Preliminary Development of a Nearly-Instantaneous Three-Dimensional Imaging Technique for High-Speed Flow Fields

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Recent advances in high-repetition rate laser and camera technology present a new opportunity to develop three-dimensional diagnostics for high-speed flows. The design of a three-dimensional imaging system based on a pulse burst laser, a high-speed laser scanner and a high speed camera is described here. The pulse burst laser system is the 5th of its kind in the world and can produce high energy pulses at up to 10 MHz repetition rates. A high-speed optical deflector, such as a rotating mirror or acousto-optic deflector, can be used to rapidly deflect a laser sheet through the flow field. A high-speed camera can then be used to collect images at different planes in the flow field, from which a three-dimensional image can be reconstructed. The state-of-the-art of these technologies are described. The high-speed characteristics of an acousto-optic deflector were tested using an Nd:YAG laser where it was found that a full sweep through at least 32 resolvable spots could be completed in 10 μsec. Future work will include testing of a galvanometric scanning mirror and assembly of a complete system.

I. Introduction

The ability to make three-dimensional flow measurements is highly desirable as many flows of practical interest are characterized by unsteady, three-dimensional flow phenomenon such as turbulence and shocks. For high-speed flows, the technique must be capable of acquiring data in a matter of a few microseconds for the measurement to be considered instantaneous. Over the last few decades, the pursuit of high-speed 3-D flow diagnostics has been bolstered by advances in laser and camera technology, but broad application of these techniques have been limited by the specialized equipment necessary for their implementation. Recent advances in high-repetition rate laser and camera technology, however, have made much of this equipment more readily available. This presents a renewed opportunity to develop 3-D flow diagnostics that have the potential to expand their application to a greater number of fluid dynamic problems. The Advanced Laser Diagnostics Laboratory at Auburn University has recently launched an effort to develop a laser-scanning 3-D imaging technique based on a 3rd generation MHz rate pulse burst laser system, a commercially available high-speed camera and a high-speed scanner. *This paper discusses some of the basic concepts of 3-D laser scanning flow diagnostics and presents the design and preliminary development of a high-speed 3-D imaging system.*

A number of efforts have been made over the years to develop 3-D flow measurement systems. These include stereographic,[1] holographic,[2-4] tomographic,[5] and laser sheet scanning[6-15] methods. In principle, stereographic, holographic and tomographic based techniques are capable of acquiring instantaneous, three-dimensional flow data, but practical implementation is limited by complex and sensitive optical set-ups, restricted optical access in flow facilities, limited camera resolution, costs, and various other factors. The approach that has received the most attention and is adopted in this effort is laser scanning flow visualization. In this technique, a laser beam, formed into a sheet using cylindrical lenses, is scanned through the flow field using an optical deflector, such as a rotating mirror. As the laser sheet passes through the flow field, a sequence of images at different planes in the flow field is acquired. A 3-D image can then be reconstructed from the stack of images. A significant advantage to this method is that it can utilize many of the measurement concepts and principles already developed for conventional planar techniques, such as particle image velocimetry (PIV) and planar laser induced fluorescence (PLIF). For the most

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part, the application of 3-D diagnostics has been restricted to low-speed flows (< 1 m/s) due to the limited repetition rate of available lasers and cameras.

For high-speed flow applications, Long and Yip[7] and Yip et al.[8] used a resonant scanning mirror to deflect the output of a dye laser with a 1.4 μsec duration pulse through the flow field. During the sweep of this single pulse, 12 images, each with a resolution of 58 x 120 pixels, were acquired with an electronic framing camera operating at 10 MHz framing rate. This technique was improved upon by Patrie et al.[9] using a higher energy pulsed dye laser (10 J/pulse), a 12 sided polygonal mirror rotating at 500 Hx and a camera capable of acquiring 20 images at a resolution on the order of 120 x 90 pixels for each image. Island et al.[11] subsequently used the technique to perform the first instantaneous 3-D flow visualization of a supersonic flow.

Hult et al.[14] used a cluster of four double-pulse Nd:YAG lasers, a galvanometric scanning mirror and an eight CCD (i.e. 8 frames) high-speed camera to obtain a sequence of eight images (576 x 285 pixels each) in a 15 m/s reacting flow field over a timespan of ~88 microseconds. Their technique utilized laser-induced incandescence to measure soot volume fractions in a flame. Although not as fast as the previously mentioned technique, the advantage of their approach was the use of pulsed (~10 nsec duration) Nd:YAG lasers whose output can be more efficiently converted to 2nd, 3rd and 4th harmonics and is used in a large number of existing planar techniques. In both techniques, the speed, resolution and maximum number of frames of the high-speed camera as well as the capabilities and flexibility of the laser system were limiting factors.

Recently, the availability of high repetition rate lasers has increased significantly with the development of a MHz rate Nd:YAG pulse burst laser system.[16-19] Currently, there are five systems in operation with construction of the most recent system nearing completion at the Advanced Laser Diagnostics Laboratory at Auburn University.[20] This laser represents a 3rd generation design and has been modified to operate over a broader range of repetition rates (from 10 kHz to 10 MHz) with more uniform pulse energy distribution over the burst. It should also be noted that one of the systems currently in use was acquired commercially as a custom product. This indicates that any techniques developed based on the pulse burst laser system have the potential to reach and be used by a much broader group of researchers beyond that of the laboratory in which it was developed. In addition, since these early 3-D imaging systems were developed, the number of high-speed camera manufacturers has increased significantly and high-performance, high-speed cameras are much more readily available than previously. The goal of the current program is to develop a high-speed 3-D imaging technique based on these recent technological advancements.

II. High-Speed 3-D Imaging Technique

The high-speed 3-D imaging technique currently being developed by the ALDL is illustrated in Figure 1. A pulse burst laser system is used to create a burst of high-energy (10 – 100 mJ/pulse), high-repetition rate (up to 10 MHz), short duration (20 nsec) laser pulses. Each laser pulse is subsequently deflected along a different path by a high-speed optical deflector and formed into a sheet using cylindrical lenses. Particle scattering (e.g. Mie Scattering from smoke or particles for PIV measurements) and fluorescence (e.g. acetone fluorescence for density measurements) are possibilities for visualization of the flow with images captured by a high-speed digital camera. The sequence of planar images can then be reconstructed into a single 3-D image with exposure time dependent on the speed of each of the components. The fundamental components are the pulse burst laser system, the optical deflector and the high-speed camera. Presently, development of the overall system is in the very early stages; the main components of the system, however, are fairly well developed and will be described here. *The main focus of this paper is on describing the overall design of the 3-D imaging system, particularly with respect to the individual components that will enable this technique to be successfully developed and applied.* Future work will focus on proof-of-concept demonstrations and characterization of the overall system.

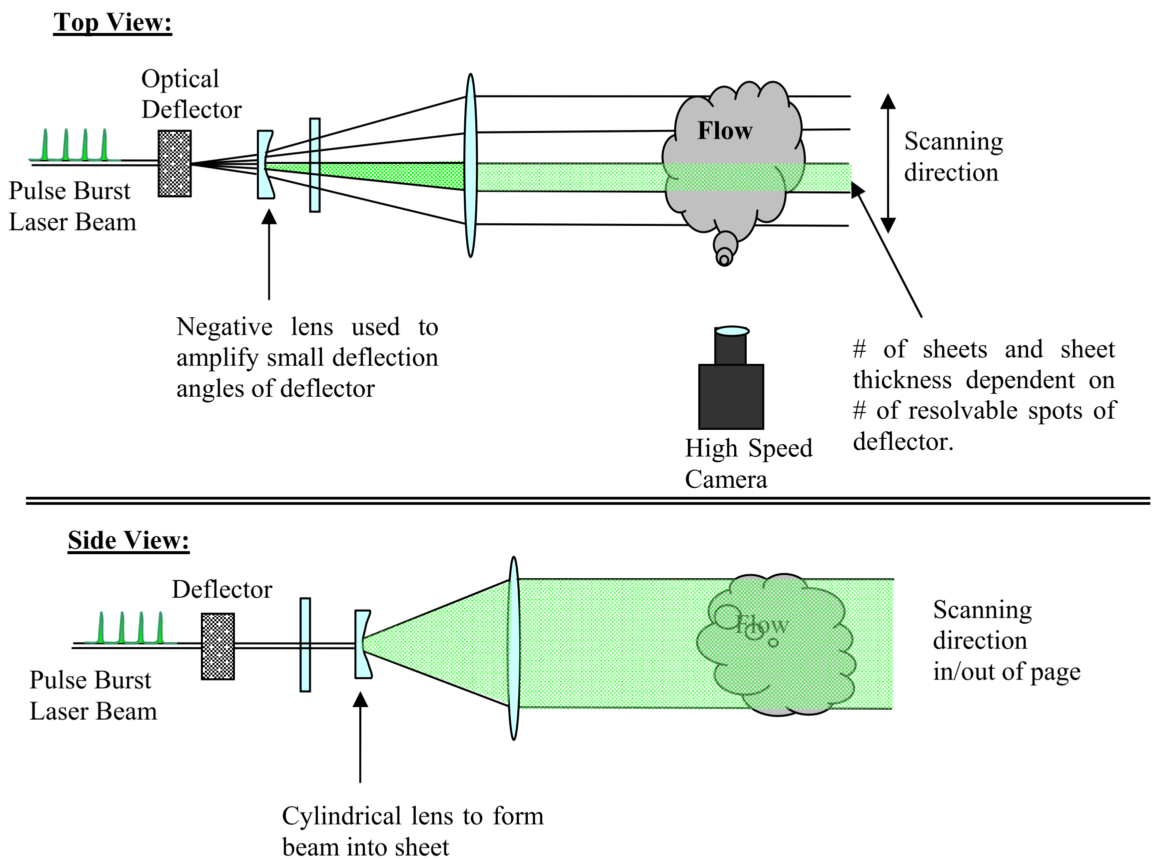

Figure 1 – Schematic of proposed volumetric flow measurement system.

A. Pulse Burst Laser System

The construction of a 3rd generation pulse burst laser system is currently near completion at the ALDL. Details of the design and preliminary results were recently presented in Thurow and Satija[20] with a brief description given here. The system is similar in design to systems described by Lempert et al.[17], Wu et al.[19] and Thurow et al.[19] The pulse burst laser achieves high repetition rates by slicing a burst of pulses from the output of a continuous wave (cw) Nd:YAG laser. In previous designs, the slicing was achieved using a pair of high repetition rate Pockels cells. In the current design, the slicing is achieved using an acousto-optic modulator (AOM). Figure 2 presents a schematic of the AOM pulse slicer arrangement. The cw laser has an average power of 100 mW; the sliced pulses, being 10-20 nsec long, thus only contain ~1 nJ of energy at this stage. Originally, the spatial filter was incorporated to increase the contrast ratio of the pulses to the background with preliminary measurements indicating contrast ratio on the order of 15,000:1 immediately after the spatial filter. More recent measurements taken after passage through the entire system indicate improved contrast ratios of ~60:000:1 with or without the presence of the spatial filter. As the primary source of background light intensity is off-axis scattering of laser light from impurities within the AOM crystal, it is believed that the increased path length and presence of numerous apertures in the system helps to filter out this source of noise. Thus, the spatial filter has been removed from the system.

The use of an AOM for pulse formation also provides more flexibility than with Pockel cells as repetition rates in excess of 10 MHz are possible. Previous designs were limited to 1 MHz by the drive electronics. This is significant with respect to 3-D imaging as this should allow for higher scan rates and subsequently faster measurements. Lastly, and perhaps more importantly, it should be noted that an AOM is an order of magnitude cheaper than a pair of high repetition rate Pockels cell.

To achieve higher pulse energies, the burst of low energy pulses produced by the pulse slicer is passed through a sequence of three flashlamp pumped Nd:YAG rod amplifiers. The amplifier system was built by LaserPath Technologies (Oviedo, FL) and designed for a total system gain of ~10^7. It consists of three double-pass amplifiers with rod diameters of 4, 5 and 6.35 mm, respectively. Preliminary measurements provided by LaserPath using a single 1 nJ input pulse indicate amplification of 10^7, thus yielding ~10 mJ/pulse. A key improvement over earlier designs is the extension of the gain envelope duration to ~1 msec from 0.15 ms in earlier systems. This will allow for the burst of pulses to be created over a longer period of time, increasing the range of applications that the laser is suited for. This could be significant in the development of a 3-D PIV system where two 3-D images need to be acquired over a short timespan. The power of the system can be increased by adding more amplifiers to the system with pulse energies in excess of 100 mJ/pulse having already been demonstrated in other systems.

Overall, the utility of the pulse burst laser system is similar to that of other Nd:YAG laser systems and has been demonstrated for both MHz rate PIV[21] and planar Doppler velocimetry[22] measurements. The fundamental output of the laser system is at a wavelength of 1.064 microns. 2nd harmonic generation at 532 nm using a Type II KTP non-linear crystal has been demonstrated with 40-50% efficiency. 3rd (355 nm) and 4th (266 nm) harmonic generation are also possible with expected efficiencies on the order of 20-25%; this opens up the possibility of various fluorescence measurements, such as acetone 3-D LIF.

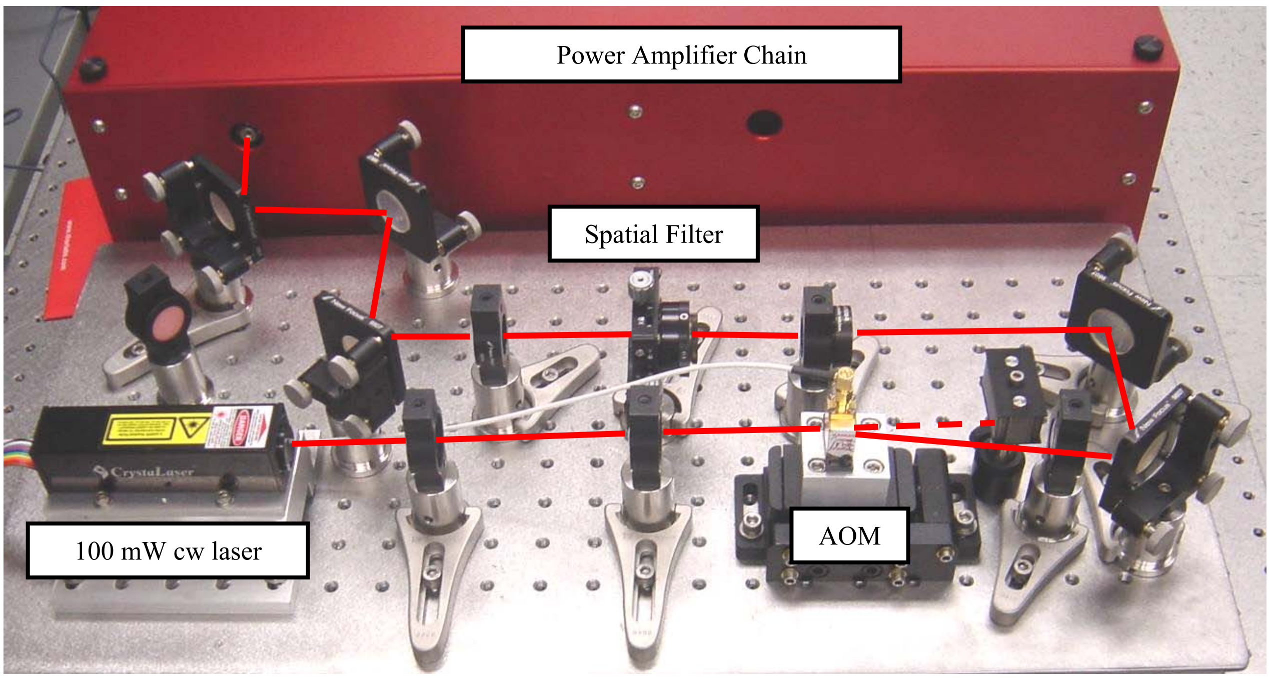

Figure 2 – Photograph of AOM pulse slicer arrangement.

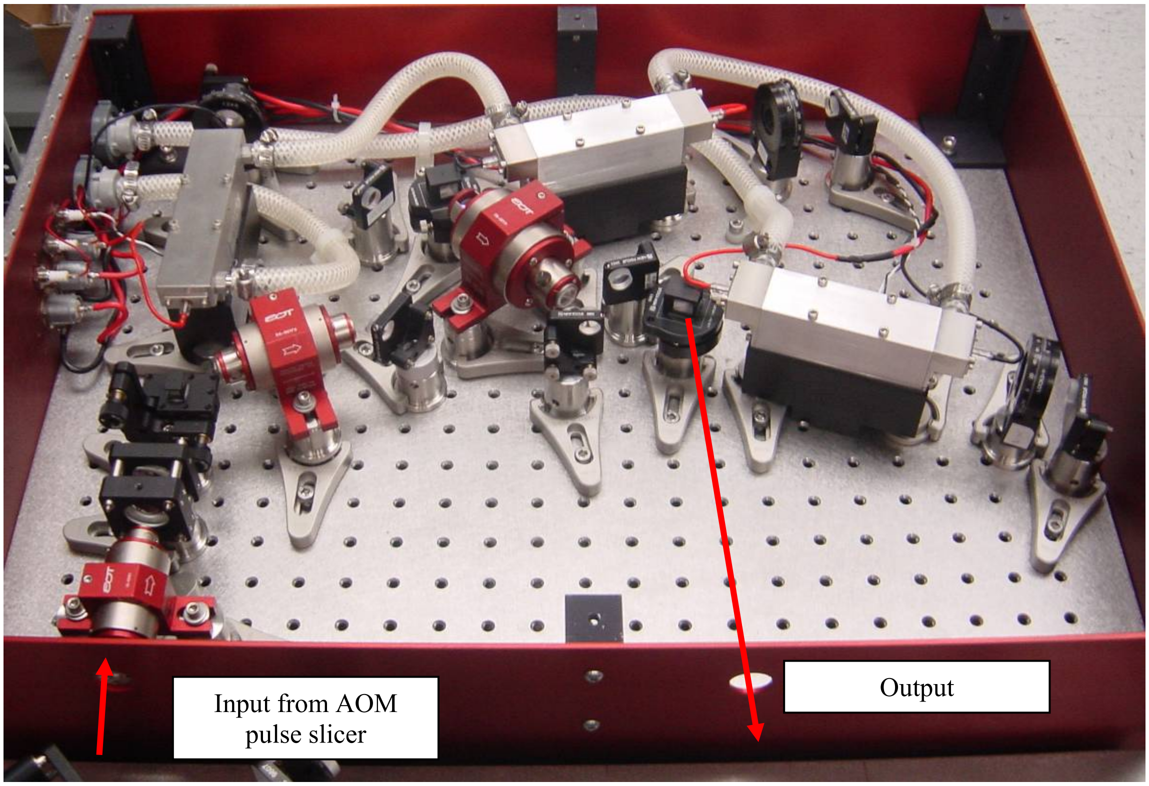

Figure 3 – Photograph of power amplifier chain for AU pulse burst laser system.

B. Laser Scanning

For 3-D imaging, the output of the pulse burst laser system must be rapidly deflected to produce laser sheets along different planes in the flow field. A number of methods are available to do this and include rotating/galvanometric scanning mirrors, acousto-optic deflectors and electro-optic deflectors. Each of these technologies will be considered here. The performance of any scanner can be characterized by the number of resolvable spots, the deflection efficiency, the slew rate and the random access time. The number of resolvable spots, N, is the number of discrete angles, or positions, that the scanner can access over its full range. This is given by:

$$N = \frac{\Delta\alpha}{\Delta\phi} \tag{1}$$

where $\Delta\alpha$ is the total deflection angle of the device and $\Delta\phi$ is the total angular spread of the incident beam. For a Gaussian laser beam, the minimum angular spread is given as:

$$\Delta\phi = 1.27\frac{\lambda}{D} \tag{2}$$

where λ is the wavelength and D is the beam's diameter. Thus, each laser pulse must be deflected by $\Delta\phi$ in order to obtain a distinctly new position. From this standpoint, a larger aperture device is preferred.

The slew rate characterizes the rate at which the deflection angle can change and can be represented by an angular velocity or number of spots accessed per unit time. The random access time is the time it takes for deflector to go from one arbitrary position to another arbitrary position. For rotating mirrors, each spot must be accessed in sequential order and thus a linear sweep can lead to high slew rates. Random access times, however, will be quite long due to the inability of the mirror to reverse directions quickly. Acousto-optic and electro-optic deflectors, on the other hand, are not constrained by mechanical motion and can achieve both high slew rates and short random access times. For 3-D imaging, a short random access time may provide a benefit as it would allow for a randomized sequence of laser sheet locations, which could help minimize any bias resulting from a linear sweep of the sheet. This would also allow a quick repeat of the laser scan to allow 3-D images to be taken in rapid succession. This type of scanning may be required for PIV measurements or time-resolved 3-D measurements.

In the selection of a suitable scanner for the current application, the capabilities of the overall system must be considered. While the pulse burst laser is capable of higher speeds, the camera expected to be used in this system has a maximum framing rate of 1 MHz over a total of 32 frames. Thus, we would like to select a scanning device with at least 32 resolvable spots and a slew rate of 1 spot per microsecond (i.e. 1 MHz). A high deflection efficiency, short random access time, optical damage threshold, device timing and cost are also important parameters that must be considered. In the following analysis, a 6 mm diameter laser beam at 532 nm with 100 mJ/pulse of energy will be considered. This corresponds to an angular spread of ~89 μrad and an optical power density of ~ 18 MW/cm^2 (0.35 J/cm^2) for a 20 nsec pulse. Thus, to a achieve 32 spots in 32 μsec, a scanner must deflect the beam at a rate of at least 89 rad/sec (14 Hz) over a total angle of at least 2.85 mrad. Preferably, the scanner should exceed these requirements to allow for future improvements to the technique.

Rotating/Galvanometric Scanning Mirrors

The most straightforward method of deflecting a laser beam is a rotating mirror. Rotation can be achieved using an electric or gas turbine drive or a galvanometer. For turbine driven mirrors, the mirror continuously rotates at high speeds; whereas, in the case of a galvanometer, the rotation is restricted to a finite angle. The speed and response time of a rotating mirror is dictated by the mirror inertia, balance and tuning of the system. Rotational speeds up to 20,000 Hz using gas turbine drives have been realized in practice and have found use in some models of ultra-high speed cameras (e.g. Cordin Camera). A 500 Hz rotating mirror was used by Patrie et al.[9] in their 3-D imaging work. The main drawback to a rotating mirror is the slow response time of the mirror to an external command due to the angular momentum and inertia of the mirror. This makes it difficult to the time the mirror's position with an external event (e.g. passage of a turbine blade, rotation of a crankshaft, etc.) and limits the overall flexibility of the system. An additional problem with respect to the pulse burst laser system, is that the mirror must be in the starting scan position sometime within the 1 msec gain window of the amplifier system. This can be circumvented somewhat by using a multi-faceted polygonal mirror; however, this adds complexity to the system and variations in the manufacturing of each mirror surface can cause jitter in the position of the laser sheet.

Galvanometric scanning mirrors, on the other hand, have a fairly fast and repeatable response time, thus making precise timing with the laser system and other events much easier. Although they cannot obtain the same top speeds as continuously rotating mirror systems, their speed is still sufficient for the desired measurements. For example, a commercially available unit with a 6 mm clear aperture (GSI Group, VM500) can scan across a 100º angle in less than 0.8 msec, which corresponds to a slew rate of 2180 rad/sec (347 Hz), which is more than sufficient for the current measurements. An encoder attached to the mirror can be used to determine the mirrors position to within tens of μrad and the movement of the mirror can be timed to an external input command. A similar scanning mirror was used by Hult et al.[14] in their high-speed 3-D imaging work, demonstrating its utility for the current application. Other benefits to galvanometric mirrors are high deflection efficiencies, which are aided by the ability to apply high reflectivity (>98%) and high damage coatings (>100 MW/cm^2) to the mirror as well as their reasonable costs (order of a few thousand dollars). As mentioned earlier, the primary drawback to these devices is the slow random access time, which may present an obstacle if PIV or a similar technique is to be applied. We are currently in the process of obtaining a galvanometric mirror to confirm these characteristics.

Acousto-Optic Deflectors

Acousto-optic deflectors (AODs) offer an intriguing alternative to scanning mirrors. They are electronically driven, possess random access times on the order of 1 μsec and come in a compact package making them quite flexible and easy to operate. Commonly used for laser light shows, projection systems, printing applications, and q-switches within laser cavities, these devices have a proven track record for laser deflection. Acousto-optic devices operate on the principles of the acousto-optic effect, where an acoustic wave traveling through a crystal or liquid causes a small variation in the index-of-refraction. This variation appears to an optical beam passing through the medium as a sinusoidal phase grating with wavelength equal to the acoustic wavelength. The light is diffracted, where the angle of diffraction is proportional to the frequency of acoustic waves. Thus, by modulating the acoustic frequency, via a piezoelectric transducer bonded to the crystal, the deflection angle of light can be controlled. When operated in the Bragg regime, the majority of incident light can be directed into the 1st order.

The primary limitations of AODs, however, is the limited number of resolvable spots and diffraction efficiency, which can vary by as much as 50% across the entire scan angle due to divergence of the beam from the Bragg angle. The number of resolvable spots for an AOD is given by:

$$N = \left(1 - \frac{t}{T}\right)\left(t \times \frac{BW}{1.34}\right) \tag{3}$$

where BW is the bandwidth of the RF driver, T is the total scan time and t is the random access time. The random access time of acousto-optic devices is defined by the time it takes for an acoustic wave to pass across the beam aperture. It is given by:

$$t = \frac{D}{V} \tag{4}$$

where D is the beam aperture in the acoustic direction and V is the acoustic velocity within the device. With acoustic velocities of several thousand meters per second, access times less than one microsecond can be achieved.

It should be noted that the total scan time can be significantly less than the product of the number of spots and the random access time. This is because the random access time is calculated assuming that the acoustic frequency is constant across the entire beam. Allowing the frequency to vary, such as would be produced by ramp input (e.g. frequency chirp), can produce faster scans, but introduces a cylindrical lensing effect, which can be easily modeled and accounted for. From Eq. 4, however, it can also be seen that this also reduces the number of resolvable spots for the device.

The most common acousto-optic material is Tellurium Dioxide (TeO_2), which has a high acousto-optic figure of merit. Specifications for one commercially available device indicate that an AOD constructed from TeO_2 could achieve 32 resolvable spots with a total scan time of 1.27 microseconds, well within the required range for the current technique. The manufacturer, however, had concerns about the use of this material with short duration, high intensity laser pulses and suggested fused silica as an alternative. This is particularly of concern as the incident beam must be reshaped and focused into the device to get maximum efficiency. Fused silica has a much higher damage threshold and can be used at UV wavelengths, making it suitable for use with 3-D UV fluorescence measurements, whereas TeO_2 is limited to wavelengths greater than 400 nm. AODs are also reasonably priced (order of a few thousand dollars) relative to other components in the system.

The biggest drawback to AODs, however, is that the deflection efficiency ranges from 35 – 65% across the entire range of deflections angle for the specified application. This is significant due to limited laser power and camera sensitivity at high-speeds. In addition, expanding the capabilities of AODs to a higher number of resolvable spots is somewhat limited due to an inherent tradeoff between diffraction efficiency and spots.

Electro-Optic Deflectors

Another interesting alternative for beam deflection is the use of an electro-optic deflector. Electro-optic deflectors are commonly found in laser q-switches. They are able to precisely deflect a beam using the electro-optic effect where the index of refraction of a crystal varies with applied voltage. The access time is limited by the passage of an electromagnetic wave across the beam aperture, thus allowing much higher deflection speeds than can be achieved with an acousto-optic deflector. Deflectors with 20 MHz bandwidth (random access time of 50 nsec) are commercially available with deflection efficiencies greater than 90%, an important factor in applications where pulse energy is critical.

The primary limitation of electro-optic deflectors is their cost. To achieve usable deflection angles (and therefore a large number of resolvable spots), these devices require voltages on the order of kV. In general, electro-optic deflectors are driven towards small apertures because the deflection sensitivity is inversely proportional to the square of the aperture. One commercially available deflector recommends a 0.3 mm diameter beam size, which drives $\Delta\phi$ to 1.78 mrad (Eq. 2). With a sensitivity of approximately 5 mrad/kV, 32 resolvable spots would require a ~12 kV high-speed driver. The small beam size would also make optical damage a concern, thus necessitating a larger aperture device and therefore much larger drive voltages. While this may be technically feasible, it would also be quite expensive when compared to the alternatives. Still, there may be some unique applications where this approach is desirable. More work is needed to fully characterize the capabilities of an electro-optic deflector for this application.

C. High-Speed Cameras

The last component necessary to construct the 3-D imaging system is a high-speed camera. The number of high-speed camera manufacturers has grown significantly over the last decade. For moderately high-speeds (up to ~250,000 frames per second at reduced resolution), the most commonly used cameras are high-speed CMOS cameras. CMOS cameras are distinguished from CCD cameras by the electronic architecture used to read out the signal from the sensor. In CMOS cameras, each pixel contains the necessary electronics to convert the accumulated charge to a voltage and amplify it. This allows for rapid read out of signal from the chip, which can be done in parallel (as opposed to in serial with a CCD camera). CMOS sensors are typically considered to be noisier than CCDs, but for high-speed applications this is a bit of a misnomer. The largest source of noise in CMOS cameras is due to the electrical noise of the on-chip circuitry. For high-speeds, however, this noise does not have as much time to accumulate and is a significantly smaller factor than in low-speed imaging applications. The on-chip circuitry, however, does have the negative effect of blocking some of the incident light, thus reducing the fill factor of the camera and reducing its sensitivity. High-speed CMOS cameras alleviate this issue by building custom made chips with relatively large pixels. The speed of CMOS cameras is ultimately limited by the A/D conversion process. The parallel architecture of CMOS cameras allows the user to select a region of interest. As the frame rate depends on the number of pixels being read out, higher frame rates can be achieved selecting smaller regions of interest. For example, the Phantom v7.2 (Vision Research Inc.) has a resolution of 800 x 600 pixels at 6,688 fps. By reducing the resolution to 512 x 512, 11,527 fps is possible. 100,000 fps is achieved for 256 x 64 resolution. These cameras cost on the order of $25 – 75k depending on speed and options and are best suited for applications in the 5-50k fps regime.

For the higher speeds targeted in this work (1,000,000 fps or better), CCD sensors are the sensor of choice with a variety of approaches used to achieve high frame rates. In all cases, the total number of frames that can be acquired is finite and a significant limiting factor. One approach (e.g. Cordin Camera) is based on a gas turbine driven rotating polygonal mirror, which projects an incident image along an arc surrounding the mirror. Originally film, and now CCD sensors, are located around the arc, each with its own imaging lens to capture the image as it moves around the arc. These cameras tend to be bulky and somewhat inflexible due to the mechanical nature of the technique. Their strength, however, is their speed and image resolution, which can reach as high as 25 million frames/sec with image resolution as high as 1k x 1k pixels for each image. The total number of frames that can be captured at these high rates is only limited by the number of CCD sensors that can be fitted around the arc with models currently available with 128 frames. They are fairly light sensitive as all of the incident light is directed toward the active sensor at any given moment. The large number of CCD sensors that must be used and integrated together leads to rather high costs, but recent reductions in sensor prices has reduced the price of these cameras rather significantly.

Other cameras (e.g. Cooke Corp., DRS Hadland, LaVision) also use multiple CCDs to acquire high-speed images, but use beam-splitters instead of a rotating mirror to direct the light along different paths. This dramatically lowers the intensity of the incident light at each sensor and necessitates the use of intensifiers to control the exposure and to increase signal intensity. In addition, intensifiers add noise to the images and increase the costs of the overall system. Thus, these cameras tend to have a limited number of frames.

An alternative approach to achieving high framing rates is to manufacture a CCD chip with electronic storage bins located next to each photo-detector. High framing rates can be achieved by rapidly shifting the charge produced at each pixel to the neighboring storage unit until the entire sequence of images is read out from the chip. Variations of this approach have been used by various manufacturers (e.g. Princeton Scientific Instruments, Shimadzu, Kaman Aerospace) to produce cameras with framing rates as high as 100 MHz. Similar to CMOS cameras, however, the storage bins take up a large area of the sensor necessitating very large pixels to get moderate fill factors. The image resolution is also reduced. As an example of a recent camera built on this concept, the Shimadzu HPV-1 can record 100 frames at a 1 MHz with a resolution of 312 x 260. The main advantage of a single sensor high-speed camera is that it constitutes a compact and robust imaging system that is fairly flexible and easy to operate. These cameras, however, are quite expensive as the CCD chips must be custom-built and a limited volume keeps unit prices quite high. The basic architecture, however, has the potential to see much lower prices in the future.

An interesting variation of this concept (Dalsa 64K1M, now discontinued) is to use a mass produced (i.e. lower cost) high-resolution CCD chip and apply a physical mask on top of the chip to block light from several of the pixels. In this manner, the active pixels are selectively chosen with the blocked pixels serving as the on-chip storage. Thus, in a similar manner, high framing rates can be achieved by rapidly shifting the charge into these pixel locations. The major downside of this approach is that the mask severely reduces the fill factor (<3% for the 64K1M) as most of the incident light falls on the mask. This can potentially be alleviated by the addition of a lenslet array in front of the mask, but, due to significant development costs, has not yet been incorporated into a high-speed camera design. Because many of the components are standardized, this could lead to high framing rate cameras at a fairly reasonable price point.

For the 3-D imaging technique described here, all of these cameras can be externally triggered and are therefore compatible with the proposed technique. The ultimate choice of a camera depends on the budget and desired speeds of the system as well as the availability of the camera. The ALDL is in the process of selecting and purchasing a camera using funds made available through a DURIP award. It is estimated that a 32 frame camera with 1000 x 1000 resolution and 1 MHz framing rates can be obtained. It is clear that the capabilities of high-speed cameras have significantly improved since the first high-speed 3-D imaging techniques were developed. It is hoped that this will lead to more diagnostics based on the high-speed lasers and cameras, such as that being demonstrated here.

D. Additional Concerns

In addition to the equipment needed for 3-D imaging, a number of technique specific issues must be addressed. For quantitative measurements based on the technique, a major concern is the quality of the images. It is expected that the images will inherently be noisier with a high-speed camera than a cooled, scientific grade CCD low-speed camera. As mentioned, this noise increase may not be as high as one might expect as the short exposure times actually reduces many of the common noise sources (e.g. dark noise) typically associate with digital imaging. For multi-CCD systems, variations in properties from one sensor to the next can introduce errors, particularly for intensity dependent measurements such as fluorescence based species concentration. These errors can potentially be removed through proper calibration and post-processing of the images, but will require some effort to identify the noise sources and develop efficient and appropriate calibration and post-processing schemes.

Another issue that must be addressed and can pose a problem is the depth-of-field (DOF) of the imaging system. With 3-D images, the camera must capture images at varying distances from the camera for a single optical setting. A first order approximation of the DOF in a typical imaging system is:

$$DOF \approx 2 f_{stop} C \frac{M+1}{M^2} \tag{5}$$

where f_{stop} is the f-stop of the lens (i.e. f/# 4), C is the size of the circle of confusion (i.e. minimum resolvable spot due to defocus) and M is the magnification. From this equation, it is clear that the DOF is proportional to the image resolution (C being the smallest feature). The DOF can be improved by reducing the aperture of the lens (increasing f_{stop}), but this will result in lower signal levels due to a decreased solid angle for light collection. As an example, assuming M = 0.5, C = 1/64", and DOF = 1", a lens with f/# of 5.3 or greater will have to be used to ensure properly resolved images. If the f/# is increased too much (>16), however, the image resolution can become diffraction limited as opposed to DOF limited. The primary concern is the lost signal when operating at increased f/#. This puts a greater strain on the power of the laser system, the efficiency of the deflector and the sensitivity of the camera. The effect of this restriction will vary depending on the technique being applied. Techniques like PIV can withstand some amount of defocus and still produce accurate results, while other techniques depend on accurately resolving the flow field. It may be possible in the future to correct for some of this using adaptive optics, but the bandwidth is currently too low to accommodate the high-speeds needed here.

III. Preliminary Results: High-Speed AOD

The core components discussed in Sec. II are currently being acquired by the ALDL in order to develop a high-speed 3-D imaging system. At this point, measurements have been limited to preliminary tests done on a high-speed AOD. A galvanometric scanning mirror is also being acquired for laser scanning and the purchase of a high-speed camera is pending. Rotating and galvanometric scanning mirrors have been demonstrated by Patrie et al.[9] and Hult et al.[14] to be capable of obtaining the speeds necessary to perform 3-D imaging with the pulse burst laser. The primary drawback to these devices, however, is their slow random access time. While this may not present a major problem for basic 3-D imaging, it could limit the ability to perform measurements such as 3-D PIV, which requires that a 2nd 3-D image be acquired soon after the first. Both acousto-optic and electro-optic deflectors present this capability. As such, a high-speed AOD was acquired and experiments conducted in order to verify its speed and operation. The AOD was constructed of fused silica with a 6 x 1 mm aperture with the acoustic direction along the major axis. The speed of sound within the AO medium is 5960 m/s, which corresponds to a ~1 μsec random access time for a 6 mm aperture. Acoustic energy was provided a 4 W RF driver with frequency tuning from 75 to

125 MHz yielding a total of 50 resolvable spots. If only 32 resolvable spots are necessary, the sweep time can be reduced to 7 μsec according to Eqn. 3.

To verify the high-speed operation of the AOD, the output from a Nd:YAG (New Wave Research) laser operated at ~5 mJ/pulse was focused into the AOD with a 100 mm cylindrical lens, producing a 2 mm wide elliptical spot within the crystal. Figure 4 is a photograph of the set-up. The output of the PIV laser had an angular spread of ~1.4 mrad, which is five times the diffraction limit for a 2 mm beam (see Eq. 2). The frequency of the AOD was adjusted from 75 to 125 MHz to span the full 4.5 mrad deflection angle of the device. The number of resolvable spots observed was ~4-5, which is consistent with Eq. 1. Resizing the beam to a 6 mm aperture and precisely collimating it would have produced a greater number of spots, but the appropriate lenses were not available in time for these experiments. The speed of the device was determined by providing a step command to change the device frequency from 75 to 125 MHz and altering the delay between the step and the laser pulse. The limiting factor was the AO driver's finite response time to the step input. It was found that the beam could deflect from the starting position (f = 75 MHz) to the end position (f = 125 MHz) in ~10 μsec. According to Eq. 3, over 33 spots over the 10 μsec sweep should be possible with a properly collimated input.

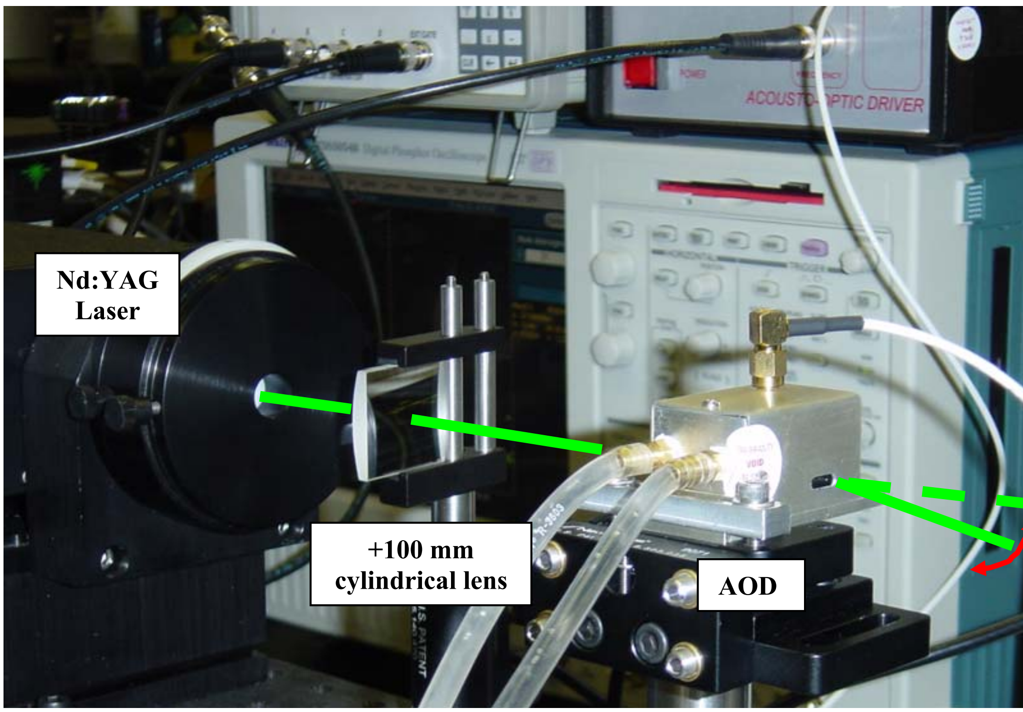

Figure 4 – Photograph of acousto-optic deflector experimental set-up.

IV. Conclusions and Future Work

Although high-speed three-dimensional imaging techniques have been developed in the past, the specialized equipment necessary for their implementation has hindered their further development and expansion. Recent technological advances in laser and camera technology, however, present an opportunity for renewed efforts to develop 3-D imaging diagnostics. The technique described in this paper is based on a MHz repetition rate pulse burst laser system. The system at Auburn is the 5th in the world and demonstrates the potential for further growth of this valuable technology. The remaining elements of the technique, a high-speed laser scanner and high-speed digital camera are both available commercially. In terms of high-speed laser scanners, rotating mirrors with the necessary speeds have been demonstrated in the past and a high-speed acousto-optic deflector with the appropriate characteristics is demonstrated here as well. Both technologies are economical. A galvanometric mirror appears to be the most suitable device for simple 3-D imaging, but acousto-optic deflectors present a viable alternative for applications where random access time might be important. In past efforts, the availability of high-speed cameras was one of the main limiting factors. Over the last decade, however, the number of manufacturers has more than doubled and numerous options now exist. The cost of these camera systems still remains a difficult hurdle to overcome; however, the design of many of these systems is such that the price of these systems could drop substantially in the near future.

For the current line of work, the pieces are finally coming together to begin more substantial development of the 3-D imaging technique described in this paper. The pulse burst laser system is nearly complete and an AOD has been acquired and demonstrated to work at high-speeds. The current analysis indicates that a galvanometric mirror may present a more reasonable alternative to an AOD, at least initially, and one has been ordered for use in this system. Lastly, we are in the process of selecting and purchasing a high-speed camera, which will complete the system and allow this work to move toward putting together a proof-of-concept demonstration of the technique. Long term goals include the development of 3-D PIV and LIF measurement techniques to extract quantitative 3-D data such as velocity or density.

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