Multi-point laser ignition of internal combustion engines using a spatial light modulator

Zheng Kuang¹, Hua Cheng², Elliott Lyon¹, Vincent Page², Tom Shenton², Geoff Dearden¹

¹Laser Group, Centre for Material and Structures, School of Engineering, University of Liverpool, Liverpool L69 3GQ, UK
²Powertrain Control Group, Centre for Material and Structures, School of Engineering, University of Liverpool, Liverpool L69 3GH

Email: Z.kuang@liv.ac.uk

Abstract: Multi-point laser ignition (LI) is one of the key potential advantages that LI can offer over conventional spark ignition (SI). Previous research found that multi-point ignition produced more stable and faster combustion. This paper demonstrates a diffractive multi-point LI technology which is experimentally attempted at Liverpool University Laser Group. Sparks with arbitrary geometrical location in three dimensions are created by diffractive multi-beam through an optical plug. The diffractive multi-beam patterns are generated using a spatial light modulator (SLM) on which computer generated holograms (CGHs) are displayed. A Gratings and Lenses (GL) algorithm is used to accurately modulate the phase of the input laser beam and create multi-beam output.

1. Introduction

Recent research in laser-induced ignition (LI) of air–fuel mixtures in internal combustion (IC) engines has demonstrated there to be many potential advantages over conventional electrical spark ignition (SI) [1]–[5]. Spark plugs offer only limited possibilities for optimizing engine efficiency, due to their fixed position within a cylinder and the protrusion of electrodes which disturb the cylinder geometry and can quench the flame kernel. Laser radiation is non-invasive and has greater flexibility in terms of the ignition position, allowing the possibility of multi-point ignition [6]. Other potential benefits of LI include reduced emissions, faster ignition, more stable combustion, lower idle speeds, and better cold engine performance when compared to conventional SI.

Multi-point LI is one of the key potential advantages that LI can offer over conventional spark ignition (SI). Previous research found that multi-point ignition produced more stable and faster combustion [7]–[8]. This paper demonstrates a diffractive multi-point LI technology which is experimentally attempted by Liverpool University Laser Group. Air breakdown sparks with arbitrary geometrical location in three dimensions are created by diffractive multi-beam through an optical plug. The diffractive multi-beam patterns are generated using a spatial light modulator (SLM) on which computer generated holograms (CGHs) are displayed. A Gratings and Lenses (GL) algorithm is used to accurately modulate the phase of the input laser beam and create multi-beam output.

2. Experimental and methodology

Fig. 1. Experimental setup

The laser used was a ‘Mini-Q’ flashlamp pumped Q-switched Nd :YAG, manufactured by GSI Group, operating at the fundamental wavelength of 1064 nm. Schematic of the experimental setup is shown in figure 1. The laser output ($t_p = 10$ ns, $\lambda = 1064$ nm) passed through a half wave plate used for adjusting the linear polarization direction, a beam
expander ($M \approx \times 4$), and then illuminated a reflective SLM, oriented at <10 degree angle of incidence. The model of the SLM is HOLOEYE LC-R 2500, which is a liquid crystal on silicon (LCoS) device with 1024 × 768 pixels and broad band coating for visible and near infrared (reflectivity $\eta > 80\%$). Computer Generated Holograms (CGH) were displayed on the SLM to create diffractive multi-beam patterns. The multi-beam pattern then reached an optical plug (as shown in figure 2(a)) and focused by a 2mm thick sapphire plano convex lens ($f = 12$mm) to generate multiple focal points. Multiple sparks were created when the electrical field of the focused laser beams is sufficient to cause dielectric breakdown of the air (i.e. the laser irradiances in excess of $10^{11}$ W/cm$^2$[9]).

![Photograph of optical plug](image1)

![Photograph of a disassembled optical plug](image2)

Fig. 2(a). Optical plug

The structure of optical plug is slightly different from the previous design by the laser group at University of Liverpool [5]. A protection sapphire window was previously placed in front of the plug lens. However, during the laser ignition process, the lens sometimes could be damaged by the back reflection from the window. Also, since the window was place at the front of the plug, it was always dirtied by the ignition processing inside an engine cylinder. The self-cleaning [5] could only clean a small central area on the window. As shown in figure 2(a), the protection window was not used in the current plug design. Figure 2(b) shows a comparison between the protection window (from the previous design) and the sapphire plano convex lens (from the current design) after laser ignition tests. The result from laser ignition tests demonstrates that with the current design the plug lens was never damaged and kept clean after over 20 hours ignition process.

![Comparison between the protection window and the sapphire plano convex lens](image3)

Fig. 2(b). Comparison between the protection window (from the previous design) and the sapphire plano convex lens (from the current design) after laser ignition tests
The CGHs used to create diffractive multi-beam patterns were calculated by a Gratings and Lenses (GL) algorithm [10] [11]. By combining the phase of basic optical components, prisms or gratings (producing lateral shifts) and lenses (producing axial shifts), the GL algorithm can generate three-dimensional arbitrary multiple beam patterns. Due to the fast calculation speed and the high calculation accuracy, the GL algorithm has been widely used to create multiple beams for multi-point optical trapping [11] [12] and high precision ultrafast laser material parallel processing [13]-[16].

3. Results and discussions

3.1 Multi-beam pattern creation by superposition of prism phases

If the hologram plane has an inclined phase front, the spot in the image space will be laterally displaced from the optical axis. This is equivalent to passing the light through a prism with a small angle that introduces a linearly increasing phase delay \( \phi_{\text{prism}} \) across the beam. The prism phase at the hologram plane required to produce a lateral shift \((\Delta x, \Delta y)\) in the position of the focused spot is given by:

\[
\phi_{\text{prism}}(x, y) = \alpha (\Delta x \alpha + \Delta y \beta)
\]

where \( \alpha \) is a coefficient that depends on the imaging characteristics and wavelength. To generate diffractive multiple beams with lateral shifts, the phase at the hologram plane, \( \phi_h \), should be the complex superposition of the prism phases, each of which shifts a focused spot onto one of the requested positions, \((\Delta x_i, \Delta y_i)\), as shown in figure 3. Accordingly, \( \phi_h \) can be expressed as:

\[
\phi_h = (\phi_{\text{prism}-1} + \phi_{\text{prism}-2} + \cdots + \phi_{\text{prism}-n}) \mod 2\pi = (\sum_{i=1}^{n} \phi_{\text{prism}-i}) \mod 2\pi
\]

Fig. 3. Diffractive multiple laser beams generated by complex superposition of prism phases [17]

The distance of lateral shift, \( \Delta l \), is defined by the diffractive angle, \( \theta \). According to the grating equation, \( \theta = \lambda / A \), where \( \lambda \) is the wavelength of the input laser beam (1064nm) and \( A \) is the grating period. Since the size of the SLM pixel is \( ~20\mu\text{m} \), the minimum grating period \( A_{\text{min}} > 2\text{pixels} \approx 40\mu\text{m} \), hence the maximum diffractive angle, \( \theta_{\text{max}} < 0.025\text{rad} \approx 1.4\text{degree} \). Since the sapphire plano convex lens \( (f = 12\text{mm}) \) in the optical plug was used to focus the diffractive beams, the maximum lateral shift, \( \Delta l_{\text{max}} \approx 2 \tan \theta_{\text{max}} \approx 0.6\text{mm} \).
A CGH shown in figure 4 was displayed on the SLM to create 6 diffractive beams with a same diffractive angle, \( \theta = 0.01 \text{rad} \). At the focal plane of optical plug lens, the lateral shift of each diffractive beam to 0\(^{th}\) order beam (i.e. the non-diffracted beam) was \( \Delta l = 2 f \tan \theta \approx 0.24 \text{mm} \). When the total input laser pulse energy reached ~60mJ, the focused multiple beams started creating air-breakdown sparks. Figure 5 (a) shows a photograph of air-breakdown sparks created by the 6 diffractive beams and the non-diffracted 0\(^{th}\) order beam. Since the lateral shift, \( \Delta l \approx 0.24 \text{mm} \), was smaller than the size of the sparks, it is not possible to see any separation among the sparks created by different beams in the photograph.

A lens with \( f = 300 \text{mm} \) was then used to focus the multiple beams instead of the optical plug lens. Thus, the lateral shift to 0\(^{th}\) order beam increased to \( \Delta l = 2 f \tan \theta \approx 6 \text{mm} \) at the focal plane of the lens. Figure 5 (b) shows that these multiple beams breakdown the surface of a flat paper at the focal plane of the lens. The bright spot in the centre was created by the non-diffracted 0\(^{th}\) order beam, while the other 6 bright spots with a geometrical shape perfectly matched the computational reconstruction of the CGH (in figure 4) were created by the diffractive beams, as shown in figure 5(b).

### 3.2 Multi-beam pattern creation by superposition of Fresnel lens phases

To also axially shift each of the focal spots in the image space, an additional lens phase should be added, hence obtaining multiple beam patterning in three dimensions. The lens phase can be given as:

\[
\phi_{\text{lens}}(x, y) = -\frac{k}{2f} (x^2 + y^2)
\]

where \( f \) is a function of the axial shift distance and \( k = 2\pi / \lambda \) is the wave number of the light. This is equivalent to passing the light through an additional lens with focal length, \( f \). With both prism and lens phases added, the focussed spots are displaced not only laterally and but also axially, i.e. three-dimensionally. The phase of the beam at the hologram plane is required to be the (modulus 2\(\pi\)) sum of \( \phi_{\text{prism}} \) and \( \phi_{\text{lens}} \):

\[
\phi' = \left[ \sum \phi_{\text{prism}} + \phi_{\text{lens}} \right] \mod 2\pi
\]
As shown in figure 6, only the diffracted beams were converged ($f > 0$) or diverged ($f < 0$) by the added Fresnel lens phase, while the non-diffracted $0^{th}$ beam was unaffected hence creating an axial shift, $\Delta d$, as shown in figure 6. The following beam matrix equation describes the propagation of the diffracted beam from the Liquid Crystal on Silicon (LCoS) surface (A) to its focal plane (B),

\[
\begin{pmatrix}
X_A \\
\text{tg} \theta_A
\end{pmatrix} = 
\begin{pmatrix}
1 & d_z \\
0 & 1
\end{pmatrix}
\begin{pmatrix}
1 & 0 \\
-\frac{1}{f_1} & 1
\end{pmatrix}
\begin{pmatrix}
1 & d_i \\
0 & 1
\end{pmatrix}
\begin{pmatrix}
1 & 0 \\
-\frac{1}{f_i} & 1
\end{pmatrix}
\begin{pmatrix}
X_A \\
\text{tg} \theta_A
\end{pmatrix}
\]

where, $f_1$ and $f_2$ are the focal length of the added Fresnel phase lens and the optical plug lens respectively; $X_A$ and $X_B$ are the distances of the beam from the axis; $\text{tg} \theta_A$ and $\text{tg} \theta_B$ are the gradients of the beam with respect to the axis at the position A and B, respectively. Since $\text{tg} \theta_B = 0$ and $X_A = 0$, the axial shift ($\Delta d$) can be calculated by the following equation derived from the beam matrix equation:

\[
\Delta d = |d_2 - f_2| = \frac{|f_1 f_2 - f_d d_1|}{|f_1 + f_2 - d_2|}
\]

where $d_1 \approx 100$mm was the distance between the SLM and the $f$-theta lens, and $f_2 \approx 12$mm was the focal length of the optical plug lens.

![Fig. 6. Schematic showing the method to create axial shifts to zero order beam. The added Fresnel lens phase, lens 1, can work as either positive lens (upper) or negative lens (lower) to obtain the axially shift, $\Delta d$. The beam matrix equation describes the propagation of diffracted beam from LCoS surface (A) to its focal plane (B) [15].](image)

As shown in figure 7, three air breakdown sparks were created by axial shifts. The CGH was generated by superimposing two Fresnel lens phases. Each lens phase created a focal spot with an axial shift, $\Delta d$ ($\Delta d \approx 5$mm and 10mm). The spark near the plug was created by the non-diffracted $0^{th}$ order beam. The total input pulse energy was $\sim 40$mJ. The energy distribution between the diffracted and non-diffracted beam can be adjusted by rotating the half wave plate (i.e. changing the diffractive efficient). The distance of axial shift can be easily changed by varying the focal length of each added Fresnel lens phase, as shown in figure 8.
4. Conclusion and future work

This paper demonstrates a creation of multi-point air breakdown which could be used to improve the performance of Laser Ignition (LI). Air breakdown sparks with arbitrary geometrical location in three dimensions are created by diffractive multi-beam through an optical plug. The diffractive multi-beam patterns are generated using a Spatial Light Modulator (SLM) on which Computer Generated Holograms (CGHs) are displayed. A Gratings and Lenses (GL) algorithm is used to accurately modulate the phase of the input laser beam and create multi-beam output.
Online engine laser ignition tests will be carried out using the created diffractive multi-beam patterns. The geometric layout of the multi-beam pattern will be dynamically controlled during each combustion cycle to improve the engine performance.

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