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Design and control of semi-direct injection spark ignition engine fuelled by LPG

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Abstract

This paper designs a lean-burn system and its control strategies to retrofit the motorcycle engine as a semi-direct injection (SDI) engine. The lean-burn system of the SDI engine consists of a high-swirl charge, fuel injection during intake-valve opening, and liquefied petroleum gas (LPG) as the fuel. The high-swirl charge motion is generated by the new intake port with a controllable plate which is designed using the computational fluid dynamics software. The lean limit is therefore extended due to the stratified charge by higher in-cylinder swirl motion. By controlling the controllable plate, the SDI engine can be operated in stratified mode with leaner air-fuel ratio (AFR) at lower load and engine speed. The SDI engine can be switched to homogeneous mode with stoichiometric AFR for higher load and engine speed. Therefore, the proposed control strategies consist of an engine management system, adaptive intake manifold pressure control, adaptive torque control in stratified mode, adaptive torque control in homogeneous mode, and switching strategies for switching between stratified and homogeneous modes. The SDI engine and its control strategies are verified with the motorcycle test on a chassis dynamometer. The tests including driving cycle and constant speed test are executed to investigate the fuel economy of SDI engine as compared with original engine. The raw emissions of idle operation between SDI and original engines are investigated as well. Experimental results show that the SDI engine can reduce the exhaust emissions and fuel consumption as compared with original engine.

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1. Introduction

In most Asian countries, motorcycles contribute to air pollution more than other vehicles [1]. So, the motorcycle manufactures are putting efforts to improve the engine efficiency and reduce the exhaust emissions. The SDI engine is one of the methods to improve engine efficiency and reduce emissions. In this paper, the SDI engine is designed and control strategies are developed to retrofit the motorcycle engine as a SDI engine. The SDI engine consists of a high-swirl charge, fuel injection during intake-valve opening, and liquefied petroleum gas (LPG) as the fuel. The high-swirl charge motion is generated by the new intake port with a controllable plate which is designed using the computational fluid dynamics software. The lean limit is therefore extended due to the stratified charge by higher in-cylinder swirl motion. By controlling the controllable plate, the SDI engine can be operated in stratified mode with leaner air-fuel ratio (AFR) at lower load and engine speed. The SDI engine can be switched to homogeneous mode with stoichiometric AFR for higher load and engine speed. Therefore, the proposed control strategies consist of an engine management system, adaptive intake manifold pressure control, adaptive torque control in stratified mode, adaptive torque control in homogeneous mode, and switching strategies for switching between stratified and homogeneous modes. The SDI engine and its control strategies are verified with the motorcycle test on a chassis dynamometer. The tests including driving cycle and constant speed test are executed to investigate the fuel economy of SDI engine as compared with original engine. The raw emissions of idle operation between SDI and original engines are investigated as well. The experimental results show that the SDI engine can reduce the exhaust emissions and fuel consumption as compared with original engine.

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emissions of a motorcycle. Efficiency of spark ignition (SI) engines can be improved by decreasing friction losses and improving combustion efficiency. As for the friction losses, piston ring loss [2] and pumping loss are key issues that researchers now focus on. The pumping loss can be reduced by a lean-burn engine [3]. The combustion efficiency could be improved by decreasing cooling loss and time loss [3]. This could be achieved by stratified combustion found from previous many researches on gasoline direct injection (GDI) engine.

Since the lean-burn GDI engine is difficult to apply in motorcycles due to small engine size and cost limitation, Wu et al. [4] proposed a semi-direct injection (SDI) engine for application in motorcycles which can achieve lean-burn with AFR=24 by high-swirl charge and fuel injection during intake-valve opening. Their results show that the brake specific fuel consumption (BSFC) and CO emission of SDI engine can be improved as compared with original engine. Since the SDI engine can be operated under stratified combustion, the Liquefied Petroleum Gas (LPG) in gaseous phase could be an alternative fuel for an SDI engine that the mixture could have better stratification and increase the lean limit [5-6].

This paper, therefore, designs a lean-burn system for a market motorcycle engine to retrofit it as a SDI engine, which includes a high-swirl charge, fuel injection during intake-valve opening, and LPG as the fuel. The high-swirl charge motion will be achieved by a new intake port with a controllable plate that is designed and verified using computational fluid dynamics (CFD) software. Since the fuel injection of SDI engine in stratified mode will take place during intake stroke and the overall in-cylinder mixture is leaner, it is only suitable for lower load and engine speed. Therefore, we proposes a switching strategy that can switch the SDI engine from stratified mode to homogeneous mode except for idle or lower load and engine speed operation. The overall control strategies consist of an engine management system, adaptive intake manifold pressure control, adaptive torque control in stratified mode and homogeneous mode, and switching strategies. The SDI engine and its control strategies are finally verified with the motorcycle test on a chassis dynamometer.

2. Engine Design

This paper designs a SDI engine by retrofitting a market motorcycle engine. The lean-burn system of the SDI engine includes a high-swirl charge, fuel injection during intake-valve opening, and LPG as the fuel. The high-swirl charge is generated by designing a new intake port with a controllable plate that can be switched for stratified mode and homogeneous mode of the SDI engine, as shown in Fig. 1. This design is accomplished and verified using CFD software. The simulation results indicate that the high-swirl charge motion can be generated in stratified mode by the controllable plate.

3. Controller Design

The proposed control strategies consist of an engine management system, adaptive intake manifold pressure control, adaptive torque control in stratified mode and homogeneous mode, and switching strategies for switching between stratified and homogeneous modes. The engine management system, which manages idle speed, fuel amount, and spark advance, is employed to control the SDI engine in
different operation conditions. The adaptive intake manifold pressure controller is designed based on lead-lag compensator to determine the desired throttle position according to the desired intake manifold pressure. The lead compensator is used to increase the control response especially for mode switching, and the lag compensator is used to reduce the steady state error.

In stratified mode of SDI engine, the engine torque is controlled by adaptive torque controller (based on lag compensator) to generate the control command of fuel injection duration. The AFR will be controlled by controlling the intake manifold pressure that corresponds to intake air mass. As for homogeneous mode of SDI engine, the engine torque is controlled by intake manifold pressure; moreover, the AFR can be maintained at stoichiometric AFR by controlling the fuel injection duration based on a lag compensator with a feedforward compensation. Finally, the switching strategies are designed based on the ideal that the torque-bumps are small when switching between two modes. It can be accomplished by mode switching takes place at equally torque output of two modes.

4. Experimental Results

The SDI engine and its control strategies are verified with the motorcycle test on a chassis dynamometer (SuperFlow CycleDyn chassis dynamometer). The fuel economy tests for motorcycles can be divided into two modes: ECE-40 driving cycle test and 50km/h constant speed test. For the ECE-40 driving cycle test, the motorcycle is operated from cold start to follow the vehicle speed of ECE-40 driving cycle for six cycles continuously. The total fuel consumption is recorded and will be converted as fuel economy (km/l) by the fuel density and total driving distance. The constant speed test is executed by operating the motorcycle at 50km/h for the driving distance greater than 2km and will be repeated for three times. The fuel consumption is also recorded and calculated as fuel economy (km/l) for each test, and then the fuel economy will be averaged. Finally, the average fuel economy of the motorcycle will be calculated using the following equation:

\[
Fuel\ economy\ (km/l) = \frac{1}{0.6\cdot Driving\ Pattern\ (km/l) + 0.4\cdot Constant\ Speed\ (km/l)}
\]  

(1)

The raw emissions of idle operation between SDI and original engines are investigated as well. The test results can be seen in Table 1 for SDI and original engine. Since the lower heating value of LPG is difference with gasoline, so the results of fuel economy in SDI engine (fuelled by LPG) will be calculated as equivalent to gasoline. The results show that the SDI engine can improve the average fuel economy by 11.7% as compare with original engine. The raw emissions of CO and NOx can be significantly reduced by SDI engine as compared with original engine. However, the HC emission is increased for SDI engine. It could be explained that the HC emission is the consequence of incomplete combustion of hydrocarbon fuel, this might come from very lean regions at the periphery of the stratified charged fuel cloud [7-8].

<table>
<thead>
<tr>
<th></th>
<th>CO (%)</th>
<th>HC (ppm)</th>
<th>NOx (ppm)</th>
<th>ECE-40 (km/l)</th>
<th>50km/h (km/l)</th>
<th>Average fuel economy (km/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original engine</td>
<td>0.82</td>
<td>386</td>
<td>98</td>
<td>38.5</td>
<td>53.9</td>
<td>43.5</td>
</tr>
<tr>
<td>SDI engine</td>
<td>0.02</td>
<td>480</td>
<td>30</td>
<td>43.7</td>
<td>58.2</td>
<td>48.6</td>
</tr>
<tr>
<td>Improvement (%)</td>
<td>97</td>
<td>-24</td>
<td>70</td>
<td>13.6</td>
<td>7.9</td>
<td>11.7</td>
</tr>
</tbody>
</table>

Table 1. Experimental results of fuel economy and exhaust emissions
5. Conclusions

A market motorcycle SI engine is retrofitted as a SDI engine by designing a lean-burn system and its control strategies in this paper. The SDI engine can be operated in stratified mode with leaner AFR at lower load and engine speed, and it can be switched to homogeneous mode with stoichiometric AFR for higher load and engine speed. The SDI engine and its control strategies are verified with the motorcycle test on a chassis dynamometer. The tests including driving cycle and constant speed test are employed to investigate the fuel economy. The raw emissions of idle operation between SDI and original engines are investigated as well. Experimental results show that the SDI engine can reduce the exhaust emissions and fuel consumption as compared with original engine.

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References


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He is currently a graduate student from Department of Vehicle Engineering in National Taipei University of Technology. His research interests are internal combustion engines and engine management system.