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VEHICLE BASED WEIGH-IN-MOTION SYSTEM

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ABSTRACT

Numerous approaches to vehicle based measurement of dynamic wheel loads have been proposed including axle mounted bending strain gages, axle mounted shear strain gages, tire displacement, and tire pressure. Although these systems have met with various levels of success, the search for a low cost vehicle mounted system for dynamic wheel force measurement continues. A new system based on wheel deflection measurement shows reasonable promise for addressing this problem. The system is less than $1500 in cost and employs innovative data processing techniques to extract wheel force measurement information. Results of system installation on a trailer are here reported.

INTRODUCTION

The study of heavy vehicle forces on pavement is important for both vehicle and pavement. Pavement life is associated with pavement loading and vehicle response is associated with both pavement loading and ride quality. Hardware used in studies of vehicle/pavement loading have included pavement based sensors [1-7], vehicle mounted sensors [6,8-11], and road simulators [6,9,12-17]. Each of these systems has their limitations. Pavement based sensors provide pavement response data at specific locations. This data is limited to the specific location of gauges and cannot be used to survey wheel force over a wide range of in-service roads. Vehicle mounted sensors provide a means to measure wheel force on pavement over any in-service road. Vehicle mounted sensors that appear in the literature generally fall into two categories, wheel force transducers that are mounted between hub and wheel, and strain gauge bridges that are mounted to an axle. Wheel force transducers typically add weight and offset to a heavy vehicle wheel configuration. It is possible to minimize both weight and offset, but such transducers are quite expensive and are not readily available. Axle shear strain sensors have been shown to provide reasonable correlation to wheel force, but only if an axle has a relatively long and uniform cross section. For irregularly shaped axles, shear strain sensor will be affected by bending moment as well as shear. There is, therefore, a continuing need to identify wheel force measurement techniques that will not change the wheel configuration, and that will provide wheel force data at a reasonable cost. To this end, wheel deflection as measured by a capacitance displacement transducer is studied as a possible means for measuring wheel forces on pavement.

A description of experimental methods is followed by a discussion of sensor mounting, sensor calibration, and data processing algorithms. Research results and conclusions are then presented.

METHODS

This study of wheel force measurement techniques included three measurement instruments: portable scales, a strain gauge bridge, and a capacitance displacement sensor.

A description of the experimental methods used in this study begins with a discussion of instrumentation type and configuration. This is followed by explanations of calibration methodology and rolling wheel force measurement technique. Methods used for data processing are then described.

Instrumentation

Three instruments were used in this study of wheel force measurement techniques: a capacitance displacement sensor, a strain gauge bridge, and portable scales. The experimental configuration of these sensors is shown in **figure 1**. This figure depicts one axle of a flat-bed trailer having a single wheel mounted onto the left side of the axle and double wheels mounted to the right side of the axle. Figure 1a depicts a side view of one axle of a flat-bed trailer with a law-enforcement wheel scale placed beneath the single left-side tire. The scale used is manufactured by Intercomp [18] and has a digital readout with a resolution of ±89.0 N (±20 lbf). Steel balls of 0.635 cm (0.25 inch) diameter were placed beneath the wheel scale in an attempt to minimize horizontal forces under the left wheel. Figure 1b shows a cross-section through the axle and wheel assembly. The right-side wheels sit on block so that all wheels are elevated to the same height.

Strain gauges are mounted to the front and rear of the axle creating a strain-gauge bridge that is designed to measure shear strain. Strain gauges are mounted only on the left side of the axle. Each half-bridge was a two-element 90 degree rosette with an exposed tab area of 3.3 mm x 2.0 mm and a resistance of 120 ± 0.4% Ohms. The strain gauge bridge is connected to a strain gauge conditioner.

Figure 1b depicts a mounting bracket that supports a capacitance displacement transducer that is rigidly mounted to the axle. Extensions to the spring shackle bolts are used to secure the mounting bracket. The capacitance head is located in a manner that facilitates measurement of the distance between the sensor and the surface of the wheel rim. The capacitance sensor is connected to a signal conditioner. The signal conditioner provides an output voltage that is proportional to distance between the capacitance head and the surface of the wheel rim.

Data from the strain gauge signal conditioner and from the capacitance displacement transducer signal conditioner are collected using a 16-bit analog-to-digital converter board in a personal computer (PC).

Calibration

Before vertical wheel loads on a moving vehicle could be measured, instrumentation needed to be calibrated. The law enforcement scales were used as the reference measurement for calibration of other instruments. In a previous research effort, the law enforcement scales were shown to provide force measurements that were accurate to within ±89.0 N (±20 lbf) [19]. The law enforcement scales were used to calibrate both the capacitance displacement transducer and the axle strain gauge.

Calibration of the capacitance displacement sensor includes two aspects. First, it is important to characterize the relationship between wheel deflection and wheel load. Second, it is necessary to characterize the relationship between wheel rotation and displacement sensor response. The latter consideration arises from the fact that wheels are not round. Since the displacement sensor measures distance from the capacitance head to the wheel rim surface, the sensor will respond to both the out-of-round shape of the wheel and to the deflection of the rim. Eight orientations (each 45 degrees of wheel rotation) of the wheel were used for initial calibration studies. At each orientation, the rear left wheel was lifted off the wheel scale using a pneumatic jack. This provided the zero load condition. The jack was then slowly released until the digital readout on the wheel scale read approximately 2224 N (500 lbf). This process was continued in approximately 2224 N (500 lbf) increments until the fully loaded condition (approximately 15.6 kN (3500 lbf)) was reached. At each loading condition, the wheel scale reading was manually recorded and both the displacement sensor and the strain gauge bridge response were recorded using the PC based data acquisition (DAC) system.

Figure 2 is a plot of strain sensor output versus vertical applied load for each of the eight wheel orientations at 45 degree intervals. Figure 2 demonstrates that axle strain is independent of wheel orientation and that axle strain is linearly proportional to wheel force.

Figure 3 is a plot of displacement sensor output voltage versus applied wheel load. A linear approximation to each of the eight curves is also included in figure 3. The slopes of these eight linear approximations are identical. Figure 3 indicates that wheel displacement is approximately linearly proportional to wheel load, but that wheel orientation introduces an offset into the sensor response. This offset is a result of the non-circular shape of the heavy vehicle wheel. Methods of separating wheel force information from wheel shape information is a focus of this paper.

In order to use calibrated instruments to measure vertical wheel loads on a moving vehicle, wheel orientation must be known. Numerous methods exist for measuring wheel orientation. A resolver or an optical encoder can be mounted to the outside of the wheel to record wheel orientation. Rather than using an additional sensor to achieve this purpose, it was determined that the displacement sensor could be used to measure wheel orientation. To this end, a short section of 1 mm diameter steel wire was epoxied to the surface of the rim at each 45 degree interval as shown in figure 1a. The pin location appears to be on the outside of the wheel in figure 1a but, in reality, the pins are located on the surface of the rim such that, when the wheel rotates, they pass the displacement sensor as shown in figure 1b. In addition, a starting point or zero point for wheel orientation measurement was identified by placing second wire in close proximity to one of the 8 wires that were spaced 45 degrees apart. As the wheel rotates, the displacement sensor will record a spike every time one of these steel wires is encountered and each spike will represent a 45 degree wheel rotation.

With the wire pins mounted on the rim, an additional calibration test was performed. With the wheel jacked off of the scale, the wheel was manually rotated and both axle strain and displacement sensor response were recorded using the portable DAC system. Wheel rotation simulated forward motion of the vehicle. Sampling frequency was 200 Hz and sampling time was about 20 seconds. Data was recorded for approximately 3 full wheel rotations. This free spin test data was used to characterize the out-of-round shape of the wheel so that wheel deflection could be differentiated from wheel shape.

Rollng Wheel Force Measurement

The wheel scale and wheel blocks were removed and two series of moving vehicle data were collected. Sampling frequency was 200 Hz and sampling time was about 20 seconds. Data was recorded for approximately 4 full wheel rotations. This data was used to study methods for extracting wheel load information from a displacement sensor that responded to wheel deflection, wheel roundness, and pin markers at 45 degree wheel orientations.

Figure 4 presents displacement sensor response as a function of time for both the free wheel spin test and for the moving vehicle test. The low frequency component of this data corresponds to one wheel rotation. Figure 5 presents axle strain data for both the free wheel spin test and for the moving vehicle test.

Data Processing

It is desired to identify data processing algorithms that can separate wheel deflection associated with dynamic wheel forces from data that is collected using the displacement transducer. Three algorithms are here discussed. (Figure 6)

Direct subtraction

One approach to data processing is to subtract free spin displacement transducer response from moving wheel displacement transducer response. This should result in a displacement sensor voltage signal that corresponds only to wheel deflection.

Data manipulation is necessary before this direct subtraction method can be used. First, time t must be converted to wheel rotation θ. This conversion requires a knowledge of velocity. The displacement transducer data include a voltage spike at every 45 degrees of wheel rotation as seen in figure 4. The time between voltage spikes is measured and a constant velocity approximation is used over every 45 degrees of wheel rotation. Conversion from time to wheel orientation is then given by

$$\theta_{ai} = \frac{\theta_{n+1} - \theta_n}{T_{n+1} - T_n}(t_i - T_n) + \theta_n \qquad (n = 1,2,\ldots,8;\ i = 1,2,\ldots,\text{no. of samples}) \qquad (1)$$

where n is number of pin positions, T_n is the time of each peak wire pin voltage spike, and θ_n is the angle corresponding to the position n. In (1), θ_{ai} are not equally spaced. Using linear interpolation, another series of equally spaced θ_{bj} (where j=1,2, ...) is defined as shown in figure 7. Once data from free spin and moving vehicle tests are equally spaced in wheel angle θ_b, they are subtracted. Result of this direct subtraction method are compared against axle strain data as shown in figure 8.

Fourier series subtraction

In selecting data processing algorithms, it is important to recognize that all displacement information associated with wheel shape and with orientation marker pins are periodic with respect to wheel rotation. This observation suggests that the Fourier series is ideally suited for characterizing the unloaded wheel shape from free spin displacement transducer data. A Fourier series expansion of the free spin data is obtained. This requires conversion of the free spin data from time to wheel orientation as in the direct subtraction method. The fundamental period of this expansion is one wheel rotation (2π radians or 360 degrees). This expansion represents the displacement measurement that is associated with wheel shape rather than wheel deflection. Since the expansion is an analytical function of θ, this expansion can be subtracted from the moving vehicle data without having to interpolate for equal spacing in wheel angle θ. Moving vehicle data must still be converted from time t to wheel angle θ. This data processing method is further discussed in the results section of this paper.

Fourier series extraction

Rather than subtracting free wheel spin information from moving vehicle data, the Fourier series can be used to extract wheel shape directly from moving vehicle data. In this method, a Fourier series of moving vehicle data is obtained. As before, the fundamental period of this Fourier series is chosen to be one wheel rotation. Response corresponding to harmonics that are multiples of this fundamental period are assumed to correspond to undeflected wheel shape and, as such, are subtracted from the displacement transducer response so that the remainder of the signal represents load induced wheel deflection.

This method is demonstrated using three wheel rotations from the moving vehicle data that is shown in figure 4. The moving vehicle data is transformed from the time domain to the θ domain and linear interpolation is used to obtain data that is equally spaced every 1 degree of wheel rotation. The Fourier series expansion of this data is then given by

$$V_c(\theta) = \sum_{m=0}^{N} \left\{ A_m \cos(m\omega_n\theta) + B_m \sin(m\omega_n\theta) \right\} \quad \left(\omega_n = 2\pi rad / 1080^{\circ}\right) \tag{2}$$

where A_m and B_m are Fourier coefficients and N is less than or equal to one half the number of samples. **Figure 9** presents the Fourier expansion superimposed on the original data. Since the fundamental period of (2) is three wheel rotations (1080 degrees), and since the undeflected wheel shape should appear every wheel rotation, therefore, the undeformed wheel shape will be represented by every third harmonic in the expansion (2). Extracting the sum of these harmonics from (2) provides the characterization of wheel shape that is plotted in **figure 10**. **Figure 11** is a plot of (2) after subtracting every third harmonic. Figure 11 represents the dynamic load induced wheel deflection data from moving vehicle tests. Axle strain and wheel deflection sensitivities are obtained from data shown in figures 2 and 3, respectively. Using these sensitivities, dynamic wheel force from axle strain gage and from the wheel deflection Fourier series extraction methods are shown in **figure 12**.

RESULTS AND DISCUSSION

The data plotted in figure 3 demonstrates that the wheel deflection is nearly linearly proportional to wheel force. Data plotted in figure 4 demonstrates that the out-of-round shape of typical heavy vehicle wheels can dominate the response of a wheel displacement sensor. An effective algorithm is needed to extract wheel deflection data from a displacement signal. Three algorithms are discussed in this paper.

Results from the direct subtraction method are shown in figure 8. Wheel load measurements using axle strain and displacement transducer are shown to differ by 20%. Errors involved in this method arise several ways. First, free wheel spin and moving vehicle data must be aligned. This requires constant velocity assumptions and linear interpolation to obtain equally spaced data in both data sets. In subtracting the two signals, errors arising in each signal, along with alignment errors between signals, are additive. Second, the wheel bearing loading configuration differs between free spin and moving vehicle tests. Any play in wheel bearings will appear as a difference between free spin and moving vehicle data.

The Fourier subtraction method does not require that moving vehicle data be equally spaced. All other error sources in the direct subtraction method are also present in the Fourier subtraction method. Results from direct and Fourier subtraction methods are similar.

The Fourier extraction method provides significant improvement over the subtraction methods. First, for short duration signals, there is no need to align and subtract two different data sets. All errors associated with data set alignment and subtraction are avoided. Second, extracting wheel shape from moving vehicle data means that the direction of bearing loads remains constant for all data used in this method. Results from the Fourier extraction method are shown in figure 12. In this figure, axle strain and displacement transducer results are shown to differ by about 5%. Improvements to the Fourier series extraction method can be obtained by removing wire pins from the wheel rim and adding a separate sensor to measure wheel orientation. This will eliminate the constant velocity assumption from the data processing algorithm. This will also remove high frequency spikes from wheel deflection measurements.

CONCLUSION

Wheel deflection is approximately linear proportional to wheel force. This observation offers opportunity to employ deflection sensors as a means to measure dynamic wheel loads on heavy vehicles. A Fourier series extraction method shows promise as a means to differentiate between wheel shape from wheel deflection data.

There is strong motivation for pursuing additional studies of wheel deflection methods and associated data processing. Wheel deflection measurement offers several advantages over strain measurement techniques. First, mounting of a displacement sensor is significantly easier than mounting an axle strain gage. Second, it is possible to mount displacement sensors on both inner and outer wheels of dual wheel sets. This provides the opportunity to track loading on each wheel in a cost effective manner. Third, displacement sensors do not alter wheel load or wheel offset, as do various wheel force transducers. Finally, the wheel, hub, brakes and axle inertial loads that must be accommodated in axle strain methods will have minimal influence on wheel deflection methods when measuring dynamic wheel loads.

Introduction Content

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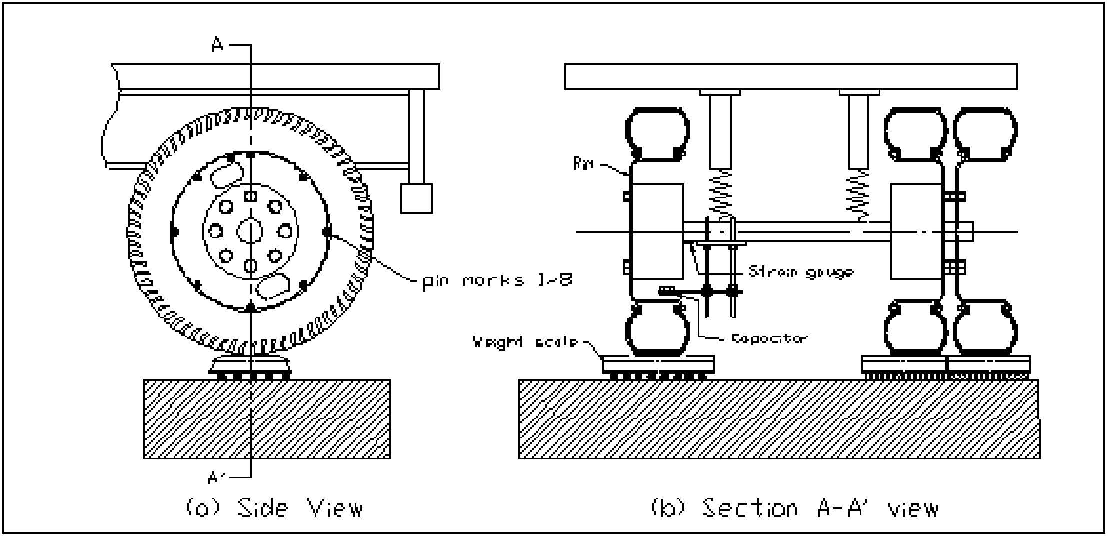
Introduction

Content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A'
pin marks 1~8
Rim
Strain gauge
Capacitor
Weight scale
(a) Side View
(b) Section A-A' view

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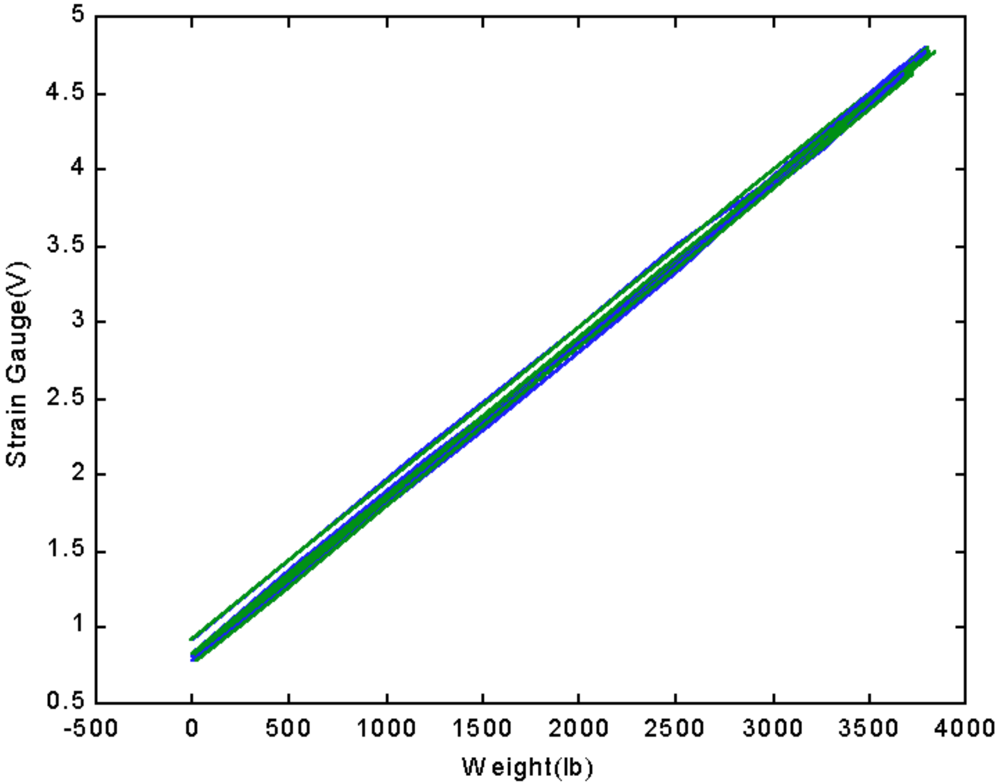

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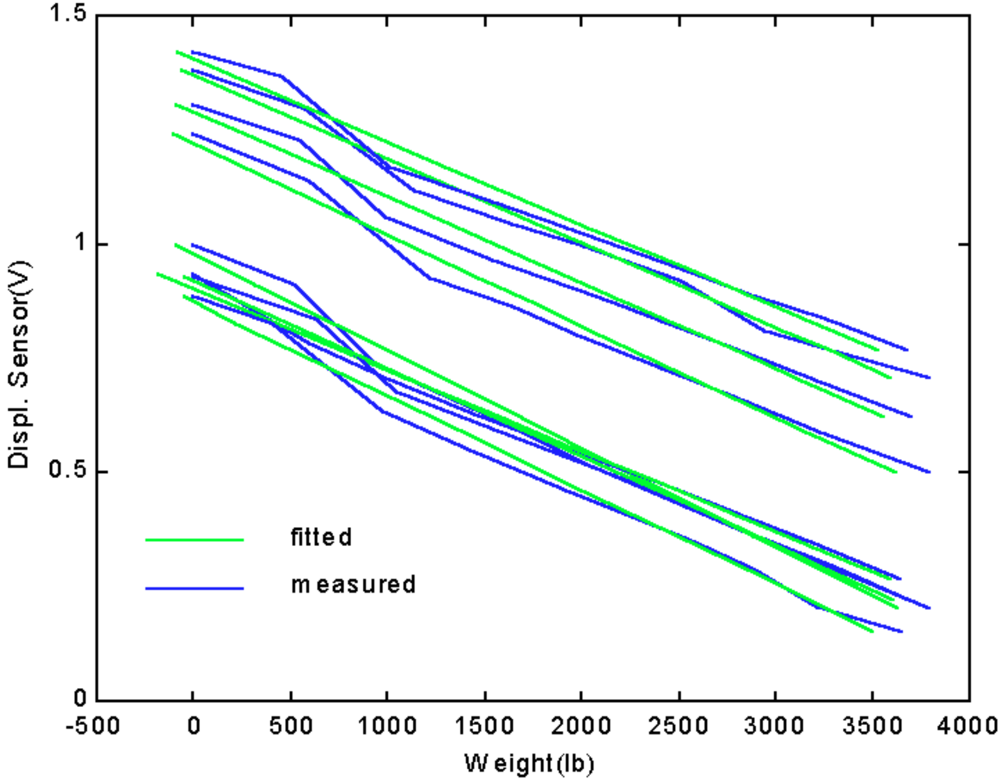

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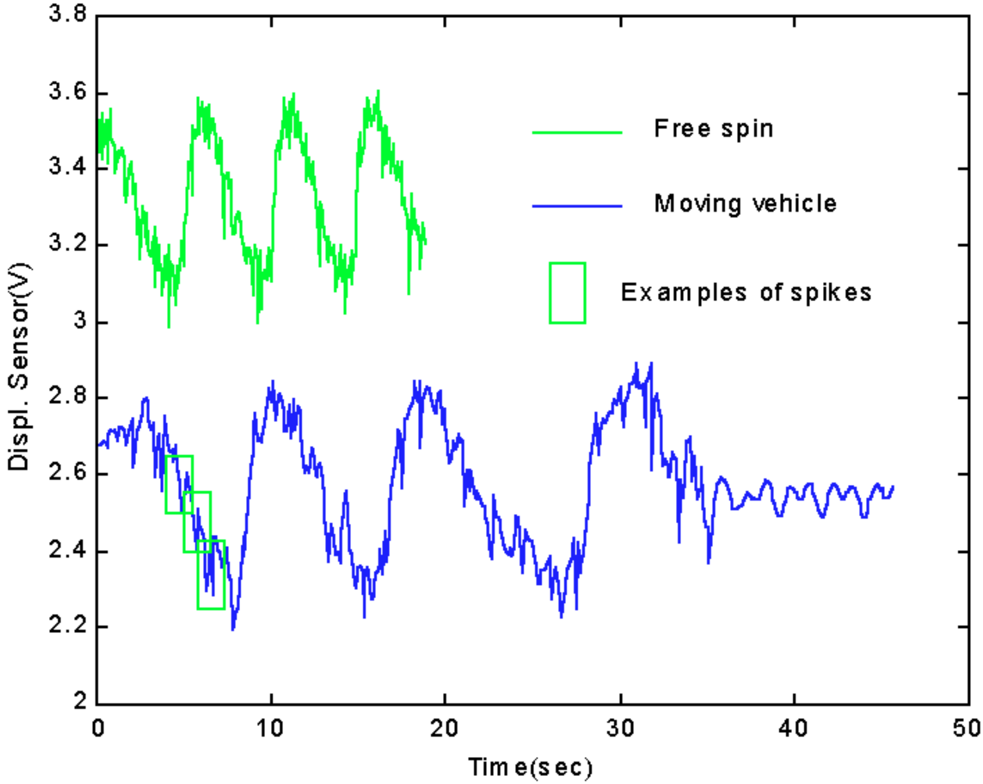

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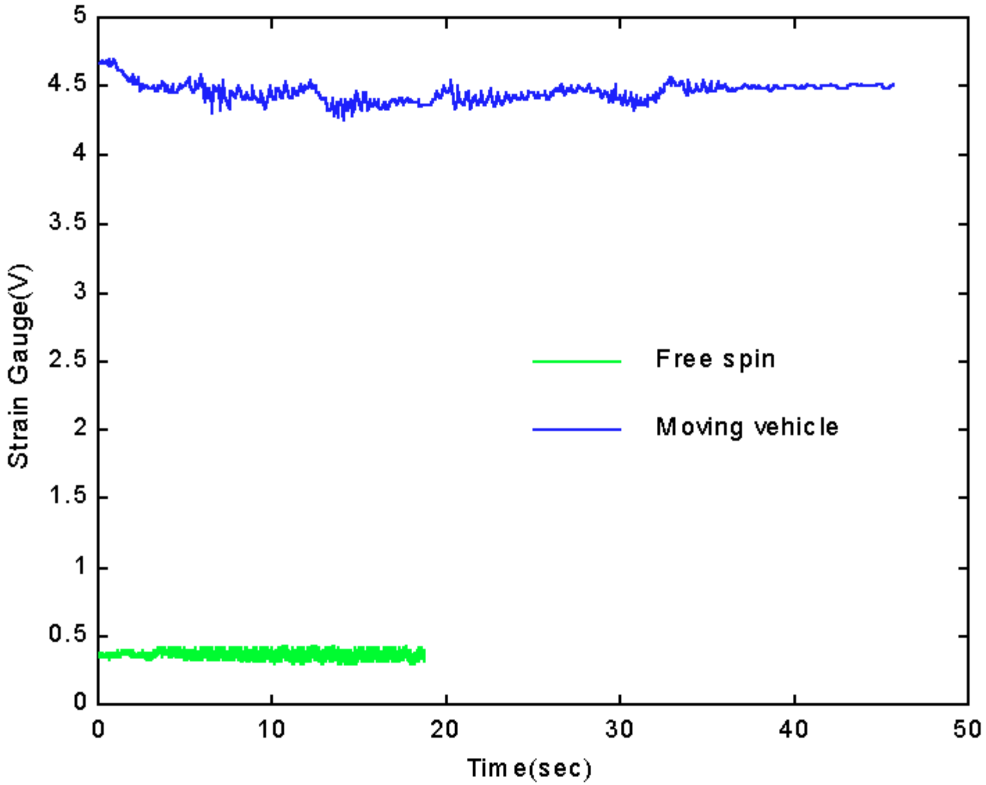

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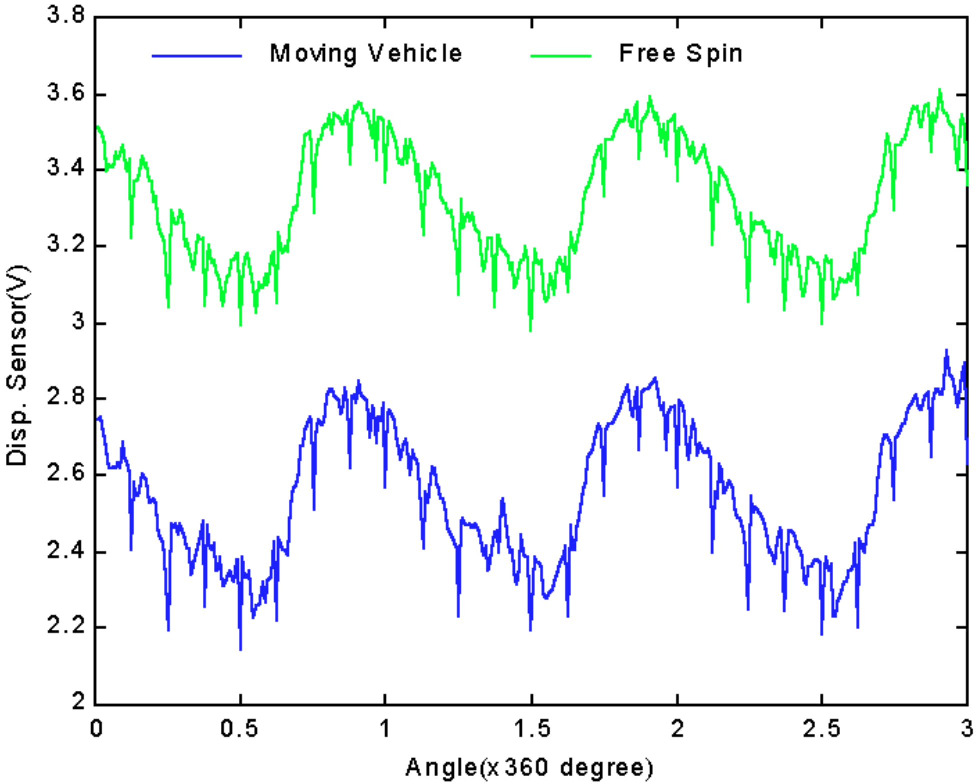

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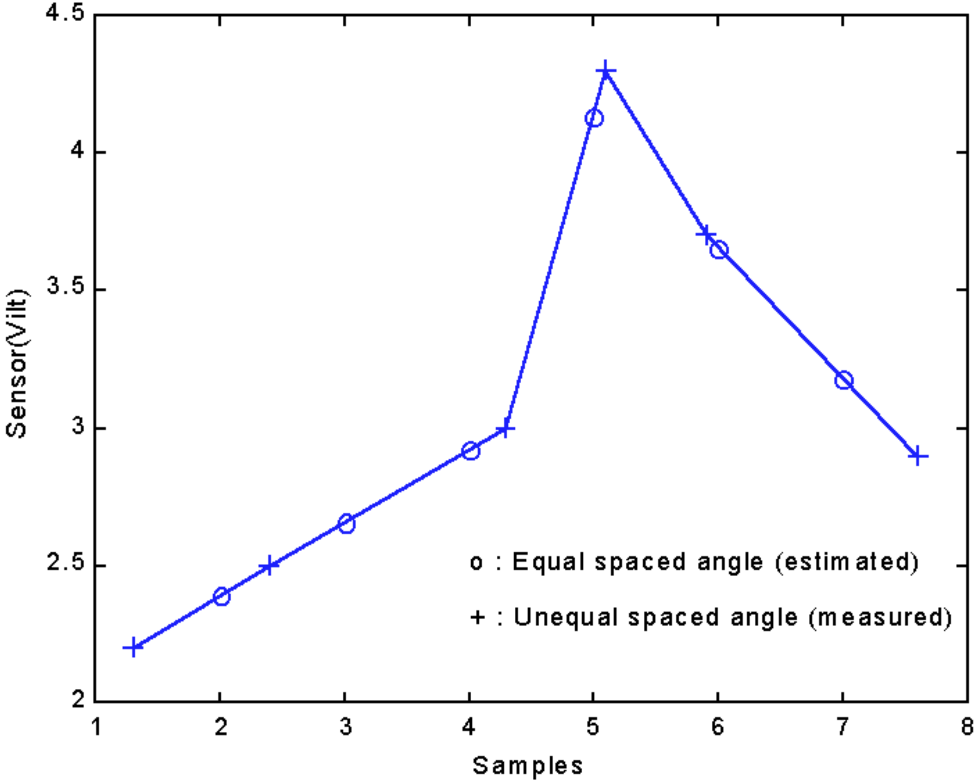

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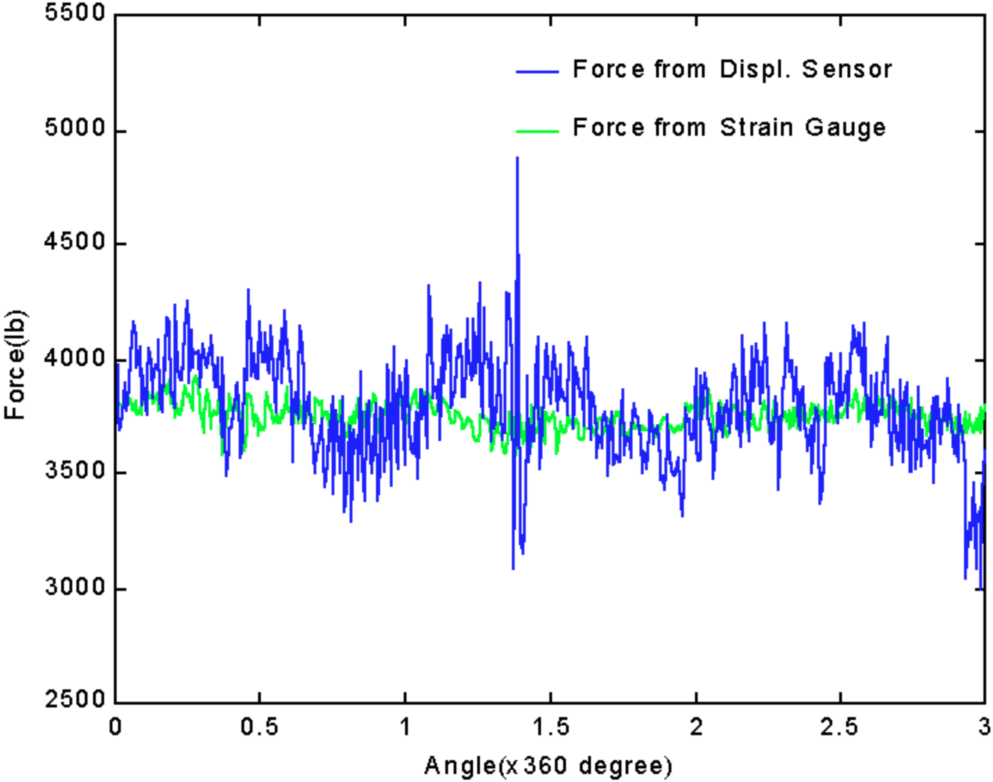

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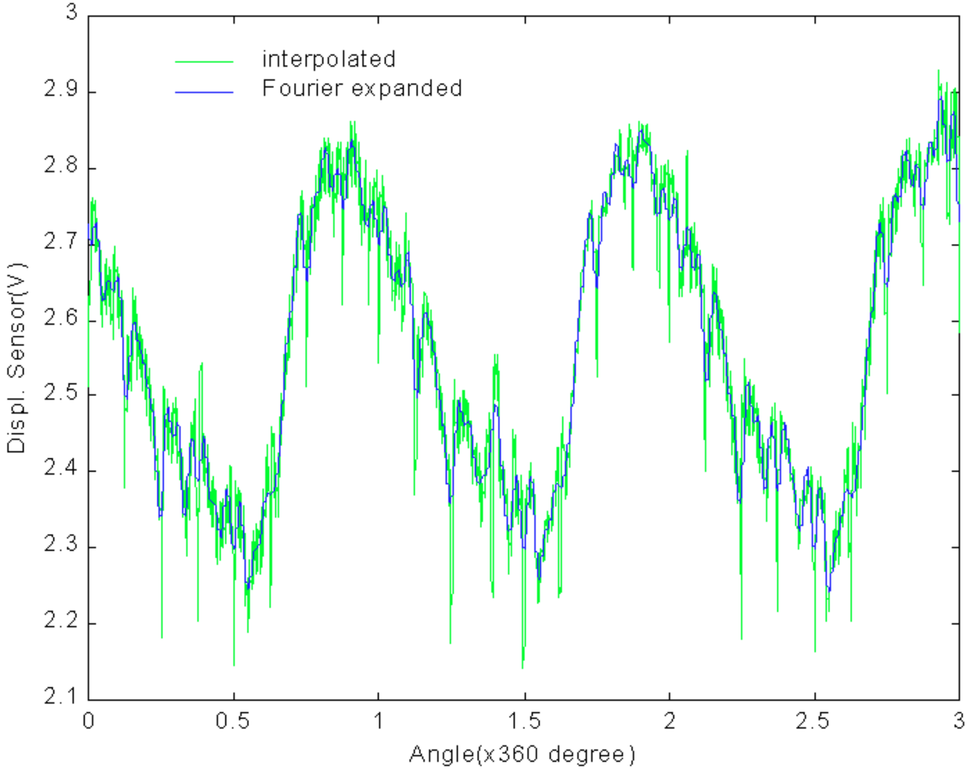

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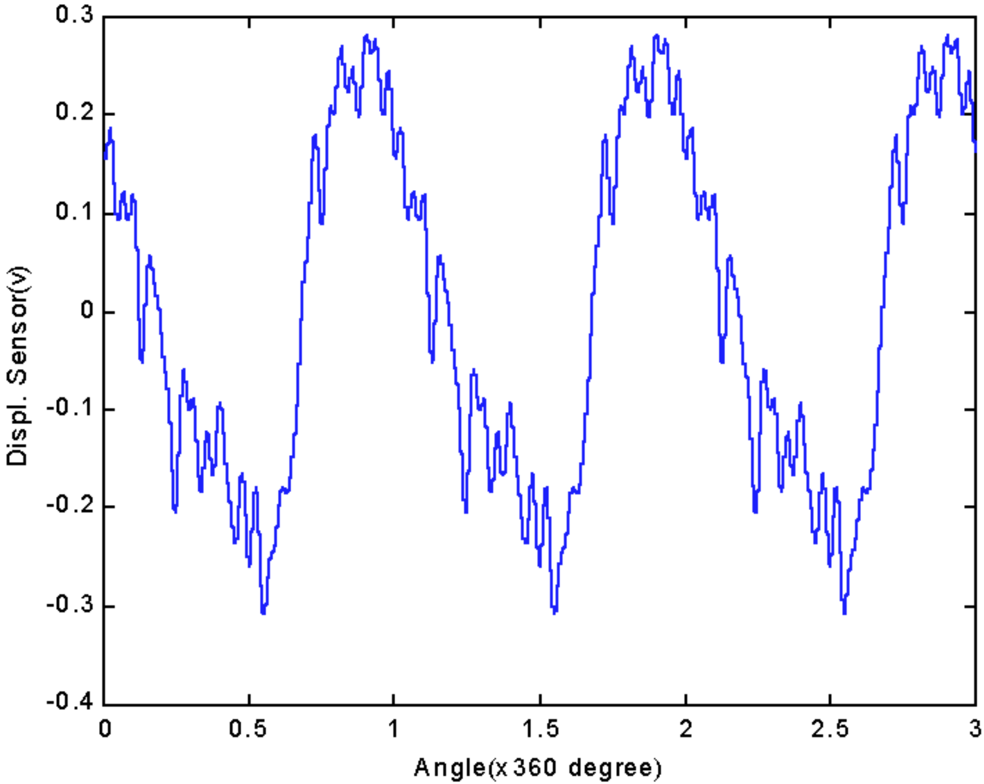

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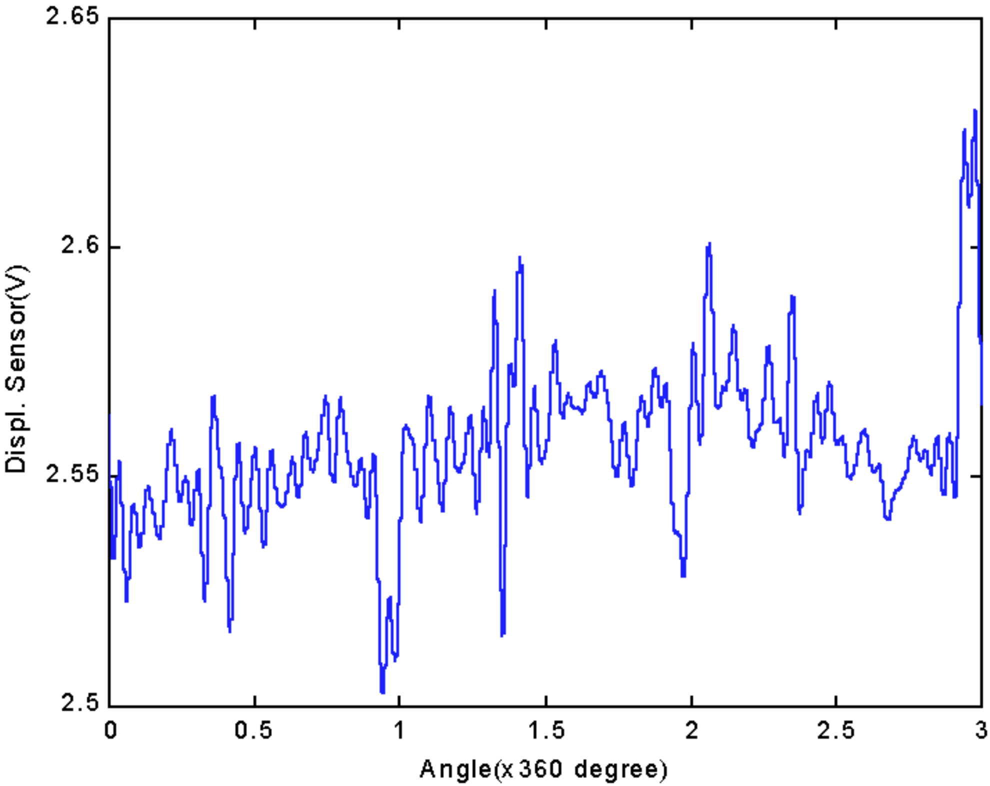

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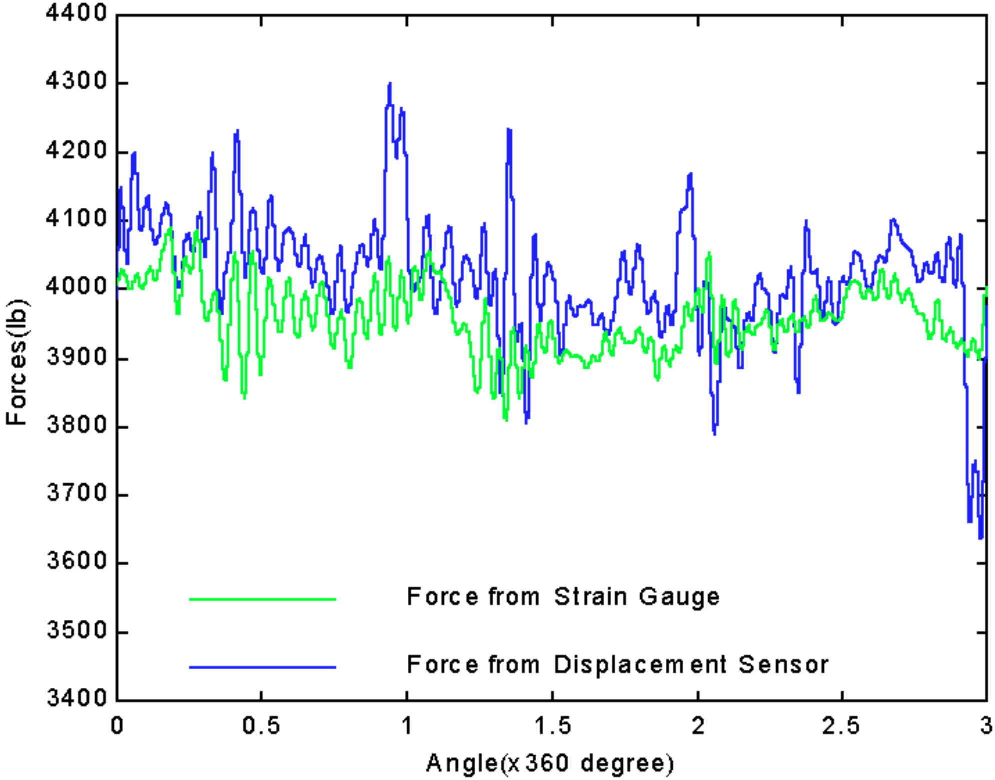

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