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Eliminating air refraction issues in DIC by conducting experiments in vacuum

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Abstract

A major and often unrecognized error source in digital image correlation (DIC) is the influence of the intervening air between the cameras and sample. Minute differences in air temperature, composition, or both can cause index of refraction changes that act as a lens and cause distortions in the DIC displacement and strain results [1]. There are limited options to correct this problem as it is both spatial and temporal in nature. One method is to use x-rays for imaging that are not affected by air refraction, but this requires costly equipment. A second method uses a vacuum chamber to minimize the intervening air to remove the distortions, but unfortunately this requires inconvenient setups.

Keywords: Digital Image Correlation (DIC), full-field, optical methods, uncertainty quantification (UQ)

Introduction

Stereo-DIC measurements are subject to many error sources that can create either bias errors or variance errors in the results. There is some discussion as to what the largest remaining error sources are for a typical DIC setup. Aliasing, heat waves and camera motion are all possibilities. Of course, this will be very setup dependent. This study looks at index of refraction changes caused by heat waves that are an often-ignored source of temporal and spatial errors. To help elucidate their effects on DIC, an experiment was setup inside a vacuum chamber with a stationary plate to determine a possible lower bound on the noise floor.

Experimental Setup

To determine the influence of the air on the DIC results we used a stereo-rig observing a stationary speckle pattern with a field-of-view of approximately 100-mm (See Table 1 for setup details and Figure 1 for a photo of the setup inside the vacuum chamber). The entire system was placed in a large vacuum chamber that was pumped down to pressures between 3 Torr and atmosphere. The minimum pressure was dictated by the chamber size and leak rate. After shutting off the pumps to minimize vibrations, we acquired images at 5 fps for 3 minutes at a variety of pressures. Images were also acquired at 140 Hz to look at the frequency response of the system. To better illustrate the influence of heat waves, a hotplate was placed under the speckle pattern at a temperature of 60˚C, which simulates the temperature of LED lights. Note that this position of the heat source is a worst-case scenario. Other tests positioned the hotplate either behind the cameras to better simulate a typical experimental lighting setup, or with no hot plate for a best-case scenario.

Table 1. Stereo-rig setup parameters

Cameras	FLIR 2.3 Mega-Pixel
Lens	Edmund Optics 35-mm
Software	Vic3D 7.2.6
Image Scale	≈20 pixel/mm
Stereo-Angle	22.7˚
Correlation	ZNSSD
Subset	35×35 pixels
Step	15×15 pixels
Strain Window	15×15 data points
Shape Function	Affine
Normalization	ZNSSD
Pre-Processing	Low Pass filter

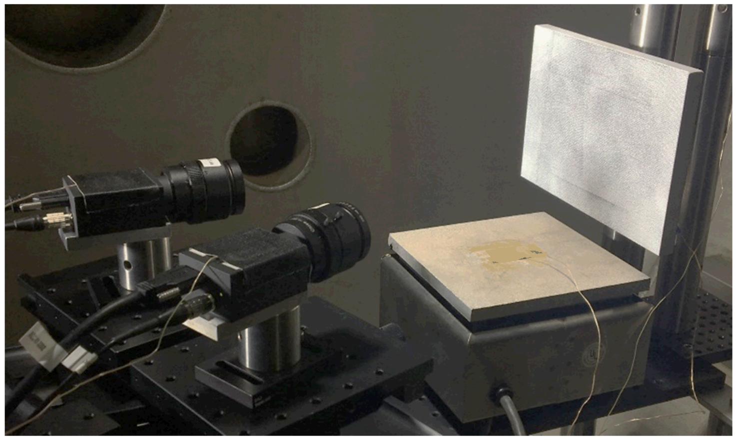

Figure 1. Setup photo of cameras inside the large vacuum chamber. A hotplate was placed immediately under the target to create heat waves.

Results

The stereo-images were analyzed using DIC software with the settings in Table 1. Approximately 900 images were analyzed (5 fps for 3 minutes) to look at both the spatial distribution of noise and the temporal distribution of noise. We noted that after removal of the air from the chamber, other error sources started to become important. For example, sample or camera motion, on the order of 200 nm and small temperature changes of 2˚C were measurable, particularly for the setup with no hotplate. We attributed the improved measurement results, even at atmospheric temperature, to the fact that the lights and other heat sources, along with disturbances from building HVAC systems were isolated outside the measurement chamber. This gave the system, even at atmospheric pressure, a better noise floor than is typically observed in a standard laboratory setting. At this point it becomes difficult to separate the different error sources. For simplicity, only the horizontal displacement (U) from the experiment with the heat source are shown. Temporal errors are measured by taking the standard deviation of the center subset through the 3-minute record time, approximately 900 image pairs. Spatial errors are the standard deviation of the U-displacement at frame 125 at 25 seconds after the start of the experiment. Figure 2 shows the results at vacuum on the left and atmospheric pressure on the right. An order of magnitude improvement is seen in the error. Figure 3 shows the steady improvement of the displacement errors, both spatial and temporal, as the air is removed. Plots are in engineering units, but the corresponding errors in terms of pixels are 0.046 pixels at atmosphere and 0.0032 pixels in vacuum. The atmospheric noise floor is a little larger than the typical rule of thumb of 0.01 pixels, mainly due to the positioning of the hotplate immediately below the sample. However, in vacuum, the value is now approaching the theoretical noise floor for DIC – even in a very poor experimental setup with a heat source immediately below the sample. Results for the hotplate behind the cameras and without the hotplate are similar in trends, but typically with lower errors. However, once below 200 Torr, vibrational motion of either the camera or the sample corrupted the results. To improve on these results, a floating vacuum chamber will likely be required as we are approaching the resolution of interferometry.

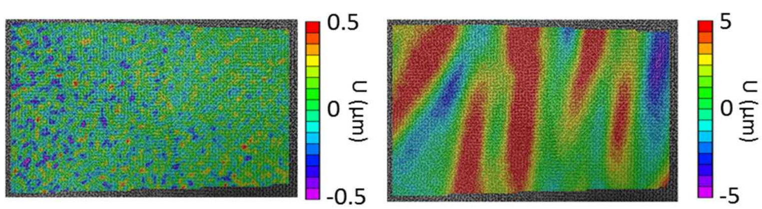

Figure 2. Noise floor characteristics between (left) vacuum measurement with heat source and (right) atmospheric with heat source both for frame 125. Notice an order of magnitude improvement in vacuum.

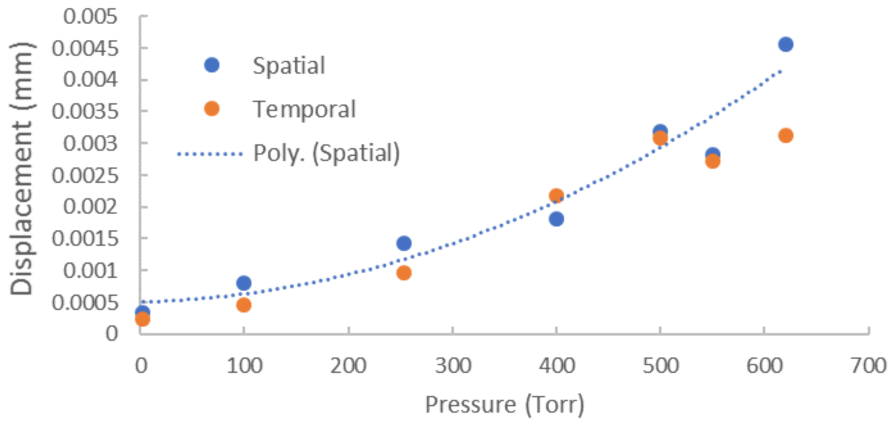

Figure 3. Spatial and temporal strain resolution at various pressures.

Conclusions

The results clearly show that index of refraction changes in the air can be an important error source for DIC. Removal of this effect via a vacuum chamber is effective, but with a more complicated experimental setup. It will be important to judge whether this improvement is important for any given experiment. The results show that typical rules of thumb of 0.01 pixels or 50 με errors in DIC results are more influenced by the air than the fundamentals of the DIC algorithms. Placing the cameras outside the chamber unfortunately did not solve the problem. Even the small amount of air within the lens and between the lens and the viewport was enough to cause measurable index of refraction errors. This helps explain why simulated image errors are typically an order of magnitude lower than experimental errors and are extremely difficult to replicate.

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References

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