Using dark fibres in existing telecommunication cables for characterization vibration levels of railway infrastructure

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Abstract
Railway-induced vibrations in dwellings alongside railway tracks can give rise to complaints. Soft soil conditions in the western part of the Netherlands is influencing this phenomenon and is getting more and more attention. Monitoring vibration levels and good maintenance help to mitigate induced railway vibrations and consequent complaints.
In our project we used existing telecommunication cables parallel to railway tracks (dark fibres) to monitor vibration levels of railway traffic. Vibration measurements were performed before and after maintenance (levelling) by a tamping machine. At the same time vibration measurements were performed using a traditional set up of accelerometers placed in an array perpendicular to the track. Data from both measurement techniques were analysed in the time and in the frequency domain.
The paper will show the influence of maintenance on the vibrations close to the track and will investigate the potential to control railway vibration levels by using the dark fibres in communication system cables.

Keywords: vibrations, fibre optics, field test, maintenance, railways.

1 Introduction

Railway-induced vibrations in dwellings alongside railway tracks can give rise to complaints. In soft soil conditions like e.g. in the Netherlands, this phenomenon is getting more and more attention. Good maintenance can help to mitigate railway induced vibrations and consequent complaints.

Alongside railway networks, there is an existing lineside telecom cable network. Within these telecom cables some optical fibres are not used, the so-called dark fibres, and could be used for measurements. The question arises whether one can use these dark fibres for vibration measurements to gain insight in the need for maintenance at all positions along the track? Application of this method avoids installation of equipment along the track, since the measuring device to collect data from the dark fibre can be installed at nodal locations in the fibre network from where one can measure 5-10 km along the railway line in both directions.

Before answering the main research question, the following three questions must be answered:
- does the maintenance lead to a decrease of vibration levels in the environment
- can this decrease be observed in the embankment
- can this decrease be observed by optical fibres in the lineside telecom cables.

The paper will describe a field test. Vibration measurements were performed using a dark fibre in the lineside telecom cables just before and after maintenance work by a tamping machine. At the same time measurements were performed using two sets of geophones just above the telecom cables together with a set of 24 accelerometers in a field close to the track. This paper will show the results of the measurements and will discuss the influence of maintenance on the vibrations close to the track and the possibility to control vibration levels by using dark fibres in the lineside telecom cable network.

2 Measurements

A measurement site at a railway crossing near Culemborg was selected on the line Den Bosch - Utrecht for the experiment and a measurement set-up was elaborated. The line Den Bosch - Utrecht is a railway line with mixed railway traffic; intercity passenger trains, commuter trains to and from Utrecht and freight trains. This specific site was chosen since train speed is limited due to track conditions and scheduled track maintenance for improving the track geometry of the track section near a railway crossing.

2.1 Lay-out of test setup

Figure 1 shows the plan view and a cross-section of the set up. The existing fibre optic cable is at the west side of the track close to the rim of the track embankment is indicated with a red line. The fibre optic cable is situated at a depth of approximately 0.7 m. The geophones are placed above the fibre optics at surface level. Two types of geophones are used: 4.5 Hz with distance 1 m geophones, indicated with black dotted line numbering HF22 to HF70, and 1 Hz geophones with distance 5-10 m, indicated with blue dots at positions LF00 to LF90. It must be noted that geophones measure vertical vibration velocity. The fibre optics cable measures horizontal strains parallel to the rails.

The accelerometers were installed in a field near the track opposite of the geophones at the east side of the track in two lines perpendicular to the track, 10 m apart. The accelerometers measure in two directions (vertical and perpendicular to the rails) or in three directions (vertical, perpendicular to - and parallel with the rails). The test site was situated well within the area of the maintenance work carried out at the site of the level crossing and the adjacent railway segments.

Vibrations generated during a train pass-by propagate dominantly in outward direction of the track. This means that waves passing the geophones parallel to the track differ physically from waves propagating in outward direction passing the accelerometers perpendicular to the track. For this research, this is not a problem: The research doesn't focus on finding an exact transfer function between the vibrations in the embankment and the vibrations in the environment, but tries to answer whether the vibration level (measured with the fibre optics) in the embankment can be used as an indicator for the change in vibration level in the environment (measured by the accelerometers).

In addition to vibration measurements, train speed and train length of each train pass-by was detected using a pair of light sender and receiver gates installed in a 25 m speed trap at the measurement site. These are indicated in Figure 1 by 'Sluis A' and 'Sluis B'. By analysing the number and the sequence of wheel pass-by's, travelling direction, speed, length and train type could be detected. Additional data could be provided using data from a nearby waysite monitoring unit of ProRail and data from rail traffic management.

2.2 Data collection

The vibrations in the three parts of the set-up were collected in three separate processes. The sample frequencies for the geophones and the accelerometers were 1000 Hz. The Fibre optics were applied with a gauge length of 10 m, with at each meter a measurement position. The sample rate of the Silixa equipment [1] is much higher (order MHz).

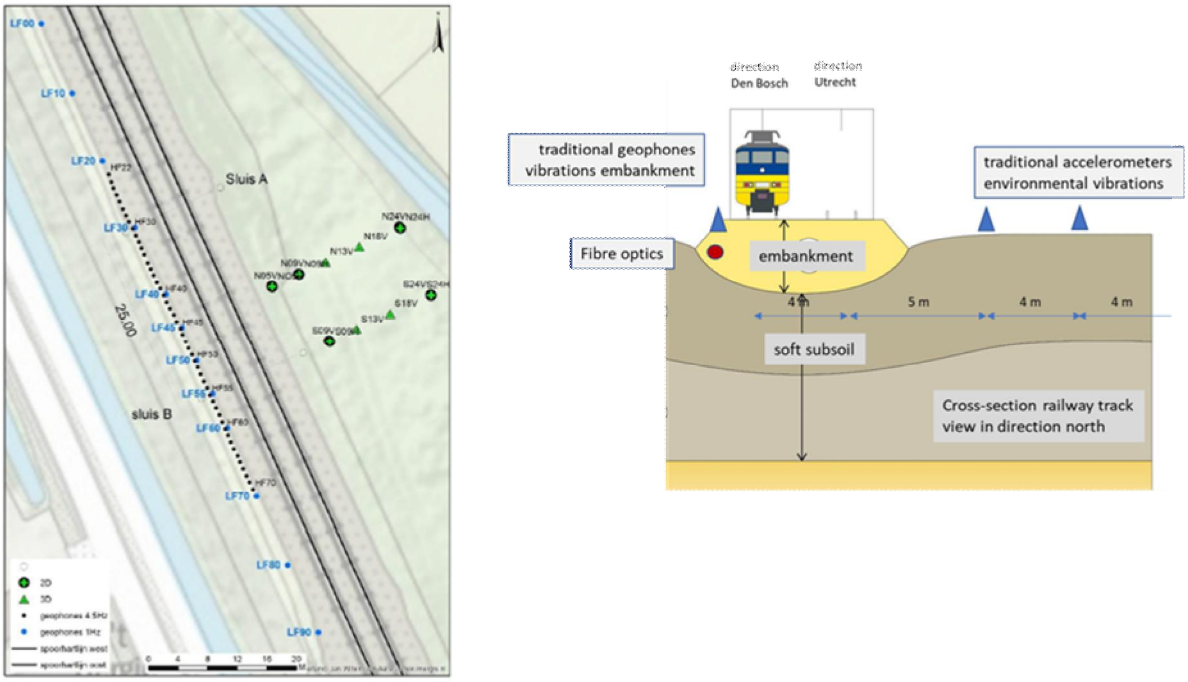

Figure 1 Overview of the measurement site south of Culemborg. Left top view, right cross-section looking in Northbound direction (from Den Bosch to Utrecht)

2.3 Measurements in the field

Due to poor track geometry near the level crossing maintenance work was carried out during night hours between November 10, 2020 and November 11, 2020 to correct the level of the rails by tamping the ballast. The measurements were carried out the day before (9 November 2021 from 14:05 to 20:15) and the day after the maintenance works (11 November 2021 from 10:05 to 19:05) during normal railway operation at daytime. During this period 6 double deck intercity and 4 local trains passed each hour in each direction.

2.4 Data post-processing

The signals of passing trains are selected based on data from a pair of light sender and receiver gates of the optical train detection. From each pass-by a time window of 30 s is taken for each type of equipment (accelerometers and geophones and fibre optic cable). The vibration data was filtered using a band-pass filter [1.0 - 100 Hz]. To evaluate the fibre optic cable data, data from a 90 m cable segment was selected, which shares its position with the position of the LF geophones string situated at the measurement site. To characterize the recorded signals in frequency domain we use power spectral density (PSD) estimation technique [3]. Although the Dutch vibration Guidelines [2] assesses the vibration nuisance on the effective vibration velocity, here the maximum vibration velocity V_{max} is used for judgement.

3 Description of measured trains and train type selection

For further analysis only trains of the same train type were selected from the data set. In addition, train pass-by's of trains travelling in opposite direction and passing each other at the measurement site, were also removed from the data set. For this analysis we selected double decker trains and commuter trains, type sprinter of the Dutch railway company NS for further analysis. In total 90 and 94 train pass-by's of the Double Decker train respectively the Sprinter were selected from the data. At least 45 train pass-by’s for each type, in each direction and each measurement day

Train speed was computed using data from the optical train detection at the measuring site. Figure 2 shows the average speed of the double decker and sprinter train pass-by's in both directions during two days of measurements. In general, the average speed of the trains ranged between 90.5 to 99.0 km/h. The commuter train (sprinters) ran at slower speed compared to the intercity double decker trains, particularly the ones running on 11-11-2020 with average speed slower of 90,5 km/h and 92.5 km/h compared to 96 km/h of the double decker trains. The differences between the speed are small. Therefore, the differences in behaviour of the rail infrastructure before and after the maintenance works can be investigated by dividing the data set into two separate groups of train types and comparing train pass-by's of the same traveling direction and the same train type only.

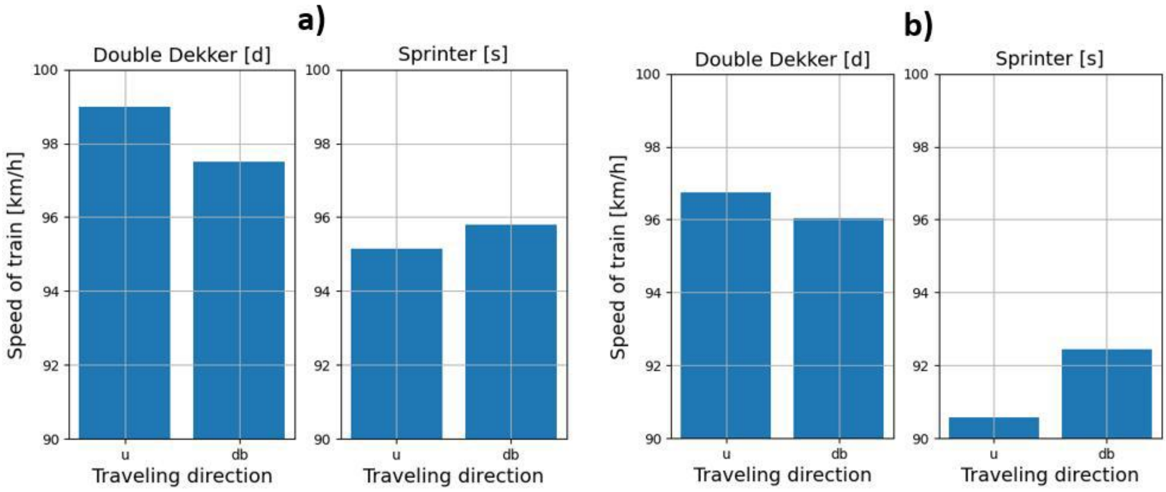

Figure 2 Average train speed during measurements a) at 9 November and b) at 11 November. u means direction Utrecht (Northbound) and db means direction den Bosch (Southbound)

4 Resulting vibrations in the environment

4.1 Comparison PSD and Vmax and train length

Comparison of the influence of the train length on the maximum vibration velocity V_{max} and the average PSD, shows that V_{max} is almost independent of train length, while the PSD in general increases with train length. The maximum velocity V_{max} occurs when the vibrations generated by all axles (accidentally) interfere. We assume that in the case of trains longer than four carriages, the distance between the measuring device and the additional axles of the fifth and other carriages is too high for generating a significant increase of the V_{max} value. This is illustrated in the Figure 3, that presents V_{max} for double decker trains as a function of train length.

Double decker passenger trains are used in a 4 or 6 carriage variant, called VIRM 4 of VIRM 6. In service the VIRM trains can be driven as a single train or as a train composition consisting of two or three elements, each with a VIRM 4 of VIRM 6 variant. Therefore, the train length can vary from 4 to maximum 12 and has an even number of carriages.

The PSD calculates an average value as function of frequency over a prescribed time window which is proportional with the amount of energy in the vibration. The duration of the vibration depends strongly on the train length, and so will the energy in the vibration and the average PSD. Figure 4 shows the PSD as a function of frequency and train length. The value of PSD increases with train length, as expected. In the actual analysis, the influence of train length is not further investigated and only train type is considered as variable, but for further interpretation this seems an important improvement.

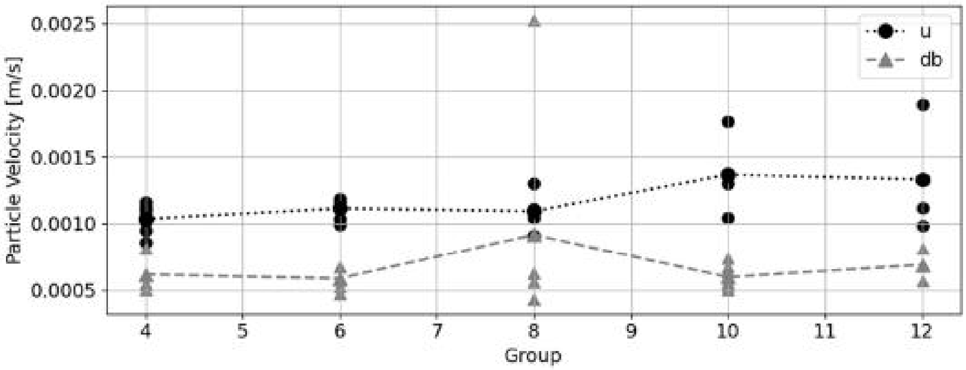

Figure 3 Vibration velocity Vmax of train pass-by's at 5 m (northbound ···●··· u) and 9m (southbound --▲-- db) as a function of train length ((number of carriages per train) for train type VIRM double decker

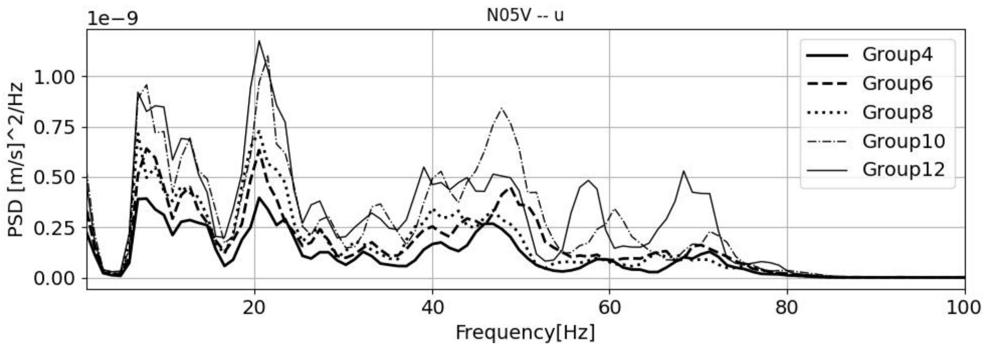

Figure 4 Power spectral density for vertical vibrations in point N05 for passing double decker, influence of train composition (group is number of wagons).

4.2 Maximum velocities of environmental vibrations using accelerometer data

First, the environmental vibrations were analysed using data from the two accelerometer arrays perpendicular to the track, see Figure 1. Figure 5 and Figure 6 show the influence of maintenance on the maximum velocity, as an average of pass-by's of the double decker train (Train type --d--) and the sprinter train (Train type --s--) for horizontal respectively vertical vibrations measured in sensor N09, which is situated 9 m from the eastern track with northbound rail traffic in the direction of Utrecht (u left side bars), and 13 m from the western track with southbound traffic in the direction of Den Bosch (db right side bars). The difference in distance between the source and the transducers fully explains the lower values observed in the transducers for the direction Den Bosch (western track). The red colour refers to vibration levels before maintenance, the blue colour refers to vibration levels after maintenance.

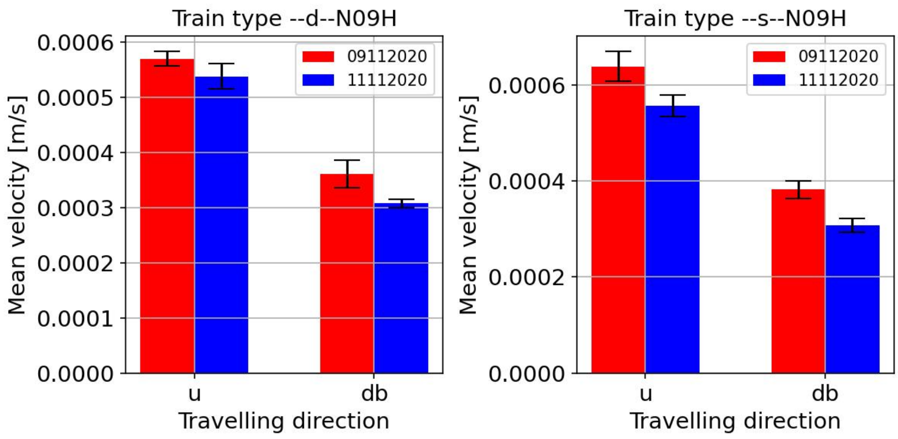

Figure 5 Comparison of maximum velocity for horizontal vibrations over all train pass-by's before (red) and after (blue) maintenance works at signal N09H. See text for more information.

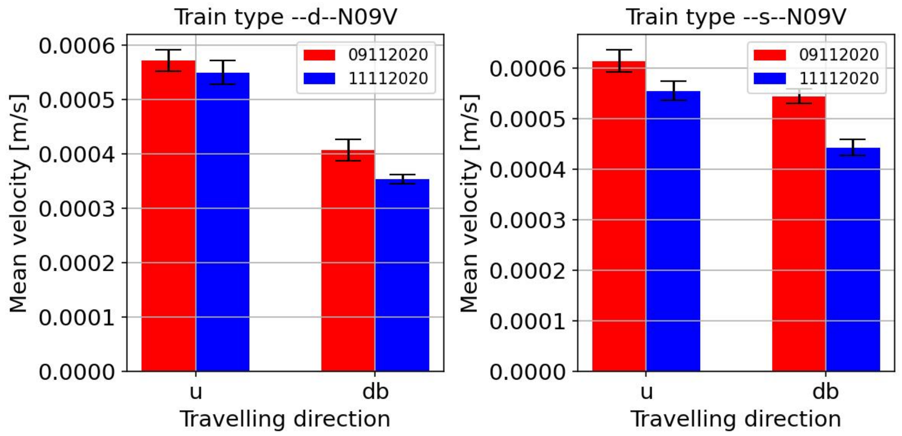

Figure 6 Comparison of maximum velocity for vertical vibrations over all train pass-by's before (red) and after (blue) maintenance works at signal N09V. See text for more information.

To determine the influence of maintenance one must analyse vibration levels in the two traveling directions separately, since the distance of the transducers to the two tracks are different, and for identical train types. The answer is given in a statistical way using a single sided test. We test the hypothesis H0: Vmax reduces after the maintenance, against the alternative hypothesis H1: Vmax doesn’t decrease We used the Student-t distribution for this test.

Figure 7 shows the result of the statistical test as a function of distance to the source. In general, a hypothesis is considered to be true if the p-value is below 0.05 (5%), meaning that the probability that the hypothesis is true is a result by accident is less than 5%.

It is concluded that maintenance at this location led to a decrease of vibration level for the sprinter train. For the double-decker trains in direction Utrecht the hypothesis must be rejected, and for the double-decker trains in direction Den Bosch is must be accepted. The results lead to a smaller calculated P-value with increasing distance. This suggests that maintenance has more effect at further distances. The difference in train type and track suggests that it might be needed to concentrate on specific frequencies for the vibrations at the embankment, e.g. wavelengths that propagate to the higher distances. The derived PSD curves might be needed for this study.

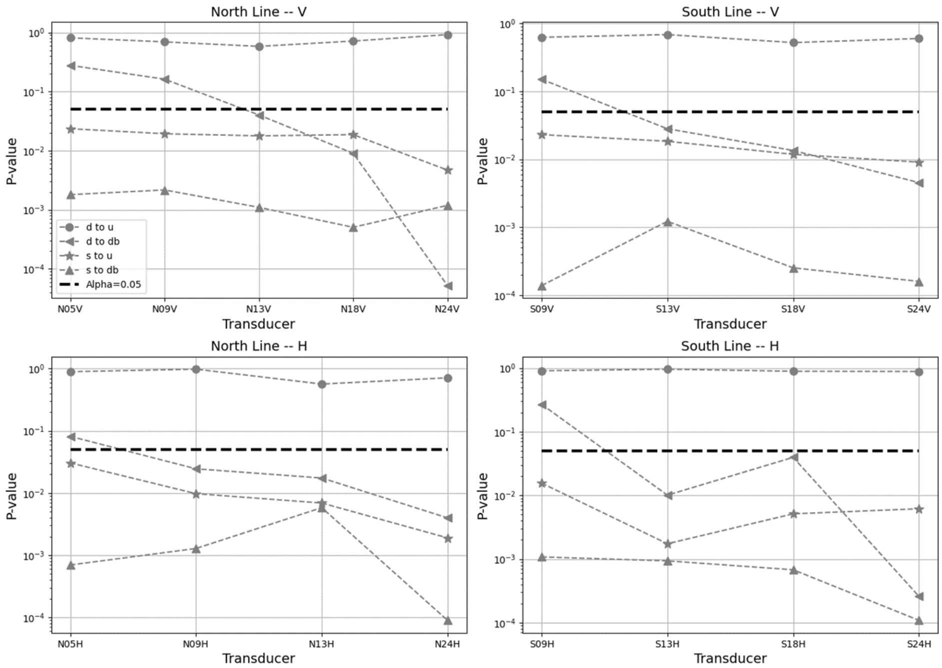

Figure 7 Critical values for hypothesis (H0 versus H1) on distance from the eastern track. Top the vertical vibrations, bottom the horizontal vibrations; left the north line, right the south line.

5 Comparison measured signals of geophones and fibre optics

First, we compare the measured signals in the embankment by the geophones and fibre optics. The comparison with the measured results in the accelerometers and the answer on the research question will be discussed in Section 6.

Figure 8 shows the results for all equipment in the embankment at 45 m. The scales might be different, since we were primarily interested in the influence of maintenance and using identical instrumentation before and after maintenance, scaling factors are not yet essential.

Three important differences are visible

- In the low frequency range, a strong response at 2 Hz is visible in signals from southbound railway traffic in the direction of Den Bosch. This is caused by the close pass-by of train bogies to the devices at about 2 m distance. The distance between device and track for northbound railway traffic in the direction of Utrecht is 5 to 6 m. There is no response visible at 2 Hz in these results . Passing train bogies cause a quasi-static deflection of the track, which is very local in space and thus not observed in the results of railway traffic in the direction of Utrecht. It is also not observed in the results of the HF geophones. This aspect dominates the average PSD value and is therefore removed from the fibre optic results with help of a 4.5 Hz high pass filter.

- The geophones show a clear peak at 45 Hz. This seems to be the frequency which is generated by the axle passing over the sleeper distance: 0.6 m with 100 km/h is 46 Hz. This frequency is visible in both geophone results, but not visible in fibre optics results.
- The fibre optics shows a relatively strong peak at 18-20 Hz, which is not visible in the geophone results, while the vibrations between 20 and 30 Hz in the geophones are not visible in the fibre optic results. These frequencies seem too high for the set-up that we used for the fibre optics.

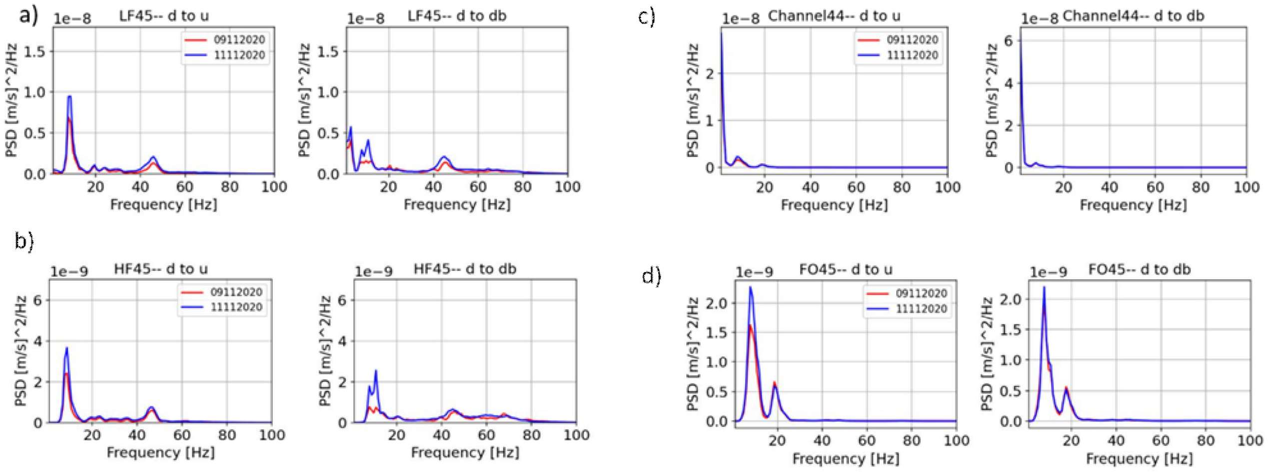

Figure 8 PSD from measurements at position 45 m on embankment. a) 1 Hz geophone, b) 4.5 Hz geophone, c) fibre optics filtered at 1 Hz (low cut) and d) fibre optics filtered at 4.5 Hz (low cut). It refers to double deckers, in both directions (to u is to Utrecht (northbound) and to db is to Den Bosch (southbound)).

We think that the tamping maintenance has the most important influence on the frequencies below 46 Hz, since the most important part of the operation is the repositioning of the sleeper in the ballast. Due to the stiffness of the rails, this leads to changes in track level with a wavelength longer then the sleeper distance. These results suggest that the set-up of the fibre optics must be adjusted to make sure that it captures the frequency range to 50 Hz accurately.

6 The influence of maintenance on vibrations in embankment and the environment

Figure 9 shows some results along the northern line. Per figure a), b) and c) the top row holds for double decker trains and the bottom row for sprinter trains. The left column shows the PSD for northbound trains, the middle row for southbound trains and the right column the averaged value of PSD over all trains. While calculating this average value no distinction in train length is made, due to the very limited number of trains per group.

For the sprinter the maintenance generally leads to a decrease of the vibrations, both in the embankment and the environment. For the double decker this result is not very clear, often an increase is observed after maintenance.

a general comparison of the change of PSD levels in the signals of the individual HF and LF geophones and fibre optic sensors (numbered LF40/HF40 to LF60/HF60 in figure 1) at the position opposite of the accelerometers This doesn’t produce a uniform picture of changes. The double deckers to Utrecht always give an increase of the vibration level, independent of the device (LF or HF geophone or optic fibre sensor).

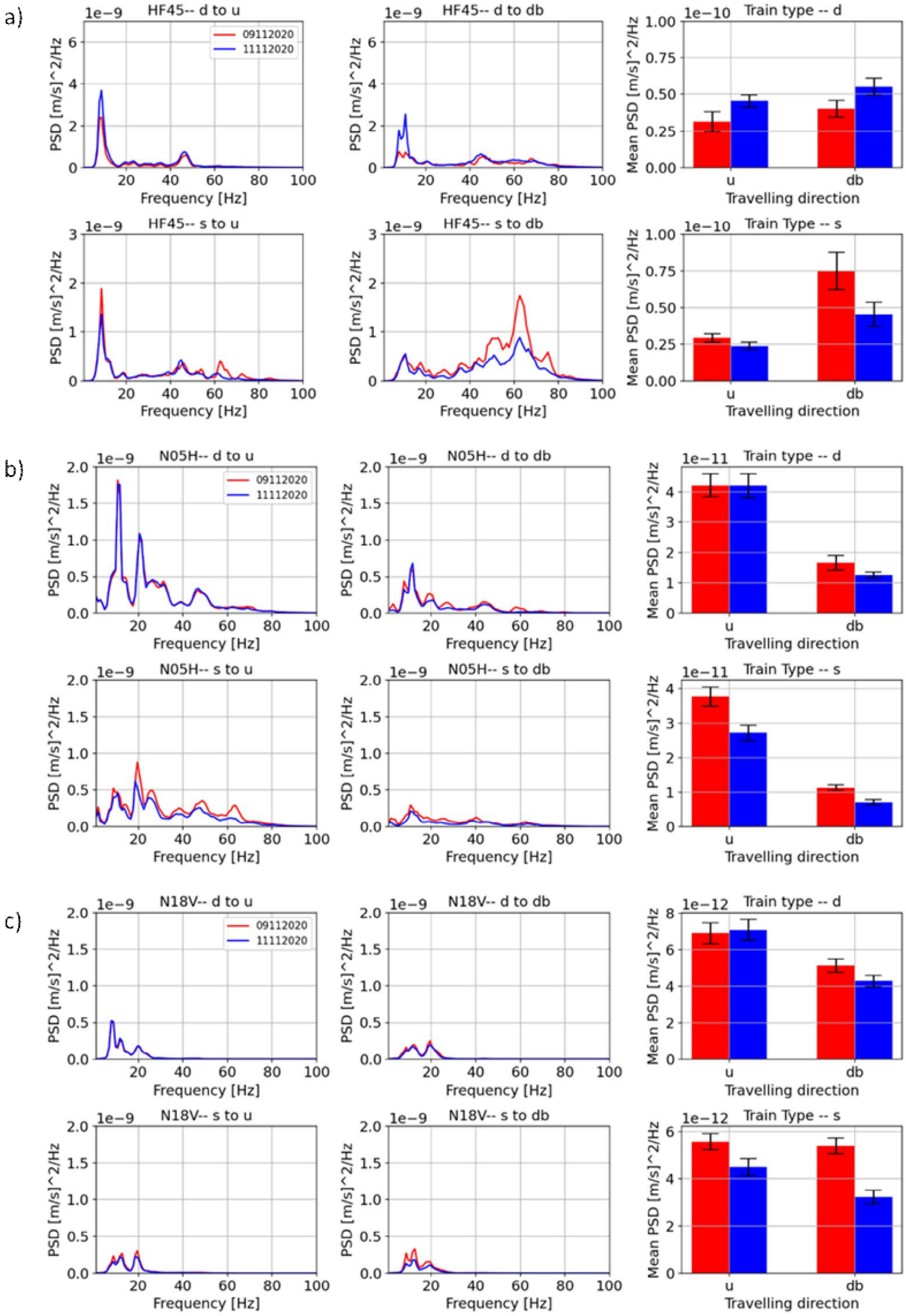

Figure 9 Comparison of the results in a) HF geophone in embankment, b) vertical vibration at 5 m from eastern track (9 m from western track) and c) vertical vibration at 18 m from eastern track (23 m from western track)

The sprinters to den Bosch always give a decrease of the vibration level, almost independent of the device (all but one exception). The other two combinations Sprinter to Utrecht, Double Decker to den Bosch) often show one device with a different direction of the change. This suggest a high variability of the results.

Table 1 Direction of change of PSD of vibration velocity due to maintenance (**+** is increase after maintenance, **-** is decrease after maintenance)

		double decker			sprinter		
position	direction	LF	HF	FO	LF	HF	FO
40	to Utrecht	+	+	+	+	+	-
	to den Bosch	-	-	-	-	-	-
45	to Utrecht	+	+	+	+	+	+
	to den Bosch	+	-	+	-	-	-
50	to Utrecht	+	+	+	+	+	-
	to den Bosch	+	-	-	+	-	-
55	to Utrecht	+	+	+	+	-	+
	to den Bosch	+	+	-	-	-	-
60	to Utrecht	+	+	+	+	+	+
	to den Bosch	-	-	+	-	-	-

It is important to realize that the fibre optics measure horizontal strains, while the geophones measure vertical velocities. Hence there is no necessity to assume that the maintenance generates the same change in these two measured properties (vertical velocity and horizontal strain).

7 Conclusions

The main result of this study:

- environment vibrations are reduced by maintenance, especially further from the track
- vibrations measured in the embankment with geophones reduces slightly after maintenance (i.e. vertical vibrations)
- no reduction could be found in the measured vibrations in the embankment with fibre optics after maintenance (i.e. horizontal vibrations)

The experiment could not proof that fibre optics can be used a potential monitor instrument to control environmental vibrations. The results were dependant on train type, distance to the track and track.

For further research it is recommended to measure much more trains during a longer time interval before and after maintenance. For the interpretation train type as well as train length must be considered. The fibre optics must be able to determine frequencies till at least 50 Hz. The interpretation must be taken place in narrower frequency bands.

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