Proving MEMS Technologies for Smarter Railway Infrastructure

David Milne[1,*] Louis Le Pen[1], Geoff Watson[1], David Thompson[1], William Powrie[1], Mick Hayward[2], Simon Morley[2]
[1] *Faculty of Engineering and the Environment, University of Southampton, U.K.*
[2]*Network Rail (High Speed) Ltd. London, U.K.*

Abstract
Quantifying how railway track responds to passing trains in terms of displacement, velocity or acceleration, can provide insights into both the performance and the condition of the track. A number of trackside monitoring technologies have been shown to be capable of providing this information; however these are primarily research tools and tend to be costly hence actual deployments are relatively limited in scope. To assess systematically the changing health of railway track, more cost-effective continuous approaches to monitoring are required. Micro electrical mechanical systems (MEMS) are commonplace sensors in consumer electronics, low cost and can be used to measure acceleration. Thus they have the potential to provide the kind of data required to assess railway track behaviour at a much lower cost and in an environmentally robust small deployment package. However confidence in the quality of the data is required. This paper discusses the criteria for the selection of MEMS devices for this application. Laboratory trials and direct comparison of trackside measurements with well-established monitoring techniques demonstrate the effectiveness of the selected MEMS devices, and show their potential for use in continuous monitoring schemes to evaluate changes in track performance. The paper thus provides evidence that these kinds of low cost technologies are suitable for railway applications, building confidence in their use and enabling their adoption in self-monitoring smart infrastructure.

Keywords: MEMS Technology, Railway Tack; Structural Health Monitoring;

1 Introduction

Measuring the motion of railway track as trains pass provides information that can be used to quantify track performance. Different types of sensor may be used to obtain measurements of accelerations,

* Corresponding author.
E-mail address: d.milne@soton.ac.uk

velocities or displacements of sleepers, rails or trackbed. Sensor types and systems available include piezo-electric or Micro electrical mechanical systems (MEMS) type accelerometers, geophones (to measure velocity), high speed video for digital image correlation (DIC), and multi-depth deflectometers (MDD) (Bowness et al., 2007, Gräbe and Shaw, 2010, Lamas-Lopez et al., 2014, Mishra et al., 2014). It is common to evaluate track performance using deflection time histories, and all these types of sensor provide data from which deflection can be obtained. Of the four sensor types mentioned, deflection is most directly found from DIC or MDD but accelerometer and geophone data can also provide deflections by using either a double or single filter-integration scheme respectively. To date trackside monitoring using these four types of sensor has primarily been in the context of research and owing to concerns of some or all of robustness, complexity, reliability an accuracy or a combination thereof, no single sensor type has yet been shown to be more advantageous than all others or has been widely deployed outside a research context.

In this paper we explore the possibility of using low cost MEMS type accelerometers for widespread use in track performance monitoring. On a per sensor basis MEMS sensors are substantially less expensive than the alternatives available: in Europe a MEMS accelerometer mounted on circuit board costs less than €20, the sensor chips are less than €5, compared to about €600 per geophone. Like geophones, their use is more versatile (i.e. suited to a wider range of site conditions) than either high speed filming (where line of site is needed) or MDDs (where disruption of the trackbed is required). However, the accuracy and reliability of MEMS sensors has so far been seen as a relative weakness.

Generally, piezo-electric accelerometers are used for research due to their perceived greater accuracy; however these are relatively costly (having a similar cost per sensor to geophones). MEMS accelerometers are widely deployed in consumer electronics for motion and orientation detection. They provide the same kind of data but are significantly less costly (up to two orders of magnitude less expensive than geophone or piezo electric counterparts). MEMS devices are small, robust and could be embedded into track components. If data from MEMS accelerometers are sufficiently accurate, the technology could enable lower cost, larger and permanent deployments; this could form the instrumentation base for a track health monitoring system.

Previous studies benchmarking MEMS against piezo-electric accelerometers found the accuracy of those MEMS sensors tested to be insufficient for vibration measurement (Albarbar et al., 2009, Thanagasundram and Schlindwein, 2006). This study presents results of a benchmark comparison of newer MEMS sensors against established monitoring technologies. Laboratory tests are presented that suggest that MEMS are sufficiently accurate and field trials show close agreement with displacements obtained using more expensive geophone sensors. Further field measurements demonstrate how MEMS sensors could be used for continuous monitoring.

2 Sensor Selection

Different types of MEMS accelerometers are available. The sensor type will affect ease of deployment, data transmission, acquisition and quality. Generally the number of measurement axes, operational range and signal type can be selected by the user. Tri-axial MEMS accelerometers with three orthogonal axes of measurement are common. MEMS operate down to 0 Hz i.e. they “see” gravity. This means inclination can be determined and measurements from an inclined triaxial sensor can be transformed into a vertical and two orthogonal horizontal components. MEMS accelerometers may be combined with a gyroscope to measure angular velocity and a magnetometer to provide a reference orientation.

The operational range is selected such that the sensor remains linear and the reading is not “clipped” for the expected acceleration range, while providing good resolution. On track the expected accelerations are affected by the line speed and support conditions. Railway track deformations are low frequency phenomena, with the quasi-static axle loads being the primary loading mechanism (Sheng et al., 2003, Triepaischajonsak et al., 2011). Transducers must provide good performance at low frequency to obtain track displacements. Higher frequency behaviour (e.g. > 20 Hz) is not significant for track displacement, thus is often removed by a low pass filter (Bowness et al., 2007).

MEMS sensors can output either analogue or digital signals. For analogue sensors the operational range and sensitivity are normally fixed. An external data acquisition system is required to sample the voltage signal. This system controls the sample rate, the resolution of the analogue-to-digital conversion and should include appropriate anti-aliasing filters. Cables of typically up to 20 m can be used to transmit the signal between the sensor and data acquisition system and supply power. Cables of greater length are not recommended as they can introduce significant attenuation of the recorded data signal, although in suitably designed systems it should be possible to account for that.

The operational range of a digital sensor is often programmable. The resolution and sensitivity will depend on the chosen range and the size of the sensor's data register. Sampling and anti-aliasing are carried out on the sensor chip and are programmable. Acceleration measurements are stored in data registers on the chip. These are updated at the specified rate. A microcontroller is required to interface with the sensor, to read the data registers and store the data. Only short cables, typically less than 1 m length, can be used between the sensor and the micro controller for high data acquisition rates.

Following initial trials two analogue triaxial accelerometers from analog devices were selected for further testing: the ADXL335 and ADXL326. These have operational ranges of ±3 g and ±16 g respectively. Both sensors were equipped with a first order low-pass anti-aliasing filter with a 50 Hz cut off frequency provided by a resistor capacitor (RC) circuit that will attenuate the signal at higher frequencies. These sensors use a 32 kΩ resistor and a 0.1 μF capacitor. Analogue sensors were selected as they could be sampled using the same data acquisition system as the high quality Ion Sensor Nederland LF-24 geophones used for comparison.

3 Laboratory Trials

Benchmarking a sensor against one of known quality is a common method of assessing the performance of a new device. Two geophones and the ±3 g and ±16 g MEMS accelerometers were mounted on the arm of a hydraulic actuator. The actuator was capable of reproducing frequencies and amplitudes associated with railway track deformations resulting from slower moving trains. The actuator was excited by a sinusoidal waveform at a fixed frequency. Tests were carried out at 1 Hz increments between 1 and 5 Hz. The signals from the sensors were sampled at 500 Hz for a duration of 20 s in each test. An electrodynamic shaker was also used to perform a frequency sweep, between 5 and 45 Hz, to check higher frequency performance. Data were calibrated for comparison in both time and frequency domains. The results from the two geophones used were in agreement so only data from a single geophone are presented for comparison.

Displacements were obtained from the velocity and acceleration data using single and double filter-integration schemes respectively. High- and low-pass Butterworth filters, with cut-offs of 0.8 and 8 Hz, were used to obtain displacements for the tests shown in Fig 1. The displacements obtained agree for the different sensors used in these tests.

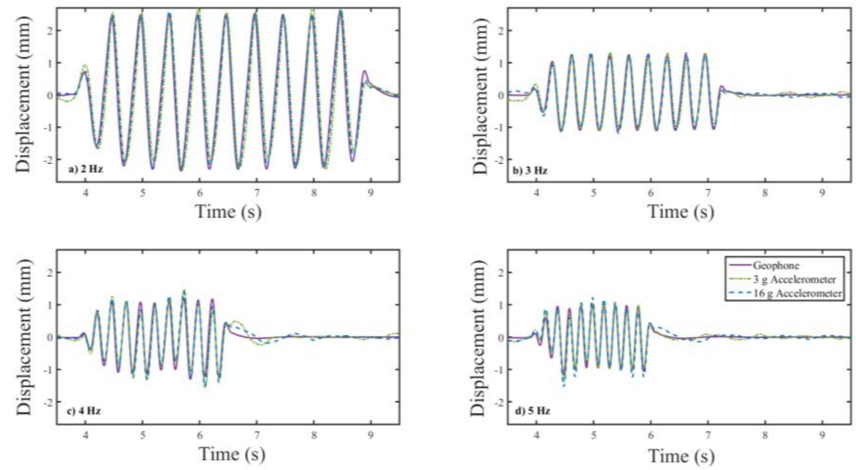

Figure 1 Displacement time histories for fixed frequency sinusoidal excitation at a) 2 Hz, b) 3 Hz, c) 4 Hz, d) 5 Hz, measured using a geophone and ±3 g and ±16 g accelerometers.

Transducer performance was verified in the frequency domain by calculating the transfer function between the geophone and accelerometer measurements. Acceleration data were integrated in the frequency domain to obtain velocities for this calculation. As the transducers were subjected to the same excitation the expected magnitude of the transfer function for calibrated velocity data is unity. In the actuator tests only the test frequencies and their harmonics were excited. The transfer function has been evaluated at each test frequency for the actuator tests (Fig. 2a). To investigate higher frequency performance the transfer function has been evaluated at the harmonics for the 2-5 Hz tests (Fig. 2b). The higher frequency performance was also investigated using a frequency sweep. The average transfer function magnitude has been calculated from this test in standard 1/3 octave bands (Fig. 2b). The frequency response for the 1st order RC antialiasing filter with a 50 Hz cut of has been plotted to show the expected attenuation of the acceleration signal.

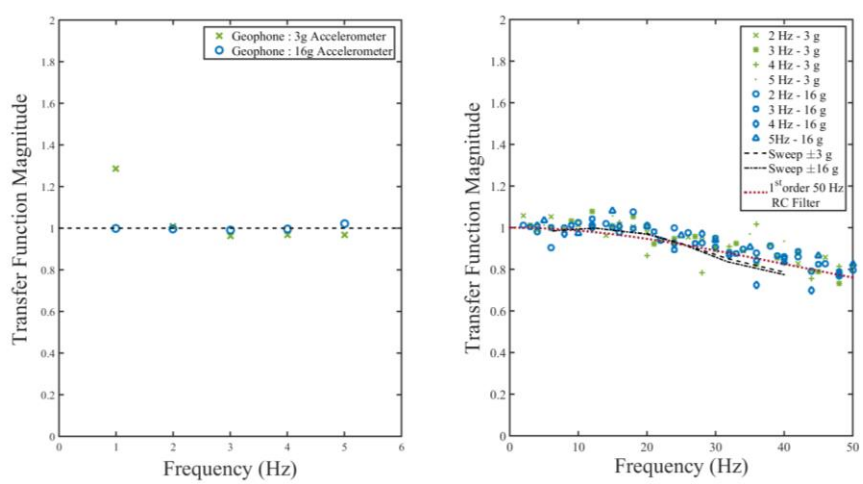

Figure 2 Transfer function magnitude between ±3 g and ±16 g accelerometers and a geophone a) at each test frequency, b) at the harmonics of each test frequency and for a frequency sweep between 5 and 45 Hz, expressed in 1/3 octave bands, and the frequency response of the antialiasing filter

The transfer function for each test frequency for most of the actuator tests was close to unity (Fig. 2a). The ±3 g accelerometer performed less well for the 1 Hz test, perhaps as a result of low frequency noise or poor performance at very low frequencies. The result was more variable when the transfer function was evaluated at the harmonics of the test frequency. These values were close to unity up to about 20-25 Hz. Above that point the magnitude began to drop. This trend is the same for the frequency sweep: the transfer function is flat up to 20-25 Hz then begins to fall. This attenuation is expected given the characteristics of the sensors antialiasing filter. Together, these time and frequency domain results demonstrate that:

- displacements can successfully be obtained from acceleration data measured using MEMS accelerometers
- the MEMS accelerometers tested offer accurate and linear performance in the frequency domain for the frequencies of track deformation up to about 20-25 Hz.

4 Field Trials

To assess the field performance a geophone and a ±16 g accelerometer were glued to the same sleeper at a study site, where six car trains pass at up to 230 km/h (~60 m/s). The ±16 g accelerometer was chosen for increased operational range.

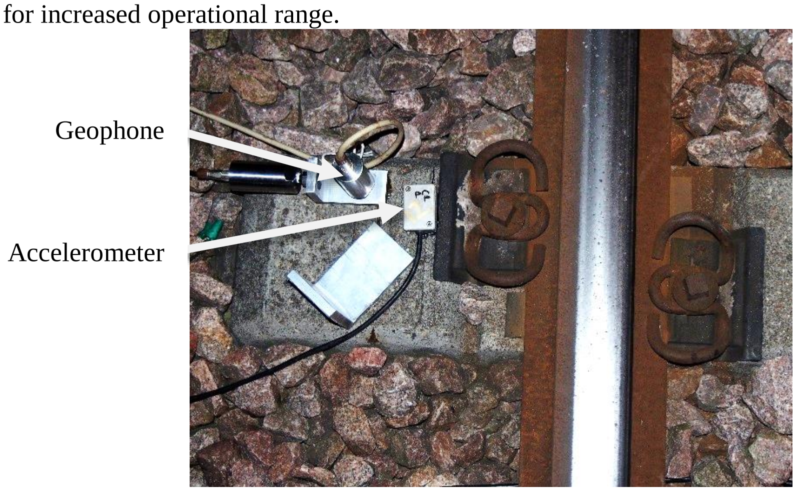

Figure 3 Photograph of instrumentation deployed on track

Measurements of sleeper acceleration and velocity were sampled at 500 Hz over a period of20 s for a number of train passages over a 12 hour period. Data were obtained and processed to obtain deflection. High and low-pass Butterworth filters with cut-offs of 2 and 24 Hz were chosen based on the measured linear range of the MEMS accelerometer. The deflections obtained and the calibrated frequency content for an example train passage are shown in Fig 4. The deflections agree broadly, each sensor showing a range of about 0.3 mm. The location of the peaks in the frequency spectra agree, but the spectral peaks in the accelerometer data are marginally lower at higher frequency. The spectrum for the accelerometer is noisier, particularly around 10 Hz.

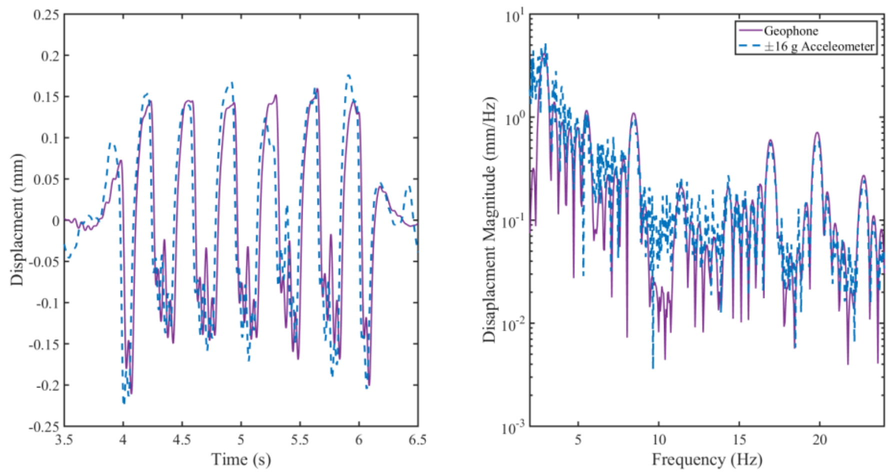

Figure 4 Data for a six vehicle train at 60 m/s from a Geophone and a ±16 g accelerometer mounted on the same sleeper processed to obtain a) displacement for a passband 2-24 Hz. b) Fourier transform of displacement.

Altogether 24 six-vehicle trains were recorded during field trials. To compare results, the mean peak-trough value of displacement for the four intermediate vehicles was calculated for each train from data from both sensors, using a peak finding algorithm. This gives an average 'characteristic displacement' (Fig. 5). Generally the results from the transducers were in reasonably close agreement. The mean characteristic displacement was 0.27 mm and 0.28 mm from the geophone and accelerometer measurements respectively. The geophone results showed less variation, with a standard deviation of 0.014 compared to 0.036 for the accelerometer data. The relative standard deviation were 11 and 5 % for the accelerometer and geophone data respectively for the single day.

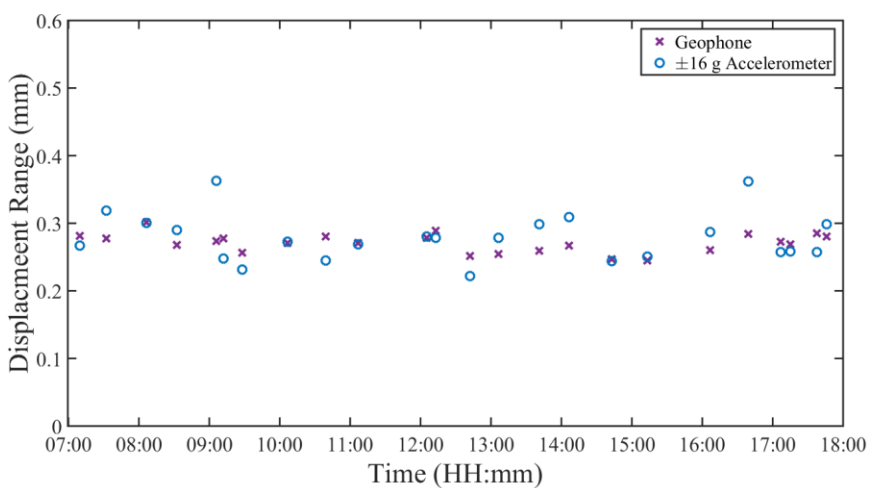

Figure 5 Characteristic displacements obtained for 24 pass by events using geophone and accelerometer measurements

5 Continuous Approaches

Agreement between the geophone and accelerometer data was better under laboratory conditions. Nevertheless, the data from field trials is promising. The results demonstrate that MEMS accelerometers are capable of providing data of sufficient quality to obtain displacements from trackside measurements that are comparable with existing methods. The low cost, robustness and increasing confidence in the quality of the data that these devices produce mean that long term deployments are achievable. To show their potential MEMS accelerometers were installed on track and logged for a period of several months Fig. 6 shows by way of example the ‘characteristic displacements’ obtained for every train passage during a month and a half of continuous monitoring at two locations, one where sleeper displacements were not changing and one where they were increasing. These are for the same six vehicle train type and were obtained using a ±16 g MEMS accelerometer. Displacements were obtained using a double filter-integration scheme with 2 and 24 Hz the high and low-pass filter cut-offs. The average range of displacement was interpreted automatically using a peak finding algorithm. The spread of results is likely due to variations in speed and load. The daily relative standard deviation varied between 11 and 6 % at both locations for the acceleration data in Fig. 6, similar to those found in Fig 5.

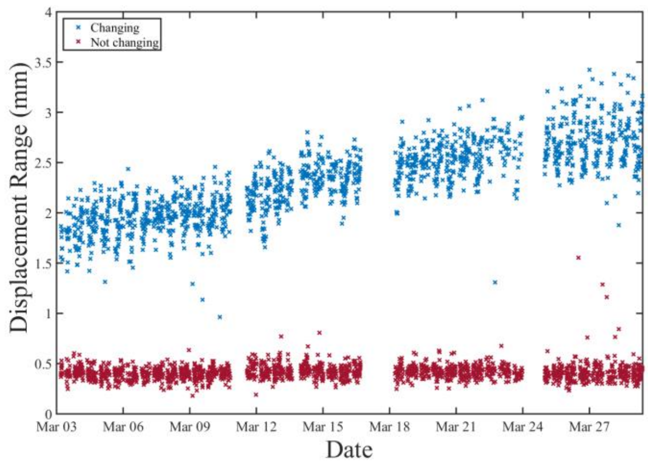

Figure 6 Displacement range obtained from displacement time history for each measured train passage during a six week period for the same train type where typical sleeper displacements were changing and not changing

These results demonstrate the potential for using continuous monitoring to capture and interpret the performance of the track using data for a large number of train passages. Changes in track performance over time are evident and can be quantified. The range of displacement, used in the study, is one of a variety of different statistics that could be adopted to describe each train passage. Identifying the most suitable is a further challenge.

Although the variation of the data obtained using MEMS devices are more significant than with existing trackside monitoring techniques, the reduced cost and longevity means that long term pervasive deployments are more achievable. In that situation the potential size of the datasets based on MEMS instrumentation would help overcome the limitations of the technology. Obtaining many records means trends will be clear within the data and ensemble averages are meaningful. Meaning that smarter, more data rich approaches to managing and maintaining infrastructure are possible. This is likely to be especially useful at known problem zones such as transitions or crossing which account for a disproportionate amount of maintenance costs.

6 Conclusion

The results of this study have shown that displacements obtained from low cost MEMS accelerometer measurements are consistent with those obtained from geophone data, in both laboratory and field trials. The measurements generally agree in terms of frequency and amplitude although the MEMS accelerometers were noisier. Despite this the data from the MEMS were found to be of sufficient quality to obtain displacements that clearly and quantifiably show trends in track behaviour. The lower cost and greater robustness of MEMS has enabled long term deployments for trackside monitoring. This kind of approach could form the basis of a track health monitoring system, where the data from continuous monitoring with MEMS accelerometers can be used to quantify changing performance of the track, especially at known problem zones.

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