Digital Image Correlation for High-Speed Flywheels

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ABSTRACT

The objective of the present work is to evaluate the suitability of using 3D digital image correlation (DIC) for measuring strains on high-speed flywheels. A two-camera DIC setup was used to characterize the effect of image blur on de-correlation and to measure strains on the surface of three 32-cm diameter plastic disks rotating in air at low speeds (2,000 rpm). In one set of experiments, images were taken at different exposure times to characterize the effect of image blur on de-correlation. It was established that the DIC algorithm yielded errors in strain measurement with approximately ten pixels of image blur. This result serves to establish performance requirements for imaging hardware, scalable to higher rotor speeds. In other sets of experiments, strains were measured on the surface of discs. Measured strains compare well with analytical and finite element analyses.

INTRODUCTION

High-speed rotating machinery is currently used to supply pulse-power for the Army's EM Gun systems [1]. These machines are complex structures that incorporate multiple sub-components and many different materials and interfaces. While mathematical models have enabled the design of the rotor, it is ultimately necessary verify the design by measuring deformations at many locations on the rotor under operating conditions (high-speed rotation). To maximize structural efficiency (stored energy per unit volume or mass), the rotor must operate at the highest possible speed, i.e. many of the rotor components must operate under very high loads.

Measuring strain on an object rotating at high-speed presents a special challenge to the experimentalist, and previous research has been conducted in this regard. Several researchers developed techniques for using electrical resistance strain gages [2-5]. Strain measurement using X-ray diffraction has also been investigated [6]. Other research employed electronic speckle pattern interferometry (ESPI) [7-8], and optoelectronic means [9-10]. Each of these techniques has one or more weaknesses that limit its usefulness. Table 1 lists some of the relevant limitations of these techniques, most of which are strengths for digital image correlation.

Digital image correlation (DIC) is a non-contact, optical method used to track and measure the surface displacements of an object as it deforms. This technique tracks the gray level scale of a speckle pattern on the deforming object's surface over a series of sequential digital images. The algorithm in the DIC program processes the pixel displacements in the images and subsequently computes strains. In recent years, several commercially available DIC systems have emerged as practical alternatives to conventional electrical resistance strain gages. Using two digital cameras in a stereo setup, full field out-of-plane measurements can be achieved.
Images captured from digital cameras with frame rates up to 100,000 fps have been successfully used for image correlation in dynamic impact events.

Table 1. Limitations for various techniques for rotating strain measurement.

<table>
<thead>
<tr>
<th>Technique</th>
<th>Error sensitivity to out-of-plane displacements</th>
<th>Field of view</th>
<th>Strain resolution</th>
<th>Rotational speed capability</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain Gage</td>
<td>None</td>
<td>Point</td>
<td>Excellent</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>X-Ray Diffraction</td>
<td>n/a</td>
<td>Point</td>
<td>Good</td>
<td>n/a</td>
<td>Moderate</td>
</tr>
<tr>
<td>Optoelectronic</td>
<td>Moderate</td>
<td>Point</td>
<td>Good</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>ESPI</td>
<td>High</td>
<td>Full-field</td>
<td>Excellent</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>DIC</td>
<td>None</td>
<td>Full-field</td>
<td>Excellent</td>
<td>High</td>
<td>Moderate</td>
</tr>
</tbody>
</table>

Previous work has been done in which DIC was used to measure flywheel strains [15]. While that work showed that it was possible to capture images and correlate at high speeds, no attempt was made to compare measured strains with model predictions. The present work describes results of experiments carried out at ARL with the objectives of validating rotor strains measured by DIC, and characterizing the main source of error (image blur) to determine hardware performance requirements for planned high-speed rotor testing.

**APPRAOCH**

For the objective of characterizing the effects of image blur, a set of low-speed spin trials was conducted. In each trial, the rotor was slowly spun up to a relatively low maximum speed (600 rpm) while images were periodically captured at a given exposure time by the DIC system. Subsequent trials with different exposure times enabled the investigation of speed-independent image blur, and image correlation results were analyzed to characterize the amount of blur that could be sustained before the correlation algorithm broke down.

For the objective of validating the DIC strain measurements by comparing them with model predictions, three rotors were spin tested and results were compared to analytical and finite element model predictions. In the interest of expediency, tests were conducted in open air at low speeds (2,300 rpm maximum). This necessitated the use of a low-modulus material for the rim.

**EXPERIMENTAL METHODS**

**Spin Tester**

All tests were conducted on a custom-built “benchtop” spin test facility at the Army Research Laboratory. Figure 1 shows a simplified schematic of the spin tester (side-view cross-section) with labels. The spin tester is designed for discs of 16cm maximum diameter and a maximum speed of 20,000 rpm. The facility has provision for a vacuum cover (not shown) over the rotor, which is necessary to reach speeds higher than approximately 2,300 rpm. Present tests, however, were conducted in open-air. The rotational speed was measured using an optical tachometer that was triggered from a small piece of adhesive-backed metallic foil attached to the bottom face of the rotors. This tachometer signal also served to trigger the DIC cameras.

**Rotors**

Three rotors were tested. The rims for all three rotors were comprised of low density polyethylene material with 2.5cm-thickness, and inner and outer diameters of 10 and 32cm, respectively. All rims employed an aluminum-alloy clamp-style hub as shown in Figure 2. The hub incorporated a small steel sleeve to accept the steel driveshaft. Prior to spin testing each of the three rotors as described below, rotors were balanced using a graphical single-plane balancing method. Balance weights were added to the hub.

The first rotor incorporated a monolithic annular rim. The strain measurements from this rotor were compared to analytical (closed form) predictions.
The second rotor was identical to the first except it incorporated two holes drilled through the thickness of the rim at a radial location of 13.5 cm and 180-degrees apart (for balance). The third rotor was identical to the second, except that steel plugs were adhesively bonded into the holes. This type of structure (rotor with high-density, large-stiffness, through-thickness inclusion) is particularly pertinent to flywheel pulse power supplies. Strain measurements from Rotors 2 and 3 were compared to predictions from finite element analysis.

**DIC Setup**
The setup consisted of two 1.3-megapixel cameras [16] with 28-105mm lenses placed approximately one meter above the surface of the top rotor surface. The entire top surface of the rotor was painted with canned spray paint, black base and white speckles. The field of view of the cameras was set to a “patch” of approximately 40x40 mm on the rotor surface. Images were captured and analyzed using VicSnap and Vic-3D software [17].

**Blur Characterization**
For these tests, Rotor 1 (monolithic rim) rotor was slowly spun up to 600 rpm while images were manually and periodically captured at a given exposure time by the DIC system. After a trial at a given exposure time, the rotor was decelerated and another trial was conducted with the cameras set to a different exposure time but otherwise identical conditions. Exposure times in the range of 40x10^{-6} to 500x10^{-6} seconds were investigated. For these tests, lighting was provided by two 250-watt halogen lights. The point location in the field of view that was used for measuring the blur strains was at a radial location of 89 mm.
**Strain Measurement**

For the strain measurement tests conducted on Rotor 1, the rotor was slowly spun up to a maximum speed of 2300 rpm while images were captured occasionally. Three trials were conducted, each looking at a different radial location for the “patch”, in order to measure the strains over the entire radial span of the rim. For the spin tests of Rotors 2 and 3, strains were only measured over a single patch centered on one of the holes, and speeds were limited to 2000 rpm maximum speed. For these tests, a strobe light was used, set to 2x10^-6 seconds, and the camera shutter speed was set to 27 x10^-6 seconds.

**ANALYSIS**

**Rotor 1**

A closed-form, plane-stress, axisymmetric model for nested assemblies of anisotropic elastic annuli of uniform thickness was used to predict the radial, \( r \), and tangential, \( \theta \), strains for Rotor 1. The model accepts static rotational and thermal loads (though changes in rotor temperature were neither measured nor used in any of the analysis). The hub was considered in two different analyses using this model. These two analyses serve as bounding cases for the actual experiment. In the first case, the hub was considered as “fixed” to the plastic rim, i.e. continuity of radial stress and displacement across the boundary was enforced. In the second case, the plastic rim was considered as “free”, i.e. the hub was discounted in the analysis. Material properties used in this analysis are listed in Table 2.

**Rotors 2 and 3**

The strains in the non-axisymmetric Rotors 2 and 3 were predicted using ABAQUS finite element analysis (FEA). A quarter-symmetry mesh was built that included 5600 elements and 5746 nodes. Only the “free” rim case was modeled (absent the aluminum hub), and the only loading was a static spin load of 2000 rpm. Element type CPS4I (Continuum Plane-Stress 4-Node Incompatible mode) was used. Material properties used in this analysis are listed in Table 2. It should be noted that these properties were not measured on any of the material that was used in the experiments, rather these properties were chosen for expedience. Values for steel and aluminum are well known, but the literature reports a wide range of modulus and density for the LDPE.

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s Modulus (GPa)</th>
<th>Density (g/cm³)</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDPE (plastic)</td>
<td>0.24</td>
<td>0.88</td>
<td>0.4</td>
</tr>
<tr>
<td>Aluminum alloy</td>
<td>70</td>
<td>2.7</td>
<td>0.3</td>
</tr>
<tr>
<td>Steel</td>
<td>210</td>
<td>7.5</td>
<td>0.3</td>
</tr>
</tbody>
</table>

**RESULTS / DISCUSSION**

**Blur Characterization**

Figure 3 shows apparent radial strain in Rotor 1 versus speed for different exposure times. For clarity, only a subset of the data collected at exposure times up to is shown in this plot. This plot shows that shorter exposure times are necessary for higher speeds. Figure 4 shows the same strain data plotted against “blur”, where “blur” is the number of pixels that traverse the field of view at a given rotational speed and exposure time. In terms of blur, the data from Figure 3 collapses onto a single curve with an inflection point at approximately ten pixels. It is precisely this finding that supports the conclusion that DIC will yield accurate flywheel strains so long as the blur in the images is kept below ten pixels. A relatively inexpensive means to effectively achieve short exposures is to use a long-exposure-time camera with a fast strobe light.

**Strain Measurements in Rotor 1**

Figures 5 and 6 show tangential and radial strains, respectively, versus radial location measured at 2300 rpm on Rotor 1. Three trials were conducted in order to measure strains representative of the entire radial range of the rim (hence, Figs. 5 and 6 show DIC patches 1-3). Strains typically fall between the bounding “fixed” and “free” analytical predictions, closer to the “fixed” prediction. While conducting these tests, a significant amount of out-of-plane displacement was observed in the rotor. Inspection of the z-component of displacement indicated that this
displacement might be a manifestation of one or more flexural vibration modes that were excited in the rotor as it spun. As a consequence of this vibration, a number of frames were averaged to construct the strain plots in Figures 5 and 6, and this is reflected by the inclusion of error bars at each data point.

It should be noted that all strain results in this report likely also include some thermal loading, as a result of the illumination (two 250-watt halogen lights) that was maintained on the rotor during the tests. It is likely that the rotor cooled due to convection as the speed was increased. Thermal loading was neither measured nor included in the model predictions.

Figure 3. Apparent radial strain versus RPM for different exposure times in the blur characterization tests.

Figure 4. Apparent radial strain versus blur for different exposure times in the blur characterization tests.
Figure 5. Predicted and measured tangential strain versus position for Rotor 1.

Figure 6. Predicted and measured radial strain versus position for Rotor 1.
Strain Measurements in Rotors 2 and 3

Figure 7 shows the comparison between the FEA predictions and the DIC measurements of radial strain near the hole in Rotor 2. Comparison of these strain values at the 12 o’clock and 6 o’clock positions shows that there is good agreement between FEA and DIC, considering that the material properties of the LDPE used in the analysis were not actually measured but represent a “middle of the range” of values reported in the literature. There is also good qualitative agreement in the shape of the strain distribution around the hole.

Figure 8 shows the same strain field for Rotor 3 (with the steel plugs). Agreement is very good at the 6 o’clock position, but poor at 12 o’clock. This disagreement may be due to one or more factors (e.g., incorrect material properties for LDPE, partial disbond of the adhesive between the plug and hole, thermal loads). Conversely, this disagreement may indicate that, in reality, properly modeling the strains at the interface between disparate materials is difficult and that experimental measurements are ultimately necessary.

CONCLUSIONS AND FUTURE WORK

The blur characterization tests served to define requirements for imaging hardware. The threshold amount of image blur at which the correlation algorithm started to break was ten pixels. The strain measurement
experiments, which were intended for verification, showed reasonable agreement with theory for Rotors 1 and 2. For Rotor 3 (steel plug in the hole), theory and measurement showed significant disagreement. This may be caused by error in modeling inputs and/or experimental error, or this may instead illustrate the need to actually experimentally measure such structures that contain interfaces between materials with disparate mechanical properties.

Future work will include measuring strains using DIC at higher speeds in a containment vessel and investigating the feasibility of capturing images through a transparent window. Techniques for using DIC to monitor rigid body displacements of the rotor will also be investigated.

ACKNOWLEDGMENTS

Mr. Michael Minnicino and Mr. Robert Kaste performed the finite element work that was included in this report, and their efforts are appreciated. Commercial products have been identified in this paper for the sole purpose of specifying the experimental hardware and procedures that were followed in this work. In no case does such identification imply a recommendation by the US Army Research Laboratory.

REFERENCES