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Non-Invasive Techniques for Measuring Vertical Transient Track Displacements

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ABSTRACT

This paper presents two systems for non-invasively measuring transient rail and tie displacements using high-speed video cameras and accelerometers. The purpose of selecting these instruments is to develop a non-invasive instrumentation system that can monitor track performance under a range of environmental conditions. High-speed video cameras have many advantages such as tracking multiple rail and tie locations with a single camera, not needing to be base-isolated, and providing a visual account of the loaded track. Three cameras are used to illustrate rapid changes in rail displacement along short sections of track. Accelerometers are capable of measuring tie displacements and have many advantages such as being able to function if the optical view is blocked, e.g., rain, snow covering, or center of tie, and to measure lateral displacements.

Keywords: High-speed video cameras, video cameras, accelerometers, double-integration, tie-ballast gap, poor support, transient track displacements

INTRODUCTION

Measuring the transient vertical displacements of railroad track is useful for track assessment because greater track displacements typically correlate to low values of track modulus and greater substructure settlement (*1,2*). Increased track displacements and loads can also accelerate track geometry problems and component degradation. Multiple tools are available to measure different aspects of vertical track displacement. For example, track geometry cars are beneficial for quickly measuring train axle displacements and accelerations along track. If the track behavior at a single location is desired, stationary measurements using Linear Variable Differential Transducers (LVDTs) can measure rail and tie displacement time histories of a passing train. For example, LVDTs can be attached to the bottom of the rail to monitor rail displacement (*3*) or installed with depth using a borehole to measure tie and substructure displacements (*4*).

Optical techniques, typically lasers or high-speed video cameras, are becoming increasing popular for stationary measurements because they directly and non-invasively measure rail and tie displacement. For example, laser measurements are highly accurate and can accommodate sampling rates of over 1,000 Hz (*5*). Lasers have been used to measure open track tie displacements in Brazil and transition zone rail displacements in Portugal (*5,6*). The primary disadvantages of lasers are safety concerns of a laser near traffic and only a single location can be measured with each individual laser, therefore requiring a stable base. Alternatively, high-speed video cameras can be used for stationary measurements and can monitor multiple locations without laser related safety concerns. Vertical displacements can be derived from video camera recordings using Particle Image Velocimetry (PIV) or Direct Image Correlation (DIC) to track targets attached to the rail and ties (*3,7,8*). High-speed video cameras are capable of measuring multiple targets in a single shot, do not require a completely stable foundation, and provide a visual account of the moving track. The disadvantages include more complicated image processing and typically lower accuracy or sampling rates than lasers. Advances in both laser and high-speed video technology in the past decade have made both of these methods more practical to use and analyze.

The integration of velocity and acceleration time histories offer an indirect method of non-invasively measuring tie displacements. Velocity measuring geophones have been used by the University of Birmingham to measure tie displacements with successful results (*7-9*) and accelerometers have been used to measure both tie and substructure displacements (*9-11*). Accelerometers, as opposed to geophones, provide the additional benefit of measuring high-frequency tie movement, which allows for the evaluation of track support and wheel-rail, rail-tie, and tie-ballast interaction and impacts to be investigated (*12,13*). This gives accelerometers a dual-benefit while geophones are typically limited to estimating tie displacements after single integration. However, the double-integration process to estimate displacements from acceleration time histories is less stable than single-integration of a velocity time history (*10,11*).

This paper describes a non-invasive monitoring system that measures rail and tie displacements using high-speed video cameras and double-integration of acceleration time histories. While accelerometers are also used for high-frequency analysis, e.g. impact loads, vibrations, and applied loadings, this paper focuses on how these two systems can be used to measure transient track displacement time histories. The benefit of accelerometers for measuring impact and vibration are described elsewhere (*12-14*).

INSTRUMENTATION

High-Speed Video Cameras

Consumer high-speed video cameras (Figure 1a) were selected to directly and non-invasively measure transient rail and tie displacements. The high-speed cameras are capable of measuring two rail and tie locations in a single shot and typically record at a frequency of 240 frames per second (fps). Non-high-speed video cameras with capabilities of 30 fps are also used to test its effectiveness for railroad applications. The literature indicates that camera monitoring initially used 30 fps (*7*) but higher values of 100 fps (*3*) to 500 fps (*8*) are now typical because of advancements in camera technology.

A MATLAB code was developed herein that tracks the movement of the targets attached to the rail and tie. An orange target color is used because it is distinct from common background colors and can be isolated during post-processing (Figure 1b). The code locates the targets by creating a binary image in which all pixels with the pre-selected orange color is converted to white while all non-orange pixels are converted to black. Secondly, the code calculates the centroid of each target, i.e. white pixels, in each frame and produces a time history by tracking the centroids during the course of the video. The influence of ground vibrations are minimized by also tracking a target attached to a 0.5 m (18 inch) stake that is driven into the ballast shoulder about 0.3 m (1 ft.) from the tie edge and subtracting the stake time history from the rail and tie time histories. This method reduces setup and image processing time compared to established PIV, DIC, and lasers methods (*6*-*8*) but sacrifices accuracy if low displacement values (<0.25 mm) are desired. The video cameras are capable of tracking both transient vertical and longitudinal displacements but only vertical results are presented herein.

(a) (b)

Figure 1: Photographs of (a) consumer high-speed video cameras and (b) orange targets attached to rail, timber tie, and stake locations.

Accelerometers

A second non-invasive tie displacement measurement tool is the double-integration of railroad tie acceleration time histories. This is an indirect measurement of transient displacements but has the advantage of measuring tie locations when the optical view is blocked and when many tie locations are required because the numbers of sensors used is only limited by the Data Acquisition (DAQ) System. Sampling rates of 8,000 Hz are typically used, which is high enough to capture the desired accelerations (*13*). While uniaxial accelerometers (vertical direction only) are discussed herein, triaxial accelerometers are also available if longitudinal and lateral displacements are desired.

The accelerometers are 13 mm long (one half inch), weigh less than 3 grams (0.1 ounces), and are bonded to the concrete or timber tie with superglue (see Figure 2). The accelerometers do not interfere with train operations and can be set up in 20 to 30 minutes, making them suitable for short-term monitoring, i.e., a single train pass or day, as well as long-term monitoring during wet and inclement weather conditions because weather resistant accelerometers are also available.

Figure 2: Photograph of accelerometer attached to a timber tie.

DISPLACEMENT MEASUREMENTS – CAMERAS

To assess the practicality of measuring rail and tie displacements with consumer high-speed video cameras, the cameras monitored the south-end of an open deck bridge transition zone. The train traffic is considered Class 4 for operations and consists of empty, mixed, and loaded freight trains passing at velocities of 48 to 96 km/hr (30 to 60 mph) and accumulating 60 MGT annually. The spacing of the timber ties is 0.5 m (19.5 inch) and the bridge is a 15 m (50 ft.) steel open deck bridge. Because of increased settlement in the southern transition zone, nearly every tie has either a rail-tie and/or tie-ballast gap. Ballast fouling is also prevalent in and around all of the ties based on visual inspection. The rail-tie gaps were found within 4.6 m (15 ft.) of the bridge abutment and tie-ballast gaps were 4.6 m (15 ft.) or greater from the bridge abutment.

Six rail and tie locations over a span of 3.4 m (11 ft.) were measured on 10 June 2015 to investigate the rapidly changing track behavior with two consumer high-speed video cameras (240 fps) and a single non-high-speed video camera (30 fps). The non-high-speed video camera measured the east rail and tie locations 2.7 m (9 ft.) and 3.4 m (11 ft.) from the bridge abutment while the two high-speed video cameras measured the east rail and tie locations 4.3 m (14 ft.) , 4.9 m (16 ft.) , 5.5 m (18 ft.), and 6.1 m (20 ft.) from the bridge abutment. These ties will be referred to as Tie #1 (9 ft.), Tie #2 (11 ft.), Tie #3 (14 ft.), Tie #4 (16 ft.), Tie #5 (18 ft.), and Tie #6 (20 ft.) herein.

To eliminate ground vibration effects on the cameras, a subtraction method is used. This method involves subtracting the stake displacement time history from the rail and tie time histories. The stake is placed about 0.3 m (1 ft.) into the ballast shoulder and should experience minimal vertical displacement from passing trains. Sample results of raw rail, stake, and corrected transient vertical rail displacement time histories are displayed in Figure 3. To ensure the stake is far enough in the ballast shoulder, the stake time history can be checked for evidence of recurring vertical displacements. Small displacements (<0.05 mm) are observed in Figure 3(a) but it is not apparent if the displacements are from surface displacement or vibrations from the ground and/or wind.

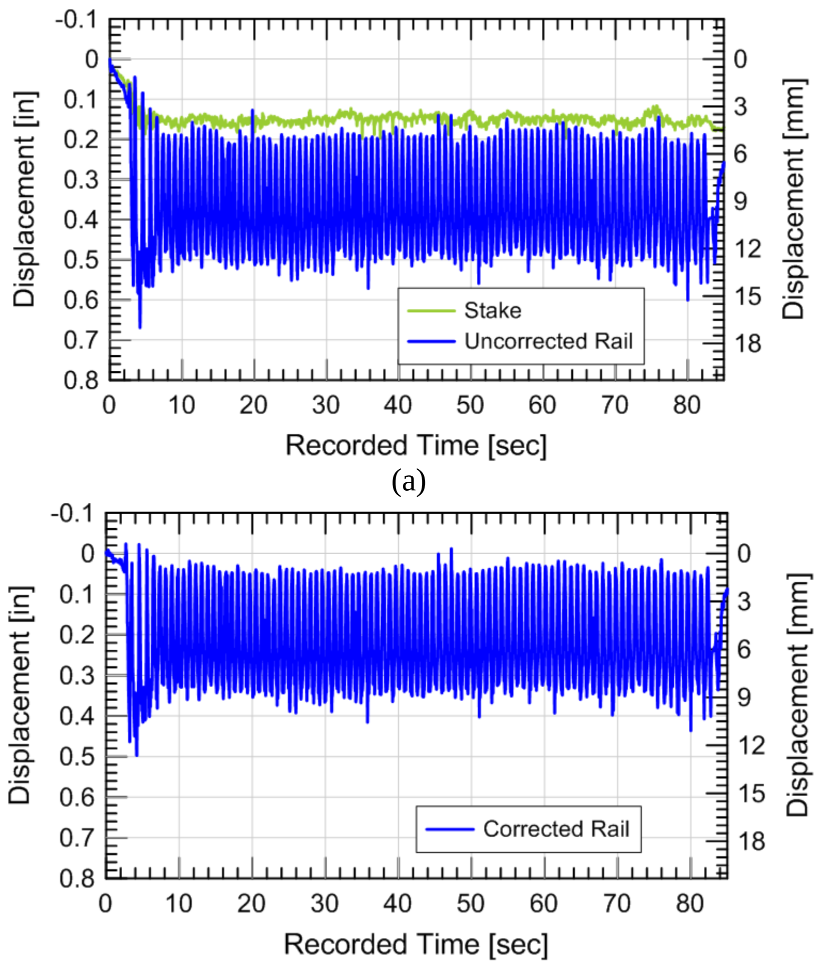
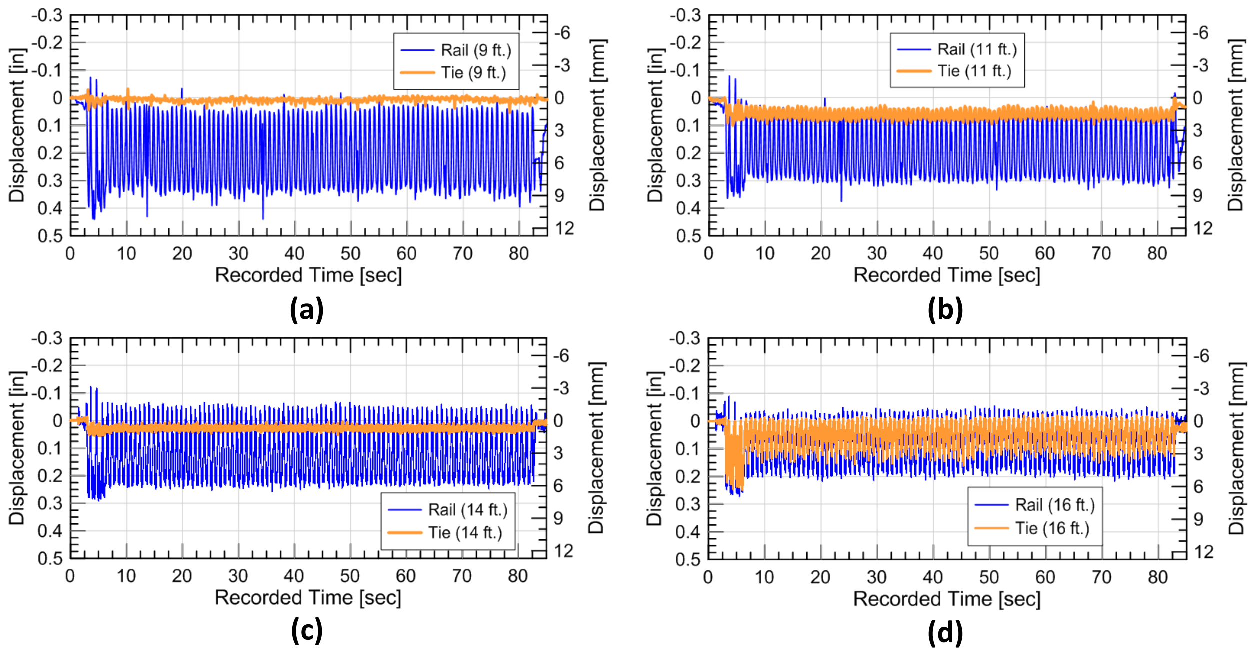


Figure 3: Typical results of: (a) raw vertical rail and stake displacement time histories and (b) corrected vertical rail displacement time history.

Figure 4 shows the corrected vertical rail and tie displacement time histories of an empty freight train at 76 km/hr (47 mph). The results show consistent rail and tie behavior except for the first few heavy locomotive axles. The average peak rail and tie displacements at each location from the empty cars with estimated wheel loads of 35 kN (8 kips) are also displayed in Table 1. The results show significant variation in track behavior with the track locations closest to the bridge abutment displaying peak rail displacements of about 9.0 mm (0.35 inches) and tie displacements of about 0.5 mm (0.02 inches) while rail and tie displacements of 3.0 mm (0.12 inch) are observed farther away from the bridge abutment. The rapid decrease in rail displacement as the train moves farther from the abutment (6.0 mm in 3.4 m or 0.23 inches in 11 ft) translates to a rail slope of roughly 1:500 and can result in increased loading within the transition zone (*15*). Additionally, a change in tie behavior is observed 4.6 m (15 ft.) from the bridge abutment where the track switches from having rail-tie gaps to tie-ballast gaps. This switch implies the upward reaction force when two wheels are surrounding the tie is great enough within 4.6 m (15 ft.) to partially pull out the tie spikes. Rail-tie gaps, tie-ballast gaps, and track modulus can still be estimated using these measured displacements (*16*).

Figure 4(g) and (h) present the rail and tie time histories in the frequency domain. The results show a dominant frequency of 1.2 Hz with the majority of information ranging from 1 to 5 Hz. Ideally, the sampling rate should be ten times the highest desired frequency, 5 Hz in this particular case, meaning the 240 fps recording is sufficient. The 30 fps recording does capture peak displacements because the majority of peak displacement information have frequencies below 3 Hz but frame rates above 50 would be ideal. This is relevant as 30 fps is typically the frame rate of consumer video cameras and high-speed cameras are not always available and may not be practical for long-term monitoring.



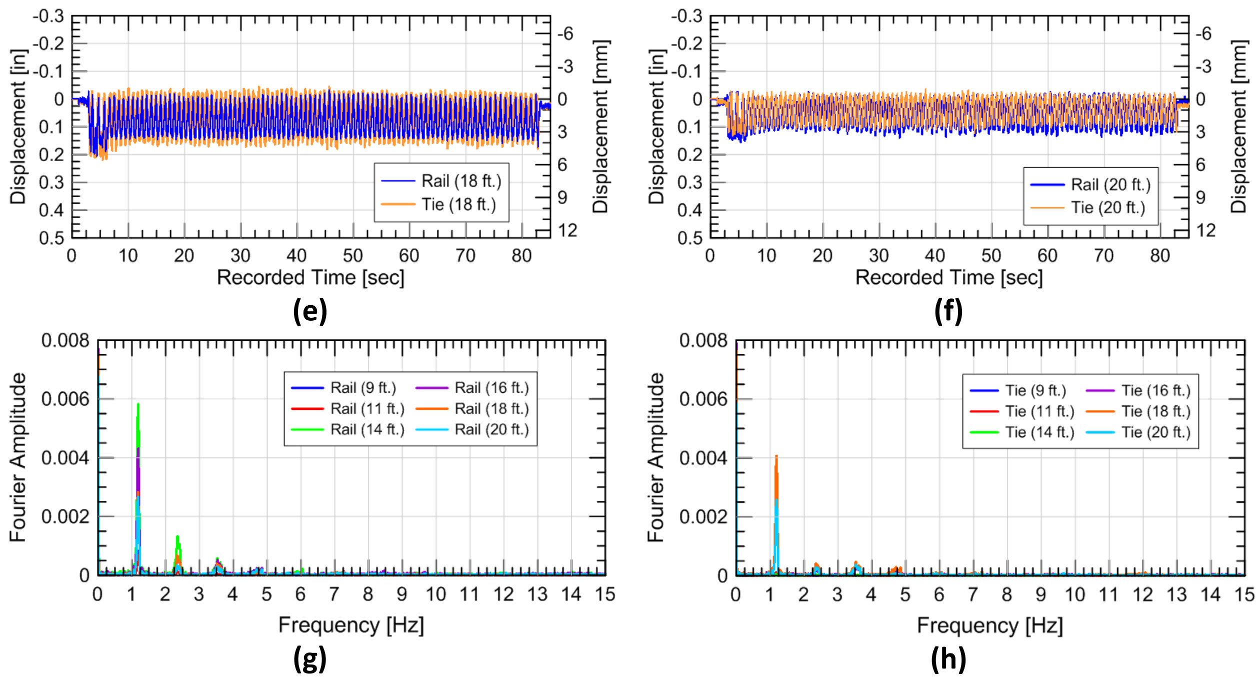


Figure 4: Vertical rail and tie displacement time histories of: (a) Tie #1 (9 ft. from bridge), (b) Tie #2 (11 ft.), (c) Tie #3 (14 ft.), (d) Tie #4 (16 ft.), (e) Tie #5 (18 ft.), and (f) Tie #6 (20 ft.) for an empty freight train passing at 76 km/hr (47 mph).

Table 1: Peak vertical rail and tie displacements for an empty freight train passing at 76 km/hr (47 mph)

	Rail		Tie	
	[mm]	[in]	[mm]	[in]
Tie #1 (9 ft.)	9.0	0.35	0.5	0.02
Tie #2 (11 ft.)	8.0	0.31	2.0	0.08
Tie #3 (14 ft.)	6.0	0.24	1.0	0.04
Tie #4 (16 ft.)	5.0	0.20	3.0	0.12
Tie #5 (18 ft.)	3.5	0.14	4.0	0.16
Tie #6 (20 ft.)	3.0	0.12	2.5	0.1

In summary, the high-speed video cameras sufficiently measure rail and tie displacement time histories. The results also show that a 30 fps video camera at Tie #1 (9 ft. from bridge abutment) and Tie #2 (11 ft.) is also able to capture full displacement time histories but it is not recommended that this slow frame rates be used if high-speed video cameras are available because high-speed video cameras (240 fps) can capture individual impact events that a 30 fps video camera cannot capture.

DOUBLE INTEGRATION

Theory

A second non-invasive tool for measuring transient tie displacements is double-integration of acceleration time histories because of the relationship between acceleration and displacement. Analyzing tie acceleration from accelerometers is more complicated than tie displacement time histories from video cameras because railroad track is a coupled multi-layer system and railroad tie acceleration is influenced by the motion and impacts from the wheel, rail, fastening system, ties, ballast, and subgrade. Some examples include: (1) wheel-rail impacts, (2) wheel-rail vibrations such as braking, (3) rail-tie impacts, (4) tie loading, (5) track and tie vibrations, (6) tie-ballast impact, and (7) tie displacement from train loading. Each factor tends to produce a unique acceleration signature and can often be identified by analyzing the acceleration record in both the time and frequency domains (*12-14*). All of these influences except factor (7), i.e., tie displacement from train loading, produce high-accelerations (5 to 500g), high-frequency motion (>100 Hz), and low vertical displacements (<0.1 mm). This means factors (1) through (6) dominate the acceleration time histories but have negligible influence on the double-integrated displacement time histories. Therefore, these factors are filtered out before double-integration is performed as discussed below. Factor (7) is tie displacement from train loading which is a low-acceleration (<1g) and low-frequency (<5 Hz) motion, which controls the magnitude of the transient vertical displacement obtained from the double integration process. This low-acceleration (<1g) and low-frequency (<5 Hz) motion is difficult to identify by reviewing the acceleration time history in the time domain but can be easily identified in the frequency domain because of its low-frequency signature. As a result, the acceleration time histories are first converted to the frequency domain and then filtered to remove the high-frequency motions before double-integration is performed to calculate the displacement time history as discussed below.

A complication arising from the double integration procedure is the inherent noise within the accelerometer and track systems. It is important to remove the noise because it results in unrealistic displacements during double integration. Noise exists at all frequencies but is more prevalent at low- and high-frequencies. This range depends on the accelerometer system and external track factors but the primary source of noise in the acceleration time histories is from the accelerometers themselves. There are two main types of accelerometers, piezo-electric and Direct Current (DC), and each has its own frequency range of noise. Piezo-electric accelerometers typically allow for a wide range of acceleration magnitudes and frequencies, e.g., +/- 500g and 0.7 to 20,000 Hz, and are therefore beneficial for measuring both tie displacements and impacts. DC accelerometers typically have a restricted magnitude (+/- 50g) and frequency range (0 to 500 Hz) but are designed to have limited noise at low-frequency motion and are more expensive. In general, piezo-electric accelerometers are better suited for measuring the wide range of railroad acceleration and loadings while DC accelerometers, similar to geophones, are better suited if double-integration is the primary purpose of the instrumentation.

To remove the inherent noise and higher frequency motion in acceleration time histories, signal filtering must be performed (*10,11*). Signal filtering essentially removes frequencies of a specified range from a time history by multiplying any frequency outside the range by zero (0) and any frequency inside the range by unity (1). Filters can generally be described by the mathematical filter and frequency range the filter passes. Multiple types of mathematical filters exist and differ based on the mathematical equation used to smooth the transition from the filtered and non-filtered range but the commonly used Butterworth Filter is used herein because it is simple to use and sufficiently filters the signal. The frequency range can be specified by selecting one of three types of filters: low-pass, high-pass, or band-pass. Low-pass filters allow frequencies lower than the frequency cutoff and attenuate higher frequencies. High-pass filters allow frequencies higher than the frequency cutoff and attenuate lower frequencies. Band-pass filters allow frequencies between two frequency cutoffs and attenuate frequencies outside the cutoff range. To demonstrate how low-frequency noise is removed from an acceleration time history in the frequency domain, Figure 5 shows the effect of a high-pass Butterworth filter with a cutoff frequency of 0.75 Hz.

For the double-integration procedure to be successful, the tie displacement signature must either be of a different frequency than the noise so the noise can be removed by filtering or the signature must produce a significantly greater magnitude signal to overpower the noise. Because tie displacement frequency, e.g., the number of times the tie moves up and down in a second (Hz), is a function mainly of train speed, the double integration procedure is restricted by train speed. For example, trains moving between 40 to 80 km/hr (25 and 50 mph) typically produce tie displacement frequencies between 1 and 5 Hz. Slower trains produce lower tie displacement frequencies and make it difficult to isolate and filter out the noise component.

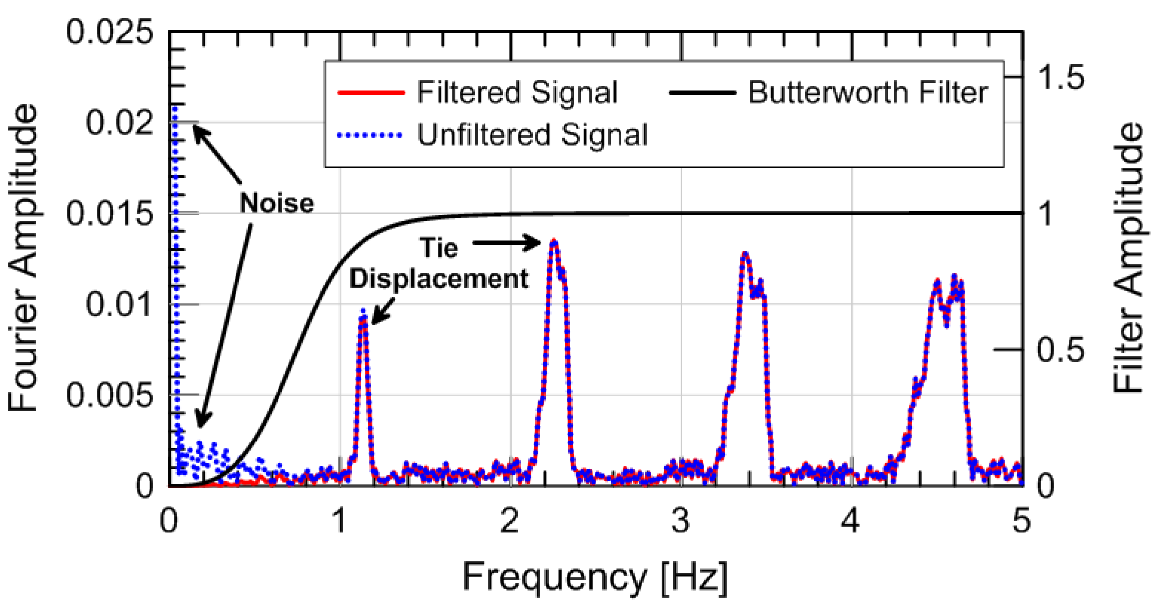


Figure 5: High-pass Butterworth filter with a cutoff frequency of 0.75 Hz applied to a tie acceleration time history presented in frequency domain.

Analysis Procedure

While the focus of this paper is transient track displacement measurements, the goal of the accelerometer instrumentation is to non-invasively measure track displacements, support, and impacts so the high-frequency measuring piezo-electric accelerometers were selected. However, the procedure for piezo-electric and DC accelerometers are identical with the only difference being the frequency cutoff used for filtering. The double-integration procedure includes the following steps:

1. Passing the acceleration time history through a band-pass Butterworth filter (0.75 to 50 Hz) to eliminate low-frequency noise and high-frequency motions. The lower frequency cutoff is set by the accelerometer while the upper limit is more arbitrarily set because high-frequency tie accelerations (>50 Hz) have negligible effect on the calculated tie displacements. An upper limit value of 50 Hz was selected because it removes the high-frequency motion and generally isolates the tie displacement component.
2. Integrating the acceleration time history using the trapezoidal method to obtain a velocity time history;
3. Passing the velocity time history through a high-pass Butterworth filter (0.75 Hz) to remove residual noise from the integration process;
4. Integrating the velocity time history using trapezoidal method to obtain a displacement time history.

This procedure is illustrated in Figure 6 which shows the unfiltered and filtered tie acceleration time histories, the integrated tie velocity time history, and double-integrated tie displacement time history. The significant reduction in acceleration magnitudes (~10g to ~1g) when the raw acceleration time history is passed through the band-pass filter reinforces the prevalence of high-acceleration magnitude and high-frequency motion in track. The acceleration spikes greater than 30g are inconsistent and likely from passing wheel flats while the consistent 10 to 15g accelerations are likely from impact loads within the track system during wheel loading and therefore are not associated with vertical tie displacements. The velocity and displacement time histories show consistent values which is expected from a passing train and can be used to estimate peak-to-peak tie velocity and displacements. This means the difference between the minimum and maximum tie displacements from the double integration procedure is the difference between the minimum and maximum tie displacement from the high-speed video camera. The exact displacement signature from video cameras will not be replicated by accelerometers because some signal information is filtered from the acceleration time history, which is explained in more detail below.

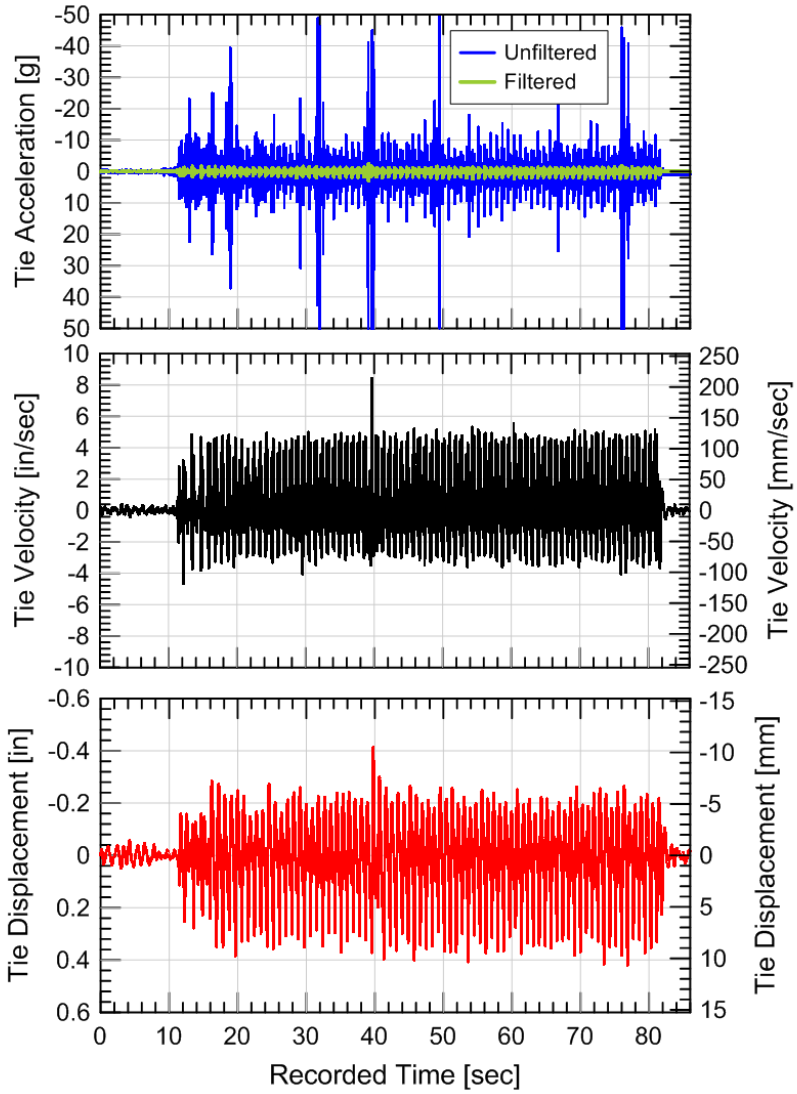


Figure 6: Comparison of unfiltered and filtered acceleration (top), integrated velocity (middle), and double-integrated displacement (bottom) time histories.

Comparison of Transient Displacements

Tie displacement time histories from a high-speed video camera and double-integrated accelerometer time histories are compared using the procedures explained above. Figure 7 compares the high-speed video camera and double-integrated displacement time histories for a loaded coal train moving at a velocity of 63 km/hr (39 mph). Figures 7(a) and 7(b) compare the full time histories while Figures 7(c) and 7(d) display only ten seconds of this time history to facilitate comparison of the displacement signatures. The peak-to-peak tie displacement values of the high-speed video camera (12.75 to 14 mm or 0.5 to 0.55 inches) and accelerometers (12.75 to 15.25 mm or 0.5 to 0.6 inches) are comparable. A key difference in the time histories is the high-speed video camera data (Figures 7a and 7c) show the tie moving downward (downward displacement is positive) from the origin while the double-integrated time history is more "symmetric" about the origin. The lack of "symmetry" in the video camera data is caused by the existence of low-frequency movements (<0.05 Hz) that are filtered out in the accelerometer signal (Figures 5 and 8). The 10-second data in Figures 7(c) and 7(d) shows the exact signature is not matched well but this is expected when comparing filtered and double-integrated data from piezo-electric accelerometers.

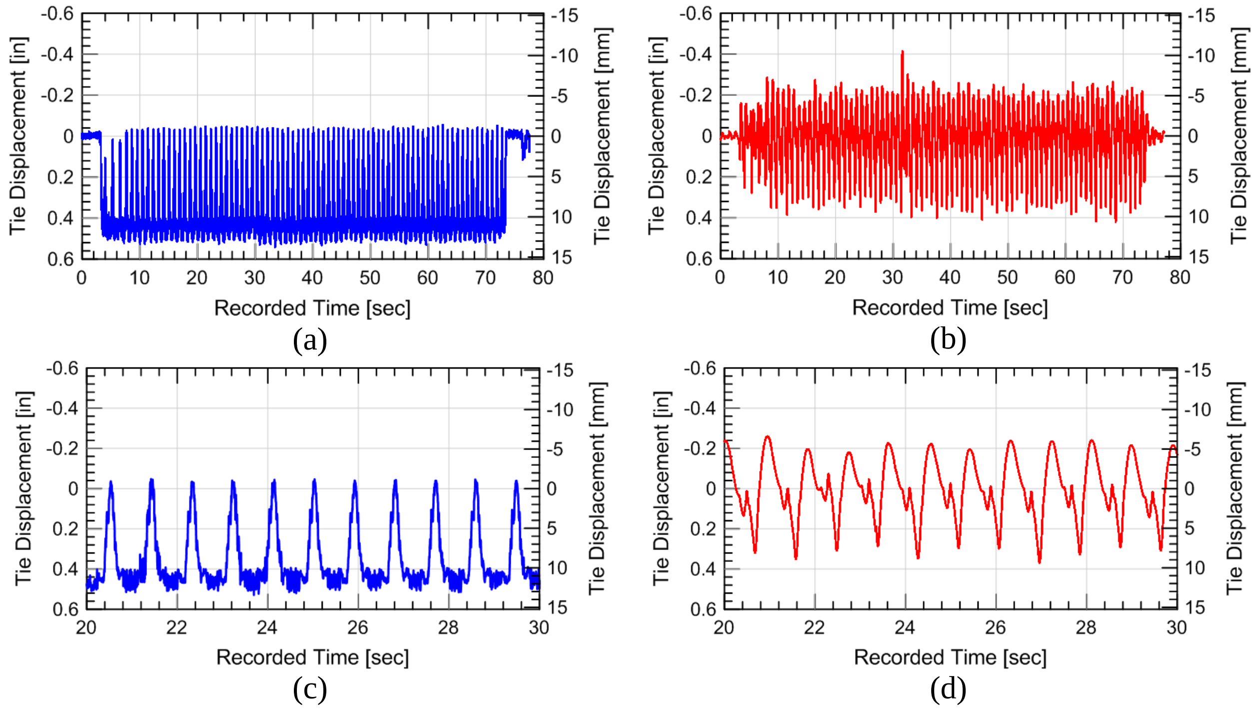


Figure 7: Tie displacement time histories of a passing coal train with a velocity of 63 km/hr (39 mph): (a) entire train with high-speed video camera, (b) entire train with double-integrated accelerometer, (c) 10-seconds of high-speed video camera and (d) 10-seconds double-integrated accelerometer.

Figure 8 compares the high-speed video camera and filtered accelerometer time histories in the frequency domain and shows the amplitudes are in agreement for a range of tie frequencies (1.15, 2.3, 3.45, and 4.45 Hz). The magnitude of the Fourier Amplitudes differ in Figure 8, which is in agreement with the difference in displacement signatures in Figures 7(c) and (d). A second difference is the high-magnitude, low-frequency (<0.05 Hz) movement in the high-speed video camera signal, which makes the video time history lose its "symmetry" about the x-axis but does not affect the peak-to-peak displacement values. This low-frequency motion was filtered out in the acceleration time history because it shares the same frequency as the noise from the accelerometer system.

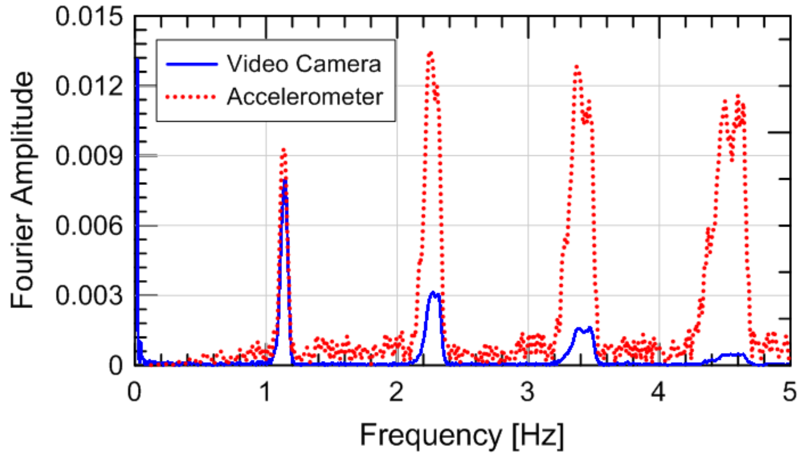


Figure 8: High-speed video camera and filtered accelerometer time histories in the frequency domain for a passing coal train with a velocity of 63 km/hr (39 mph).

Table 2 compares the high-speed video camera and double-integrated accelerometer results of six recorded trains. The results show acceptable matches for Trains 2, 3, 5, and 6 and detailed results for Train 5 are shown in Figures 7 and 8. Trains 1 and 4 have poor matches because the dominant frequency of tie movement is lower than the 0.75 Hz filter cutoff used in the double-integration procedure. Train 1 slowed from an initial velocity of 80 km/hr (50 mph) to 40 km/hr (25 mph) at the end of recording and the unusually low dominant frequency of Train 4 is postulated to be from the wheel and truck spacing. An important observation from Table 2 is the while the train velocity and dominant frequency are related but they do not perfectly correspond. From the authors' experience, train velocities of 40 to 48 km/hr (25 to 30 mph) typically correspond to a dominant frequency of about 1.0 Hz but this is not always the case. Lastly, distinct tie frequencies were observed for all six recorded trains (see Figure 8) but if distinct tie frequencies are not apparent, the double-integration process will not be successful because the displacement components will be lost in the noise from the accelerometer. From the author's experience, this can be an issue for ties with low displacements (<3 mm or 0.1 in). In these cases, geophones or DC accelerometers may be more suitable instruments.

Table 2: Comparison of peak tie displacements between high-speed video camera and double-integrated accelerometer data

Train	Train Velocity [mph]	Direction	Type	Dominant Frequency [Hz]	Camera Range [mm]	Accelerometer Range [mm]
1*	50 to 25	North	Mixed	1.0 to 0.5	10.0 – 11.5	5.0 – 12.7
2	59	North	Mixed	1.25	11.5 – 12.7	11.5 – 14.0
3	36	South	Loaded	0.95	12.7 – 15.3	10.0 – 15.3
4	31	South	Mixed	0.47	11.5 – 12.7	6.5 – 8.0
5	39	South	Loaded	1.15	12.7 – 14.0	12.7 – 15.3
6	30	South	Loaded	0.9	11.5 – 12.7	10.0 – 14.0

*Train 1 slowed from 50 mph to 25 mph during recording

SUMMARY

This paper describes the use of high-speed video cameras and accelerometers to non-invasively measure transient rail and tie displacements. These instruments combine to create a non-invasive, instrumentation system that can monitor track performance under a range of environmental conditions. Some of the main findings of this study are:

- High-speed video cameras and accelerometers are capable of measuring multiple rail and tie locations to analyze differing support conditions along the track or transition, which results in uneven load distribution, increased dynamic loads, and progressive track degradation.
- Comparable transient rail and tie displacements can be obtained using high-speed video cameras and double-integration of acceleration time histories if distinct tie frequencies above 0.75 Hz can be obtained. This generally limits the piezo-electric accelerometers to train velocities and tie displacements greater than 40 km/hr (25 mph) and 3 mm (0.10 in). For situations out of this range, geophones or DC accelerometers are probably better suited.

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