Optical strain measurement for fault detection in haul-truck tires

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Abstract. Tire condition is integral to the safe operation of heavy machinery, such as ultra-class haul trucks. A new approach to haul truck tire monitoring is being investigated based on optical strain measurement, which has the advantage of providing quantitative information from sensors that do not contact the tire. A laboratory-scale apparatus has been constructed to monitor a tire as it is subjected to various loads and pressures. Digital image correlation is used to calculate the deformation in the tire. Using this method, damage resulting from a horizontal and vertical cut created on the tire surface could be detected. A three-dimensional surface reconstruction of the tire was created to assist in the characterization of more complex damage types such as wear and fatigue. In addition to providing information for a possible industrial scale damage detection system, this apparatus will also further the understanding of damage mechanisms in tires.

1. Background

Tires used in the transport and excavation of materials such as metals, minerals, and soils are subject to extreme variations in loading, temperature, and other environmental conditions. On ultra-class haul trucks, these tires can measure up to 4m in diameter, with a weight of 5,300 kg. There are a limited number of manufacturers that can produce sufficiently durable tires for usage in harsh environments and the cost of tires is high. As a result, tire failure is not only a safety hazard, but also a costly and time-consuming complication to operations, reducing productivity.

Typically, tire condition is assessed through visual inspection by trained technicians, who can then remove the tire for further testing and maintenance if necessary. However, some types of internal damage are not always detectable using this procedure, such as fatigue or belt separation. Additionally, depending on the availability of personnel, inspection may not be frequent enough to identify damage to the tire before the damage becomes too serious to repair.

Pressure and temperature monitoring systems have also been implemented on-site to detect tire damage. While these methods are useful for detecting certain types of damage, other types, particularly highly localized damage, can remain unnoticed. Hence, there is utility in developing other monitoring solutions that can be incorporated into a maintenance plan that detects tire damage, extending tire life and preventing dangerous failures from occurring.

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To achieve these goals, a laboratory-scale apparatus has been commissioned to establish the feasibility of using optical strain measurement to diagnose tire damage. This equipment can be used to obtain two and three-dimensional measurements on a tire surface under multiple pressure, load and temperature conditions. Previous work established that planar strain due to applied loading could be observed and quantified [1]. This paper will investigate the feasibility of three-dimensional surface measurements and the detection of simple surface cuts using digital image correlation and optical strain measurement techniques.

Numerous techniques were investigated for application to large tire monitoring [1]. Safety, timeliness, durability and cost-effectiveness were emphasized in the search for candidate technologies. Ultimately, digital image correlation (DIC) was chosen for further investigation, as it could potentially provide quantitative measures of tire condition from a distance without the need for the truck to be taken out of service for inspection.

Digital image correlation is used to compute the strain field of an object from a series of images. This is accomplished by using an intensity-based weighting function to compare neighbouring subsections of a set of images to determine the likely displacement of the region between frames [2]. It is predicted that the strain exhibited at the tire surface will change as it undergoes wear, fatigue, separation and other forms of damage. It is necessary to verify this prediction before proceeding to a full-scale industrial monitoring system using DIC techniques. In addition to fault detection, optical strain measurement can also be used to gain a deeper understanding of the mechanisms leading to tire damage and how faults propagate through a tire. This information is valuable in the design of resilient, durable tires that can withstand extreme loading conditions.

2. Theory

Digital image correlation uses statistical correlation between sets of images to determine the displacement of a particular region, or window, between successive images [3]. This is accomplished by subdividing the region of interest into multiple windows of a given size N. Each window is then compared to its neighbours over an N/2 radius in subsequent images. A function evaluates the correlation factor between windows to determine the position of the original window in the next frame, returning its displacement vector from one image to the next. This relies on the intensity of a given feature remaining consistent between frames. The calculated displacement can be used to map the strain at different locations over an object.

A commercial software package (DaVis 8.0, LaVision GmbH) was used for manipulation and processing of data. An advantageous feature provided by this software is the ability to perform multi-grid correlations, where displacement calculated over larger windows is used to provide an offset for smaller regions. This allows for a wider range of deformation to be quantified in an image compared to using a single window size. The software also provides the option to iteratively refine calculated displacement vectors to increase accuracy. [4]

To accurately measure small displacements, images must be scaled and de-warped. Calibration mitigates inaccuracies caused by camera and lens distortions. For these experiments, a custom calibration plate was used. A pattern of 3 mm dots arranged in a grid 15 mm apart was applied to a flat plate that covers the entire tire area. One image per camera is sufficient to correct distortions and scale the image for two-dimensional measurements. Two or more images at differing depths must be taken to calibrate the system for three-dimensional distance measurements. Using this technique, an error of less than 0.3 pixels has been achieved in image reconstruction, which typically translates to a physical distance of 0.05 mm or less for these experiments. The calibration is only valid at a specific focal length, so care is taken to keep the focus and position of each camera constant between images.
Although 2D displacements can be measured using a single camera, two or more cameras are required for 3D measurements [5]. This introduces additional complexity (and processing time) to the correlation process. As a starting step, a 3D reference surface must be calculated, using a process similar to triangulation, from which subsequent deformation will be determined. While this is relatively simple for a flat surface, it becomes more difficult for irregular surfaces. Surface creation is accomplished in the software by iteratively refining a series of user-defined point correspondences between cameras [4].

3. Equipment and Apparatus

An apparatus, shown in Figure 1, was commissioned to provide accurate, repeatable tire data. This consists of a vertical end mill retrofitted with a mounting hub that attaches to a radial tire with a 45.7 cm (18”) outer diameter. Calibrated strain gauges applied to the hub are used to measure the amount of force applied to the tire, which ranges from 0 to 200 kg, while a spindle dial is used to record its angular position. If desired, the rotational speed of the tire can also be controlled using the mill controls and measured with a tachometer attached at the hub.

**Figure 1.** Tire Testing Apparatus.
To make planar measurements at the tire surface, only a single camera and calibration target are required. For three-dimensional stereo photogrammetry, two or more cameras are necessary. Two consumer grade commercial cameras (Rebel XT and Rebel XTi, Canon Inc) mounted at 14º from the centreline of the tire axis, were used in the experiment, providing 3456 x 2304 pixel and 3888 x 2592 pixel images respectively. The cameras were equipped with 18-55mm and 28-105mm zoom lenses that were optimised to provide approximately the same field of view. Two 500W floodlights illuminate the tire surface so that high-contrast images can be recorded at a shutter speed of 1/20 seconds at f.18. Using a smaller aperture ensures that the entire tire surface is in focus.

Cross-correlation is most effective when a unique, high-contrast texture is visible in the images [6]. Comparing successive images of a uniformly coloured tire would result in weak correlation between the two. To increase correlation accuracy, a high-contrast speckle pattern was applied to the tire. Most dots measure between 0.2 and 1mm, which typically translates to 2-8 pixels in diameter in the image. The scaling is a function of the camera distance, zoom, and resolution.

4. Two-Dimensional Damage Detection

One of the purposes of the tire testing apparatus is to examine how fault data can be collected with optical measurement techniques. For initial study, simple cuts were made on the tire sidewall perpendicular and parallel to the direction of loading. These faults cause predictable behaviour in the tire and can be correlated with existing theoretical tire models.

It was predicted that the primary distortion caused by the cuts would be planar to the tire surface, which was confirmed by visual inspection of the tire. As most of the deformation occurs in-plane, two-dimensional strain measurement techniques can be applied. The deformation caused by the cuts becomes more apparent as load is applied to the tire. Images were taken of the tire before and after its surface was cut, with a 140 kg load applied upwards, perpendicular to the bottom of the tire. An inflation pressure of 165 kPa was maintained.

4.1 Radial Sidewall Cut

A cut 15 mm long and 3 mm deep was made on the tire surface, parallel to the tire radius. The location and orientation of the cut are shown in Figure 2. Load was applied to the tire from the surface below, parallel to the radius of the tire.

![Figure 2. Position and Orientation of Radial Cut.](image-url)
The tire was photographed under the 140 kg load, to cause stretching, before and after the cut was created, illustrated in Figures 3a and 3b. A two-dimensional correlation was performed on these images to calculate the deformation of the tire caused by the cut. It was observed that the cut caused stretching of the tire in the horizontal (x) direction.

![Figure 3a. Sidewall Before Cut.](image1)

![Figure 3b. Sidewall After Cut.](image2)

Figure 4 shows the deformation of the tire caused by the introduction of the fault. As expected, the areas immediately surrounding the fault are shown to stretch away from the cut in the x-direction under load. In this figure, red areas are displacing to the right, blue areas are displacing to the left, and green areas have zero horizontal displacement.

![Figure 4. Horizontal Displacement Caused by Introduction of Radial Cut in Tire.](image3)
4.2 Tangential Cut
A second cut was applied at a 180° rotation from the first, in a direction tangential to the curve of the tire. This cut measures 20mm long and 3 mm deep. Using the same process as the radial cut, the deformation due to the tangential cut was calculated. The area of interest and corresponding displacement are shown in Figure 5. Vector direction and magnitude, which has been magnified for clarity, is shown by the black arrows. Contrary to the radial cut, the tangential cut caused significant displacement in the y-direction, parallel to the direction of loading, with deflections as predicted by theory of shells. [7]

![Figure 5. Vertical Displacement Due to Introduction of Horizontal Cut in Tire Wall.](image)

Altogether, the data collected from the radial and tangential cuts shows that surface damage, for simple cases, is detectable using digital image correlation. This is promising for future research into tire condition monitoring using optical techniques. Future work will investigate more complicated damage, such as wear and fatigue, to determine how well it can be observed using digital image correlation.

Additionally, further studies are required to translate laboratory results into a practical field implementation. Current results are collected under ideal conditions and it will be necessary to examine how environmental effects affect damage visibility. Furthermore, a suitable method of applying visual texture to the tire must be determined.

5. Three-Dimensional Measurement
At this point, the faults investigated have not shown significant out-of-plane deformation. This may change as new faults are examined, particularly wear and thinning of the tire wall, which could cause bulging perpendicular to the tire surface. Hence, it is of interest to expand the capabilities of the tire
monitoring system to include out-of-plane (3D) strain measurement. However, 3D measurement introduces additional complexity to the measurement process as it requires a reference surface from which to calculate subsequent distortion. [5]

In this experiment, both cameras are placed at an equal angle from the centreline of the tire. As the angle between cameras increases, so does the accuracy of out-of-plane measurements. Simultaneously, the perspective of each camera also changes, rendering surface reconstruction more difficult. Both factors were reconciled in a series of tests to provide accurate depth measurements and good reconstructions of the tire surface.

Figure 6 shows a successful reconstruction of the tire surface using the commercial software, using a two-camera set-up with a 28º angle between cameras. The depth of each feature is measured relative to the calibration plate placed in front of the tire prior to image correction. At this angle, the correlation between images is strong enough to resolve even minor details, such as the embossed writing on the surface of the tire.

![Figure 6. 3D Surface Reconstruction of Tire.](image)

A set of images of a flat plate was taken at various distances from the calibration plane. Comparing the calculated depth of the plate to the known position of the plane, the error in depth measurements for this particular set-up was found to be +/- 0.5 mm. Additional changes are required to improve this accuracy for detailed strain measurements.
6. Conclusions and Future Work
Undetected damage can lead to premature failure of large tires, which is costly and time-consuming to remedy. Optical strain measurement has the potential to be used to monitor the condition of these tires. A laboratory-scale system has been commissioned to explore the feasibility of using digital image correlation and other techniques to detect tire damage.

Two surface cuts were made to an 18” tire, which was subjected to a 140 kg load. Images taken before and after the cuts were made were analysed using commercial software to calculate the deformation caused by the damage. The resulting displacement field shows that noticeable stretching could be observed and quantified using digital image correlation. This is promising for further investigation of fault detection using this system. It can also be used to gain a better understanding of damage mechanisms and propagation in tires.

Currently, fault deformation has been measured on the tire surface. To expand the system capability to include out-of-plane measurements, a three-dimensional surface has been reconstructed from stereo images of the tire taken at a 28º angle. Future work will focus on expanding the 3D measurement accuracy of the system to better characterize more complex damage types such as wear and fatigue, with an end goal of developing an industrial prototype that can be implemented on-site.

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