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Valve timing optimisation of a spark ignition engine with skip cycle strategy

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ABSTRACT

Skip cycle strategy (SCS) is a stroke volume modulation method leading to reduction in pumping loss through deactivation of engine valves under part-load conditions. Although SCS achieves a significant fuel economy, it increases regulated pollutant emissions such as nitrogen oxide and unburned hydrocarbon in comparison to normal 4-cycle engine operation. This paper investigated normal cycle strategy, skip cycle strategy as well as combination of skip cycle strategy and variable valve timing strategy for a spark-ignition engine using one-dimensional numerical model. The skip cycle engine was modelled at several steady-state operation points and then optimised at best ignition timing providing maximum brake torque at each simulation case. The numerical results obtained for both normal cycle and skip cycle have been validated against the experimental data. After completing the validation of numerical results with engine test bench data for both normal and skip cycle operations, optimisation of intake and exhaust valve timing profiles have been carried out regarding advancing or retarding camshaft relatively to the crankshaft position. In case of SCS and variable valve timing application together, NO_x concentration was reduced by 35.1%, 39.4%, 26.8% and HC emission was reduced by 54.9%, 49.3% and 47.4% on average for brake mean effective pressure load levels of 1, 2 and 3 bar respectively at all among engine speed ranges between 1200 and 1800 rpm compared to stand alone SCS strategy. Furthermore, no remarkable additional brake specific fuel consumption was observed for SCS plus variable valve timing strategy compared to stand alone SCS.

1. Introduction

High gas exchange losses and low volumetric efficiency are the main problems effective on fuel consumption and pollutant emissions under urban traffic conditions of spark ignition (SI) engines in which load is conventionally controlled by throttle valve employed between air filter and intake manifold. Due to less fresh charge requirement and the airflow restriction by closer throttle valve position, SI engines are forced to do much more gas exchange work in addition to less power production under part-load conditions [1]. This issue causes poor combustion quality, insufficient combustion speed, and also unexpected further fuel consumption with regards to excessive low indicated efficiency during power cycle at part-load conditions compared to high-lead conditions [2]. In addition, road transport emissions are shown the main source of air pollution and aimed to keep under control by several legislations, policies and regulations [3] (e.g. European Union Directives and Regulations on Motor Vehicles) to ensure a high level environmental protection. In order for adaptation of Euro 6 emission standards to passenger cars and light commercial vehicles in a real driving emission (RDE) test procedure, a new regulation [4] has been reported recently to reflect vehicle emissions along a total trip including urban, rural and motorway route segments better than laboratory testing. Since all reasons described above, instead of conventional load control based on just throttle valve position, alternative SI engine load control technologies such as variable valve timing (VVT), variable valve lift (VVL), camless engine valve control (CEVC), fuel stratification, turbocharging (or supercharging) and stroke volume modulation strategies have been investigated for two decades to manufacture environment friendly vehicles with a better fuel economy [5]. Thanks to electronic engine control management (EECM) systems which have recently become an essential factor for gasoline engines to perform high engine efficiency and low exhaust emissions while satisfying in driving comfort and road holding issues, these high technology and complex engine solutions are widely used in most of the gasoline engine market [6].

Variable valve timing options such as earlier or later valve opening-closing than default valve profile in terms of rotating camshaft back or forward relatively to the crankshaft, shifting valve duration or valve lifting are very effective on fuel consumption over reducing pumping losses and pollutant emissions over changing in-cylinder states such as pressure and averaged temperature [7–15].

The opinion of camless engines in terms of eliminating camshaft and

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Nomenclature

SCS	skip cycle strategy
NO_x	nitrogen oxide emission
HC	unburned hydrocarbon emission
N	normal cycle
S	skipped cycle
F	fired cycle
SI	spark ignition
MBT	maximum brake torque
AFR	air-fuel ratio
BSFC	brake specific fuel consumption
BMEP	brake mean effective pressure
IMEP	indicated mean effective pressure
GMEP	gross mean effective pressure
PMEP	pumping mean effective pressure
rpm	revolution per minute
CA	crankshaft angle
TDC	top dead center
ATDC	after top dead center
BTDC	before top dead center
CA50	location of 50% mass fuel burned
BDUR	burning duration
ppm	particles per million
P_{max}	maximum cylinder pressure
P_{min}	minimum cylinder pressure
cm^3	cubic centimeter
V	cylinder volume
K	kelvin
RDE	real driving emission
CEVC	camless engine valve control
VVT	variable valve timing
VVL	variable valve lifting
EIVO	early intake valve opening
LEVO	late exhaust valve opening
DoE	design of experiment

timing belt allowing valve control by electromagnetic or pneumatic actuators has been afforded for a short time past [16–18]. In this camless concept, an electronically controlled solenoid system allows a fully flexible valve actuation, valve duration shifting and lift adjustment depending on cyclic load and crankshaft speed levels. Although a few engine research and development companies have been working on camless engine prototype experimentation on test bench [19–21], no mass car production has been presented into market yet due to lack of expected valve activation sensitivity, noise and electrical safety problems.

Fuel stratification method enables a wider throttle valve area and less fuel consumption by supplying a rich mixture near spark plug and a very lean mixture at other regions of combustion chamber [22–26]. Turbocharging and supercharging meet same power requirement with a smaller engine displacement (i.e. engine downsizing) so it offers a better fuel economy and reduced friction losses [27–32]. Stroke volume modulation strategy can be categorised into three groups such as cylinder deactivation (cylinder cut-off), skip fire and skip cycle strategies. Cylinder deactivation can be applied for a cylinder or a group of cylinders permanently during desired operation conditions either by deactivation of intake and exhaust valves to reduce the active stroke volume allowing a reduction in pumping losses as well as heat transfer losses under part-load conditions [33]. A few recent studies have also been reported deactivating a cylinder by means of valve deactivation and combination of spark cut-off and fuel cut-off [34–37]. Skip fire strategy is based on just cutting spark fire in order to deactivate a cylinder depending on driver torque demand [38–39] or skip a power cycle with both ignition and injection disabling [40–42].

Skip cycle strategy (SCS) is another type of stroke volume modulation strategy to vary the power frequency of SI engines under part-load operation conditions [43]. This technique is based on a principle in which valve engagement, fuel supply and spark arc are disabled in several cycles to reduce pumping (throttling) losses therefore to achieve an equivalent power level. In this technique, the fresh charge is increased in sequential cycle as seen in fired cycle section of Fig. 1. However, in contrast to part-load conditions, SCS is not expected to play a major role on fuel economy at full-load conditions due to lower pumping losses and higher volumetric efficiency as a result of wide open throttle (WOT).

Possible combination selections from among the methods mentioned above could present various advantages in order to overcome efficiency problem of SI engines. The one possible combination studied in the literature was VVT and supercharging combination [44–46]. A few studies were also reported for VVT and cylinder deactivation combination [47,48]. Other combinations investigated were: supercharging with stratified charge mixture [49]; supercharging with VVT and VVL [50]; cylinder deactivation, VVT and VVL with stratified charge [51]. A recent study reported a camless fully flexible electromagnetic valve train system (without a mechanical valve deactivation) combined with a skip cycle approach with optimum valve timing and lift adjustments to reduce pumping losses [52].

However, combined effect of mechanical skip cycle and variable valve actuation on SI engine performance and emissions has not been investigated so far. Previously, the authors have presented a self-developed novel skip cycle mechanism which has been manufactured to engage or disengage the intake and exhaust poppet valves [53]. Despite achieving significant fuel saving under part-load operation conditions in this experimental SCS investigation, nitrogen oxide (NO_x) concentration could increase due to higher fresh charge and averaged cylinder temperature rise as observed in [54–56], hydrocarbon (HC) emissions in terms of incomplete combustion products could also increase due to undesired oil suction from crankcase to cylinder as mentioned in [57–60], flame quenching on cylinder wall as discussed in [61–63], and deposit of unburned mixtures in crevice cylinder volumes such as piston liner, valve seat and spark plug thread as discussed in [64–66] in comparison to normal (N) 4-cycle engine operation.

The objective of the present study is to mitigate the unfavourable exhaust gas emissions of a skip cycle SI engine under part-load conditions. Two variable valve timing strategies (EIVO: early intake valve opening, LEVO: late exhaust valve opening) along with skip cycle strategy are investigated for an SI engine using a one-dimensional simulation model. Firstly, the skip cycle strategy was modelled and ignition timing was optimised based on minimum spark advance for maximum brake torque (MBT) at 15 steady-state simulation points including low load (break mean effective pressure, BMEP: 1–2–3 bar) and low engine speed (1200–1350–1500–1650–1800 rpm) ranges. Secondly, the simulation results for both normal engine and SCS were verified with the experimental data for a four cylinder water-cooled naturally aspirated SI engine with 1.8 L stroke volume and stoichiometric air-fuel ratio (AFR = 14.6) in which SCS was carried out. Then intake valve timing and exhaust valve timing were optimised and integrated into the model in a way that the valve duration and the valve lift are kept default in the engine configuration. The comparative results regarding engine performance and engine-out emissions will be presented for normal operation, SCS and SCS with variable valve timing (SCS&VVT) strategies. The findings of this study will help to identify the advantage of combining skip cycle strategy with variable valve timing in achieving lower engine exhaust emissions with better fuel economy.