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Monitoring of ground and building vibrations caused by train wheel defects

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Abstract. Rail vibrations cause nuisance to people living near rail transport routes. Especially cargo transport is known to cause the highest vibration levels. The Netherlands have an intensively used railway network, forming one of the important cargo transport corridors from the Port of Rotterdam to other countries in Europe. With increasing use of the rail network, both in terms of the number of trains and higher speed of passenger trains, nuisance caused by rail vibrations is expected to increase as well. ProRail, the operator of the rail network in The Netherlands, has lauched the 'Innovatieagenda Bronaanpak Spoortrillingen' (IBS) research programme in order to develop more knowledge about rail vibrations and evaluate the effectiveness of potential mitigating measures. One of the project under this IBS research programme specifically addresses the contribution of train wheel defects to rail vibrations and their effects on nearby buildings. Witteveen+Bos is executing this project, working closely with ProRail and it's scientific partners. A measurement setup was developed optimized for linking ground vibrations to train wheels. This measurement setup has been operated at different locations along the Dutch rail network. Data analysis of the monitoring results has generated interesting insights into the characteristics of ground vibrations caused by train passages and the contribution wheel defects may have.

Keywords: rail vibrations, vibration monitoring, wheel defects, wavelet transform

Introduction

Train induced vibrations are affected by wheel quality and wheel maintenance [1], [5] and can cause nuisance. ProRail, the operator of the Dutch railway network, is investigating on behalf of the Ministry of Infrastructure and Water Management which measures can reduce track vibrations at the source. Various research projects and measurement campaigns together form ProRail's research programme 'Innovatieagenda Bronaanpak Spoortrillingen' (IBS). As part of IBS, a project concerning wheel defect induced vibrations was tendered by ProRail in 2022. Tenderers were challenged to propose a measurement setup and data analysis strategy optimized to evaluate specifically the contribution of train wheel defects to the overall signature of rail induced vibrations and the nuisance cause to people living near

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especially rail routes. Witteveen+Bos was awarded this project by ProRail. The availability of direct train wheel profile measurements executed at specific vehicles of interest allows the project team to compare this information with the ground vibrations signature of corresponding passages. The sensors at different distances from the rail track allow to study how waves caused by wheel defects attenuate with increasing distance from the source. This combined set of information is unique for ProRail and allows for more thorough analyses compared to earlier studies. Past research in this field, among other [1], [2], [3], [5], indicate that for specific vehicle types there is potential to reduce vibration excitation by maintenance. Results indicate that a small percentage of freight wagons give high vibration values and if these freight wagons could be maintained the extreme vibration levels can be reduced. Other studies however do also indicate other parameters to affect rail induced vibrations, like train velocity [4], or track smoothness. The present project aims to develop further knowledge about specifically the contribution of wheel quality and evaluate the potential to reduced nuisance in the context of the present rolling stock on Dutch railways.

1. Measurement setup

In the first phase of the project the measurement setup developed was realized at two locations and evaluated for its possibility to identify train induced vibrations on the individual axle level. An overview of the setup is shown in Figure 1.

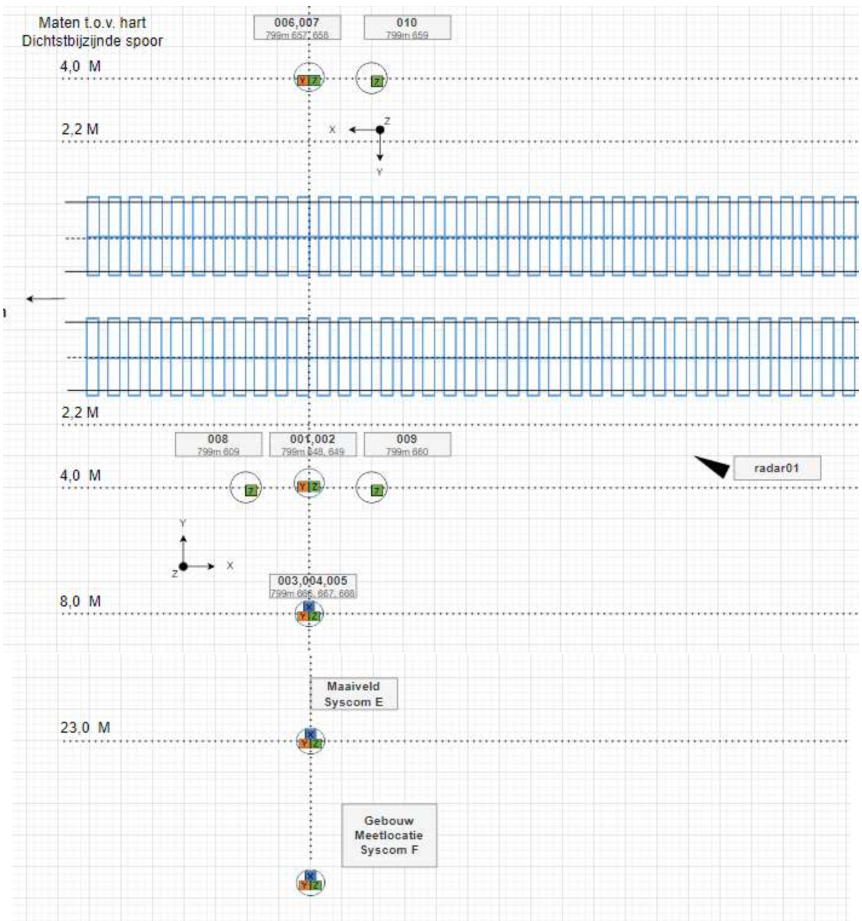

Fig. 1. Schematic of the measurement setup

The setup has sensors in an array at distances 4, 8 and 25 m from the rail. During phase 1 a second array was realized for verification. During phase 2 the setup was optimized to a single array, but a few additional sensors at the opposite site of the double rail track were added to the setup.

The sensors used are Wilcoxon 799M highly sensitive ultra-low noise accelerometers, sampled at 1000 Hz. All the ground vibration sensors are coupled to the same HBM data acquisition system, as is a photoelectric sensor for the axle detection. Coupling of the vibrations sensors and the axle detection to the same data acquisition system allows to have superior time synchronization (< 1 ms) and link vibrations perfectly to individual passing train axles. Sensors are mounted to plates fixed to the subsoil with concrete. In addition to the ground vibration measurements, also sensors in nearby building(s) are part of the overall measurement setup. These sensors are of type Syscom 3000M, and allow to study the transfer of ground vibrations to nearby buildings. The speed and direction of a train is measured by a Sivers IMA radar sensor. Lastly, a camera system is part of the monitoring setup, allowing the identification of the train type for a specific passage. Some pictures of the measurements setup are shown in Figure 2.

Fig. 2. Pictures of the measurements setup

2. Data processing

2.1 Data processing steps

Apart from the data collected by the equipment installed at the measurement location, also other data has become available in this project. The most important being the train data from

Quo Vadis systems provided by ProRail. These datasets contain train-related parameters such as type, length and weight of train and static and dynamic wheel forces. The main objectives of data processing performed in this project are the extraction of relevant features from the data and coupling of ground vibration data to Quo Vadis data from the same trains and eventually direct wheel measurement data for selected vehicles. In addition, other meta data corresponding to the measured vibrations was collected, like ground water levels, meteorological data and track smoothness data provided by ProRail's BBMS.

The process of data combination and analysis is schematized in Figure 3. The first step is the construction of a structured and enriched database from the available data. This includes the extraction of features from the vibration signals (E.g. Vrms, Vmax and octave bands) for the passing axles, bogies, vehicles and trains. Next an iterative analysis process is conducted focussing on different aspects of the data. The main objective of this step is to identify and quantify relations in the data using Random Forest (RF) models [4]. The process is iterative because the results of one analysis may be used as input for the next analysis. Finally, the results are related to nuisance for the environment and local residents.

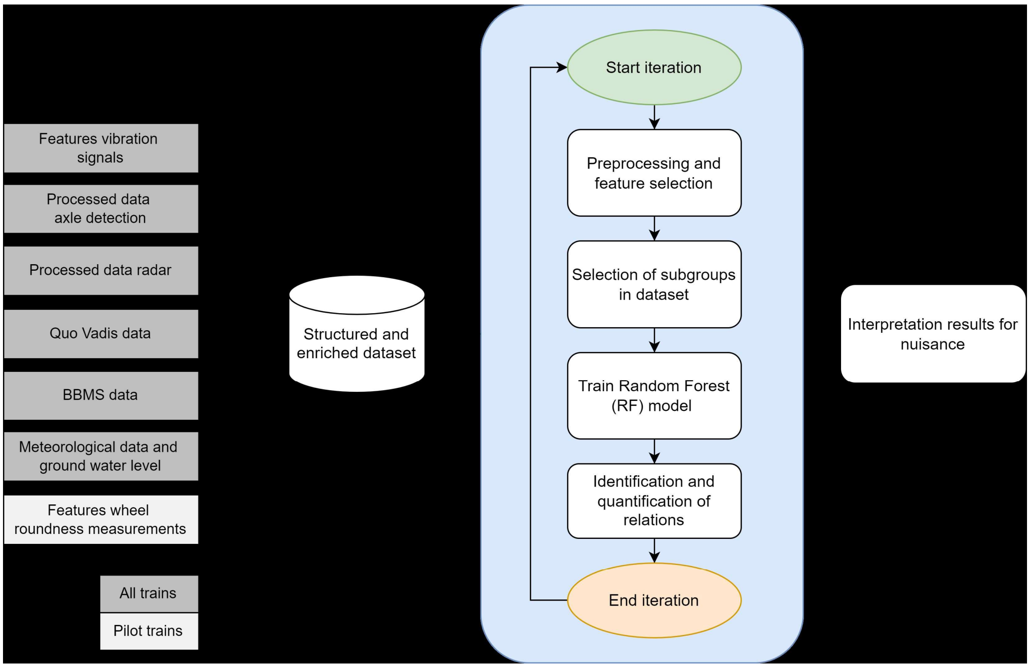

Fig. 3. Flowchart for data combination and analysis

2.2 A glimpse of the processed monitoring data

This paragraph shows a selection of raw and processed monitoring data. An example of the processed data is shown in figure 4. The top axes shows the signal from the axle detection, from which the exact times of axle passages can be extracted. The remaining axes show the vibration signals at 4m, 8m and 25m from the track. At 4m, the pass by of different bogies can easily be distinguished from the signal.

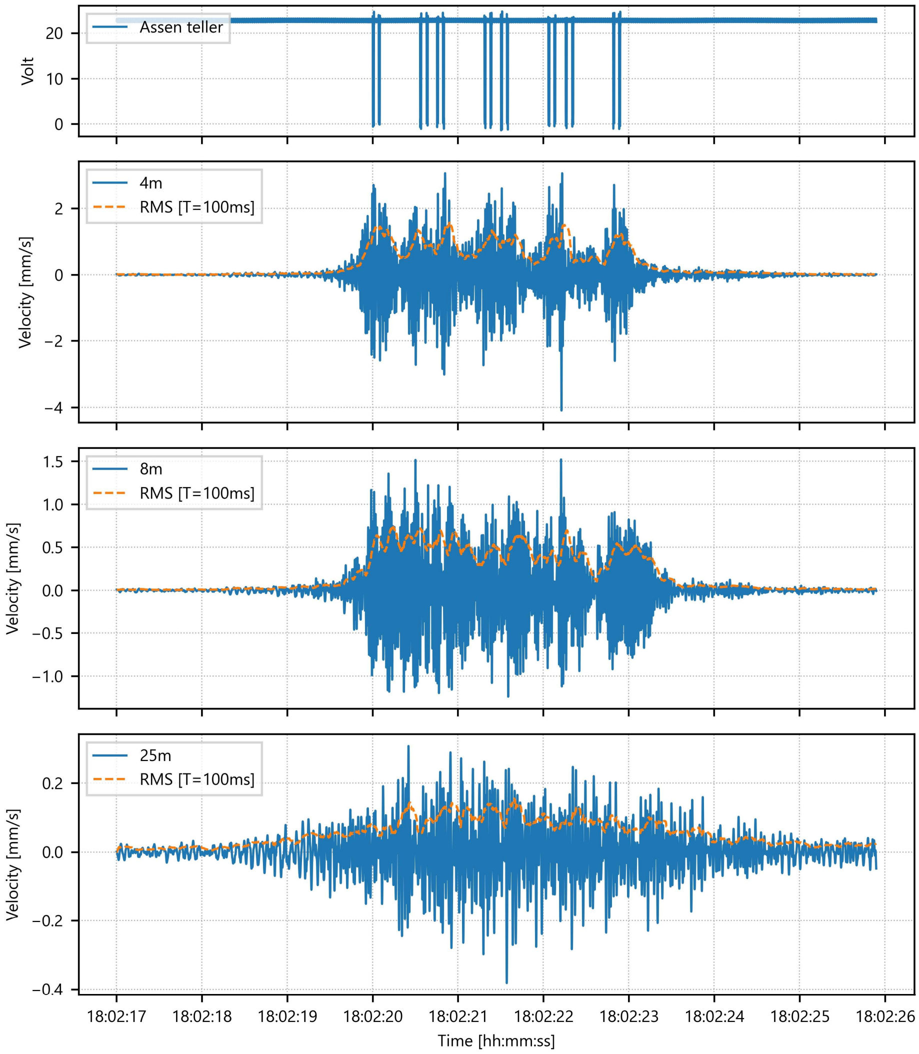

Fig. 4. Example vibration signals at 4m, 8m and 25m from track including the axle detection signal (top) during the passage of a passenger train

The axle-detection signal is used to determine the time intervals for the passing axles. The time intervals for bogies/vehicles/trains are constructed by taking the union of the axle intervals. Vibration features are extracted from the different time intervals allowing the correlation analysis to be performed on various detail levels.

Direct wheel measurements are performed for a selection of vehicles, measuring the radius deviation at every 1 mm of wheel circumference. An example of the measured wheel profiles for eight wheels of a freight vehicle is shown in Figure 5. The vehicle contains different wheel defects ranging from excentric wheels (wheel 5 and 6) to severe wheel flats (wheel 1-4).

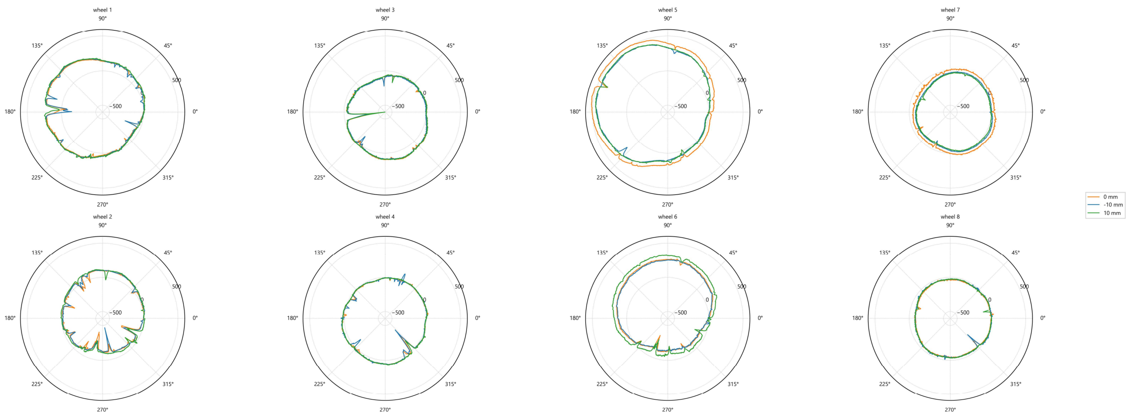

Fig. 5. Polar plots of direct wheel measurements for eight wheels of a freight wagon

Figure 6 shows the average roughness spectrum for measured wheels from different vehicles types (anonymized for privacy reasons), which is a similar representation as reported in e.g. [8], [11] and [12] for different train populations. Wheels of the freight vehicles have typically larger values for wavelengths close to 250 cm corresponding to the circumference of the wheels. These corresponds to low order wheel defects.

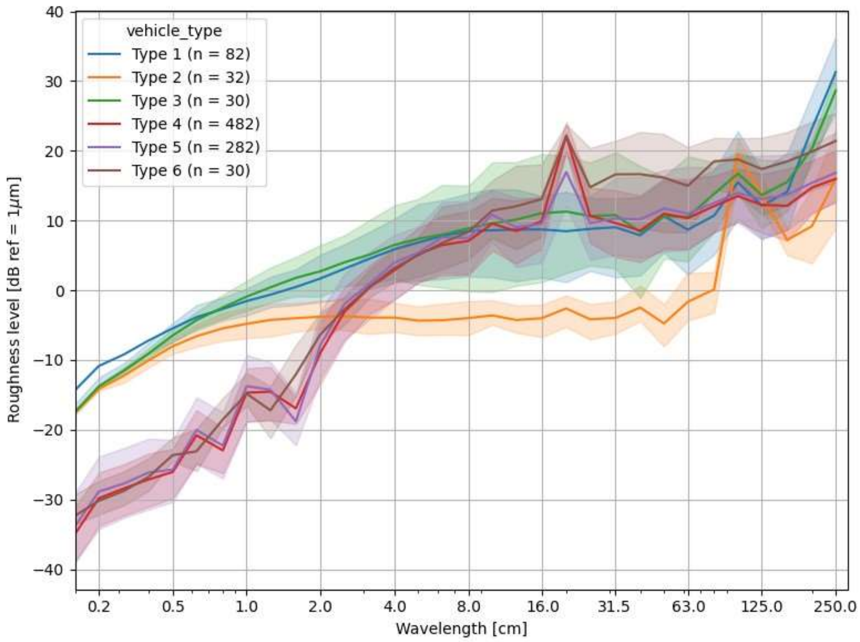

Fig. 6. Roughness spectrum of different vehicle types

3. Data analysis

This chapter shows a brief selection of the data analysis results, revealing interesting insights in the signature of rail induced vibrations and specifically the contribution of train wheel defects. More elaborate results are planned for a separate publication after finalizing the project.

3.1 Scatter in ground vibrations for identical vehicles

Variations of ground vibration levels for various rolling stock types, both locomotives and freight wagons, are analysed and compared. This is illustrated for a various types of locs and for 3 specifically selected freight wagon types causing high vibration levels in Figure 7. It is clear that whereas locomotives in general cause higher vibration levels, the scatter for freight wagons is much larger. Specific freight wagons cause vibrations near the track that exceed significantly the levels generated by locomotives. At larger distances from the track this effect reduces due to higher damping of energy associated with higher frequencies caused by wheel defects. It is noted that, apart from vibrations, these wagons do also produce substantial noise. Nuisance due to increase noise levels also supports studies related to train wheel quality.

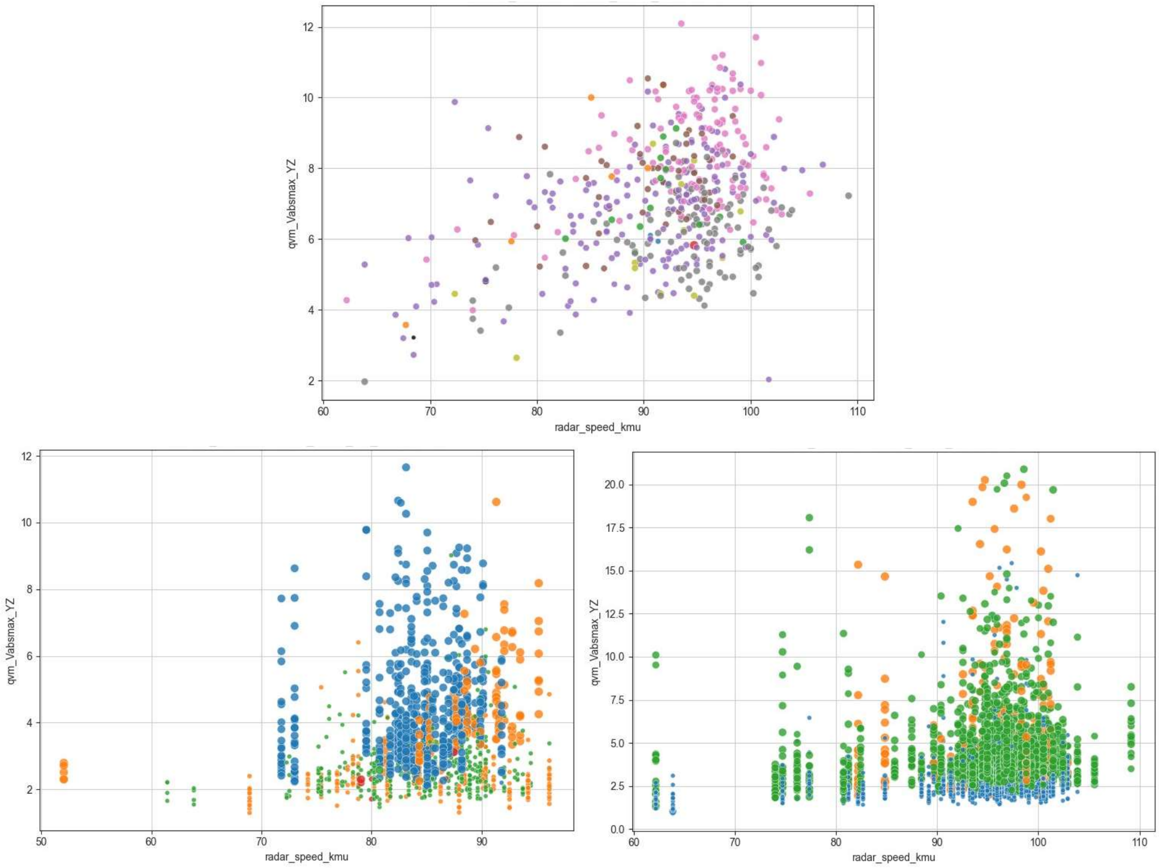

Fig. 7. Scatter of ground vibrations at 4 m from the nearest track for various loc types (top) and for various specific freight wagon types (bottom). Dot sizes indicate vehicle weight where locs are typically all around 75 tonnes and freight wagons range from around 30 unloaded to over 100 tonnes loaded.

3.2 Wavelet transforms as a tool to analyse vibration signals

Identification of the contribution of individual train wheels to the signature of ground vibrations requires time-frequency domain analysis, because of the time-invariant nature of the signals generated by multiple moving vibrations sources. Wavelet transform based analysis procedures were used for this purpose [9]. This allows us to identify the dominant frequency content of vibration signals for relatively short duration time intervals isolated from the full vibrations signal of a train passage [7]. To be able to relate the results of this analysis to wheel out-of-roundness, the frequency bins are converted to pseudo-wavelength bins using the speed of the train. Both frequency and pseudo-wavelength are used for the wavelet transform spectrogram presented in this paper. In the representation used in this paper we show combined the wavelet transform spectrogram, the time domain vibration signal, and the Quo Vadis wheel load measurement results.

3.3 Effects of wheel maintenance for FLIRT passenger train

Figure 8 shows the processed vibration signal for a FLIRT passenger train. Clearly, during the passage of the third axle of this FLIRT train there appears a significant variation in the measured ground vibration levels near the rail track.

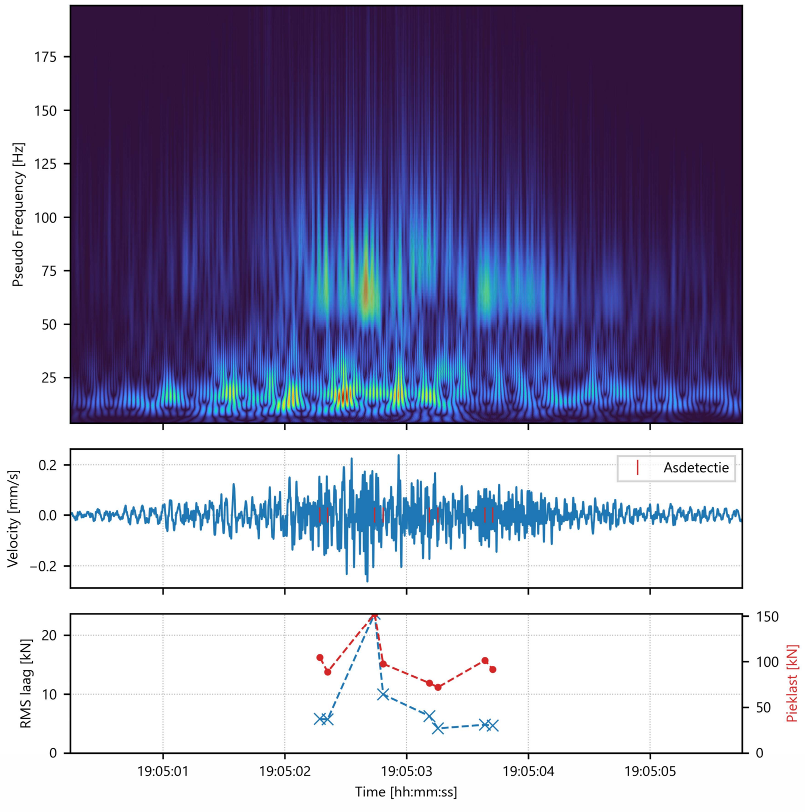

Fig. 8. FLIRT passage ground vibrations measured at 4 m from the track

From direct wheel measurements (Figure 9) the wheel out of roundness was concluded to be of order 5-7, For a train velocity of 35 m/s and wheel circumference of 2.38 m this order relates to an excitation frequency of 75-100 Hz, which can clearly be identified from the processed ground vibration results. Wavelet transform herein allows to generate these insights, which wouldn't be so clearly identifiable from a Fourier transformation of the entire vibration signal.

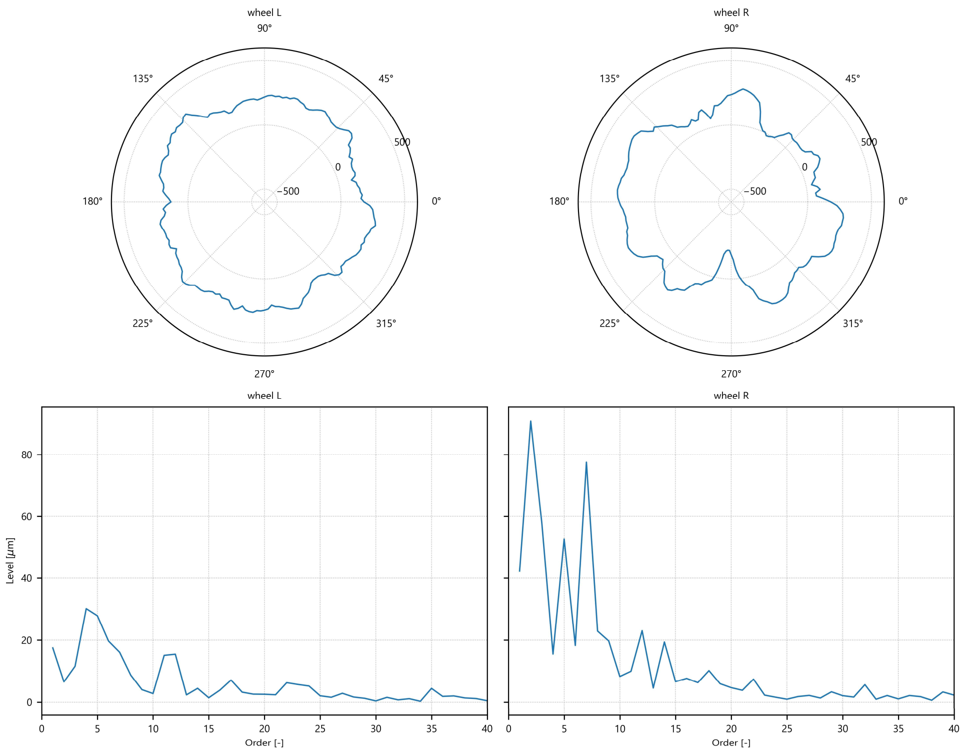

Fig. 9. Wheel profiles (top) and order spectra (bottom) from direct wheel measurements of the third axle of the FLIRT train

3.4 Extreme events with freight wagons causing higher ground vibration levels compared to the locomotive

Figure 10 and 11 show processed ground vibration measurement data for a freight train in our database for 4 and 25 m distance from the track respectively. The event shows highest vibration levels for the sensor near the track at the moment of passage of specific wagons, rather than extreme levels being caused by the locomotive. The dominant frequency is around 30 Hz, which corresponds to a pseudo-wavelength around 100 cm, and implies a 3rd order out of roundness. For the locomotive the dominant frequency falls around 50 to 60 Hz with a corresponding pseudo-wavelength around 50 to 60 cm, which relates to the sleeper distance. These cases are obviously of extreme interest for the present study. Were the 4 m sensor for many occasions show even higher levels of vibration when a specific wagon is passing the sensor, the signature is typically different for the 25 m sensor. For this event however at larger distance from the track the vibration levels associated with locomotive and the specific wagons still are of almost equal level. Apparently stronger attenuation with distance from the source has taken place for the wagon, which can potentially be explained by stronger geometric damping (energy spreading) of the load caused by the individual wheel of interest. It is also interesting to note that the Quo Vadis train load identification system parameters that are associated with frequencies larger than 50 Hz (E.g. ‘RMS laag’) don’t track the low frequency vibrations of the specific wheel of interest.

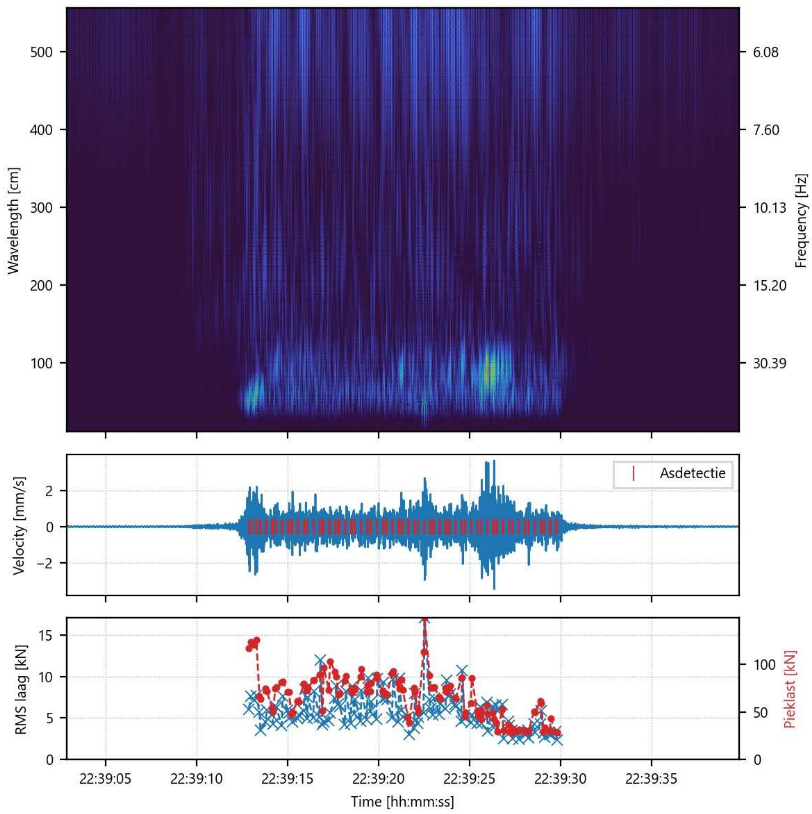

Fig. 10. Freight train passage ground vibrations in vertical direction recorded by the ground surface accelerometer at 4 m from the nearest track

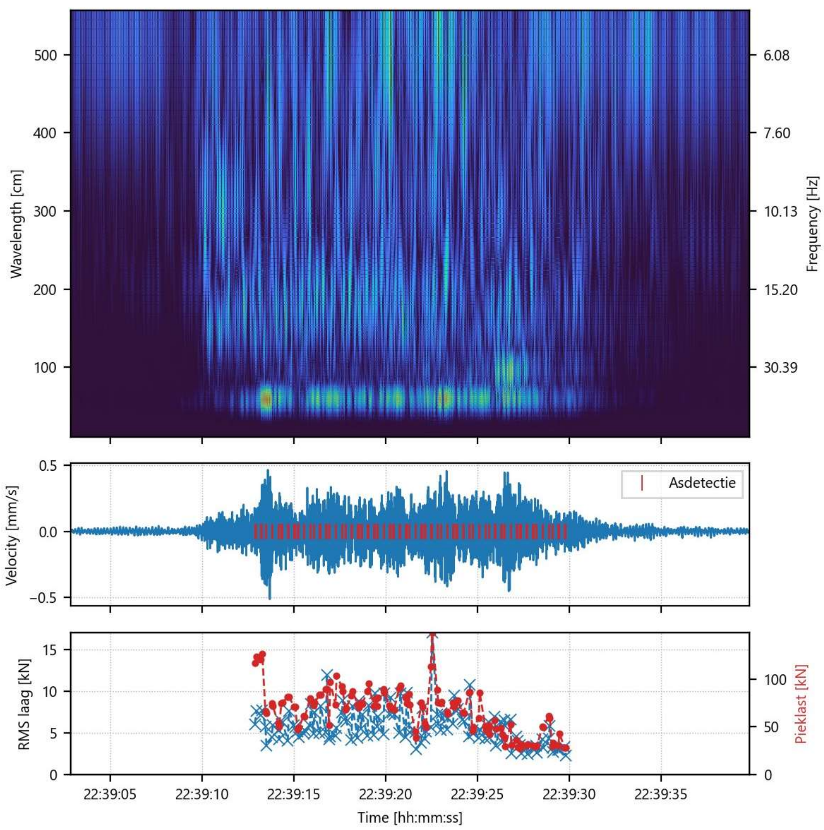

Fig. 11. Freight train passage ground vibrations in vertical direction recorded by the ground surface accelerometer at 25 m from the nearest track

3. Conclusions and discussion

This paper presents the scope, approach and some preliminary results of the present research project on train wheel defect induced vibrations that Witteveen+Bos is performing for ProRail. At this stage the project is ongoing, and no more results can be shared. Future publications are planned to share more results of this study with the research community on rail vibrations. Results so far prove the effectiveness of the developed measurement setup and show how vibration levels vary over passages of apparently similar vehicle types. Vehicle characteristics, among which wheel quality, are therefore concluded to clearly affect generated ground vibrations. Moreover, the results show how wavelet transform can be very well used to generate understanding of the signature of ground vibration signals caused by passing trains. Using wavelet transform analysis ground vibrations could directly be linked to measured wheel out-of-roundness. Whereas a clear link between wheel quality and ground vibrations near the rail has been identified, it is still unclear under which circumstances also at larger distances from the rail ground vibrations are significantly increased due to poor wheel quality. Ongoing analyses aim to further quantify this significance of wheel defect induced increase of vibration levels for overall vibration induced nuisance. Analysis techniques like reported in [6], [7] and [10] are used. Results of these analyses are planned for Q3 2024.

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