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DETECTING FLAT WHEELS WITH A FIBER-OPTIC SENSOR

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ABSTRACT
This paper describes a multimode optical sensor that is deployed on or near railroad tracks, and detects the presence of flat wheels rolling on the rails, based on spectral characteristics of their induced vibrations. The sensing mechanism uses optical interferometry in which modally dispersive coherent light traveling through the multimode fiber mixes at the fiber's terminus, resulting in a characteristic pattern of light and dark splotches called speckle. The laser speckle is stable as long as the fiber remains immobile, but flickers when the fiber is vibrated. The system works by measuring the time dependence of this speckle pattern and applying digital signal processing to the fast Fourier transform (FFT) of the temporal data.

INTRODUCTION
This paper briefly reviews the phenomenon of flat wheels, including what causes them, and their deleterious effects. The paper also provides a brief explanation of the theory of operation for fiber sensors that are based on speckle interferometry. The body of the paper describes test results obtained in cooperation with a mass transit operator in a major North American city, showing the efficacy of the fiber sensor with regard to the identification of rail cars with flat wheels.

Flat wheels result when the brakes are applied fully, causing the wheels to lock and skid, grinding flat part of the wheel surface in the process. Skidding can also be caused by a damaged bearing that seizes. Extreme flat wheels produce an audible "clank-clank" noise, due to the flat surface impacting the rail with each turn. The high impact forces from a flat wheel cause stress in the rail, and in extreme cases can break the track or cause the wheel to jump off the track, resulting in a derailment.

Various methods have been proposed for detecting flat wheels. One method is to employ inspectors to listen to the trains as they move through a particular location. Some flat wheels are found through routine inspections when the cars are being serviced. A wide range of sensors have been proposed for detecting flat wheels. These employ a range of technologies from optical systems that gauge the wheels in real time to sensors that look for vibrations and stress (Berndt [3], Welles [4], Gutauskas [5], Harrison [6]).

One of the challenges for sensors is the need to operate remotely in harsh environments with exposure to wide temperature ranges as well as rain, snow, slush, dirt and grime. Another challenge for sensors is the need to offer flat sensitivity with wide frequency range over long distances.

Fiber optic sensors have inherent advantages in all these areas. The sensor is all dielectric and passive, requiring no on-site electrical power at or near the sensing element. Extended fiber optic sensors are also ideally suited for severe environments. Low-loss optical fibers developed for the telecommunications industry are readily available at competitive prices. These fibers are available in standard armored cables capable of withstanding virtually any harsh environment.

Since the sensor is based on coherent interferometry, it is highly sensitive. Furthermore, because of the low loss of the fiber, the response of the speckle to disturbances is flat over a wide acoustic bandwidth that extends well beyond the frequencies of interest when detecting flat wheels. Since the sensing fiber is all dielectric, the sensor is inherently immune to electromagnetic effects that might otherwise damage it or interfere with the vibratory signal. And since optical fiber has very low loss (less than 0.2 dB/km at wavelengths of 1550 nm), the sensor can be deployed at remote locations that are many tens of kilometers away from the processing electronics.

Vibrations in the track result from other phenomena besides flat wheels. Often, these phenomena can be characterized by a unique spectral fingerprint, characterized by both amplitude, phase, and frequency components. This should make the sensor useful for detecting not only flat wheels but wheel pitting and irregular motion in the bogie, such as hunting or boxing.

NOMENCLATURE

In classical electro-magnetic theory, light travels through a waveguide, such as optical fiber, in distinct modes. Mathematically, these modes correspond to solutions of Maxwell's equations, subject to the boundary conditions inherent in the design of the fiber. Each mode is characterized by a propagation constant, β, which describes the accumulation of phase as a function of propagation along the axis of the fiber. For oval-core fibers the propagation constant has been given explicitly by Shiraishi [1] as

$$\beta_{m,n}^2 = (n_0 k_0)^2 - n_0 k_0 \left[\frac{(2m+1)}{A_{gx}} + \frac{(2n+1)}{A_{gy}} \right] \qquad (1)$$

where n_0 is the refractive index at the center of the core, k_0 is the wave number in vacuum, A_{gx} and A_{gy} are the normalized x- and y-directional core radii, respectively, defined by $a_x/(2\Delta)^{1/2}$ and $a_y/(2\Delta)^{1/2}$, respectively, where Δ is the relative index difference defined by $(n_0^2 - n_1^2)/2n_0^2$, where n_1 is the refractive index of the cladding.

Each mode is defined by the integers, m and n, and has the unique propagation constant defined by Eq. (1). The number of guided modes depends on the fiber construction, including parameters such as core diameter, cladding diameter, wavelength, and the index of refraction of the material used to construct the fiber. The number of modes carried by the fiber can be controlled through proper design of the fiber parameters. Generally, by increasing the diameter of the fiber core, the number of bound modes increases.

The mode numbers m and n describe the number of nulls in two orthogonal transverse directions, generally labeled "x" and "y," with "z" representing the direction of propagation. In the absence of stress each spatial mode consists of two degenerate polarization modes. The presence of bending stress causes these degenerate modes to split, with one polarization of the spatial mode having a different propagation constant than the other.

Coherent light transmitting through a multimode optical fiber randomly couples among the different modes. This modal distribution depends on the manner in which light is launched into the optical fiber, as well as how the fiber is bent and twisted. Because the propagation constants are different for the various modes, light in each of the modes accumulates different amounts of phase while propagating along the length of the fiber. Since the different modes have spatial overlap, the phase differences between the modes result in optical interference at the end of the fiber, characterized by a pattern referred to as laser speckle (see Fig. 1)

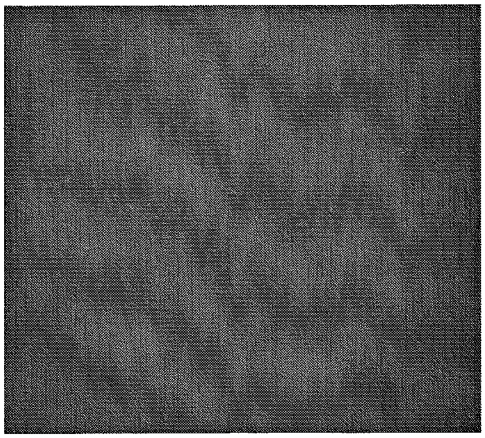


Figure 1. Example of laser speckle projected from the end of a multi-mode optical fiber, illuminated with coherent laser radiation.

Bending and longitudinal stress differentially change the propagation constants of the various spatial modes (Smith [2]), which changes the phase differences, and cause the speckle pattern to flicker. This changing speckle pattern can then be measured and used to detect vibration of the fiber, and indirectly the material to which it is mounted.

Various techniques may be used to measure the time-varying nature of the speckle pattern. One approach is to project the speckle pattern onto a two-dimensional detector array. This involves relatively expensive optics, a relatively expensive two-dimensional array, and enough computing power to calculate the two-dimensional FFT. On the other hand, this approach captures nearly all the light, so it has a relatively high dynamic range.

A simple detector for measuring time-varying speckle can be made using a single large-area detector (on the order of one mm in diameter) and a screen with a small pinhole. The screen is fixed between the end of the fiber and the active area of the detector, and the pinhole is sized to have the same diameter as the RMS value of the bright/dark spots in the speckle pattern, as shown in Fig. 2.

When the fiber is disturbed the speckle pattern changes. As the speckle pattern changes, bright and dark fringes pass over the pinhole, resulting in a time-varying signal that is indicative of the vibration of the fiber. For small perturbations, the frequency of this signal is equal to the frequency of the physical disturbance.

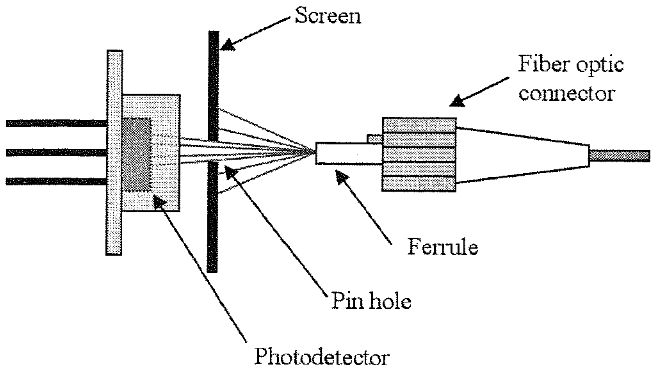


Figure 2. Detector and pinhole assembly used to measure temporal changes in speckle pattern.

The advantage of the pinhole/detector system is low cost and simplicity. For visible and near-infrared light, large-area detectors are readily available for modest cost, and can be readily assembled with a built-in pinhole and fiber-optic connector, making field assembly simple and straight forward. This design also lends itself to simpler digital signal processing, as it can be used with the one-dimensional FFT.

Because of the limiting aperture of the pinhole, the design in Fig. 2 has poor optical efficiency, wasting up to 90% or more of the incident light. This inefficiency is not important in most applications, however, because of the relatively high output power of lasers (typically over 1 mW), the low acoustic frequencies involved (usually below 1 kHz) and the low noise floor of available solid-state optical detectors and electronic amplifiers.

For a given fiber-optic waveguide, the waveguide will support only one spatial mode (which splits into two polarization modes in the presence of birefringence) if the wavelength of light is longer than a critical limit called the cutoff wavelength (Neumann [7]). Standard single-mode fiber used in the telecommunications industry has a core diameter of about 9 microns, and is single mode for wavelengths longer than about 1.290 microns.

Telecommunication lasers with wavelengths of 1.310 and 1.550 microns are readily available and inexpensive. If the sensor system is designed to use one of these laser wavelengths, the pinhole detector can be implemented in a way that also provides for insensitive fiber leading into the sensor, as shown in Fig. 3.

The single-mode fiber that leads into the multimode sensor has no speckle pattern precisely because it is single mode, and has no modal interference. At the output of the multimode sensor, where it interfaces with the second single-mode fiber, only those portions of the multimode speckle pattern that overlap the single-mode fiber will be transmitted through the single-mode fiber and to the detector. The single-mode fiber thus acts as the pinhole in front of the detector. The single-mode fiber can be affixed to the multimode fiber by either a fiber-optic connector, or by fusion splicing the two waveguides.

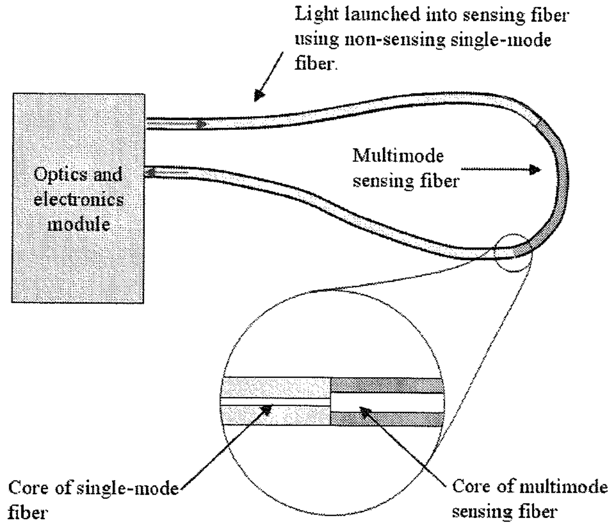


Figure 3. Single-mode fiber used for insensitive lead and as pinhole.

Using single-mode fiber as the pinhole improves the cost and simplicity of the design, as well as adding greater utility and flexibility. Using single-mode fiber as the lead-in fiber (as shown in Fig. 3) gives the fiber sensor considerably more versatility, since the sensor can be remotely located precisely where needed, and the sensing signal can be recorded many km away with high dynamic range and fidelity. And, because the sensor is all optical and dielectric, there is no possibility of signal degradation from electromagnetic interference.

The prior discussion describes an interferometric sensor based on fiber optics. Unlike traditional interferometers, however, this one has many optical paths, and the optical power in each path (mode) is largely uncontrolled and randomly distributed. Typical multimode optical fibers, for example, may have hundreds of modes.

Physical disturbances differentially affect the various fiber modes. Bending introduces birefringence causing the degenerate modes to split into spatially identical modes with polarization-dependent propagation constants. Longitudinal stretching differentially changes the propagation constants of modes, depending on their radial extent from the fiber axis.

Because of the stochastic nature of the sensing, modal sensors are generally not suitable for applications that require calibrated sensing of parameters like temperature and pressure. They are, however, suitable for measuring typical vibration frequencies, though with somewhat less accuracy than other techniques. In applications involving flat wheel sensors, however, the accuracy of the frequency measurement is well with the required range, and the fiber sensor offers significant advantages, including low price, flat response, low loss, ruggedness, and the ability to be remotely located without signal degradation.

The sensor derives its high sensitivity to the use of optical interferometry. And because the fiber has low loss, it can sense vibration over a long distance, maintaining that sensitivity over the entire range. The sensor also benefits by using fiber designed for the telecommunications industry. These fibers are mass produced and designed for low cost, yet they are armored and capable of surviving in extremely harsh environments including direct burial and placement alongside railroad tracks. Fig. 4 shows one fiber-optic sensor installed on the underside of steel gratings used in the pedestrian access area of the Light Rail system run by a major North American metropolitan city.

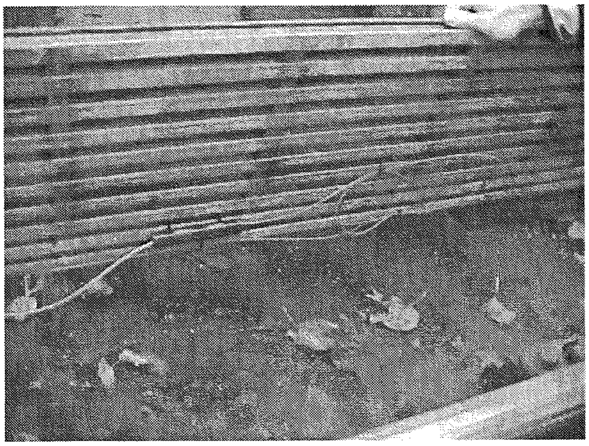


Figure 4. Example of fiber sensor placement on the underside of metal grating alongside rail track. The sensing cable is brown. The blue cable is non-sensing single-mode lead-in fiber.

In field tests we have conducted, the fiber was tied directly to metal grates (using plastic zip ties) in the pedestrian station of a mass transit system. These metal grates are located near the track (seen in the lower right-hand corner of Fig. 4) and are thus vibrated by trains arriving and departing from the station. Alternatively, the fiber could be buried alongside the rail, or attached to other structures.

When a damaged wheel travels along a steel rail, it periodically strikes the rail, setting up characteristic vibrations. These vibrations are distinguishable based on both frequency and energy content. Characteristic frequencies differ for good wheels as opposed to flat wheels and wheels that are compromised in other ways. However, how the cable is mounted, and the structures to which it is mounted, affect the amplitudes of the detected frequencies.

A convenient way of viewing the sensor data is to display two graphs, one above the other, as shown in Fig. 5. The lower graph displays time-domain data, and the upper graph displays spectral (frequency-domain) data. The time-domain data (lower curve) shows the integrated sensor signal as a function of time, with 100-msec resolution. The numbers on the horizontal axis of this graph are units of time, in seconds.

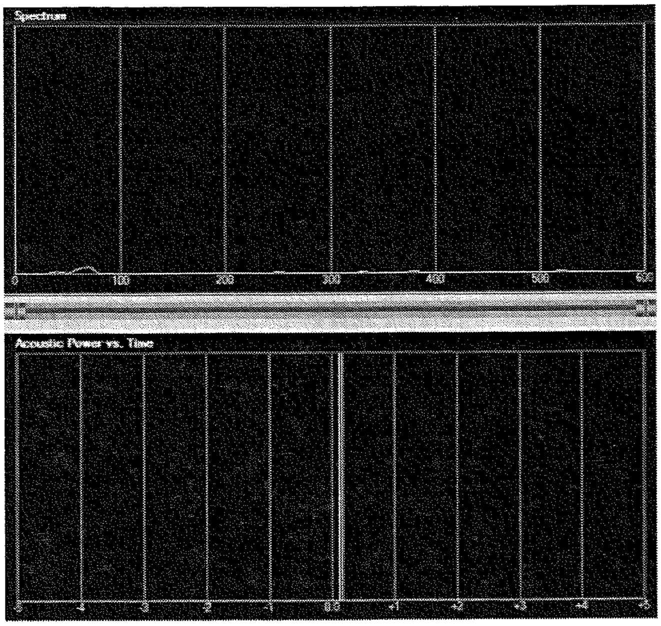


Figure 5. Time/frequency plot for a good wheel.

The top curve is the spectrum of the time-domain data bounded between the two vertical cursors in the time-domain curve. Although the graph shows time-domain data with 100-msec resolution, computer memory holds temporal data with a much higher sampling rate; 128 samples in each 100-msec window. This higher-frequency temporal data is then used to calculate the FFT for the spectral data, which is shown in the upper curve. The units along the horizontal axis of spectral curve are Hz.

In the application software developed for this study, the location and separation of the two vertical cursors is adjustable so that the time period over which the spectral data is evaluated (the separation of the two vertical cursors in the time-domain curve) can be adjusted, along with the location of the pair of cursors in the time-domain.

Fig. 5 shows the time-spectral data for a good wheel. Compare the signature of the good wheel with the time-spectral data for two flat wheels (Fig. 6 and Fig. 7). The signatures of the flat wheels are characterized in the time domain by a series of bumps, and in the frequency domain by high spectral power at frequencies below 100 Hz.

Because of their distinct temporal and spectral signature, digital signal processing algorithms can be readily designed to identify the signals associated with flat wheels. This sensor can then be integrated into a larger system used to locate, track, and repair/replace flat or otherwise damaged wheels.

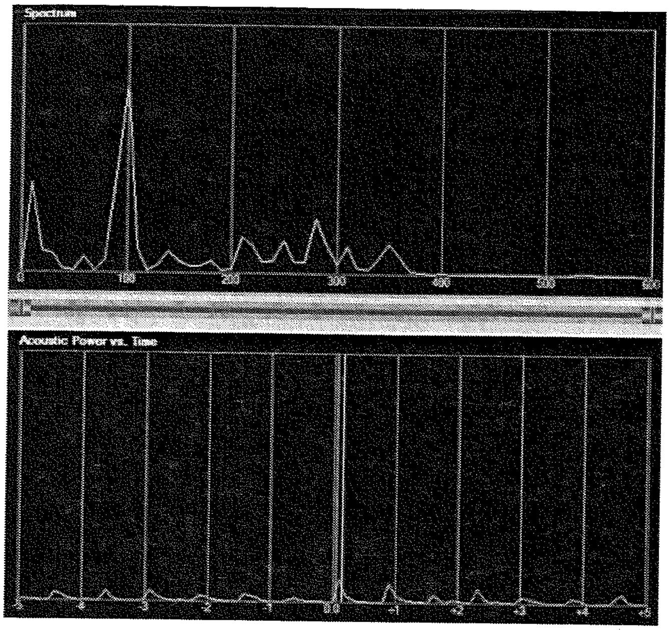


Figure 6. Time/spectral data for a flat wheel. For this test station, flat wheels are characterized by high energy content in frequencies lower than about 100 Hz.

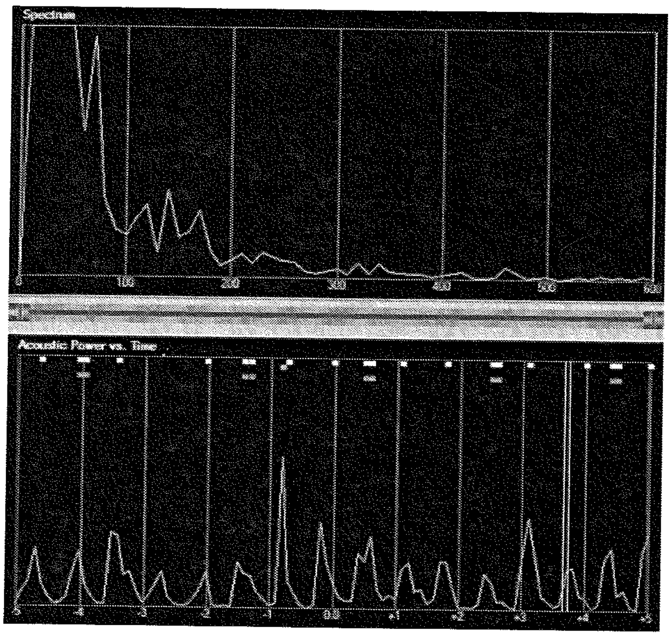


Figure 7. Time/spectral plot for an exceptionally bad wheel.

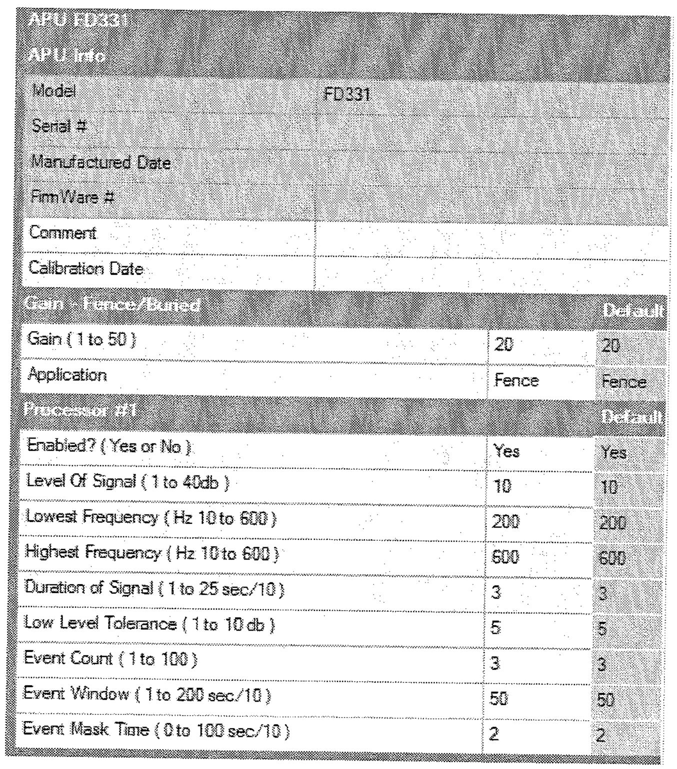
Two critical metrics are important in characterizing any sensor. One characteristic is the sensitivity of the sensor, which can also be described in terms of the signal-to-noise ratio. The other is the rate of false events. False events are, by definition, signals that are of no particular interest. False events may be due to spurious noise in the system electronics, but they can be, and often are, the result of environmental effects.

In terms of the false event rate, multimode speckle sensors have several advantages. As already noted, they are all optical and all dielectric, and thus unaffected by local electromagnetic interference. Environmental effects that vibrate the rail, or the ground nearby, are potentially problematic. To distinguish between these effects and flat or otherwise damaged wheels, spectral analysis is necessary.

Our initial tests show that flat wheels have characteristic frequencies below about 100 Hz that are spectrally distinct from other effects such as people walking along the track, rain, rail cars with good wheels, and local car and truck traffic on adjacent roads. Flat wheels also create spectral signatures with comparatively high energy, which further makes them distinguishable, as shown in Fig. 5, Fig. 6, and Fig. 7.

These results are encouraging and suggest that modalmetric fiber-optic sensors can be used as effective flat wheel sensors. This work was done with sensors designed primarily for perimeter security applications, where the sensor is mounted on a fence, or buried, and used to detect intruders trying to climb, cut, or walk through the perimeter.

The system used in this series of tests is relatively flexible in its time-frequency analysis capabilities, though it requires further optimization for fully automatic flat wheel detection. Figure 8 shows a user interface that is essentially identical to the one used in this study, for tuning the system for specific intrusions. This interface offers a simple threshold-based detection scheme within a frequency range defined by low- and high-frequency bands. The user can further define desired signals in terms of duration, and the number of times (counts) that the frequency-domain signal exceeds the pre-set signal level.



APU FD331		
APU Info		
Model	FD331	
Serial #		
Manufactured Date		
FirmWare #		
Comment		
Calibration Date		
Gain - Fence/Buried		Default
Gain (1 to 50)	20	20
Application	Fence	Fence
Processor #1		Default
Enabled? (Yes or No)	Yes	Yes
Level Of Signal (1 to 40db)	10	10
Lowest Frequency (Hz 10 to 600)	200	200
Highest Frequency (Hz 10 to 600)	600	600
Duration of Signal (1 to 25 sec/10)	3	3
Low Level Tolerance (1 to 10 db)	5	5
Event Count (1 to 100)	3	3
Event Window (1 to 200 sec/10)	50	50
Event Mask Time (0 to 100 sec/10)	2	2

Figure 8. User interface used to tune the sensor for specific signatures.

This work shows that the modalmetric fiber sensors have promise for detecting flat wheels. However, additional work needs to be completed in measuring, logging, and characterizing a wider array of wheel signatures, to ensure that the digital signal processing properly identifies wheels that need replacement or repair, while maintaining a low incidence of false events. A more specific user interface also needs to be developed, which would allow characteristics unique to flat wheels to be measured and identified by the digital signal processing algorithms.

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