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Multi-location laser ignition using a spatial light modulator towards improving automotive gasoline engine performance

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ABSTRACT

We report on a study into multi-location laser ignition (LI) with a Spatial Light Modulator (SLM), to improve the performance of a single cylinder automotive gasoline engine. Three questions are addressed: i/ How to deliver a multi-beam diffracted pattern into an engine cylinder, through a small opening, while avoiding clipping? ii/ How much incident energy can a SLM handle (optical damage threshold) and how many simultaneous beam foci could thus be created? ; iii/ Would the multi-location sparks created be sufficiently intense and stable to ignite an engine and, if so, what would be their effect on engine performance compared to single-location LI? Answers to these questions were determined as follows. Multi-beam diffracted patterns were created by applying computer generated holograms (CGHs) to the SLM. An optical system for the SLM was developed via modelling in ZEMAX, to cleanly deliver the multi-beam patterns into the combustion chamber without clipping. Optical damage experiments were carried out on Liquid Crystal on Silicon (LCoS) samples provided by the SLM manufacturer and the maximum safe pulse energy to avoid SLM damage found to be 60 mJ. Working within this limit, analysis of the multi-location laser induced sparks showed that diffracting into three identical beams gave slightly insufficient energy to guarantee 100% sparking, so subsequent engine experiments used 2 equal energy beams laterally spaced by 4 mm. The results showed that dual-location LI gave more stable combustion and higher engine power output than single-location LI, for increasingly lean air-fuel mixtures. The paper concludes by a discussion of how these results may be exploited.

1. Introduction

Engine ignition systems with electric spark plugs have been developed for the automobile industry for over a century. However, they offer only limited possibilities for optimizing engine efficiency, due to the fixed position and protrusion of their electrodes within the cylinder, which can quench the flame kernel. Recent research on laser ignition (LI) of air–fuel mixtures in internal combustion (IC) engines has revealed a number of potential advantages over conventional electrical spark ignition (SI) [1–5]. LI offers, in principle, the potential to deposit ignition energy at any location, including multiple points [6–8]. Other benefits foreseen include reduced emissions, faster ignition, more stable combustion, lower idle speeds and better cold engine performance. However, challenges remain, self-cleaning of the window into the cylinder has not been demonstrated over long time periods, and the cost of the laser system needed is prohibitively high. Tauer et al. [9], Morsy et al. [10] and Dearden et al. [11] recently reviewed progress in research on laser ignited engines. Previous work on LI of IC engines found that simultaneously igniting in more than one location resulted in more stable and faster combustion [7]. Two previous attempts to create laser induced sparks in multiple locations for engine ignition were a complex arrangement of external conical cavities [7] and the use of three independent lines to pump a passively Q-switched Nd: YAG/Cr4+ laser cavity [8]. These were able to generate two and three foci, respectively, but only at fixed locations within the combustion chamber. We recently reported on an optical technique for multi-location spark generation in air using a spatial light modulator (SLM), for potential use in LI [12]. There, several sparks with arbitrary spacing in 3-dimensions were created by variable diffraction of a single pulsed laser beam and its transmission through a lens. However, before the benefits of the method could be properly evaluated on a test engine, the following questions were technical challenges to be addressed: i/ How to deliver a multi-beam diffracted pattern through a small opening into an engine cylinder, while avoiding clipping? ii/ How much incident energy can a SLM handle (optical damage threshold) and how many simultaneous beam foci could thus be created? ; iii/ Would the multi-location sparks created be sufficiently intense and stable to ignite an engine and, if so, what would be their effect on engine performance

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compared to single-location LI? This study firstly addresses each of these three questions. To address i/, we design and develop an optical system set-up incorporating the SLM, which aims to avoid clipping of the multi-beam pattern along its path into the combustion chamber. This was challenging, given the spatially diffracted beams must be carefully aligned and cleanly transmitted through the internal bore (minimum diameter 6 mm) of an optical plug, which replaces the SI plug and is vibrating with the engine, before final focusing into the cylinder. To address ii/, an experiment was carried out to assess the optical damage threshold of Liquid Crystal on Silicon (LCoS) samples provided by the SLM manufacturer. Here, the aim was to determine a maximum safe energy that could be applied to the SLM, and hence the energy available to distribute into multiple beams. To address iii/, based on the upper safe limit of energy derived from ii/, experiments were performed to analyse the stability of laser induced sparks generated in multiple foci by the SLM. The aim was to determine the minimum energy per foci needed for spark creation and thus how many beams with sufficient energy could be generated (under the specific optical conditions). The study then goes further to apply this SLM based technique to a single cylinder automotive gasoline IC engine and to evaluate the effect on engine performance of multi-location LI, comparing in this case the results for dual-location and single location LI.

2. Experimental

2.1. Optical system development and alignment simulation

Fig. 1 is a schematic of the experimental optical system designed and developed for multiple laser beam generation and delivery to a single cylinder IC test engine. Fig. 2 illustrates the engine system comprising engine, diagnostics and data acquisition. As shown in Fig. 1, the laser used was a flashlamp-pumped Q-switched Nd: YAG laser (Litron LPY 764-30), delivering up to 500 mJ output energy at a wavelength of 532 nm. The SLM used was a LCoS device (Hamamatsu X10468) with 800×600 pixels and dielectric coating for 532 nm operation (reflectivity >99%). Computer generated holograms (CGHs) were displayed on the SLM to create multi-beam patterns by diffraction [12–15]. ZEMAX optical modelling software was used for optical design and simulation of beam alignment and propagation performance. 1×2 and 1×3 beam arrays were generated using binary linear grating CGHs. Arrays with higher numbers of beams (e.g. 1×5) were created using Dammann grating CGHs [14,15], according to the grating equation:

$$d(\sin\theta_i + \sin\theta_m) = m\lambda \quad (1)$$

$$\theta_m = \arcsin\left(\frac{m\lambda}{d} - \sin\theta_i\right) \quad (2)$$

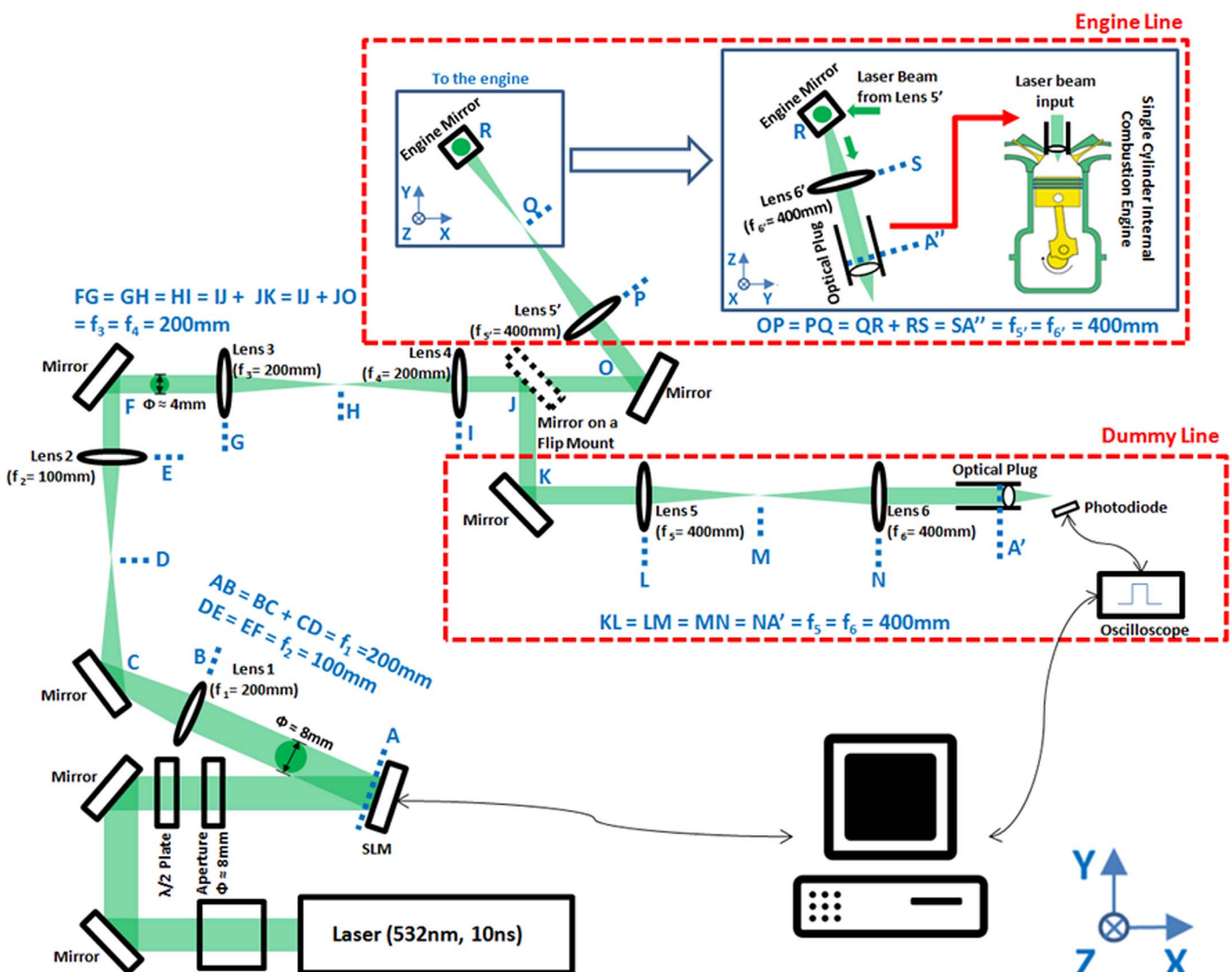

Fig. 1. Experimental setup – Optical system for multi-beam generation and delivery to the test engine.

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