Ultrafast Imaging of a Gas Turbine Spark Igniter

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1. Introduction

Experimental and computational techniques for the visualization of fluid flows have emerged as essential tools for increasing our understanding of the physics and chemistry of these flows. Indeed, many—if not most—of the breakthroughs in fluid mechanics and dynamics can be attributed to the understanding achieved through imaging of the various multidimensional structures in fluid flow. Flow visualization has played a powerful role in the process of validating computational models through comparisons of experiment and theory. For example, the development and validation of the UNsteady Ignition and COmbustion with Reactions (UNICORN) code at Wright-Patterson Air Force Base have been achieved through continuous improvement and refinement based on comparisons with experimental flow-visualization data.[1]

Spark-ignition systems play a critical role in the performance of essentially all gas turbine engines. Demanding applications such as cold start and high-altitude relight require continued enhancement of ignition systems. To characterize advanced ignition systems, we have developed a number of laser-based diagnostic techniques designed to exploit an ultrafast-framing charge-coupled-device (CCD) camera and high-repetition-rate laser sources including modelocked Ti:sapphire oscillators. Spontaneous-emission and laser-schlieren measurements have been accomplished with this instrumentation and the results applied to the study of a novel Unison Industries spark igniter that shows great promise for improved cold-start and high-altitude-relight capability as compared to that of igniters currently in use throughout military and commercial fleets.

The behavior of a spark igniter represents an ideal case study for the demonstration of ultrafast real-time imaging. Our experiments have been designed to exploit laser schlieren for visualizing refractive-index gradients in the flowfield produced during firing of the spark igniter. These simple schlieren experiments are straightforward to implement and require only a high-repetition-rate laser source for generation of the signal. The spatial variation in spark location from event to event limits the applicability of techniques that utilize a two-dimensional light sheet for illumination. Schlieren yields a line-of-sight image that captures the spark despite variations in position and morphology.

Early developments in real-time imaging based on flashlamp-pumped sources and modelocked lasers coupled with analog recording devices have been reviewed by Sklizkov.[2] Hanson and coworkers[3-6] accomplished instantaneous three-dimensional visualization of combusting flowfields by sweeping a single high-energy laser sheet through the flow using a scanning mirror and capturing a sequence of planar slices using a fast-framing camera system. More recently, Ben-Yakar and Hanson[7] developed an ultra-high-speed schlieren system to study cavity flameholders for ignition and flame stabilization in scramjets. Long and coworkers[8-10] explored high-speed digital imaging of turbulent flows, recording time-evolving digital images of gas concentrations and instantaneous three-dimensional fuel-concentration profiles through Mie scattering and biacetyl-fluorescence techniques. Lempert, Wu, and Miles[11,12] recently applied a megahertz-rate, pulse-burst laser system and a Princeton Scientific Instruments (PSI) ultrafast-framing camera to study supersonic shock-wave/boundary-layer interactions through images obtained via filtered Rayleigh scattering. Finally, at the Lund Institute of Technology, Kaminski and coworkers[13] have utilized high-speed visualization to study the effects of turbulence on spark-kernel evolution through PLIF measurements.

2. Experimental Apparatus

Spark events produced by a Unison Industries Vision spark-ignition system were visualized using an ultrafast real-time imaging system. The Vision system, which is utilized in both military and commercial aviation, is designed to produce a tailored ignition spark at the tip of the igniter plug through delivery of a pulse (nominal energy 4-12 J) from the Vision-system igniter box. The plug tip is composed of a ring electrode encompassing a center electrode. Upon delivery of the igniter-box pulse, an arc occurs across the center-electrode/ring-electrode

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gap. Because the location and physical characteristics (morphology, etc.) of this arc can vary from shot to shot, an ultrafast real-time imaging system is required to capture the detailed time-dynamics of the process. If the spark event were highly reproducible from shot to shot, phase-locked imaging could be applied rather than the real-time approach described below.

Laser-schlieren techniques were employed to visualize propagation of the shock produced during firing of the Unison Industries Vision-system spark igniter. The characteristics of the spark event demand high temporal resolution and ultrafast real-time imaging for capture of the physics of interest. To accomplish the required temporal resolution, two different high-repetition-rate laser sources were considered. The first is the Spectra-Physics "Merlin" intracavity-frequency-doubled Nd:YLF laser, and the second is the Spectra-Physics "Tsunami" mode-locked Ti:sapphire laser.

The Merlin laser is a Q-switched Nd:YLF laser that operates at kilohertz repetition rates. The device installed at Wright-Patterson Air Force Base is configured for 50-kHz operation and produces a 13-W pulsetrain (260 μJ/pulse) at 527 nm through intracavity doubling of the Nd:YLF fundamental in lithium triborate (LBO). The multi-mode output beam provides a uniform spatial beam profile ideal for flow-visualization applications. While the Merlin's high spectral brightness and mode characteristics proved to be excellent for studies of the spark igniter, its repetition rate proved to be insufficient for resolving the shock phenomena of interest. This situation motivated a series of studies that employed the pulse-selected Tsunami as an excitation source.

The Tsunami modelocked Ti:sapphire laser employed in these studies is configured to produce an 82-MHz pulsetrain, spectrally tunable over the wavelength range 800-900 nm. Experiments were accomplished at 850 nm for all cases described here. When pumped by the 5-W, 532-nm output of a Spectra-Physics Millennia V intracavity-doubled (LBO) $Nd:YVO_4$ laser, the Tsunami provides ~1 W output power (12 nJ/pulse). The 82-MHz repetition rate is excessive for imaging the spark igniter while using the 1-MHz ultrafast framing camera described below; therefore, the repetition rate of the modelocked Ti:sapphire laser is reduced using a Spectra-Physics Model 3980 pulse selector. This device employs a TeO_2 acousto-optic modulator to select subsets of pulses from the full 82-MHz output pulsetrain. Losses in the pulse selector reduce the laser energy to 8 nJ/pulse.

Laser-schlieren images of the Unison Industries spark igniter were captured using a PSI ultrafast framing camera. This device features a CCD image sensor that can be exposed at rates up to 1 MHz and provides an on-chip storage array for 32 images. The array associated with the camera employed in these experiments is 180x90 pixels.

3. Data-Acquisition Strategies and Results

A number of configurations for experimental visualization of the spark igniter via ultrafast real-time imaging were explored. Preliminary experiments were designed to capture the spontaneous emission produced during firing of the spark igniter. Synchronization and timing of the various experimental events were achieved easily during these experiments. The camera was configured with an appropriate lens and placed to view the tip of the spark-igniter plug. In addition, a photodiode was arranged to collect light from the spark-ignition event. The camera was configured in the pre-trigger mode in which data frames are acquired continuously and processed through the on-chip storage array in a first-in-first-out (FIFO) arrangement. The spark igniter was fired via user-entered commands to a personal computer that was driving the Unison exciter box and the spark plug itself. The signal produced at the photodiode was employed to trigger the camera, terminating data acquisition in the pre-trigger mode and capturing the spark-igniter-image data in the on-chip storage array.

Laser-based schlieren studies of the spark igniter required a more sophisticated experimental arrangement, with greater attention to the details of synchronization and timing. Three unique strategies for schlieren-data acquisition were explored. In the first approach, the Merlin Q-switched Nd:YLF laser provided light for the schlieren measurements, and the 50-kHz laser served as the master oscillator for the experiment. The ultrafast framing camera was configured in the "multi" external trigger mode, with triggers being supplied by the spark-igniter event and the laser. Under these conditions, 32 frames of camera data were acquired in synchrony with the laser during the 640-μs period spanning the spark event. This approach provided tremendous optical energies and saturating signals at the camera; therefore, neutral-density filters were inserted into the optical path to attenuate the laser beam. Unfortunately, the 50-kHz repetition rate of the laser proved insufficient to resolve the progress of the spark-initiated shock wave adequately.

This situation prompted experiments conducted via the second approach in which the pulse-selected Tsunami Ti:sapphire laser was utilized for production of the schlieren signal. As in the previous experiments, the laser served as the master oscillator, and the camera was slaved to the laser and the spark event via the "multi" external trigger mode. This arrangement permitted the acquisition of image data at framing rates up to 800 kHz, improving the temporal resolution over that achieved in the Merlin experiments by a factor of sixteen.

The third and final approach, however, produced the optimum visualization and enabled spark imaging at the full 1-MHz data-acquisition bandwidth of the camera. For these experiments, the camera served as the master oscillator, and the pulse selector—and, therefore, the laser—were slaved to the camera. A block diagram of the experimental apparatus is depicted in Figure 1. The Millennia/Tsunami/pulse selector provide the laser pulse for schlieren measurements. The output pulsetrain is expanded to a nominal diameter of ~32 mm through two 4x telescopes. The collimated, expanded laser beam traverses a sample region in which the spark-igniter plug is suspended. A lens collects the transmitted light, which is focused to a point where a knife edge is inserted. Light traveling past the knife edge is imaged through a neutral-density filter (ND=1) and an interference filter (center frequency=850nm, bandwidth=10 nm) onto the ultrafast framing camera using a Nikon lens.

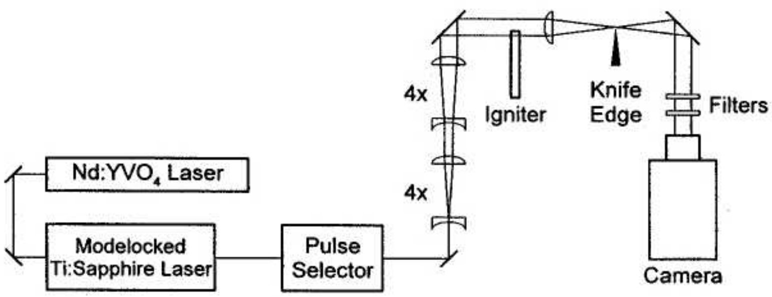

Figure 1. Experimental apparatus for ultrafast real-time laser-schlieren imaging of a Unison Industries spark igniter.

Details of the synchronization and timing are presented schematically in Figure 2. The ultrafast framing camera is configured in the post-trigger mode and, therefore, acquires images continuously until a spark event occurs. The spark event is initiated by the experimenter through entry of commands at the personal computer. These commands trigger the Unison exciter box, firing the spark plug and producing a trigger via the remote module that drives a digital delay generator (DDG). This DDG triggers the camera. Once the camera is triggered, it acquires and stores the 32 images that comprise the final data set. Trigger delays are carefully adjusted to ensure that the frames are acquired during the spark event. Once triggered, the camera is responsible for driving the pulse selector and synchronizing the laser with the image-acquisition process. The camera is configured to record images at its full 1-MHz acquisition rate. During each frame, the camera generates a vertical-strobe pulse that drives the pulse selector. This strobe pulse is shaped and further processed with a pulse generator and then mixed with the ~41-MHz signal from the Ti:sapphire modelocker. This process ensures that a single laser pulse is selected from the 82-MHz pulsetrain during the exposure time associated with each of the 32 camera frames. The vertical-strobe-driven pulse generator can be adjusted to select an envelope of pulses from the 82-MHz train during each framing event. For example, experiments were accomplished with 10 and 100 laser pulses per frame; however, the data presented in this paper were achieved with a single pulse for each frame. Those data, depicting the propagation of the spark-initiated shock, are presented in Figure 3.

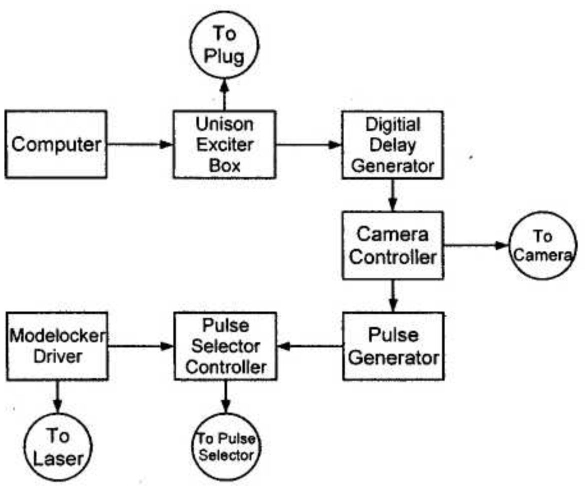

Figure 2. Diagram of electronic timing connections for ultrafast real-time laser-schlieren measurements.

4. Conclusions

Ultrafast real-time imaging of the shock structure produced by a Unison Industries spark igniter has been accomplished. Spontaneous-emission and laser-schlieren techniques have been demonstrated in conjunction with a number of high-repetition-rate laser sources (50-kHz, Q-switched Nd:YLF laser; pulse-selected, 82-MHz modelocked Ti:sapphire laser) and an ultrafast-framing CCD camera (framing rates up to 1 MHz). Future activity will be focused on applying the ultrafast methodology to measurements of other key spark parameters through the use of various advanced laser-based diagnostics including PLIF and planar Rayleigh scattering.

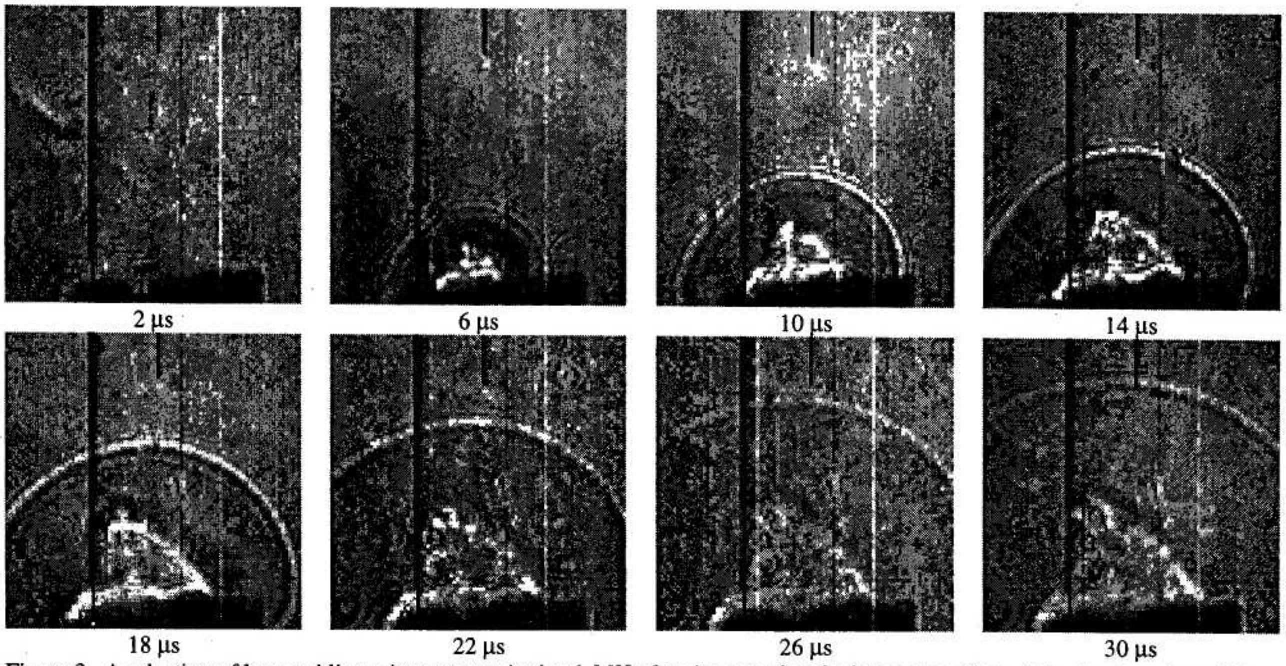

Figure 3. A selection of laser-schlieren images acquired at 1-MHz framing rate that depicts propagation of the shock produced during firing of the Unison Industries spark igniter.

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