Laser Doppler Velocimetry: Flow Measurement Using a Digital Micromirror Device

Dawei Kuo

Advisor: Dr. John P. Sharpe

California Polytechnic State University, San Luis Obispo

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Abstract

In this experiment we utilize a Texas Instruments Digital Micromirror Device to impart a phase shift to the beams of a laser Doppler velocimeter. The advantages of this approach include low cost, low power consumption, a precisely known phase-stepping frequency, and the capability of working with a broad range of optical wavelengths. The velocities measured with the set up shown here are of order 1 cm/s.

Keywords: Laser Doppler Velocimetry, Texas Instruments LightCrafter, Digital Micromirror Device

1 Introduction

Laser Doppler velocimetry (LDV) is a non-intrusive technique for measuring the velocity of flows and solid surfaces using laser light proposed by Yeh and Cummins in 1963 [1]. By illuminating the flow or object with a laser light and measuring the scattering caused by movement, it is possible to calculate its speed. In this experiment we overlap two coherent beams at the point of interest to create a periodic intensity pattern of bright and dark fringes as shown in figure 1. As particles cross this intersection they scatter light, causing a periodic fluctuation in the intensity. An issue that arises from this set up is that the direction of motion of the particle remains ambiguous. To remove the directional ambiguity, a phase or frequency shift is imposed on one of the beams in order to make the fringe pattern translate at constant velocity. This allows one direction to result in a frequency shifted up and the other direction to result in a frequency shifted down. This also shifts the frequency from being centered at zero, away from low frequency noise. Common ways the directional ambiguity is removed is by using a rotating diffraction grating or by employing a Bragg cell [1]. Here we use a modified version of a technique suggested in [2] which is to step a grating discretely. While the original concept used a grating mounted on a piezo stage and was very slow, here we use a device that can sequentially display the required gratings at high speed.

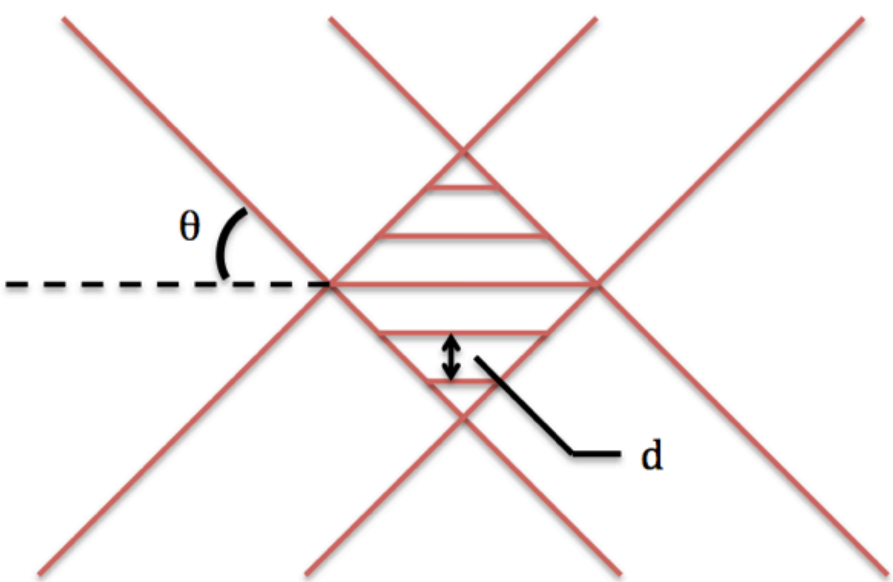


Figure 1: Close up of the fringe pattern in the beam intersection

For two beams crossed at a half-angle of theta, the fringe spacing, *d*, is found using equation 1.

$$d = \frac{\lambda}{2sin\theta} \quad (1)$$

The wavelength, λ, is the wavelength of the laser. Theta is the half angle of the two beams between the focal lens and the flow. This is shown in figure 2.

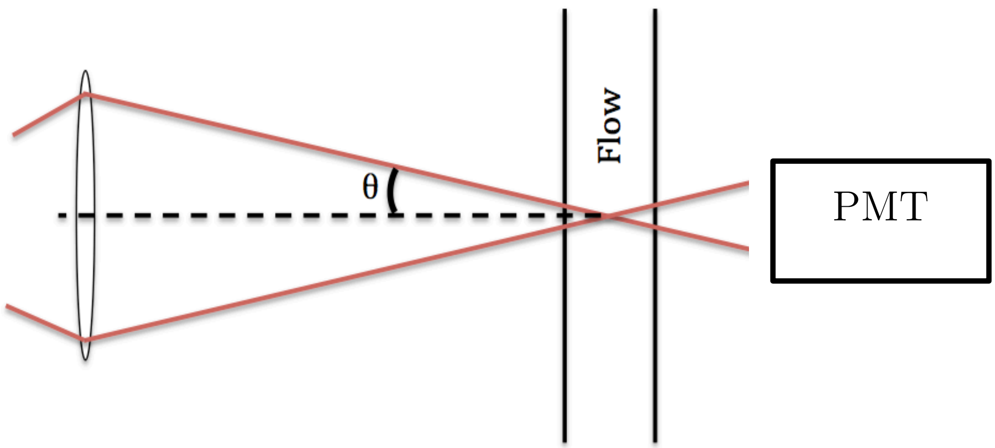


Figure 2: Diagram showing the beam crossing at the location of the flow. In this drawing, the laser light enters from the left and scatters off the particles in the flow. The scattered light is collected using a photodetector (PMT) and read into an oscilloscope.

As particles in the flow pass through the fringe pattern, they scatter light from the periodic fringe pattern, creating a periodic signal at the photodetector (see figure 2). This signal can be recorded and processed to find its frequency. The relation between the velocity and the frequency is given by equation (2).

$$v_{LDV} = d\Delta f \quad \text{Velocity from Doppler shift (2)}$$

The value *d* represents the fringe spacing at the location of the beam crossing and Δf represents the Doppler shift due to the scattering.

The Texas Instruments DLP LightCrafter (LCr) features a digital micromirror device (DMD), which has the capacity to display patterns of 1-bit images at a frame rate of up to 4 kHz [3]. The utilization of DMD technology as a tool for laser Doppler velocimetry is a new application for the device and a new method for performing LDV. To test this

method, we use a small glass mounted on a continuously rotating motor to simulate a flow. We also show that the system functions properly with actual fluid flow by using a syringe pump.

The goal is to show that the LCr can be used to replace the motorized grating pattern and Bragg cell. Bragg cells are prone to being affected by mechanical shock and require a bulky power supply. Another key feature of this technique is cost reduction. A Bragg cell, driver, and power supply can cost up to $5000. The LCr costs $600 and if the DMD could be ordered independently, the price could drop dramatically. Another key difference is that the frequency of the shifting is extremely well known; the clock of the circuit driving the mirrors determined the frequency. The trigger period was accurately set and displayed on the LCr GUI. Lastly, this technique accurately measures slow flows, which has applications in fields such as perfusion.

2 Apparatus

An overview of the apparatus is shown in figure 3.

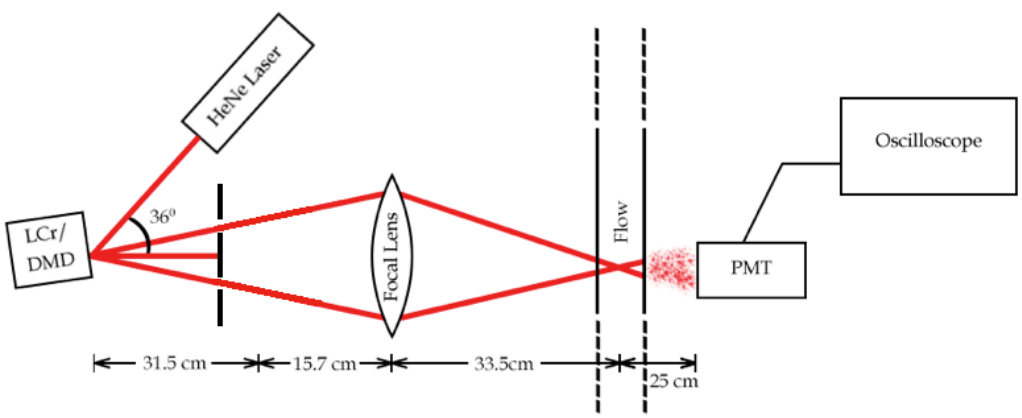


Figure 3: Schematic of apparatus. Light is incident on the DMD and two beams selected using holes in aluminum foil. A lens causes the two beams to cross in the flow, and scattered light is collected into a PMT.

The light engine that was covering the DMD was removed [4]. Note: Instructions included in the appendix. The resulting LCr module is shown in figure 4.

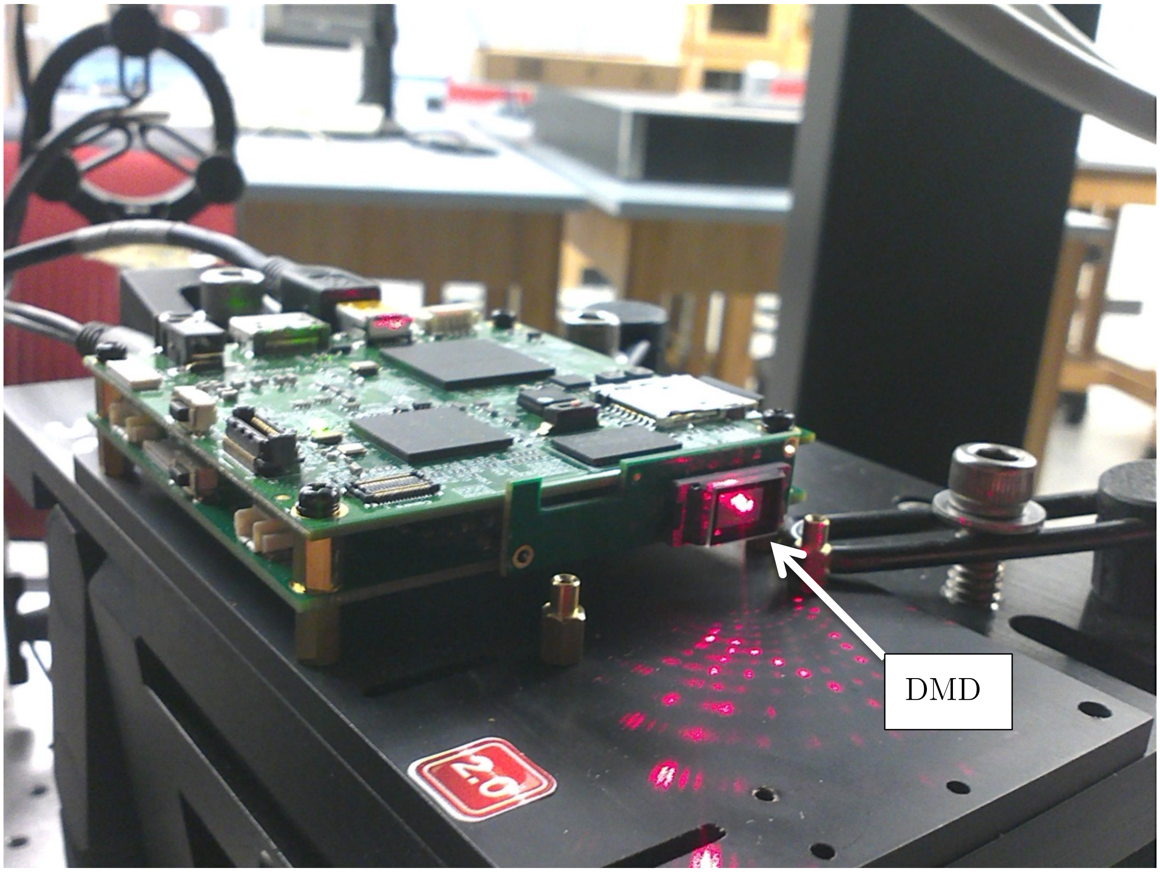


Figure 4: LightCrafter with light engine removed; exposing the digital micromirror device.

A microscope was used to take photos of the DMD while active. These are shown in figure 5.

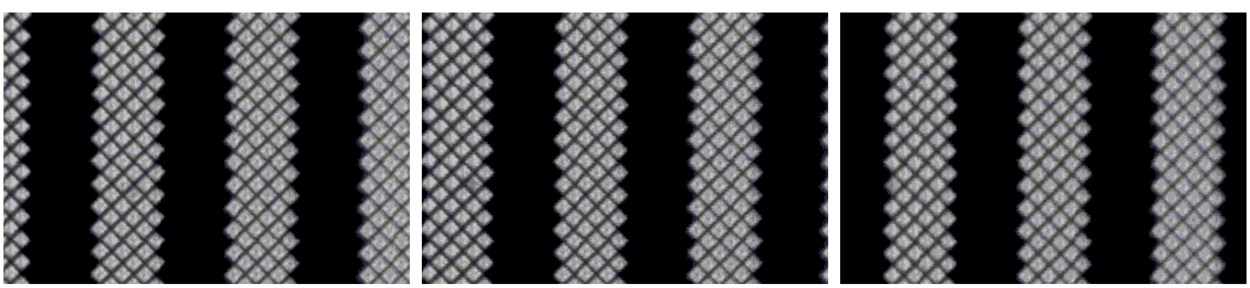


Figure 5: Images of a small portion of the surface of the DMD showing the grating at the three discrete phase positions. The dimensions of the images are approximately 200x150 µm.

The laser used was a JDS Uniphase HeNe laser with an output of 5 mW and a wavelength of 632.8 nm. The PMT used was the Hamamatsu Photosensor Module H5784-

01. The motor used was a Servo City 6-RPM Precision Gear Motor powered by a Digital Manual Speed Controller. The syringe pump used to create a true flow was the NE-300 “Just Infusion.” The syringe used with the machine was a 10 mL Norm-Ject Luer Lock.

3 Results and Discussion

3.1 Measurements

The spacing between the fringes was measured by using a translation stage and a PMT. Figure 6 shows an image of the fringe pattern projected onto a piece of paper using a short focus length lens. To measure the intensity profile a PMT with a pinhole in front of it was placed in the fringe pattern image. The PMT scanned the local maxima of the pattern by moving across while on a translation stage.

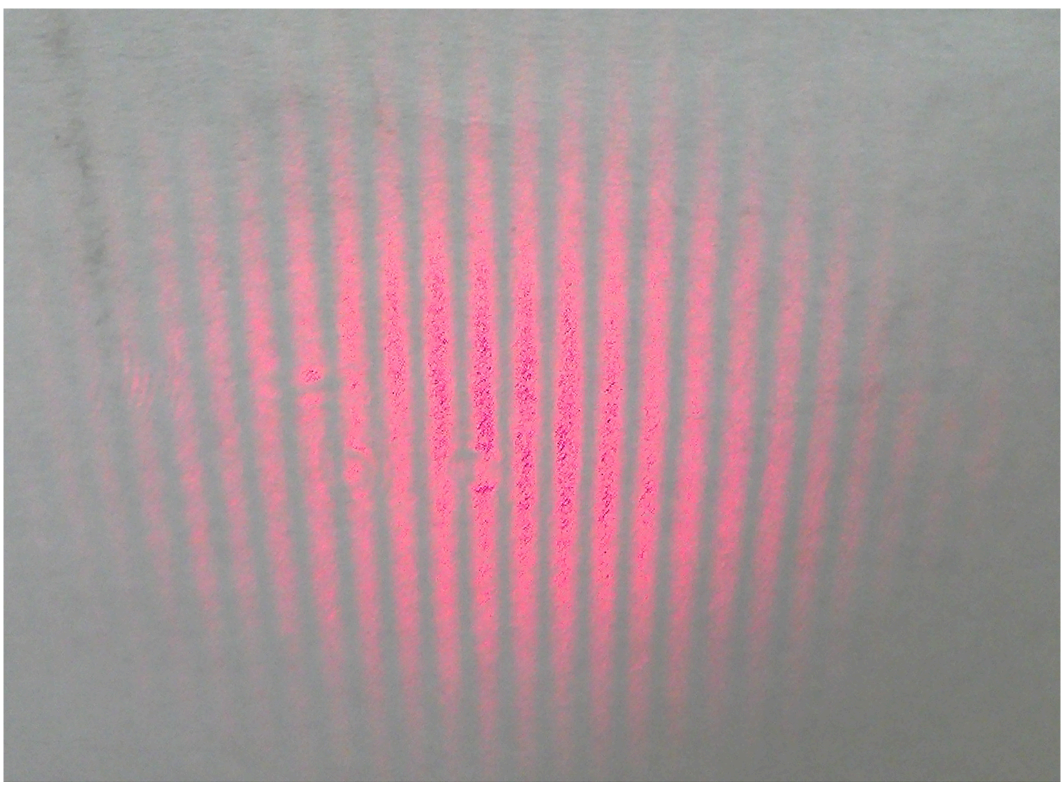


Figure 6: Projected fringe pattern.

The plot of the signal intensity from the PMT against the distance moved is shown in figure 7.

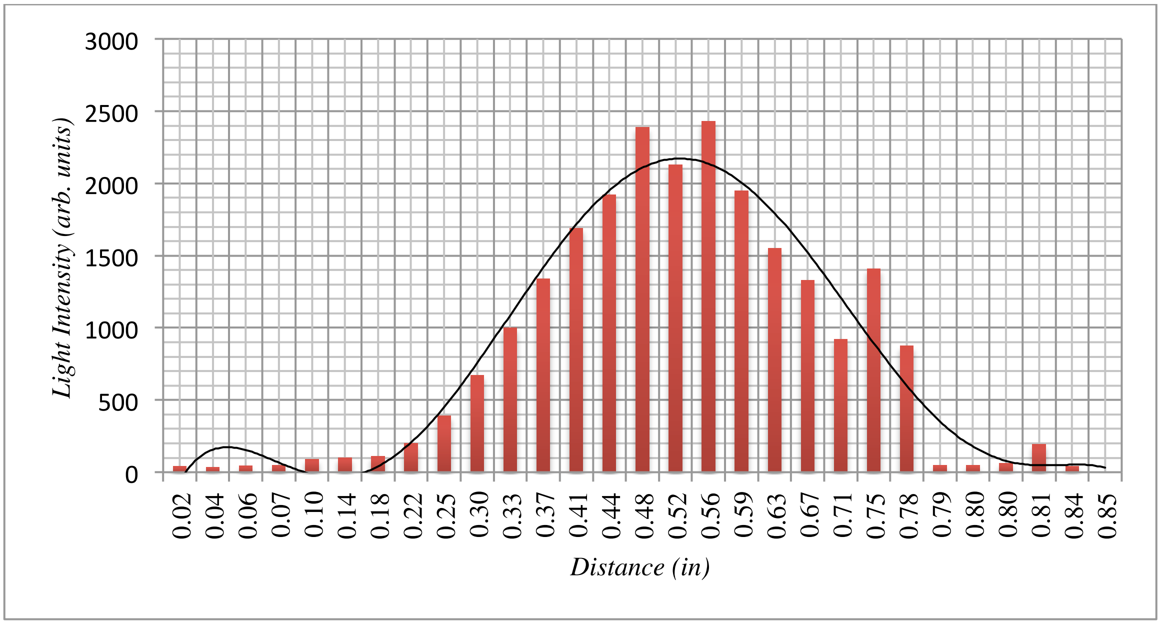


Figure 7: Plot of fringe pattern showing intensity and distance between projected fringes. To obtain this the PMT was moved to find local maxima of intensity. The solid line is a polynomial fit to guide the eye.

In our first test we used a ground-glass screen mounted on a motor so it could be rotated at a constant speed. The speed of the ground glass was measured using equation 3.

$$v_{timer} = \frac{2\pi R}{T} \qquad \text{Linear velocity of a rotating surface (3)}$$

R is the distance from the center of the glass disk to the beam intersection and T is the period of one rotation. The distance, R, is shown in figure 8.

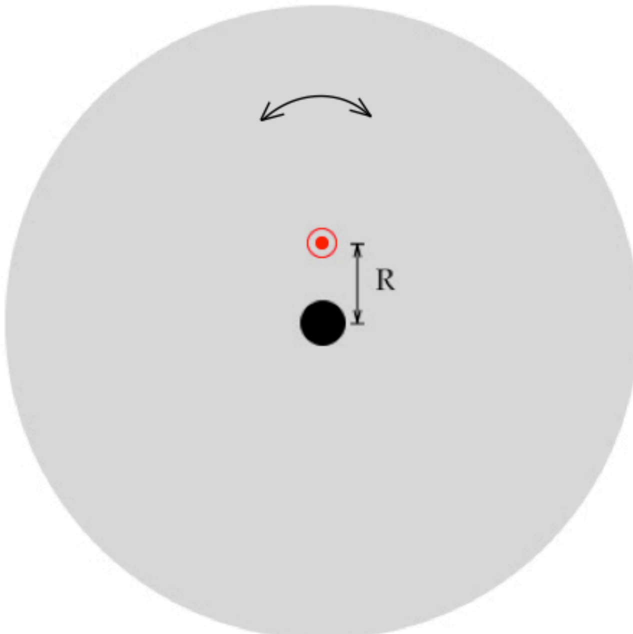


Figure 8: Ground glass used to make a pseudo flow. The location of the intersecting laser beams with respect to the center of the glass is shown.

The syringe pump displayed volumetric flow rates, which required a different type of conversion than the motor setup.

$$v = \frac{4 * flow\ rate}{\pi * (pipe\ diameter)^2} \quad \text{Velocity from flow rate (4)}$$

Intensity data was sensed by the photodetector and the signal acquired using a digital oscilloscope.

The frequency is found by using the Fast Fourier Transform (FFT) either on the oscilloscope itself or by transferring the data to a PC over a USB/GPIB link. Three images stepping at a rate of 4 kHz causes a primary peak at 1.33 kHz when no movement occurs. As a flow begins to move, laser light is scattered which causes the FFT peak to move left or right depending on the direction of the flow. The direction of the frequency shift and the new peak locations are measured. As the flow moves, the Doppler shift, Δf, is the difference between the peak location at 1.33 kHz and the new location. A visual inspection is sufficient in determining which direction the flow moves. For our experiment, the direction is measured from the perspective of the LCr looking toward the PMT. If the peak shifted down in frequency, the flow is defined to be moving to the left. If the peak

shifted up in frequency, the flow is said to be moving to the right. Spectrums of zero velocity and moving flows are shown in figure 9.

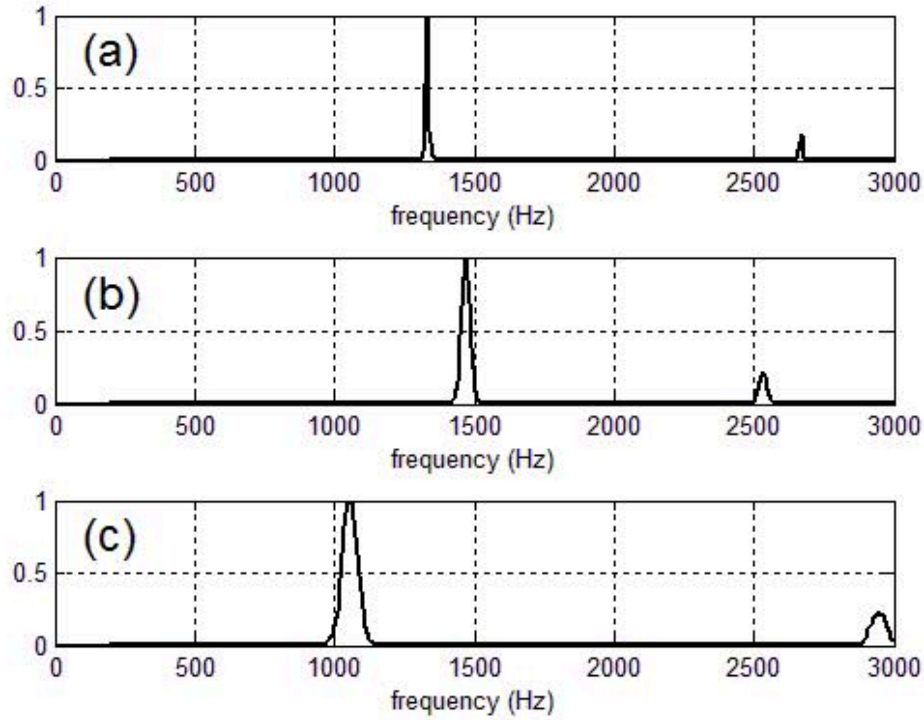


Figure 9: Typical spectra obtained using the ground glass screen. Data was transferred from the oscilloscope to the PC and the spectrum was calculated using Matlab. (a) No movement. Principal spectral peak situated at 1333 Hz. Note the harmonic at 2666 Hz due to the quantized nature of the phase stepping (b) Spectrum obtained when the velocity at the observation volume was +3.3 mm/s (c) Spectrum obtained when the velocity at the observation volume was -6.3 mm/s

3.2 Results

It was seen that a peak moved left or right on the spectrum on the oscilloscope depending on which direction a scattering object moved (in this case a piece of ground glass attached to a motor). Velocities found through the frequency shift were plotted against velocities found by using a timer, resulting in figure 10.

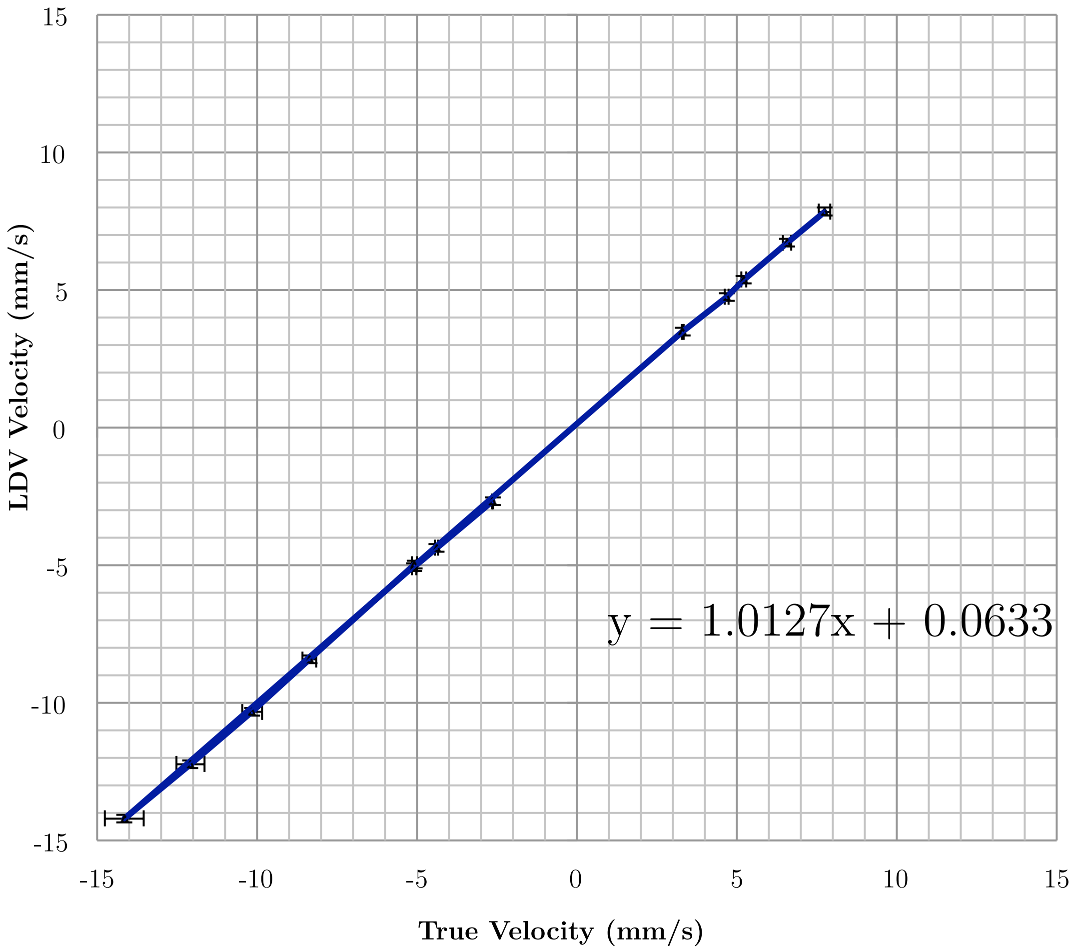


Figure 10: Velocity comparison using a glass connected to a motor with an error of 1%. There are more velocity points in one direction because the motor control was not symmetric and allowed higher velocities in one direction.

Once it was shown that the system worked with a rotating glass, testing was done with a fluid flow by using a syringe pump. The results from the test are shown in figure 11.

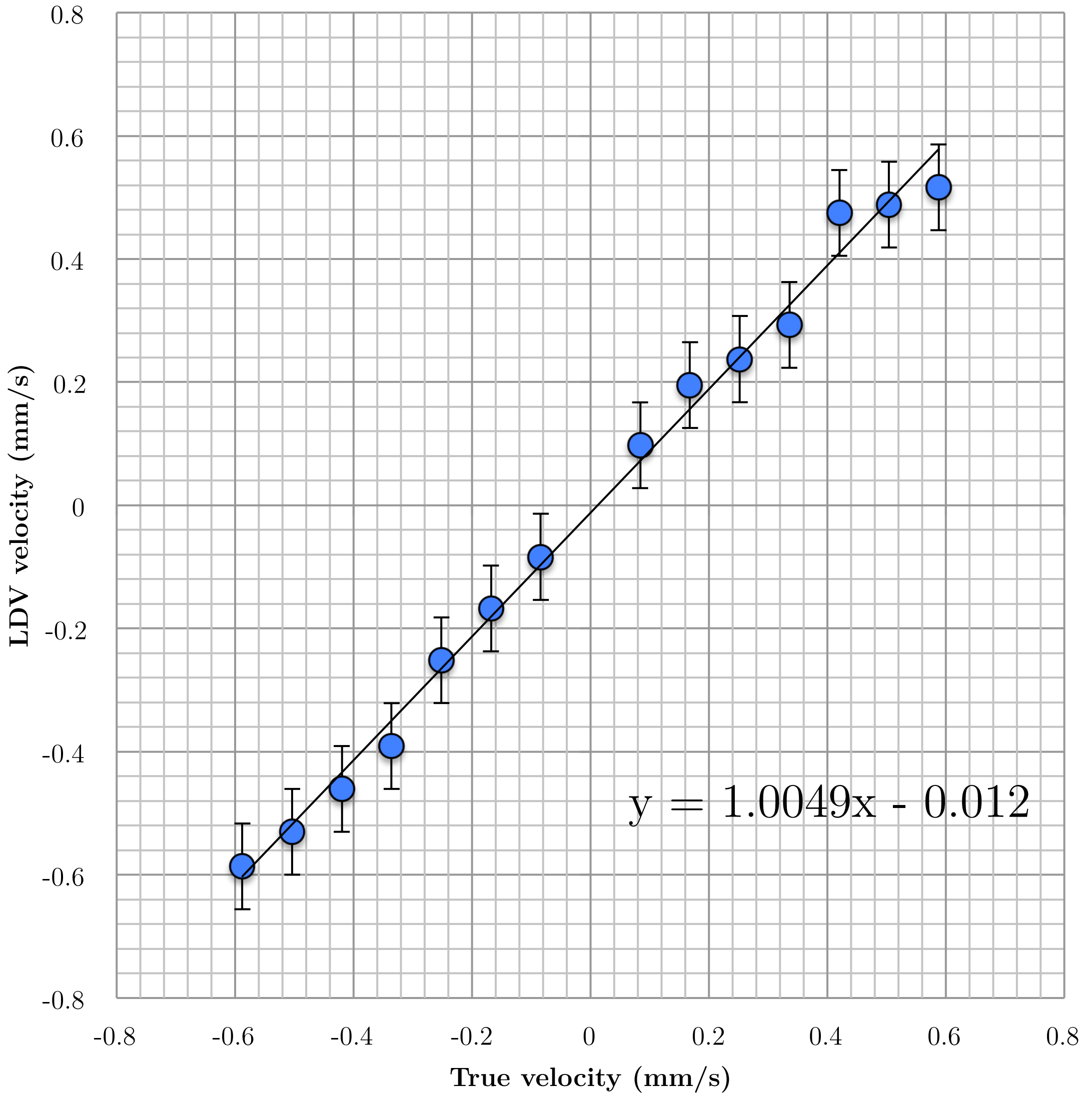


Figure 11: Test with syringe pump with 0.5% error. Previously, higher error was found which was remedied by repositioning of the beam intersection to cross closer to the center of the flow.

4 Conclusions

The phase stepped grating technique in combination with the LCr's DMD technology can be used to replace the motorized grating pattern or Bragg cell. With the phase-stepped pattern replacing the Bragg cell, the apparatus can be more stable and miniaturized.

It was proven that by using the pattern sequence feature on the LCr we were able to remove the directional ambiguity and accurately measure the speed of a flow. It was also shown that a new technology combined with the phase-stepped grating technique could be used to replace certain components typically used in LDV. The spectrum shows broadening at higher flow speeds and further exploration is needed to relate it to the turbulence of the flow.

Considering several other factors could miniaturize the apparatus further. The apparatus could be moved much closer together by changing the focal length of the lens. Another possibility would be to use optical fibers instead of allowing the beams to travel through air. This would help miniaturize the configuration and allow more control regarding where the beams crossed. If an embedded system were created using only the DMD, the apparatus would be miniaturized even further. This will be a task requiring further research into how the DMD technology works. At the final stage, a printed circuit board would need to be created and embedded with code as well as the three phase-stepped images required for this technique. If this were done, costs would also decrease.

The maximum frequency of the LCr used for this project was 4 kHz. The maximum frequencies of such devices are constantly increasing. Less than a year after the start of this project, Texas Instruments has developed devices, which can display patterns at 32 kHz. This increased frequency increases the upper limit of the velocities measurable using this technique.

References

[1] Durst, F., A. Melling, and James H. Whitelaw. Principles and Practice of Laser-Doppler Anemometry. London: Academic, 1981. Print.

[2] Sharpe, John P. "A Phase-stepped Grating Technique for Frequency Shifting in Laser Doppler Velocimetry." Optics and Lasers in Engineering 45.11 (2007): 1067-070. Web.

[3] "Changing Optics on DLP LightCrafter." - DLP LightCrafter Development Platform Forum. N.p., n.d. Web. 03 July 2013. <http://e2e.ti.com/support/dlp___mems_micro-electro-mechanical_systems/f/850/t/159950.aspx>.

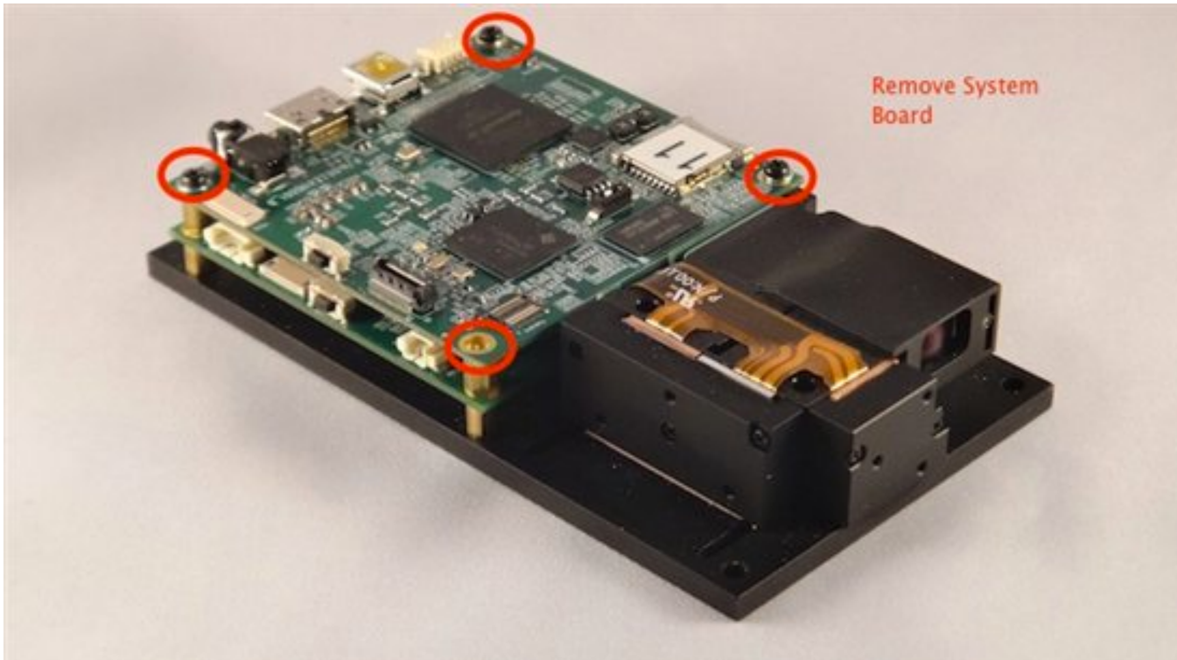
[4] "DLP® LightCrafter™." - DLPLIGHTCRAFTER. N.p., n.d. Web. 01 July 2013. http://www.ti.com/tool/dlplightcrafter

[5] "Boot Issues with MSP430 Firmware v 2.6." - DLP LightCrafter Development Platform Forum. N.p., n.d. Web. 03 July 2013. <http://e2e.ti.com/support/dlp___mems_micro-electro-mechanical_systems/f/850/t/268292.aspx?pi201799=1>.

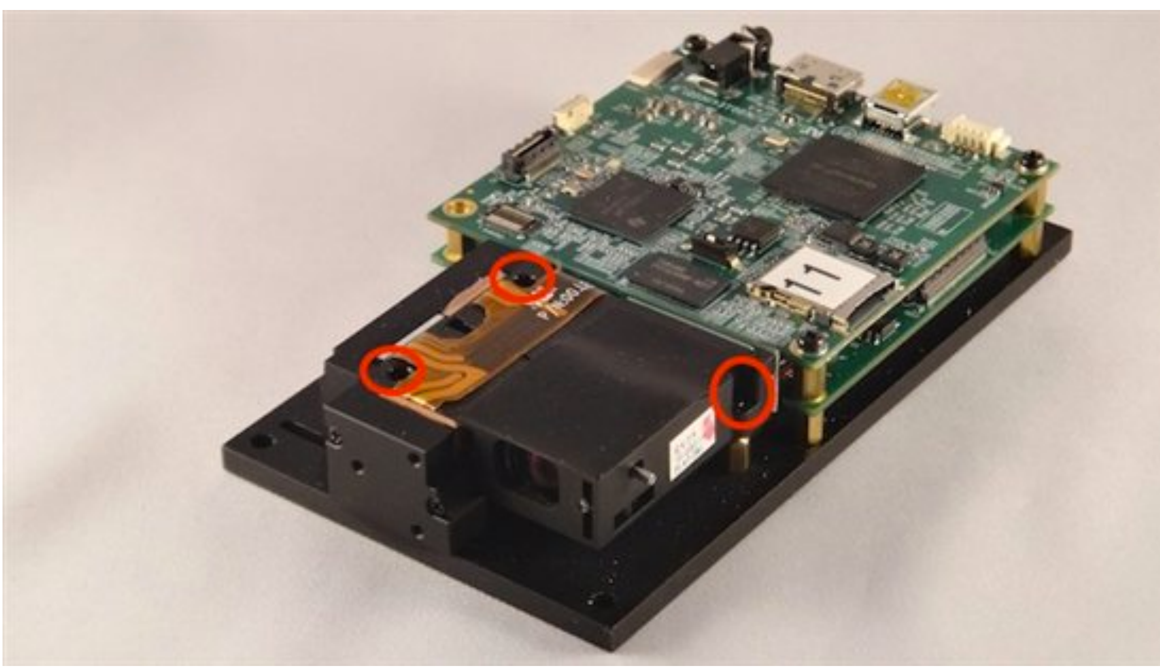
Appendix

1 Removing Light Engine

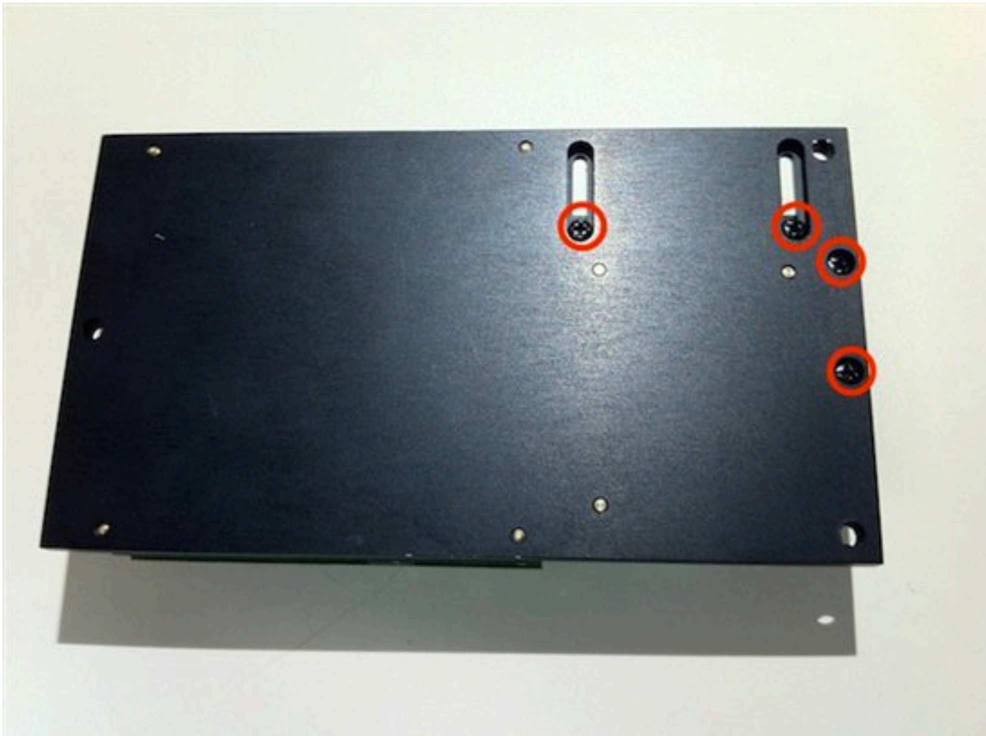
1) Remove the system board (top board) by removing the four screws in the corner posts



2) Remove the three screws from the top of the light engine, you will need a Phillips P00 screwdriver



3) Remove the four screws on the bottom thermal plate holding the LED heat sinks



4) Remove the ribbon cables from the driver board (bottom board). Just pull-up the plastic tab and pull-up the ribbon cable. Be careful, these ribbons are fragile and easy to break while pulling.

5) Remove the two little back screws on the board holding the DMD to the light engine. This is the vertical standing board connected to the driver board.

6) Gently pull out the light engine. The light engine lies on the support posts, so it needs to be raised a little and gently pulled. The connector of the DMD is in the socket.

7) Remove the DMD by removing the two P00 screws on the light Engine.

8) Remove the metal plate and carefully remove the DMD. You can mount the DMD on the socket back on the board. Note the notches on the DMD for proper orientation when placing it back on the connector. The large square notch on the package is on the left, while the triangular notch is on the right.
9) I have re-arranged the boards around to have the DMD without the thermal plate sticking out.

2 Software

1) Downloaded software package from http://www.ti.com/tool/dlplightcrafter

2) LCr required firmware update, but not the MSP430. That needed to be an older version (Ver. 2.5) because the current update prevented the LCr to be run without the light engine. A version mismatch message is shown in figure 12; it can be ignored.

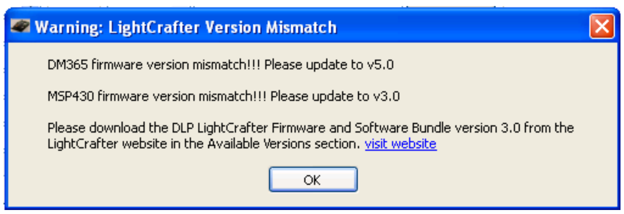


Figure 12: Error message; can be ignored [5].

3) Created 3 phase-stepped images (Code in Appendix 3).

4) Connected LCr to PC via USB.

5) Configured settings on GUI shown in figure 13.

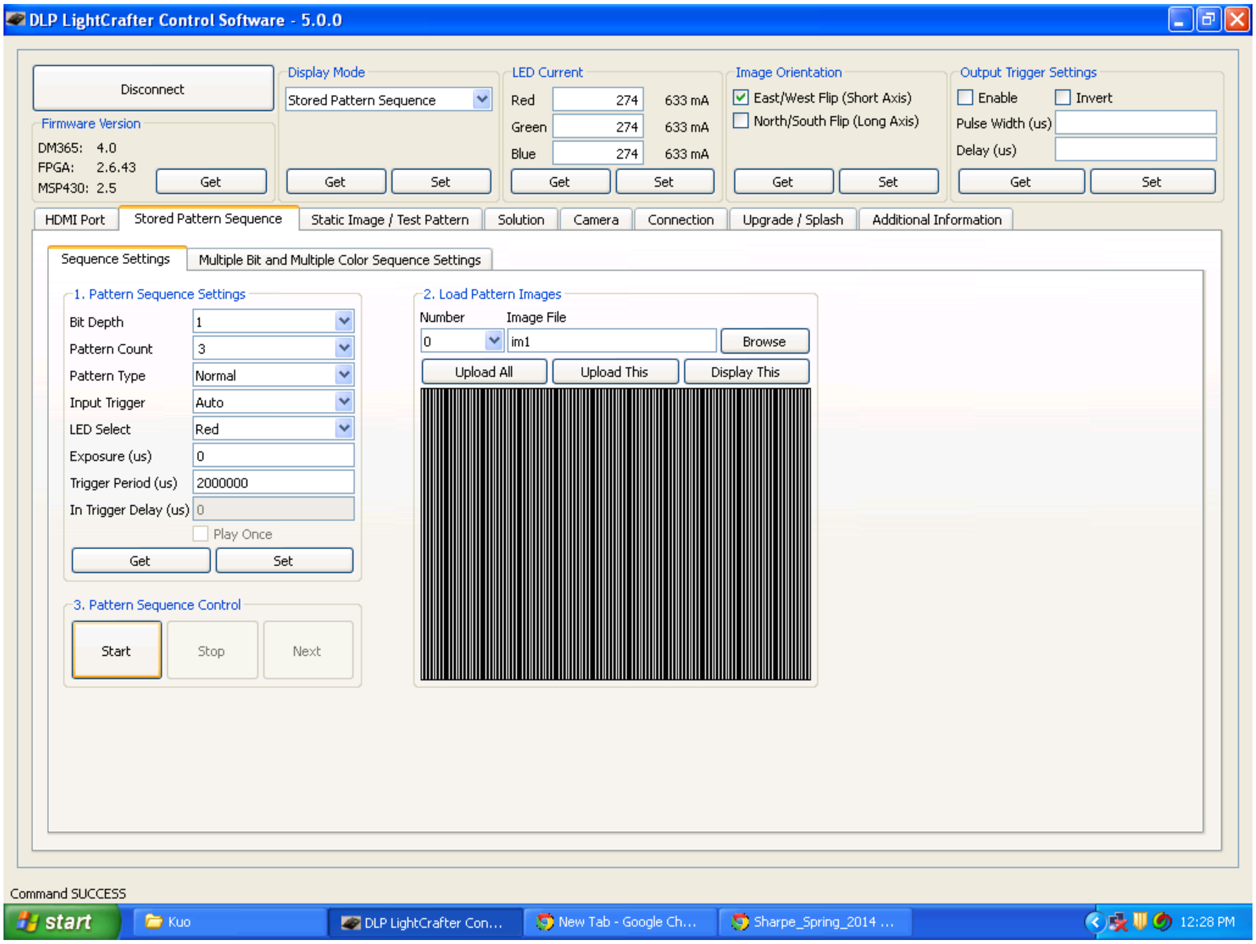


Figure 13: Settings for experiment. Vary the "Trigger Period" to change the frequency of the shifting.

6) Click "Start" to begin the pattern sequence.

3 Code

Creating pattern of three phase-stepped images for the DLP:

```
% making a series of frames to display on the dlp. uses 3 pixels
% for each period so that a 1 pixel shift is one third of a period

clear all

colormap(gray)

szex=608;
szey=684;

x1=zeros(1, 608);   %the first grating

for i=0:3:604
   x1(i+1)=1;
end

x2=zeros(1, 608);   %the second grating

for i=1:3:604
   x2(i+1)=1;
end

x3=zeros(1, 608);   %the third grating

for i=2:3:604
   x3(i+1)=1;
end

im1=zeros(608,684);
for i=1:684
im1(:,i)=x1;
end
im2=zeros(608,684);
```

```
for i=1:684
im2(:,i)=x2;
end
im3=zeros(608,684);
for i=1:684
im3(:,i)=x3;
end
im1=im1';
im2=im2';
im3=im3';

% for i=1:100
%     imagesc(im1);drawnow
%     pause(0.5)
%     imagesc(im2);drawnow
%     pause(0.5)
%     imagesc(im3);drawnow
%     pause(0.5)
% end

%imwrite(im3, 'im3.bmp','bmp');
```