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Investigating the Use of Digital Image Correlation for Cracked Axle Detection

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Summary

TTCI is exploring the feasibility of using a vision-based, three-dimensional (3D) strain measurement technology known as digital image correlation to detect cracks in axles. After performing a series of experiments to test the sensitivity of the 3D digital image correlation on an axle with thin notches cut into the axle body to simulate shallow cracks, the results demonstrated that strain produced near the notch was about 300 microstrain when the axle was subjected to the maximum static load (full weight of a loaded car at 263,000 pounds). It was determined that an order of magnitude improvement in sensitivity of the digital image correlation system is needed to detect the strain localization around the flaw. Resolution of this system was not sufficient to detect the stress concentration due to a notch cut into the axle. Implementation issues such as surface preparation were not addressed in this work; rather, this was a preliminary investigation of the sensitivity of the technique and whether it was sufficient for inspection of axles without removing them from the train.

The fundamental premise of this test is that axles with internal defects or cracks to the surface will experience a stress concentration near the defect. This stress concentration will result in the localization of the strain field near the geometric discontinuity. The abnormal strain should be detectable if the technique is sensitive enough and has sufficient resolution. Such an optical approach can inspect only the portions of the axle that are visible via line of site, which is the area between the wheels. Portions of the axle that are hidden by the wheels and bearings cannot be evaluated with this approach.

An initial evaluation under the Association of American Railroads' Strategic Research Initiatives Program, of a non-modified, commercially available 3D digital image correlation system was performed under conditions that would approximate the measurement environment for inspecting the visible portion of axles on a moving train. Although this technique did not provide the sensitivity needed to detect the simulated flaw in the axle under the applied quasi-static loading conditions, digital image correlation is well suited for the characterization of strains both in the elastic and plastic ranges due to its capability for fast data acquisition over a large area.

TTCI will test other alternative whole field nondestructive evaluation techniques such as laser shearography or infrared thermography for their potential applicability to cracked axle detection.



BACKGROUND

Axles are safety critical components for the railways, as their sudden failure poses safety, reliability, and efficiency concerns for railroad operators. Hence, there is demand for novel nondestructive evaluation (NDE) techniques to evaluate and identify axles with internal discontinuities such as flaws or cracks.

Axle failure can be related to mileage, tonnage, and service time. Periodic inspections are required to identify and characterize any growing fatigue cracks in axles. To avoid taking vehicles out of service, on-line, real-time monitoring is demanded. TTCI is exploring the feasibility of applying vision-based digital image correlation for detecting surface strain anomalies in notched axles. Digital image correlation is a non-contacting, whole field, relatively fast measurement technique that may have application for detecting flaws in axles.

INTRODUCTION

Digital image correlation employs tracking and image registration for accurate two-dimensional (2D) and 3D measurements of small changes in the images.^{1,2,3} It is a technique based on surface analysis methods and involves monitoring and identifying changes in a pattern on the surface of an object subjected to some form of mechanical load. It requires a high contrast, random pattern on the surface of interest. A digital image of the surface is captured in an un-deformed state. A load or deformation is then applied to the specimen and a second image is captured. The images are then compared (correlated) to determine the surface strains. The patterns can be created artificially, or might exist naturally in the object.⁴ For example, Figure 1a shows a typical speckle pattern for digital image correlation measurements. A random speckle pattern can be created artificially with spray paint. Some materials, such as carbon fiber (Figure 1b), have a naturally occurring pattern. The key is that the pattern be random, isotropic, have high contrast, and a uniform distribution.

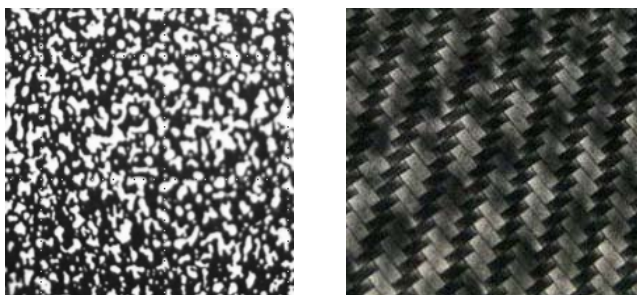


Figure 1. (a) Artificially Painted Speckle Pattern, (b) Naturally Occurring Surface Pattern in Carbon Fiber Laminates

3D DIGITAL IMAGE CORRELATION

A 3D digital image correlation is based on a simple binocular vision concept similar to human depth perception. Two cameras are used to view the surface from different directions. Figure 2 illustrates the setup for the binocular vision model.

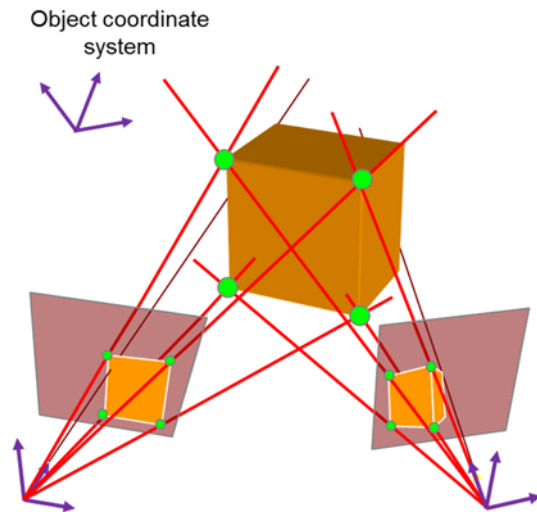


Figure 2. Binocular Vision Model

Information about the shape of the object can be obtained by comparing the locations of corresponding speckles taken by the two cameras. The relationship between the camera coordinates and the system coordinates can be obtained with a one-time calibration aligning the camera and system coordinate systems. Transformation from system to camera coordinates is a simple mathematical operation that can be carried out quickly on a laptop computer. The projection from camera coordinates to sensor coordinates is derived from similar triangles.⁵

Digital image correlation relies upon the appearance of “fingerprint” digital grey-scale patterns locally over the sample. Camera focal length, width of view, and angle will all affect the view of the pattern. System sensitivity is determined by the pixel resolution and the nominal size of the speckles.

Experimental Approach and Setup

TTCI performed a series of experiments to test the sensitivity of 3D digital image correlation for detecting axle defects. An axle with thin notches cut into the axle body was selected. The notch tested was the one nearest the center of the axle. This is also the one under the greatest bending stress, which should show the greatest strain localization. This notch was approximately 1 inch long, 0.125 inch deep, and approximately 0.020 inch wide.

Speckle pattern is very important for analysis. Several studies have demonstrated that measurements can be influenced by the speckle pattern quality, including speckle size, shape, distribution, and density. Extra care was taken to generate speckle pattern of uniform size and distribution. As shown in Figure 3, a base coat of flat white latex paint was applied on the cleaned axle. Latex paint is selected because it can flex with the sample. Finally, flat black latex paint was sprayed in such a manner that the spray paint fell onto the sample instead of hitting the sample directly; thus creating random patterns.



Figure 3. Application of the Speckle Pattern

A general rule of thumb is that speckles should cover between four and five pixels at minimum. This is the key for digital image correlation measurement. The speckle pattern created corresponded with the focal length for inspecting the axle from below the rail. Figure 4 shows detail of the speckle pattern at the notch.



Figure 4. Notch in the Speckled Axle, Near Center

The test axle was placed under a freight car, and the freight car was placed over a service pit. The pit allowed room for the cameras to be oriented far enough from the axle to get an adequate field of view. Figure 5 shows the test setup.

QUASI-STATIC LOADING

After a one-time calibration, TTCI applied various static loads to the axle. This was done by incrementally lowering a fully loaded car body (263,000 pounds) onto the railcar truck. Figure 6 shows the hydraulic lifting jacks and load cells used to raise and lower the car. Loading states were: (1) weight of bare wheel and axle

as baseline or reference load; (2) weight of wheel, axle, and truck components as first load state; (3) half carbody weight added to truck as second load state; and (4) full weight of carbody as third or maximum loading state.

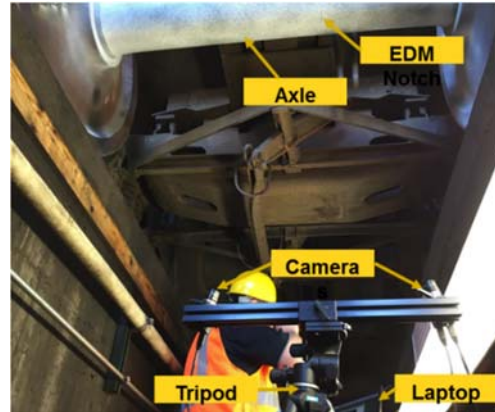


Figure 5. 3D Digital Image Correlation Test Setup



Figure 6. Hydraulic Jacks with Load Cells

ANALYSIS

A region of interest was selected prior to running the correlation, as shown in Figure 7. This region was roughly a 5-inch by 7-inch rectangle around the notch. The region of interest is analyzed for shape and displacement by the system software. The notch is roughly centered in the region of interest and is vaguely visible in the photo as a vertical line.

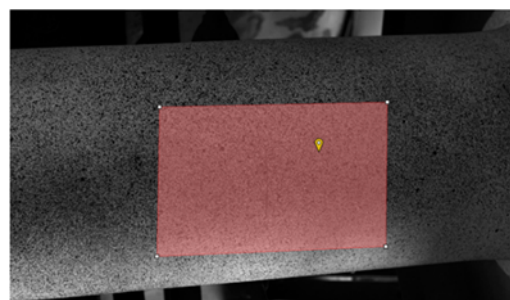


Figure 7. Region of Interest around the Notch

Whole field displacements, normal strains, and shear strains were calculated in all three principal directions using the digital image correlation technique. It was expected that a localization of the strain field near the notch would be observed, but this was not the case. It was determined that the digital image correlation system resolution was not sufficient to distinguish the localization of strain at the ends of the notch. The maximum out-of-plane deflection under full load was near 7.5 mm (0.29 inch). Figure 8 shows the whole field out-of-plane displacements within the region of interest.

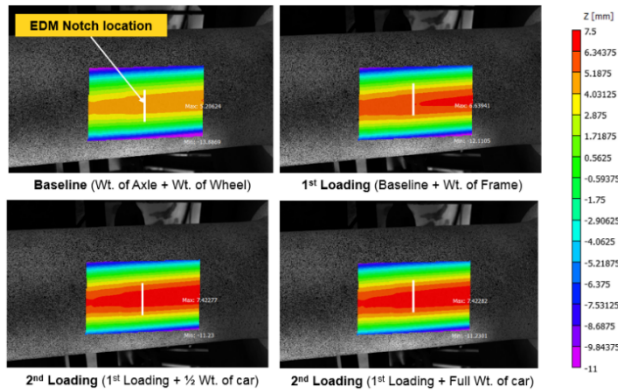


Figure 8. Whole Field Out-of-Plane Displacement in Region of Interest is near 7.5mm at Maximum Load
(White line represents the location of notch.)

Similarly, Figure 9 shows the vonMises strain, x normal strain, y normal strain, and shear strains under maximum load. It can be observed that there was no activity of the localization of strain field along the notch regions. As a result, the notch anomaly was not visible under any of these conditions. A black line is drawn into each image at the location of the notch.

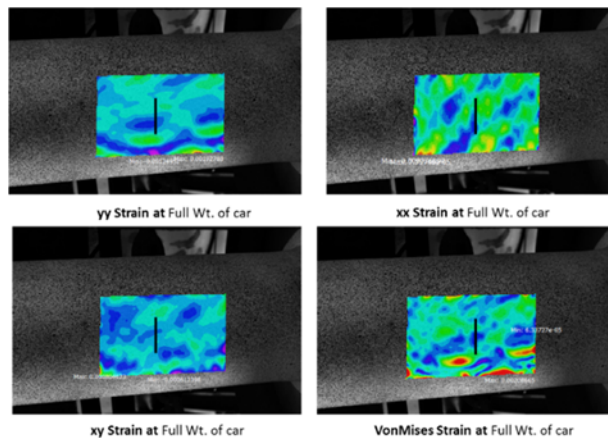


Figure 9. Whole Field Strains at Full Load

CONCLUSIONS

TTCI performed a preliminary study of a commercially available 3D digital image correlation system. This study was performed under conditions that would approximate the measurement environment for inspecting the visible portion of axles on a moving train. The bulk strain was on the order of 300 microstrain under the applied loading conditions; strain would be much higher in localized regions near the ends of a notch cut into the axle. Resolution of the digital image correlation was not sufficient to detect these stress concentrations.

Although this technique did not provide the sensitivity needed to detect the flaw in the axle under the applied conditions, digital image correlation is well-suited for the characterization of strain. Due to its capability for fast data acquisition, it can measure strain both in the elastic and plastic ranges. It offers full-field, non-contacting measurement with considerable accuracy for displacement and strain measurements and may have other applications for train inspection.

FUTURE WORK

TTCI will test other alternative whole field NDE techniques such as laser shearography, or infrared thermography for their potential applicability to cracked axle detection.

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