Single Camera PIV/Shadowgraphy and Laser Delivery on Earthquake Shake Table for Fluid-Structure Interaction Measurements

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Abstract Implementation of non-intrusive optical measurement techniques, such as particle image velocimetry (PIV), in harsh environments require specialized techniques for introducing controlled laser sheets to the region of interest. Experiments on shake tables preclude placement of the laser close to the area for measurements, as the vibrations would be irreparably damaging to the equipment. Use of high powered multi-mode step index fiber optics, provide a means to introduce light from a Nd:YLF pulsed laser, with a beam quality sufficient for PIV, to a test section in a harsh environment. In this paper, the design of the optical system will be described along with the application to the measurements of a single rod in axial flow with external seismic forcing. Coupling the ability to bring the laser light to the test section with high speed CMOS cameras that record straight to hard drive, and pulsing LED’s, high quality spatial and temporal measurements of the fluid structure interaction can be realized through PIV and shadowgraphy.

1. Introduction

Earthquakes are sources of external acceleration to components of nuclear reactors that can affect structural and material integrity. The core, that holds the fuel in which the nuclear reaction that produces heat occurs, is an intricate system that needs to be better understood in these conditions. In light water reactors, Uranium Oxide fuel pellets are stacked in long (~4 m) and slender (~ 1 cm diameter) tubes, or fuel rods. The fuel rods are held together at fixed axial distances by spacer grids forming a fuel assembly, typically composed of a 17 × 17 compact array of rods for typical pressurized water reactors (PWR). In these reactors, as many as 200 fuel assemblies make up the core and a turbulent axial water flow cools the fuel rods; turbulence has its origin at the tube wall and from the spacer grids that mix the flow. The coupling of hydrodynamic forces and external acceleration in these geometries gives rise to a complex fluid-structure interaction (FSI) problem that still eludes comprehension from first principles and requires experimental campaigns to assist in developing and validating numerical models of the processes.

Experimental work on the seismic response of fuel assemblies on shake tables has consisted previously of tests in air or stagnant fluid in an effort to characterize the added mass effect, which is the mass of the fluid entrained by the rods in the direction of fluid acceleration (Viallet, et al (2003) and Ricciardi, et al (2009)). Additionally, axial flow will have an added damping that is not captured in seismic tests with stagnant fluids. This effect has been typically tested with a hydraulic jack fixed to one of the spacer grids, see for example Ricciardi, et al (2010). However, this introduces a disturbance to the axial flow at the connection to the spacer grid. Shake table tests with high Reynolds number axial flow provide a method to induce the forcing without disturbing the flow and is also a more rigorous method to characterize the response of structures. Furthermore, when coupled with non-intrusive optical techniques, high spatial and temporal data can be obtained.

To gain insights into how to tackle this challenging phenomenon, a simplified geometry is studied on an earthquake shake table. It consists of a single rod in a concentric pipe with turbulent axial flow. This experimental campaign allows development of non-intrusive, high-spatio-temporal optical diagnostics to
simultaneously resolve turbulent fluid velocity field coupled with structure vibration in the presence of ground motion. These optical diagnostics will serve as the foundation of a large experimental facility currently under development at the George Washington University, Fig. 1. Challenges to implementation of optical measurement of the FSI in this harsh environment require adhering to a strict set of constraints. First, to resolve structure vibrations and the flow features (between the rods) that induce them, high spatial resolution is required. Hence, the optical magnification must be high - on the order of unity. Due to the size of the table and to minimize uncertainty on the location of the measurement plane, the desirable resolution can be obtained only with the cameras mounted to the moving test section; i.e. pseudo-forces affect the measured fluid and structural dynamics in this non-inertial reference frame. However, location of investigation plane is known if beam wandering is minimal. Pertinent to this constraint, laser sheets used for velocity field measurements must be thin, focusable at a large distance within the test section, and not affected by beam wandering. Second, for capturing the FSI coupling, high temporal resolution and long recording times are necessary to capture these multi-temporal scale phenomena. The ability to conduct lengthy experimental trials, beginning with a static environment and then imposing external forcing, allows for the deduction of information during transient events that are earthquakes. To obtain high-spatio-temporal data on rod vibration and coupled velocity field, two simultaneous non-intrusive diagnostics are employed: particle image velocimetry (PIV) and shadowgraphy. Both are recorded on a single high-speed CMOS camera with ability to stream directly to computer hard-drive. Laser light is delivered with high-power optical fiber, and special mounts are fabricated to rigidly fix the camera and lens.

Vibration tables have been combined with optical diagnostics for various applications ranging from the geophysical field to tank sloshing. In the geophysical field, shake tables and high-speed cameras are commonly employed to study soil liquefaction, or structure response to seismic loads. Recently, PIV and digital image correlation (DIC) algorithms have been employed to track soil granular structure near the transparent wall of the container, see for example, Liu, et al (2012); Slominski, et al (2006); White, et al (2003). With the exception of White, et al (2003), the cameras are mounted on the Galilean frame of reference on the laboratory floor. Having the cameras mounted in this fashion simplifies the design of the experiment and allows for accelerations of up to 1.2 g (g is the acceleration of gravity) to be realized on shake tables (Liu, et al 2012). To study tank sloshing, dedicated tanks are excited and surface identification has been conducted with either stationary cameras, Colagrossi, et al (2006), or cameras moving with the tank, Colagrossi, et al (2004). This was later extended to PIV in the non-inertial frame. For example, Lugni, et al (2005) utilized PIV to study the flip-through phenomena in tank sloshing, where a measurement technique that could capture fast dynamics coupled with nonlinear features was needed. In this study the cameras and tank were exposed to accelerations up to 0.05 g. Doh, et al (2011) used a 6 DOF shake table to study tank sloshing as well, with accelerations up to 0.08 g with the cameras mounted to the shake table and a laser sheet from an Nd-Yag laser that was directed to the area of interest with optics that were not fixed to the shake table. Their field of view was rather large (320 × 400 mm), which relaxes requirements on camera and beam wandering. PIV has also been performed on a tabletop lab shaker to study bioreactor stirring.
Weheliye, et al (2012); here a small solid-state laser was mounted directly onto the vibration plate along with the camera and test section.

The innate challenge of performing high resolution experiment on a large shake table is the ability to bring the laser light to the area of interest in a safe and stable manner. To study FSI in tank sloshing, Doh, et al (2011) required a large light sheet to illuminate their investigation region that was made even larger in order to accommodate displacements with amplitude equals to 10% of transversal field of view since the laser sheet did not move with the test section. This laser delivery scheme is acceptable for one dimensional vibration as long as out of plane oscillations of the test sections are smaller than the laser sheet thickness. For very thin laser planes or multi-dimensional vibrations, greater flexibility is needed in the introduction of the laser light to the moving test section. Optical fibers provide a viable, yet challenging solution that also enables efficiently illuminating the region of interest. Most notably, to obtain a delivered beam of high quality (low $M^2$) and hence easily focusable, the core diameter must be minimized without exceeding the laser damage threshold (LDT) at the fiber entrance. Since LDT mechanisms depend on pulse length and repetition rates of the laser, review of optical fibers for laser delivery is mainly focused for nanosecond long pulses. Nevertheless, optical fibers have been employed in combustion, Hsu, et al (2013), turbulence, Hand, et al (1999), in zero gravity experiments, Boxx, et al (2004), or for underwater PIV, Bertuccioli, et al (1999).

Optical fibers are available with materials and properties that must be selected for a desired application. A typical laser delivery system with optical fiber consists of a laser, coupler, fiber, and collimator. Jackson, et al (1984) demonstrated laser doppler velocimetry with a single mode step index fiber optic with a core diameter of $3 \mu$m with power up to 500 mW. With this type of fiber, the coherence, phase, and polarization are preserved along with a high beam quality. However, short pulses with high peak powers are often required for PIV and they exceed the LDT of small diameter single mode fibers. For high peak power and beam quality, hollow core fibers have the highest capacity compared to solid core fibers (Kriesel, et al 2010). In fact, very high beam quality ($M^2 \sim 10$) and peak power (100 mJ at nanosecond pulse) has been obtained with large bore (1000 µm) hollow core glass waveguide, Matsuura, et al (2002). However, the power loss at 0.3 m bending radius is nearly 3 orders of magnitude greater than in solid core fibers, Boechat, et al (1991), Kovacevic and Nikezic (2006) and the fiber lengths are limited to 2 m which would not be adequate for the larger experimental facility being constructed. As long flexible fibers are needed for this experiment, attention was focused on multi-mode step index fibers.

To deliver high peak power laser beam of nanosecond pulse length, high power multimode step index fibers with large core diameter are commonly used. The challenge in implementation of multi-mode fibers is a much reduced beam quality in comparison to hollow core fibers with the same core diameter. Large core multi-mode optical fibers are used extensively with CW lasers for which power requirements are not too restrictive. In fact Oz Optics sells Powell lenses to generate laser sheet with top hat intensity distribution. However, for pulsed lasers, balancing the power requirements with the beam quality becomes a significant challenge. Hsu, et al (2013a) utilized a large diameter (600 µm) fused-silica step index fiber optics to simultaneously introduce light to a combustion chamber for planar laser induced fluorescence (PLIF) and PIV. However, the larger diameters resulted in degradation to the beam quality limiting the attainable sheet thickness at the output of the fiber (~2 mm) and the pulse energy was limited to ~1.7 mJ. Anderson, et al (1995) saw improved results with 600 µm diameter fibers through optimization of the lens elements used to couple the laser and the fibers. They reported peak energy of 5 mJ at 10 kHz with 6-7 ns pulse lengths, and with a single cylindrical lens at the fiber output were able to achieve a light sheet thickness of 1-3.5 mm. Improved results for light sheet thickness while maintaining pulse energy were obtained with tapered fibers that had an input of 940 µm and a 2:1 taper, this increased the delivered beam quality at the cost of reduced coupling efficiency due to the taper (Hsu, et al 2013b).

An alternative to using a single large core fiber has been the use of smaller diameter fibers in a bundle to increase beam quality and peak power handling. Hand, et al (1999) utilized 19 multimode fibers of 200 µm core to launch up to 30 mJ per pulse at nanosecond pulse length. With the energy shared between 19 fibers, they were able to increase the maximum energy by a factor of 3 over a single multi-mode fiber. Furthermore, at the fiber output, no collimator was needed as the fibers were arranged linearly to form the light sheet and the thickness of the latter was controlled with a single cylindrical lens. They were able to obtain a thickness
on the order of 0.65-1 mm that was sufficient for PIV measurements in air inside a 54 mm square duct at Re≈10^4. The limitations of this setup are that at the input the laser light falling on the gaps between fiber cores is lost, with the laser-to-fiber coupling efficiencies below 35% and reduced beam quality from a single fiber. They also reported results on the durability of the fiber for only 1,000 pulses.

To minimize the fiber core diameter, and hence increase the quality of the delivered beam, special precautions are necessary to optimally launch the laser beam into the fiber. Several coupling schemes have been tested to create a focused beam with no hot spots. The hot spots set the safety factor on LDT and hence on core diameter. To sharply focus the laser beam at the fiber entrance, it is possible to use simple plano-convex lenses; however, these lenses introduce aberrations in the beam profile, which create undesirable local irregularities in the beam intensity profile and limit the spot size that can be attained by the lens. Instead, aspherical, multiple lens elements (English et al (1991)), GRADIUS lenses (Hunter et al (1997)), grin lenses, and diffractive optical elements (DOE) (Hand et al (1999); Hsu et al (2013a)) have all been tried to provide a beam spot of high quality at the fiber entrance. It appears DOE is currently the most commonly employed design.

In the aforementioned experiments nanosecond pulse widths were used similar to what will be used in this experiment, picosecond pulse widths have also been used for incoherent anti-Stokes Raman Scattering (CARS) that involve a different damage mechanism to the fiber due to the order of magnitude of the pulse length (Hsu et al 2010). They found that for 10 ps pulse lengths, the dominant mechanism for damage to the fiber is fluorescence-based lattice heating and thermal processes whereas for longer pulses (on the order of 1-100 ns as used here), dielectric breakdown is expected as the primary contributor.

The groups that have delivered high-power laser light through optical fibers for advanced diagnostics have focused primarily on the coupling optics to minimize the fiber core diameter to obtain an output beam of reasonable quality (M²<50) while not exceeding the LDT of the fiber materials, which would result in irreparable damages to the fiber. Here, we also focused on the collimator at the output of the fiber to improve the beam quality. This was an essential aspect to address, as the region of interest was not directly adjacent to the fiber output as in previous experiments, but located instead at a non-trivial distance from the test section wall.

In multiphase flows, reflections from the laser light at the interface between the phases that are not refractive index matched prevent accurate determination of this boundary from the PIV images alone. Therefore, shadowgraphy has often been coupled with PIV to discriminate between the phases. Nogueira, et al (2003) recorded both PIV and shadowgraphy on a single image for tracking bubbles in slug flow, and the particles and bubbles were discriminated by varying grey levels. Sathe, et al (2008) utilized a similar scheme recording both PIV and shadowgraphy simultaneously, but with two cameras viewing the same plane on the same optical axis. A dichroic mirror was used in combination with an optical long pass filter to separate the 532 nm laser light from the 470 nm blue LED, thus recording images of the particles and shadows of the bubbles onto the respective cameras. Hassan (2002) dedicated one camera frame per diagnostics for measurements of two-phase bubbly flow. A similar timing sequence is employed in the present experimental setup.

In the following sections, the experimental test section is defined along with the integration on to a large shake table. The instrumentation is then described in the following order; implementation of fibers, prevention of beam wandering and control of laser beam quality, mounting of extended recording time and high magnification cameras in the non-inertial reference frame, utilization of shadowgraphy, and synchronization and timing of the multiple instruments. Then results are presented of PIV and shadowgraphy on the shake table, in addition to comparisons with static cases to elucidate both the physics and the challenges of these measurements.

2. Experimental Apparatus

The experiment is a single flexible and slender Viton tube (3.18 mm OD, 1.59 mm ID) centered in a clear
acrylic pipe (37.7 mm ID, 0.3 m long). The working fluid is para-cymene, which is nearly index matched to acrylic at room temperature, $n_{\text{para-cymene}}=1.4885$ and $n_{\text{acrylic}}=1.491$ at 20°C and 589 nm, which minimizes distortions at the inner wall of the pipe. By adding a solvent and/or controlling the environment temperature, the refractive index of the two materials can be matched precisely. Details are given in Bardet, et al (2014). For this small experiment the geometry is simple and the temperature rise in the fluid is not as significant as it will be in the larger experiment due to higher pressure losses in the large flow loop. Therefore for this case pure para-cymene is utilized, in the experiment on a full fuel assembly a mixture will be used in conjunction with a chiller to maintain the fluid at constant temperature and control its refractive index. The tube is contained inside a secondary, low pressure square acrylic tank filled with the same fluid. This tank serves to contain any leaks from the annular flow and provide a flat surface for imaging inside the pipe with minimal optical distortions, Fig. 2. The test section itself is mounted inside a drip tray to collect any fluid that might escape the secondary containment or flow loop. These precautions are necessary to isolate liquid from contacting the table and potentially damaging the hydraulic lines that drive the table. A 1.5 Hp centrifugal pump, controlled with a variable frequency drive, circulates the working fluid. The pump and return tank are mounted next to the shake table to isolate the fluid contained in these parts from sloshing induced by the external forcing, which would result in pulsatile flow in the test section.

The George Washington University earthquake shake table is a large square table, 3 m on its side, with six degrees of freedom. A range of motion can be inputted with harmonics up to 50 Hz and forcing up to 1.5 g. It is rated for 36 kips (160 kN). The experiment presented here is a geometrically scaled down apparatus of a full-scale facility under design to study the seismic response of nuclear fuel assemblies. Fig. 1 shows components of the new facility being installed on the shake table. The present facility is used to validate instrumentation development and gain insights into fluid-structure interaction under seismic loads.

In the present configuration, one dimensional sinusoidal forcing is conducted with various forcing frequency $f$ and acceleration $a$, with $0 < f < 10$ Hz and $0 < a < 0.35$ g. The applied forcing is significantly higher than in previous PIV measurements on vibration tables. The PIV laser sheet is aligned with the forcing axis to capture secondary flows that might develop due to pseudo-forces as well as the main deflection of the rod. To simplify synchronization of instruments and accuracy in identifying the surface location, a single high-speed camera is employed for PIV and shadowgraphy. Here a single frame is dedicated to each diagnostics; synchronization details are given hereafter. The high-power pulsed LED strobe used for shadowgraphy is aligned with the optical axis of the camera and produces nearly collimated light, Fig. 2.

3. Instrumentation

3.1 Optical Fiber PIV beam delivery

PIV measurements are in a streamwise plane centered in the test section. For the large vibration amplitudes
expected here, it is not feasible to mount the laser sheet optics on the ground floor; small out of plane motion of the shake table, or vibration of the test section, would result in beam wandering and a fluctuating investigation plane. Hence the laser sheet optics are mounted directly to the test section. Furthermore, vibrations might damage or misalign the laser; and therefore it is installed on a vibration isolated granite table. To deliver the laser light to the shake table, mechanical arms with first surface mirrors or prisms in the articulations were considered because they allow maintaining a laser beam of high quality with minimal wandering. However, they are complex and expensive and were not judged flexible enough. Instead, 10 m-long, high-power, multi-mode, step-index optical fibers are used. Long fibers have large degrees of freedom, are affordable, and readily available. Their quality and reliability have also improved significantly over the last 20 years, and with careful mounting can offer a wandering-free beam with acceptable beam quality. To successfully design a fiber optics beam delivery system, several considerations must be taken into account, they include beam quality control and damage threshold. This has direct effects on laser launching in the fiber and subsequent beam collimation. These are presented below.

When designing a PIV experiment, it is important to select the appropriate lens combination to obtain a thin laser sheet of nearly uniform thickness over the desired investigation region. To select the optics, for higher order Gaussian beam, the beam waist, \( w_0 \), and Rayleigh length, \( z_r \), must be considered together. The beam waist that can be obtained for a length of focal length \( f \) is given by Eq. 1. This equation also takes into account the laser beam quality, or \( M^2 \), aberrations introduced by the lens (\( A \)), wavelength of the laser (\( \lambda \)), and the waist of the incident beam \( w_0 \) (Hunter, et al. 1996b):

\[
\frac{\pi w_0^2}{\lambda M^2 f} = \frac{\lambda f}{\pi w_0}
\]

Aberrations introduced by the lenses can be minimized if careful design rules are utilized in selecting the lens elements. The \( M^2 \) also negatively affects the Rayleigh range, Eq. 2.

\[
z_r = \frac{\pi w_f^2}{\lambda M^2 f}
\]

Hence a beam of low quality will result in a thicker laser sheet for a given field of view. This can lead to unsatisfactory illumination. In this experiment, the beam needs to travel through 162 mm of air and 115 mm of acrylic and para-cymene that make up the low pressure boundary before it reaches the inner wall of the acrylic cylinder that is the beginning of the measurement region. If the beam is not collimated for this distance, the light sheet thickness will continue to diverge and it would not be possible to take measurements. In Anderson, et al (1995), the measurement region was directly after the cylindrical lens used to make the light sheet, and even with this setup the beam varied from 1-3.5 mm throughout their field of view. In this experiment, the light sheet thickness needs to be at the sub-millimeter scale, which at the distance the region of interest is from the outer wall of the test section requires an \( M^2 \) less than 100.

While these effects alter the forming of the laser sheet, they also control the design of the focusing optics to couple the laser beam into the optical fiber. The beam diameter at the input of the fiber should not exceed 70% of the core diameter per recommendation of the manufacturer (Oz Optics), and thus Eq. 1-2 provide an initial estimate of the minimum diameter fiber based on laser and coupling parameters. However, this does not take into account the materials that constitute the fiber, and careful considerations must be applied to the common damage modes that can occur in the fiber during sustained operation.

LDT of the fiber core and cladding materials set the actual requirements on the fiber optics core diameter, and materials for launching the beam into the fiber. LDT is a function of pulse length, beam diameter, wavelength, surface quality, and material imperfections. Damage mechanisms can be thermal, where absorption of energy in the material can lead to failures from thermal expansion and distortion. The mechanism can also be due to dielectric processes, where the laser incurs electromagnetic field strengths that
induce dielectric breakdown of the material. High-repetition rate, continuous pump, Q-switched Nd:YLF lasers in use here have rather long pulses (∼150–350 ns) compared to low repetition rate, pulsed pump, Q-switched Nd:YAG lasers (∼1–10 ns), which relaxes the requirements on laser damage threshold. LDT is material dependent and have different threshold values both at the surface of the fiber and in the bulk. Hsu, et al (2010) and Allison, et al (1987) found that the core-clad interface tended to be the limiting factor for LDT for plastic-clad silica fiber. In the experiment conducted here, silica-core-silica-clad fibers are used that have higher LDT for the core-clad interface, and surface damage is found to be the constraint for LDT, as the facet of the fiber was found damaged when this LDT was exceeded with small core multi-mode step index fibers. Measured threshold values for the surface damage of fused silica are 150 J/cm² at 1064 nm and 15 ns pulse lengths (Mann et al. 2007). Comparatively bulk thresholds in the core are several orders of magnitude higher with measured threshold values of 3854 J/cm² at 1064 nm and 8 ns pulse lengths (Smith et al. 2008). For the damage mechanisms relevant here, these thresholds can be scaled to the current laser with eq. 3-5 where w is the beam waist and r is the pulse length.

\[
LDT_y = LDT_x \left(2w_y / 2w_x \right)^2 \tag{3}
\]

\[
LDT_y = LDT_x \left(\lambda / \lambda_x \right)^{\frac{1}{2}} \tag{4}
\]

\[
LDT_y = LDT_x \left(\tau_y / \tau_x \right)^{\frac{1}{2}} \tag{5}
\]

The LDT in the core is estimated with the energy density from a beam spot diameter based on the focal length of the lens used to introduce the beam into the fiber. The LDT for the surface is estimated with the energy density based on the area of the core. The focus of the beam entering the fiber is focused at a set distance in front of the fiber so that the beam will have diverged to 70 percent of the fiber core diameter when it reaches the fused-silica surface. Hand, et al (1999) had set the diameter at the entrance to 50% of the core diameter; however, this has a negative impact on the peak power that can be used and does not seem to impact coupling efficiency. To select the core diameter, a safety factor between three and four on laser energy density is employed to take into account divergence from the beam quality from Gaussian energy spatial distribution.

The beam quality, \( M^2 \), at the fiber output is directly proportional to fiber core radius, \( r_{fiber} \). For step index multimode fibers, the dependence on core size is given by equation 6 (Hunter, et al 1996a).

\[
M^2 = 0.86^{1/2} r_{fiber} \arcsin(NA) \frac{\pi}{\lambda} \tag{6}
\]

Hence large core diameter significantly deteriorates the laser beam quality. This makes it challenging to obtain a collimated beam of acceptable dimensions since the beam quality directly affects the smallest spot size that can be attained at the output of the fiber. The spot size and Rayleigh range for a beam quality resultant from a 250 mm lens needed to center the spot size in the test section in this experiment, are 0.20 mm and 2.0 mm respectively for a 200 µm fiber.

The numerical aperture of the fiber, Eq. 6, is based on the materials constituting the core (\(n_c\)) and cladding (\(n_d\)) and for step index fiber optics is defined as \( NA = \sqrt{(n_c^2 - n_d^2)} \). For fused-silica optical fibers employed here, \( NA = 0.22 \). They are coupled to the laser with air-gap style SMA connectors on either end that can be mounted in cage system components, Fig. 3. The laser utilized in this experiment is a dual-cavity Nd:YLF laser with a dual pulse option per cavity where a polarizing beam splitter is used to separate the polarized beams from each cavity. This laser is capable of delivering up to 60 mJ per pulse at 1 kHz and has a repetition rate adjustable from 0 to 20 kHz with a fixed wavelength (\(\lambda = 527 \text{ nm} \)).
Here a free launch system with 5 degrees of freedom is selected to couple the laser beam into fiber optics. With this system a coupling efficiency of up to 87% is achieved. The large fiber core diameter allows for providing a soft focus that is less demanding on coupling optics and can tolerate some beam wandering while preserving a good coupling efficiency.

Three different fiber core diameters are analyzed and tested to determine the most suitable for the application. A sub-millimeter thickness light sheet is desired for the measurements, thus 100 µm and 200 µm fibers are of primary interest, Table 1. They, reach their respective LDTs with a safety factor of 3 at 3.5 mJ/pulse and 14.1 mJ/pulse. 600 µm fiber, also used in this experiment, are reported as well and can handle the maximum energy density the laser is capable of at 30 mJ/pulse.

<table>
<thead>
<tr>
<th>Fiber Core Diameter [µm]</th>
<th>Theoretical M² Output of Fiber</th>
<th>Measured M² Output of Fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>Focused Beam Diameter [mm]</td>
<td>0.40</td>
<td>0.81</td>
</tr>
<tr>
<td></td>
<td>95</td>
<td>277</td>
</tr>
<tr>
<td></td>
<td>0.63</td>
<td>1.8</td>
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**Table 1: Fiber Core Diameter Effect on Beam Quality with 250 mm Lens**
The measured values for beam waist and quality are conducted with a knife edge measurement technique using a linear stage and power meter. The measured $M^2$ value is estimated as with the diameter of the beam incident on the lens being used to focus the spot size $W_0$:

$$M^2 = \frac{W_0 \pi D}{4A_f}$$  \hspace{1cm} (7)

With a limited energy per pulse for these fiber diameters, it is important to maximize the coupling efficiency at the input to the fiber. To accomplish this, the input cone of light cannot exceed the numerical aperture of the fiber. OZ optics recommends maintaining the numerical aperture of the focused rays between 30-90 percent of the fiber numerical aperture. For the selected 200 µm diameter fiber, utilization of a 30 mm focal length lens accomplishes this specification.

The collimator selected consists of a first surface parabolic mirror that nearly matches the numerical aperture of the fiber followed by a total of five optical elements, Fig. 5. This is necessary to form a collimated beam with low divergence that can be used to form a laser sheet of sub-mm thickness. After the reflective collimator the beam still diverges slightly and a long focal length lens element (LE), LE1, is used to obtain improved collimation. Next LE2 and LE3 form a beam Galilean expander to reach a smaller spot size, Eq. 1 LE4 is used to focus the beam at the center of the test section, midway between the inner cylinder wall and the Viton tube, and LE5 is a cylindrical lens used to create a vertical light sheet. A cage system holds the collimator and sheet forming optics together. This offers a rigid, light, and compact assembly that is mounted to the test section at desired locations. Special care is taken to rigidly hold the last section of the fiber before the collimator as movement there generates modes that negatively affect the beam uniformity. To further increase beam quality, future work is planned to implement spatial filters in the cage system that will have to be carefully optimized with the loss of power that will result.

3.2. Camera Fixture

While not specifically tested for conditions expected here, cameras (and lasers) are designed to resist to transportation when not operated, which follows the standard: MIL-STD-8100. Transportation conditions are not too dissimilar to the forcing encountered during runs of the experiment. To record data in the moving frame, cameras have to be rigidly fixed to the test section normal to the direction of forcing. Hence to simplify the connection there, the camera should be as light as possible to minimize its inertia. However, if a long recording time is desired, while maintaining time resolution to capture complex transients, one is typically forced to use expensive, rather large and heavy cameras with built-in memory. An alternative, that has only recently become available, are industrial grade CMOS cameras with CoaXpress transfer protocol.
that allow recording straight to hard drive at speeds up to 25 Gbit/s. Currently, the available cameras have only 8-10 bits sensor, lower light sensitivity and higher noise than scientific grade cameras. However, they are also more affordable and lighter. The selected camera here (Mikrotron EoSens 4CXP) weighs 450 g, compared to 5.5 kg for a Vision Research Phantom camera, which would require a very stiff connection to the test section. The Mikrotron camera can record straight to hard drive at 560 fps at 4 Mpixels and 950 fps at 2.4 Mpixels. The frame grabber is BitFlowCyton CX, and the data acquisition software is StreamPix 6 from Norpix. The computer, frame grabber, camera, and software were integrated by MicroDisc, Inc.

Furthermore, for the present flow, a rather high magnification ($M \sim 0.2–1$) is desired with reasonably long working distance. Hence a 55 mm micro lens from Nikon is employed. It was found that the lens moved with respect to the camera body. A special lens mount was designed and built to firmly fix the lens to the camera, Fig. 6. This mount provides satisfactory results up to 0.15 g of lateral acceleration. Above this value, small vibrations are noticeable and are likely due to the lens elements moving inside the lens body when it is fully extended. Shims where inserted between the lens groups to successfully restrict their motion and was tested up to values of 0.35 g.

Fig. 6: Camera lens mount

3.3. Identification of Flexible Rod Location

Identification of the Viton tube location from PIV data alone is challenging. Because the tube is not transparent, reflections are present at its surface, and negatively affect the resolution of the surface location. The latter is also related to the laser sheet thickness.

By employing shadowgraphy in parallel, the inner tube surface is readily identifiable, and uncertainty in its location is decreased. The latter is resolved with a 1/2 pixel accuracy. The surface location is identified automatically. In this processing, the images are first filtered to remove noise and are then converted from grayscale 8-bit images, to binary images using an optimum threshold value. The boundary between the different value pixels in the binary image are then traced and smoothed with a spline function. See Fig. 7 for a sample result. It should be noted that the brighter intensity signal near the wall in the raw shadowgraphy data is due to local heating of the black Viton tube by the laser sheet. In fact, the thermal effects are also visible in the raw PIV data near the wall.
3.4. Instruments Integration and Synchronization

The high-speed CMOS camera is operated at 949 Hz with a resolution of 2336×1024 pixels, while the laser and LED strobe operate alternatively at 474.5 Hz each, Fig. 8. The LED strobe pulse length is 1.2 μs, which is fast enough to prevent motion blur. The LED signal is also weak enough to not saturate the camera sensor and results in ghost or anti-ghost pixels on the following frame. Camera, laser, and LED are controlled with a time delay generator. TTL pulses and light signal are monitored with a high-speed mixed signal digital oscilloscope. At the present spatial resolution, 474.5 Hz repetition rate, and mean velocity, the PIV data are acquired in a time series fashion, while the shadowgraphy is oversampled. The wall location in each PIV frame is interpolated from the shadowgraphy data. The field of view is 17.5 mm × 67.7 mm with a magnification of 0.24. A total of 13,378 frames were acquired, which led to 6,688 PIV image pairs. For this study 4,096 images from three different cases are analyzed in a time-series fashion. PIV particles were 2 μm in diameter silver coated hollow glass spheres with density ρ = 3600 kg/m³. For this flow condition particle slip is negligible and the tracers follow the flow closely.

4. Results

To obtain data and statistics in static vs vibrating environments, the frames are acquired in the following fashion for the data reported below. The shake table is activated, but kept stationary. The loop is started and operated for about 30 s to establish a steady flow. Data acquisition then starts and stays active for the next phase of the experimental run. Nearly 4500 images are recorded prior to beginning the table oscillations. While the table oscillates another 6000 images are acquired, the shake table is then stopped and an additional 3000 images are recorded to compare to the initial flow.

The raw PIV images are processed in DaVis version 8.1.1. A multi-pass interrogation method is utilized, with a window starting at 128×128 pixels with 75% overlap. Five passes are conducted, with the final window size being 32×32 pixels with 75% overlap which satisfies criteria specified by Keane and Adrian (1990) for the ratio of the displacement of particle image pairs to interrogation size [ΔX]/d₀ ≤ 0.25. The
final pass results in $292 \times 72$ vectors per frame with a spatial spacing of 0.23 mm between vectors.

Sample results for $Re = 7,500$, in the vibrating environments are presented in Fig. 9. These vibration data were acquired with a command to the shake table of sinusoidal waveform of 2 Hz and 8 mm amplitude. The recorded accelerations on the shake table were $+1.5$ m/s$^2$ and $-1.5$ m/s$^2$, which is slightly larger than 0.15 g. The shake table is controlled in an open-loop fashion by inputting displacement time series. The latter is monitored by linear variable displacement transducers (LVDT) mounted in each hydraulic actuator. Additionally, six accelerometers are built-in into the table and record the acceleration along the three axes and moments.

![Fig. 9 PIV sample of fluctuation velocity with vorticity as a color plot. The inner tube is the bottom boundary and the pipe wall corresponds to the top flow domain boundary. Mean flow is left to right.](image)

In Fig 9, the mean axial flow is from left to right, and a result of the short length of the test section is that the entrance effects are noticeable in the flow. The cylinder wall is the upper boundary and the viton tube the lower, the interface of the fluid and solid viton tube is determined through the shadowgraphy measurements.

To determine the spectral dependence of the inner tube vibration, the region in the center of the field is tracked with the algorithm described above. The time history and spectrum of the tube are then computed. The most energetic harmonics are at 4, 17, and 22 Hz.

To assess the effect of forcing on velocity fields, the fluctuation velocity in the $x$-direction at the center of the flow, and associated spectra, are analyzed for three cases; (1) static test on granite table, (2) static test on shake table while table is activated, (3) shake table test with external forcing applied. Case (1) corresponds to the reference case, where the system is not vibrating. For case (2), the hydraulic pistons are activated and vibrate slightly, which can affect the measurements. Finally, case (3) corresponds to the experiment conditions.

The harmonics below 50 Hz of the spectra of $u$ are shown on Fig. 10 for cases (1) and (3). The time series are too short to draw definitive conclusions on the influence of external forcing on the spectra and flow statistics. Also, the difference in spectra may be attributable to coupling of the entrance effects with the external forcing. Nevertheless, for the static case, it appears that the harmonics reach maxima below 5 Hz, and that more energy is contained in these modes than for the shaking case. The axial velocity of the latter has also larger amplitude harmonics between 10 and 25 Hz.
5. Conclusions

We have performed PIV in a challenging environment: on a large earthquake shake table. To successfully conduct the measurement we delivered the laser sheet with an optical fiber, which provides a very flexible mean of illuminating the test section. The system achieves acceptable beam quality and durability. To perform measurement in the moving frame, special care is also taken to rigidly fix the camera to the test section and attach the lens to the camera body. By employing a combination of PIV and shadowgraphy with a single camera, optical configuration is simplified and flexible tube deflection is resolved, which could not have been obtained from PIV alone. In the future, longer time series will be acquired to gain statistical insights into the effect of external forcing on turbulent flow features.
6. References

- Kriesel JM, Gat N, Plemons D (2010) Fiber optics for remote delivery of high power pulsed laser
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