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Detecting Railway Under-Track Voids using Multi-Train In-Service Vehicle Accelerometer

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Abstract

The Siemens track monitoring system is being developed in collaboration with Rail Safety and Standards Board (RSSB) and the Institute of Railway Research at the University of Huddersfield.

It makes use of the existing on-board GSM-R cab radio present in every train in the UK, through the fitment of a sensor card, which detects track condition over three axes of train vibrations. By using advanced on-train signal processing, the system only requires a small amount of data to be transferred to the Ground System. For voided switches and crossings (S&C), the GPS location allows the S&C asset number to be identified and reported. This ensures maintenance staff are accurately directed to the location of voids, minimising time spent inspecting and maintaining track and improving safety.

The Ground System monitors the voids detected by multiple trains, to increase the reported accuracy (within 5m) of voids and to reduce false alarms. Automated void reporting, including whether the voids are located at S&C or other track types (such as plain-line track or bridges), allows maintenance to be directed and planned. The Ground System provides advanced warning of track defects, allowing more effective and prioritised preventative maintenance.

The real benefit of the Siemens system is that, by way of a simple activation, it can be present on every train within the UK. The system would therefore be monitoring the track on a large number of train journeys, providing a network-wide track monitoring system.

Recent on-train trials have shown that the small low-cost sensor is able to detect voided sleepers underneath both S&C and bridges. The repeatability between trains and for different journeys was found to be excellent.

The Network Rail upgrades to the Siemens cab radio, planned for the next 2-3 years include a GSM-R/GPS antenna, and the addition of a GPS module to the cab radio, providing a GPS connection in every train. As part of these upgrades Siemens will introduce a sensor card into the cab radio, minimising installation costs, making it hardware ready for track monitoring system. The only action needed for activation will be the upload of the software application to the cab radio.

The Siemens track monitoring system allows the network operator to make significant reductions in maintenance and delay costs, line closures, journey re-planning and speed restrictions, by having a reliable monitoring system that is non-intrusive yet gives analysis for the entire rail network, improving train safety, network reliability and passenger comfort.

1 Introduction

1.1 The Problem

In practice, the support conditions of a track system can change significantly for a number of reasons including: contaminated ballast, drainage problems (wet beds) or voids between the sleeper and ballast layer. Voids located underneath railway tracks are more of a concern when they are located underneath S&C and track that runs over bridges [1].

Due to the mechanical aspects and frequency response characteristics of the S&C track system, voids underneath them tend to have a feedback effect. A voided sleeper is not able to support the vehicle axle load and does not transfer any force to the ballast layer. Instead, the force is distributed on the adjacent sleepers around the void which causes the void to grow in size, potentially resulting in greater track movement [2]. Eventually, if unattended, such track movement causes wear and damage to the S&C which then requires repairing to allow continued operation. This maintenance has several high cost factors, including the need to potentially close the line.

Historically, in some locations where the track runs over a bridge structure, the change in track support conditions between the ballasted track and bridge can result in the development of large voids. Similarly on plain-line track, poor drainage can result in the generation of wet beds which can develop into voids if left unattended.

At all these locations increased deflection of the rail can increase the risk of rail breaks, and therefore becomes a safety concern, along with resulting in poor vehicle ride performance (e.g. passenger comfort).

1.2 The Solution

The Siemens track monitoring system is able to identify voids underneath track from the acceleration response measured in the vehicle cab, and also identify the type of track asset (e.g. S&C, structure or plain-line track) that the void is located under.

Installation of a sensor card into multiple trains provides both monitoring of the entire rail network, including small branch lines, as well as the assessment of each track-section by multiple trains.

With sufficient train installations, given the multiple journeys, by multiple trains, an automated assessment of the entire rail network could be provided within one day.

Analysis of a track section at the Ground System takes advantage of the multiple assessments that have occurred by multiple different trains. This allows the removal of false alarms, and improves the estimates of location accuracy and void sizing.

As well as reporting voids, the Ground System will also report very large vertical or lateral movements at plain track, when reported multiple times from trains.

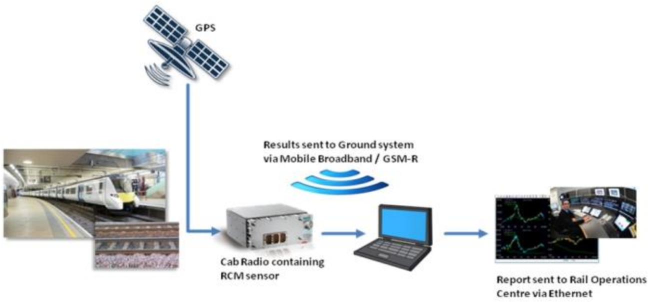

Figure 1 Siemens track monitoring system cab mobile sends void details to Ground System

2 Signal Processing & Void Detection

A prototype device was used to acquire data on a number of routes on Network Rail infrastructure. Post-processed lateral, vertical and longitudinal acceleration was analysed to identify the characteristics of the vehicle response to abnormal track features.

The frequency content of the vertical acceleration data can be seen in Figure 2. The frequency bandwidth is segmented into six bands, which corresponds to the multi-resolution analysis presented in Figure 3.

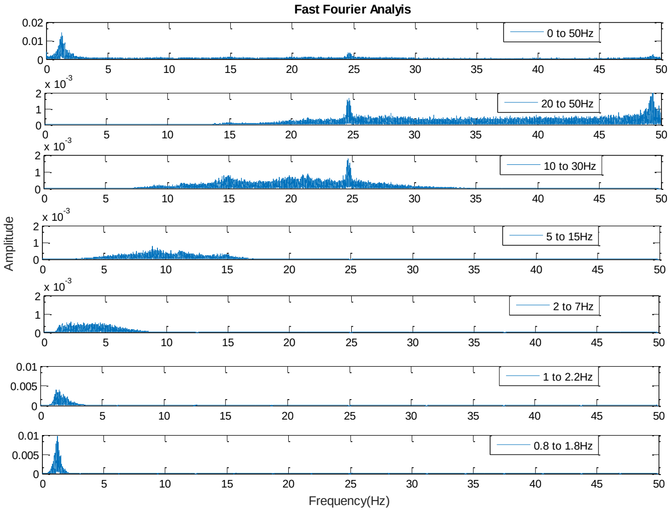

Figure 2 Vertical acceleration frequency analysis

The top subplot in Figure 2 is a Fast Fourier Transform (FFT), where it can be seen that the majority of the energy in the signal resides at the lower end of the frequency range, between 0 to 4Hz as identified on the x-axis. These frequencies correspond to the low frequency vibrations of the car body, such as those generated by irregularities in the track. The top subplot in Figure 3 shows the corresponding raw vertical acceleration data. In Figure 3 the acceleration signal is further decomposed into discrete frequency bands in successive subplots, from higher frequencies in the top subplot to low frequencies in the bottom subplot; this analysis used a discrete wavelet transform and a subsequent multi-resolution of the transform. The sub-plots of Figure 2 each show an FFT using the frequency range shown on the sub-plot label. The sub-plots of Figure 3 show the vertical acceleration experienced in the carbody of the vehicle whilst travelling on the test route, with each sub-plot having the same frequency range used in the corresponding sub-plot of Figure 2.

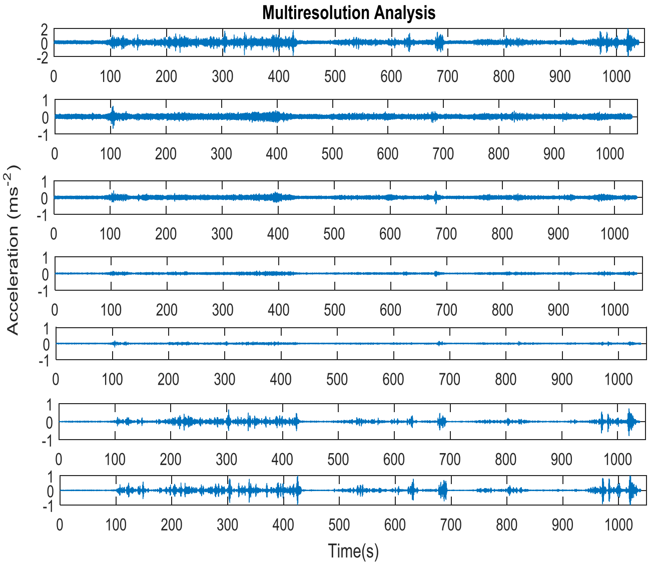

Figure 3 Multi-resolution analysis

The bottom two plots in Figure 3 are very similar in acceleration peak amplitudes of approximately 1m/s^2 which can be seen to have a corresponding frequency range between 0 to 4Hz, as confirmed in Figure 2.

The initial aim of the application of the track monitoring system is to identify features relating to poor support (e.g. voids) and irregularities in the track. Vertical acceleration measured in the vehicle is greatly influenced by the low frequency (up to 4Hz) vibration of the carbody. This vibration has been shown to be good for detecting track irregularities (such as those generated at locations with poor support conditions or voided track). When analysed in a spectrogram, as shown in Figure 4, it can be seen that the majority of the power within the vertical acceleration signal resides within this distinct frequency range.

It is possible that the system could be used to detect other features (such as corrugation and wheel flats which generate a higher frequency response) but additional, more computationally intensive, signal processing is necessary to decompose the signal onto the high and low frequency components as demonstrated in Figures 2 and 3. Similar approaches have been identified in literature [3][4] and such an approach would allow the algorithm to differentiate between a range of potential defect types.

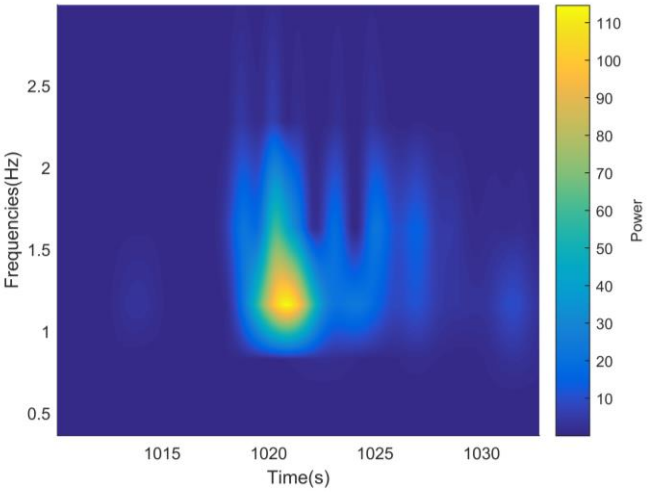

Figure 4 Spectrogram of Vertical Acceleration measured in the carbody

Knowledge of the characteristics of the carbody's vertical acceleration response was used in the design of a detection algorithm and its implementation in the state machine described below.

2.1 State Machine Design

The developed detection algorithm has four states as shown in Figure 5. The 'Idle' state is the base state of operation where the state machine reads in data packets and performs a statistical function using the Root Mean Square (RMS) of the acceleration signal and sets the RMS thresholding dynamically based on machine learning from the multi-train analysis discussed in Section 3 of this paper.

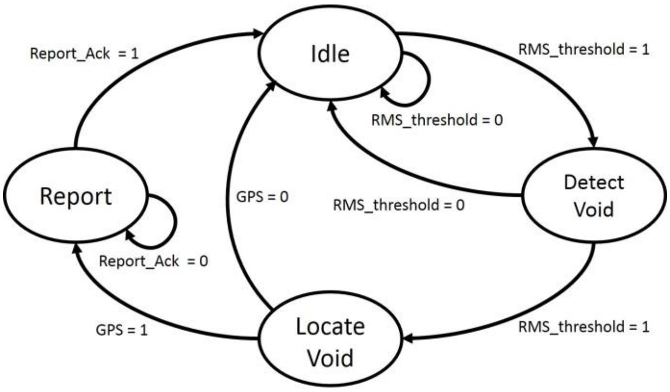

Figure 5 Void detection state machine design

When exceedances in the RMS threshold are detected, as shown in the top plot of Figure 6, the state machine transitions from the 'Idle' state to the detect state. The second plot in Figure 6 shows the algorithm in the detect state using a low-pass filtered output of the acceleration shown as red icons. The third plot in the figure shows refined selection exceedances shown in green that isolates the signature void within the segment of the sampled data set. The green circles show potential voids at this stage of the processing.

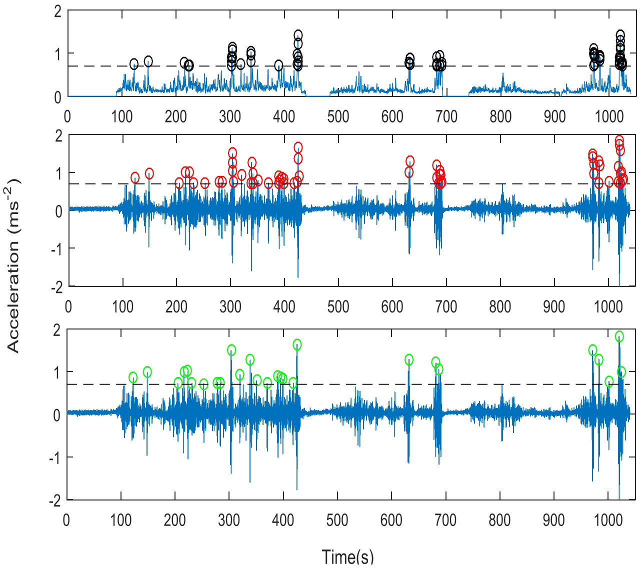

Figure 6 Void detection process

Figure 7 shows a sample of the void categorisation performed in the 'Detect' state, using a void characterisation algorithm. The vertical acceleration response to a voided track is characterised by an exponential decay function. The analysis calculates the ratio of the decay of the vertical acceleration response to the acceleration amplitude in the carbody and characterises the void severity as 'Green', 'Amber' or 'Red'.

The function also keeps track of the features which do not exhibit the natural decay characteristic of the vehicle response to a typical void, and records those instances as category 'Black' for possible further analysis by a Ground System.

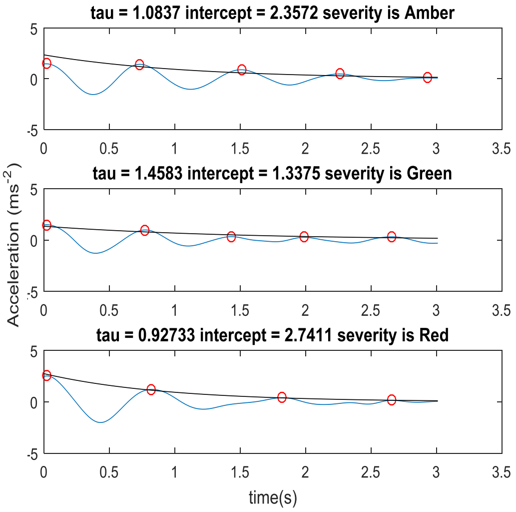

Figure 7 Isolated void signatures for characterisation

2.2 Algorithm Testing

The algorithm has been applied to a sample acceleration dataset obtained during recent testing of a prototype cab radio fitted with sensory capability.

Table 1below shows a log of the recorded exceedances processed in the 'Report' state of the algorithm. The log includes: location (in terms of GPS longitude and latitude coordinates) of the exceedance, severity (e.g. green, amber, red), time it occurred, magnitude of the acceleration, speed at which the vehicle was travelling and the track type at this location (e.g. plain line or S&C).

Void	Latitude	Longitude	time(s)	accel(m/s²)	speed(m/s)	severity	location
1	51.24	-0.583	122.83	0.854	8.385	Green	S&C
2	51.242	-0.584	148.63	0.979	13.848	Green	Plain-line
-	-	-	-	-	-	-	-
18	51.245	-0.666	425.33	1.641	12.289	Red	Plain-line
19	51.246	-0.704	632.12	1.288	11.214	Amber	Plain-line
20	51.249	-0.712	681.75	1.200	13.518	Amber	S&C
21	51.25	-0.713	687.03	1.051	9.671	Green	S&C
22	51.256	-0.738	970.77	1.492	17.356	Amber	Plain-line
23	51.255	-0.74	982.75	1.291	19.573	Amber	Plain-line
24	51.252	-0.744	1001.53	0.771	19.768	Green	Plain-line
25	51.25	-0.748	1020.03	1.823	17.274	Red	Plain-line

Table 1 Tract defect log

The reported exceedances identied in the Table 1 were compared with observations made during the practical testing and maintenance records included in the Network Rail asset management system, Ellipse. This comparison showed that a number of the exceedances coincided with the locations of observed poor ride and reported track features, such as high vertical track irregularities, voids and wet bed sites.

This comparison showed that the algorithm can successfully detect exceedances in the measured vertical acceleration and provides a good indication of the relative severity of these exceedances.

3 Multi-Train Analysis

3.1 Rapid Monitoring of Entire Rail Network

With the on-train system installed in multiple trains, the rail network would be monitored for under-track voids much more frequently than the current dedicated track recording vehicles (TRV) run.

Automated reporting could indicate the location of voided track assets to the Route Control Centre.

The rate of degradation is also monitored.

3.2 Multi-Source Data Analysis – Blending and Agreement

Accelerometer sensor data captured during train trials show some discordance over repeated journeys of a route, across all 3 axes of the sensor. Some discordance also appears in the data from different trains travelling on the same route.

Each track section will typically be used by a train for multiple journeys each day, and also by multiple different trains each day. It might also be used by multiple different train classes each day.

This means that each train journey provides a complete single source of the data for each track-section that it travels over.

Applying multi-source data analysis to the data received from multiple trains, and multiple train classes, with each train travelling multiple journeys on each day gives the opportunity to use "data blending", and find "agreement" within it.

This data "agreement" allows improvements in the confidence of void identification, size, and location, and also prevents false alarms.

3.3 Trains Report Voids at S&C and Bridges

In void detection mode the on-train software only reports suspect voids that correspond to two types of track asset: points/crossings, and under-track bridges.

As well as indicating the size and location of a suspect void, an indication of whether the void is under either points/crossings or an under-track bridge is provided.

A train sends a suspect void report to the Ground System via GSM-R or mobile broadband.

Trains also send an asset traversal report each time they travel over either points/crossings, or under-track bridges, irrespective of whether or not a void is suspected.

3.4 Location Clustering

Train trials of a Siemens “Driver Advisory System” product show that with a roof mounted GPS antenna, the GPS location of the train at various track features when repeated over a route many times appears as a set of location “clusters”.

At the Ground System, suspect void reports sent by trains are clustered together when their locations are within 5 m of each other, and at a similar GPS bearing.

The GPS bearing helps to discern between up and down lines that are very close to each other.

The average location within a location cluster can be used in a report to the central maintenance system.

3.5 Void Identification

At a time considered to be the end of the day in terms of void monitoring, the quantity of reported voids in each location cluster is compared to the number of times that the asset has been travelled over by the train population.

For each location cluster, if the quantity of reported voids in each location cluster is significant in comparison, then the void can be considered as genuine, and reported to the central maintenance system. This approach prevents false alarms.

3.6 Improving Assessment of Void Size and Self Learning

When sending a void report to the central maintenance system, the average of the void sizes at the location cluster is reported.

A confidence rating for the size of a void is given, based on the standard deviation of the sizes at the location cluster.

Also, the trend of the average void size of an asset (interpreted from the acceleration response) is recorded as reported by each train and also by each train class, to identify if different trains and train classes are reporting a location as having a different void size.

This trend data is used in a “self learning” algorithm for on-train parameter calibration.

3.7 Front or Rear Cab Installation

The train trials have shown that voided S&C near a road crossing do not appear clearly in the data, when a bogie of the vehicle in which the sensor is installed is still on the road crossing (or vice-versa).

To allow such locations to be identified when travelling in both directions, a proportion of the train population should have the Siemens track monitoring system enabled in the front vehicle, and another proportion should have it enabled in the rear vehicle. However, a more likely option is to have it enabled in both.

3.8 Data Logging Mode

This mode can be enabled for a few hours, say once every 30 days, for a few selected trains to send an RMS log for a full journey.

This log is used for rough ride analysis at the Ground System, and for on-train parameter calibration.

4 Conclusions

Currently TRVs survey the UK railway network and detect track faults. These vehicles are normally deployed on mainline routes with a high traffic frequency, but other less frequented routes have a reduced inspection cycle due to the limited availability of this resource.

This RSSB funded study has developed a viable solution in Siemens system, to allow an in-service multi-train system to be used, at very low cost atop an existing technology, for the detection of track voids and other track defects.

The detection algorithm was developed using a state machine design methodology and tested on experimental data that shows a good agreement to reported track faults at S&C, bridges and on plain-line locations of the test routes.

The system can provide an alternative low cost record of track defects feeding into existing silo’s that could provide additional coverage of the UK railway network. Increased reliability, lower maintenance costs, reduced delay minutes from line closures, and reduced speed restrictions can be seen as immediate benefits of the system. Furthermore, the multi-train self-learning algorithms can be used to predict with more accuracy the condition of large portions of the network at a high rate and with very low cost.

Acknowledgements

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