robust lift controller for these valvetrains [6,7]. In [8], a robust discrete-time sliding mode controller was designed and implemented for a linear electro-hydraulic actuator (EHA) whose displacement was regulated by a variable speed electric pump. To improve the controller robustness, the actuator total friction including static, coulomb and viscose frictions was characterized as norm-bounded uncertainty in the system model. It was shown that friction can affect the actuator accuracy performance critically if not considered. To compensate for the modeling uncertainties imposed by non-linear friction, a discrete-time sliding-mode control law (DT-SMC) was designed. State transformation was introduced to facilitate the controller design. The experimental and simulations results verified the performance and robustness of the proposed control design.

In [9], it was shown that the trajectory tracking performance of sliding mode controller designed for a hydrostatic actuator can be significantly improved by using a robust model-based state estimation strategy called variable structure filter (VSF). The designed filter helps estimating those system states which are not measured or contain high measurement uncertainties. The