

Analysing technics with optical fibre networks

Assessment of the accuracy of vibration measurements with fibre optics



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Summary

This report presents the results of Task 3.3.3, within European Rail Joint Undertaking (ERJU) In the Horizon Europe program. This task evaluates the possible application of fibre optic (FO) for the control of environmental vibrations caused by pass-bys of trains. Within this task Deltares assessed the accuracy of fibre optic (FO) vibration measurements relative to conventional vibration measurements by accelerometers. The work is based on combined datasets from Holten (2024) and Culemborg (2020), where both FO and accelerometer measurements were collected during train pass-bys.

The findings demonstrate that FO measurements reproduce low-frequency vibrations (≤ 20 – 25 Hz) with good reliability. Characteristic bogie-related frequencies (~ 11 – 15 Hz) are consistently observed in both FO and accelerometer data. Above 25 Hz, FO signals show strong attenuation under the tested gauge lengths, with high-frequency features such as sleeper-passing peaks (~ 50 – 60 Hz) absent from the FO response. It remains to be determined whether alternative interrogator configurations or smaller gauge lengths can recover this higher-frequency content.

The practical implication is that FO and accelerometers are complementary measurement techniques. FO offers dense and continuous spatial coverage of low-frequency vibrations along the railway, while accelerometers provide detailed high-frequency information at discrete locations.

Building on these results, the next phase of the work will focus on machine learning (ML) models to translate FO data into conventional vibration metrics. The first objective will be to predict peak ground velocity (PGV) from FO signals using gradient-boosted decision trees (XGBoost). PGV is a robust descriptor of soil vibration in a continuum medium and provides a practical target for initial model development. Additional information such as train type, speed, soil conditions, and sensor distance will be included as model features.

If successful, this approach will demonstrate the feasibility of extending existing dark fibre networks into a scalable monitoring tool for railway vibration assessment, aligning with the broader ambition of innovative and cost-effective infrastructure monitoring across the European rail network.

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1 Introduction

1.1 Background

This work is part of the Europe's Rail Joint Undertaking (EU-Rail) research programme, the European partnership for rail research and innovation under Horizon Europe. EU-Rail aims to accelerate the uptake of integrated, interoperable, and standardised innovations that strengthen the capacity, sustainability, and competitiveness of the European railway system. Within this framework, ProRail and Deltares collaborate on the development and validation of innovative monitoring techniques for railway-induced vibrations.

One of the work packages in this collaboration is Task 3.3.3: Analysing techniques with optical fibre networks. The motivation behind this task is the presence of unused optical fibres (dark fibres) that run alongside much of the Dutch railway network. Using Distributed Acoustic Sensing (DAS) techniques, these fibres can be transformed into dense seismic arrays capable of detecting vibrations.

There are clear advantages of using fibre optics for vibration measurements, such as: continuous coverage, low measurement costs, high safety due to limited track access, and virtually ubiquitous sensor availability. If sufficiently accurate, such data could improve the understanding of train–track–soil interaction, support infrastructure maintenance, and help mitigate environmental vibration effects on nearby communities. At the same time, several limitations must be acknowledged: DAS measures strain in only one direction (parallel to the fibre), the fibre's distance to the track is fixed but variable along the route, and the achievable accuracy remains uncertain.

Task 3.3.3 is structured around three main subtasks:

- 1 **Accuracy assessment:** What is the accuracy and reliability of vibration measurements by fibre optics, compared to standard (geophones; accelerometers) devices?
- 2 **Data pipeline development:** Develop a pipeline for the collection, transmission, processing and storing of fibre optics data.
- 3 **Machine learning development:** Develop a machine learning algorithm to establish the relation between the railway induced vibration measured by the fibre optics and the railway induced vibration at distance.

1.2 Objective

The present report addresses Activity 5: Accuracy of vibration measurements, which corresponds to the first of these objectives. Specifically, we evaluate how well FO data reproduce accelerometer recordings under real train pass-bys. The assessment is based on case studies at Holten and Culemborg, where both FO and accelerometer measurements were available for direct comparison.

1.3 Report structure

The report follows a traditional scientific structure in which conclusions are built from the ground up. We first present the available data and methods, then discuss the results, and finally draw conclusions. Section 2 provides an overview of the accelerometer and FO datasets. Section 3 describes the case studies and the methods applied to compare the data. Section 4 discusses the accuracy of FO measurements relative to accelerometers. Section 5 reflects on the implications of the findings for the next steps. Section 6 presents the conclusions and recommendations, and the report closes with the lists the references and annexes.

2 Overview of measurements and available data

Several measurement campaigns have been conducted within the scope of Task 3.3.3 at different railway sites in the Netherlands. These campaigns combine conventional vibration monitoring techniques with fibre optic (FO) measurements, providing the datasets required to assess the accuracy of FO relative to accelerometers. Table 2.1 summarises the geographical locations, dates, data types, and formats of the measurements currently available. A more detailed overview of the datasets available is given in (Deltares, 2025).

Table 2-1 Summary of measurements available.

Geographical location	Date	Data type	File format
Culemborg 2020	9/11/2020 to 11/11/2020 21/11/2020 to 23/11/2020	Fibre optics (Silixa)	.tdms
Culemborg 2020	09/11/2020 and 11/11/2020	Env. Vibration accelerometer	.dat .asc
Culemborg 2020	09/11/2020 to 23/11/2020	Geophones	.seg2
Culemborg 2024	20/09/2024 to 23/09/2024 04/11/2024 to 18/11/2024	Fibre Optics (OptaSense)	.h5
Culemborg 2024	12/2024 to 08/2025	Env. Vibration accelerometer	.xmr
Holten	27/08/2024 to 09/09/2024	Fibre Optics (OptaSense)	.h5
Holten	24/05/2024 to 27/09/2024	Env. Vibrations accelerometer	.mat
Hanzelijn	04/07/2022 29/08/2022 to 03/09/2022 18/08/2022 and 20/08/2022	Fibre Optics	.h5
Hanzelijn	04/07/2022 29/08/2022 to 03/09/2022 18/08/2022 and 20/08/2022	Geophones	.seg2
Wierden	20/09/2024 to 23/09/2024	Fibre optics (OptaSense)	.h5

For the purposes of this report, the focus is on Culemborg (2020) and Holten (2024), where both FO, accelerometer and geophone measurements were available and thus suitable for direct comparison. Other datasets, such as those from Hanzelijn (2022), Culemborg (2024), and Wierden (2024), are briefly noted in Section 2.3 but are not analysed in detail here. In the following subsections, each of these sites is described in more detail.

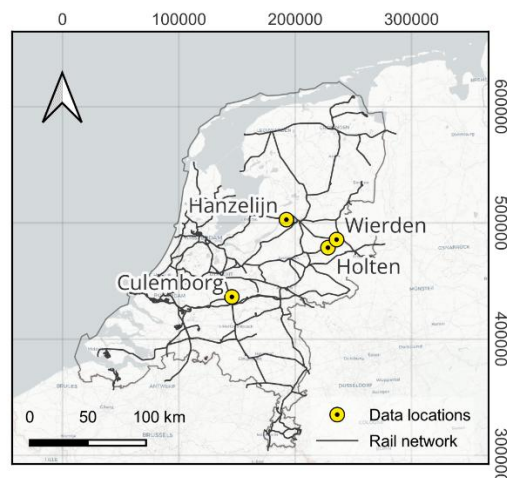


Figure 2-1 Fibre optics measurement locations.

2.1 Culemborg 2020

The first campaign relevant to this study was conducted at Culemborg in November 2020. The site is located at kilometre 21.8 of the Utrecht–Boxtel railway line, near a road crossing. At this location, fibre optic cables run ~4.5 m parallel to the western track, while multiple lines of accelerometers were installed perpendicular to the track on the eastern side. In addition, geophones were deployed on the western side of the track. Figure 2-2 provides an overview of the site layout, including the positions of the accelerometer lines and their correspondence to the fibre optic channel numbering (channel 4285 at km 21.8). This configuration enabled direct comparison between FO and traditional sensors under identical train pass-bys.

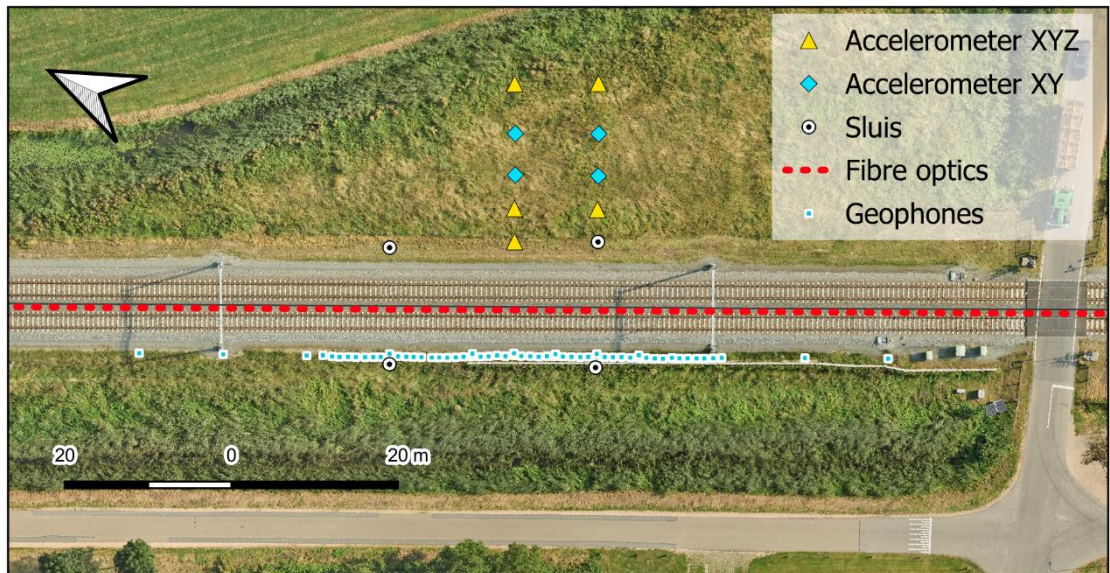


Figure 2-2 Location of the measuring points in the Culemborg database with a detailed view of the detailed measurements with accelerometers at km 21.8, corresponding to the fibre optics channel 4285.

2.1.1 Fibre optics DAS measurements

At Culemborg, fibre optic data were collected during a measurement campaign in November 2020 using a Silixa interrogator. The interrogator recorded 8000 channels with 1 m spacing, corresponding to a fibre located ~4.5 m from the centre of the western track. The measurements were performed with a gauge length of 10 m and a sampling frequency of 1000 Hz. Each file contains 30 seconds of data. The raw optical phase measurements were pre-processed into strain parallel to the track. The pre-processing included mean removal, a zero-phase Butterworth bandpass filter (1–100 Hz), time integration, and conversion to nano-strain.

2.1.2 Accelerometer measurements

Two accelerometer lines were installed perpendicular to the track on the east side (Figure 2-2). Both 2D and 3D accelerometers were used, with a total of 24 channels (including 22 accelerometer components and 2 optical train detectors). The sensors recorded at a sampling rate of 1000 Hz, with each file spanning 30 minutes. Train pass-bys were logged with time, type, and direction. The accelerometer data were delivered pre-processed in accordance with the ProRail uniform measurement protocol (We-Boost, 2022). This includes offset removal, Butterworth bandpass filtering (1–100 Hz), calibration factor application, and storage in acceleration units (m/s^2).

2.1.3 Geophones measurements

Complementary geophone measurements were made using two sets of vertical velocity sensors: 4.5 Hz high-frequency and 1.0 Hz low-frequency geophones. The array was installed ~5.4 m from the centre of the west track as illustrated in Figure 2-2. Signals were sampled at 1000 Hz and stored in .seg2 files of 15 seconds each. Pre-processing included mean removal, zero-phase Butterworth band-pass filtering (1–100 Hz), conversion of raw counts to mV using a descaling factor of 1.6985×10^{-4} (24 dB pre-amp gain), and conversion to velocity (m/s) using a sensitivity of 28.8 V/(m/s).

2.2 Holten 2024

A second major campaign was carried out at Holten between May and September 2024. The site is located at kilometre 23.4 of the Deventer–Almelo railway line, in a rural setting near a farm. Fibre optic cables run along the southern side of the track, approximately 6.6 m from the centreline. Several accelerometer arrays were installed perpendicular to the track and directly on top of the tracks, allowing for measurements at different distances and orientations relative to the source. Figure 2-3 shows the layout of the monitoring setup, including the accelerometer lines (A–D) and their correspondence to FO channel 1194 at km 23.4.

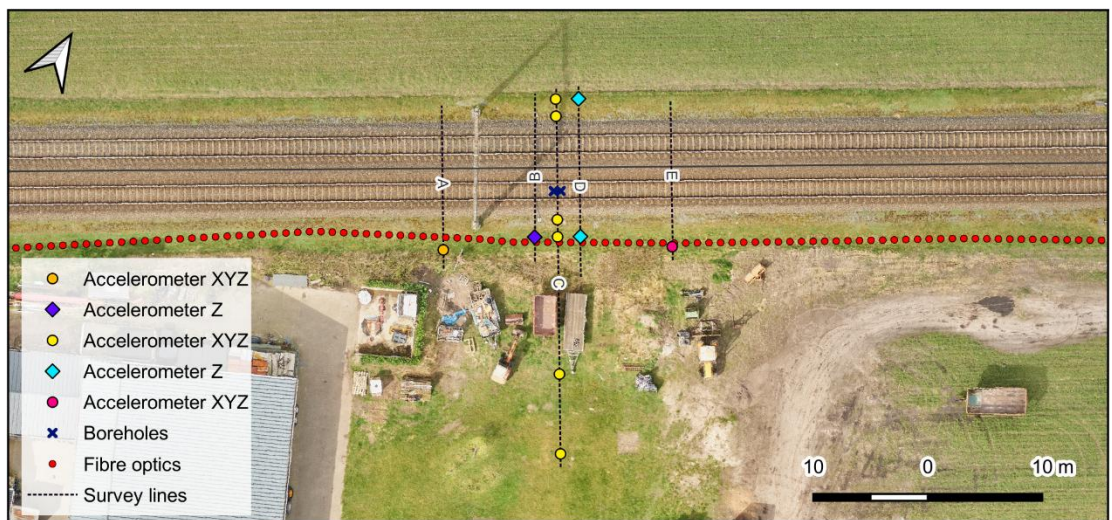


Figure 2-3 Location of the measuring points in the Holten database with a detailed view of the detailed measurements with accelerometers at km 23.4, corresponding to the fibre optics channel 1194.

2.2.1 Fibre optics DAS measurements

Fibre optics were measured at Holten using an OptaSense interrogator. The fibre was installed south of the track, ~6.6 m from the centreline. Two gauge lengths were tested: 2 m gauge length with 3000 channels (1 m spacing), and 10 m gauge length with 6000 channels (1 m spacing), both with recordings of 60-second files. All measurements were performed at 1000 Hz sampling frequency. The interrogator outputs strain-rate parallel to the track, stored in .h5 files.

2.2.2 Accelerometer measurements

Accelerometer measurements setup consisted of four lines (A–D) perpendicular to the track, with accelerometers on both sides of the track. Both 2D and 3D accelerometers were included. Data were acquired at a sampling rate of 1000 Hz, with each train pass-by stored as a separate event. The accelerometer data are available in .mat format in the STEM database. Pre-processing was minimal, as the data were already conditioned according to the standard ProRail measurement protocol (We-Boost, 2022).

3 Results of case studies

This chapter presents the results of the accuracy assessment between fibre optic (FO) and accelerometer measurements at Holten (2024) and Culemborg (2020). Three categories of train pass-bys were considered: (i) local trains (SPR(A)), (ii) intercity double-deckers (VIRM), and (iii) general selections including both passenger and freight trains over multi-day periods. Comparisons were made in the time and frequency domains, supplemented by noise analyses and gauge length tests.

In this report the axis definition is:

- x-direction: horizontal perpendicular to the track.
- y-direction: horizontal parallel with the track.
- z-direction: vertical.



(a) Sprinter train

(b) VIRM train

(c) ICM train

Figure 3-1 Principal train categories considered in the analysis.

3.1 Time-series comparison

Direct comparisons of FO and accelerometer time series were carried out for individual train pass-bys. Accelerometer records were delivered already processed according to the ProRail measurement protocol (We-Boost, 2022), whereas fibre-optic (FO) records were processed with the project pipeline.

Figure 3-2 shows a representative example of a VIRM train recorded at Holten. The two systems register the same pass-by window with comparable timing. The accelerometer traces display well-resolved peaks and multi-component detail, while the FO traces show a noisier, spatially averaged response. This behaviour is observed consistently across the three train categories and at both sites.

An offset of approximately 2 seconds is observed between the accelerometer signal and the FO time signal (Figure 3-2). The underlying cause of this offset cannot be established with certainty. Previous measurement campaigns have shown that the two systems are not always perfectly synchronised, and in the present case this may be compounded by uncertainty in the exact longitudinal position of the FO sensing location relative to the accelerometer. A series of hammer-blow tests was performed to help constrain both timing and location; a more detailed analysis of these tests in future work may clarify the origin of the observed time offset.

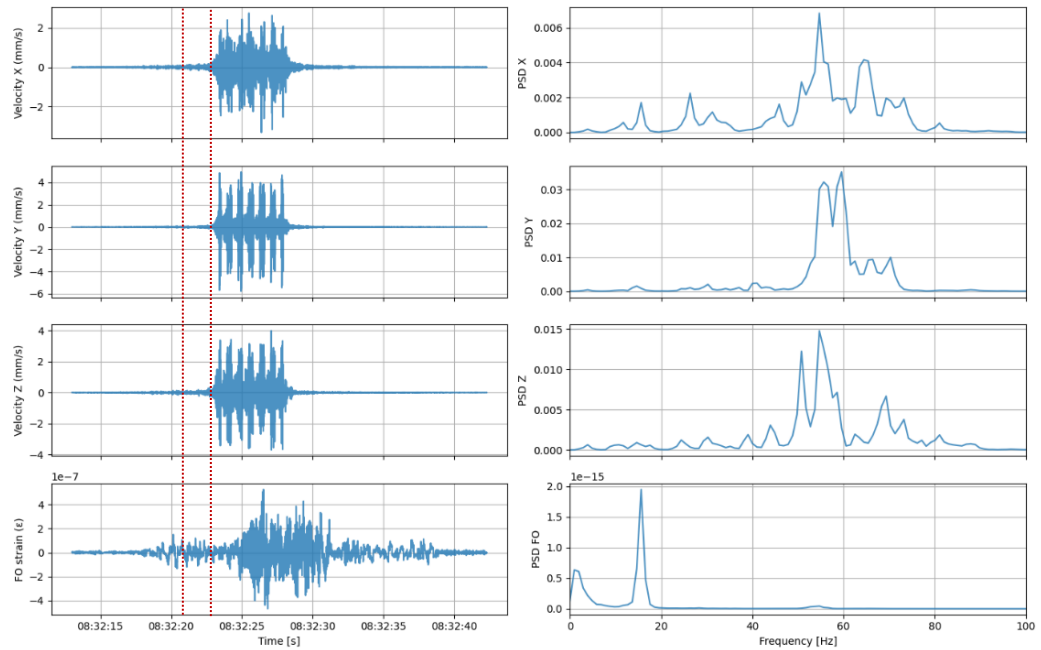


Figure 3-2 Example of a VIRM train pass-by east bound at track 1, closest to the measurement setup and closest to the FO cable parallel to the track, recorded in the accelerometer and fibre optics sensors in the Holten test side. On the left side the vibration signals in velocity (mm/s) and strain (ϵ). On the right side power spectral density signals.

3.2 Power spectral density (PSD) comparisons

The main comparison method was the power spectral density (PSD). PSDs allow the distribution of vibration energy across frequencies to be inspected directly and facilitate comparison of signals with different units.

As illustrated for a single VIRM pass-by in Figure 3-2 (right panel), the accelerometer spectrum spans a broad band with energy extending well beyond 20 Hz, whereas the FO spectrum is confined to the lower frequencies. To verify whether this behaviour is event-specific or systematic, Figure 3-3 presents the average PSD per pass-by for all trains over two days at Holten. The same pattern persists at the dataset level: accelerometers exhibit a broad response with energy up to ~60 Hz, while FO energy is concentrated below ~20 Hz. The result is consistent when the dataset is partitioned by train type (SPR(A), VIRM, ICM); detailed plots are provided in Power Spectral Density signals.

A similar pattern was observed at Culemborg (Figure 3-4). Accelerometer data close to the track contain significant energy across the 1–75 Hz range, whereas FO data are limited to frequencies below ~25 Hz.

Source of the peak value around ~16 Hz is in agreement with the bogie passing frequency while the peak ~3 Hz aligns with the bogie to bogie distance. More on this is described in Section 4.3.

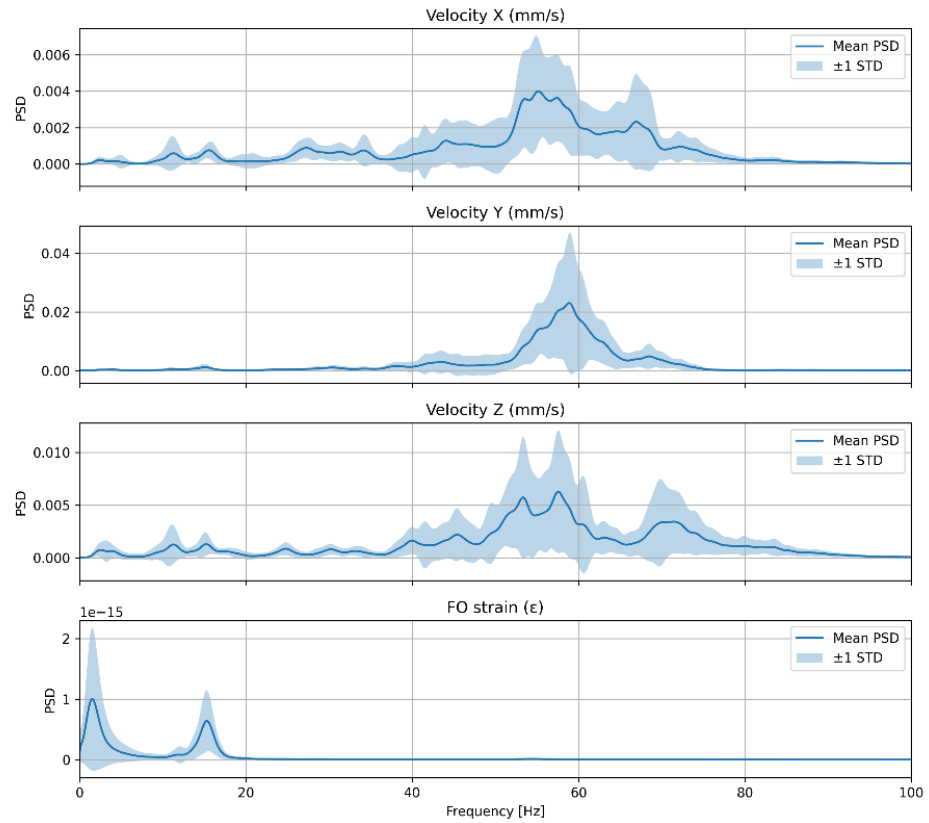


Figure 3-3 Average PSD signal from the accelerometers and fibre optics for all train types available including freight trains, measured between 29/08/2024 and 31/08/2024 in Holten with a gauge length of 10 m.

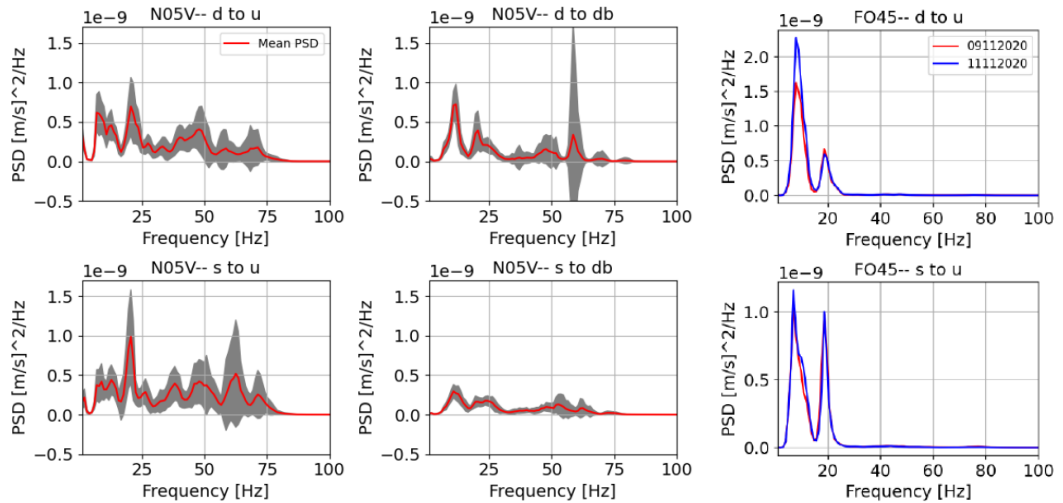


Figure 3-4 Average PSD signal from the closest vertical (left) and horizontal (right) accelerometers to the track, for double deckers (top) and sprinters (bottom), measured on the 09/11/2020 and 11/11/2020 in Culemborg with a gauge length of 10 m (Deltares, 2021).

3.2.1 Focus on the lower frequencies

To isolate the frequency band that FO captures, both FO and accelerometer data were filtered to 1–20 Hz. Figure 3-5 shows the averaged PSDs for SPR(A) trains at Holten after filtering. The accelerometer peaks align with those observed in FO, demonstrating improved correspondence once higher frequencies are excluded.

At Culemborg, a similar effect was obtained by selecting accelerometers located further from the track (~8 m), where natural attenuation reduces high-frequency content. Figure 3-6 shows that under these conditions the accelerometer and FO PSDs are in closer agreement in the 1–20 Hz band.

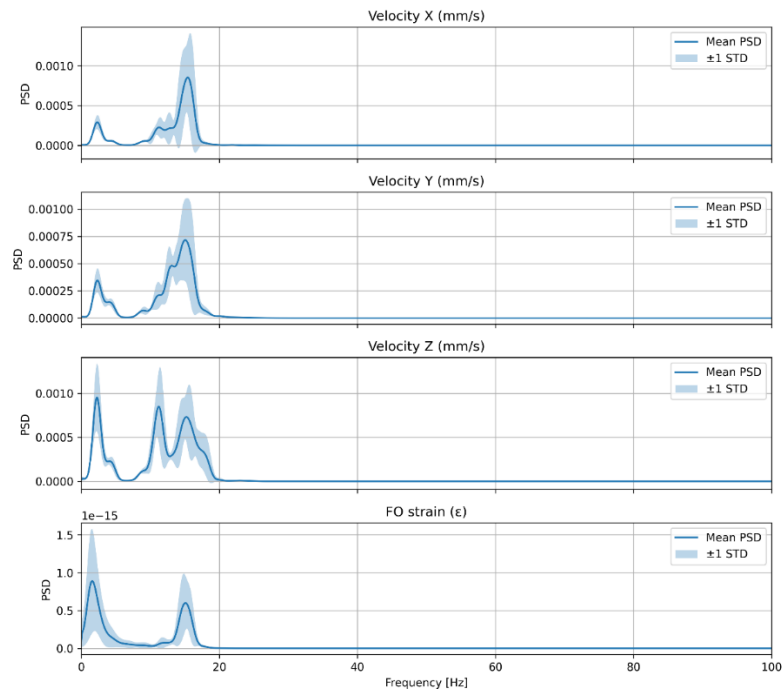


Figure 3-5 Average PSD signal from the accelerometers and fibre optics for SPR(A) train type with a bandpass filter from 1 – 20 Hz, measured between 29/08/2024 and 31/08/2024 in Holten with a gauge length of 10 m.

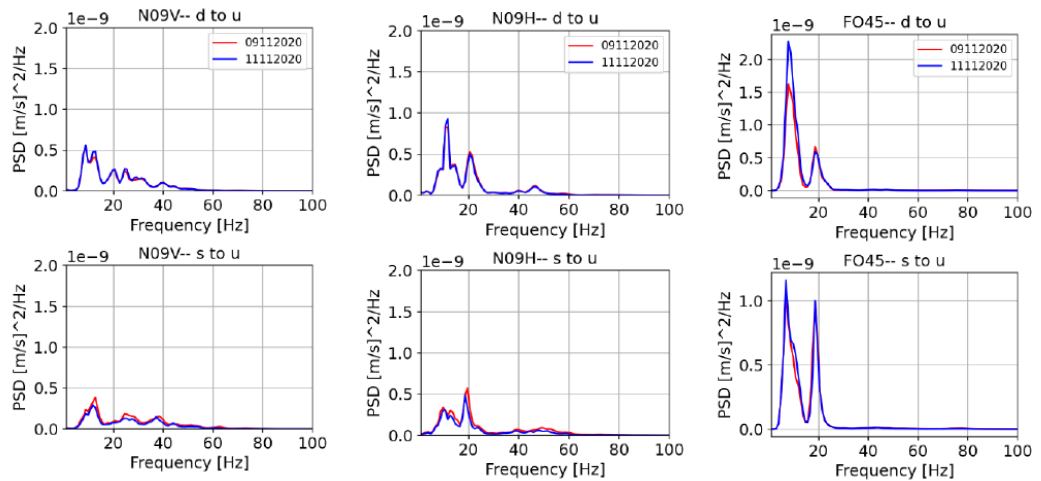


Figure 3-6 Average PSD signal from the intermediate distance to the track vertical (left) and horizontal (centre) accelerometer and fibre optics (right) for double deckers (top) and sprinters (bottom), measured on the 09/11/2020 (red) and the 11/11/2020 in Culemborg with a gauge length of 10 m.

3.3 Noise measurements

Noise levels in FO data were evaluated by selecting time windows without train pass-bys. Figure 3-7 shows a representative example from Holten. The PSD of the FO signal reveals a peak around 16 Hz with an amplitude 4–5 orders of magnitude lower than train-induced signals.

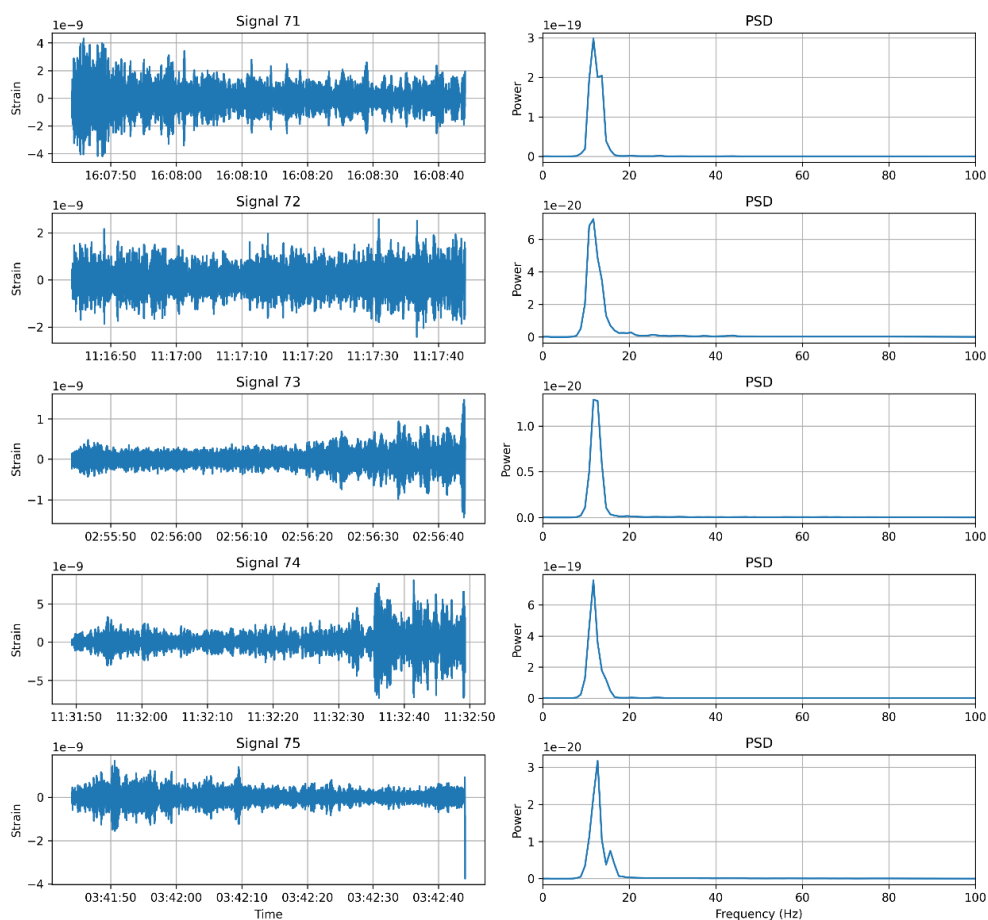


Figure 3-7 Noise measurements in the fibre optics at Holten with a gauge length of 10 m, shown as both strain timeseries and PSD with a magnitude 4 to 5 orders lower than the train pass-bys.

3.4 Gauge length effects

All of the Holten results presented in Sections 3.1-0 were obtained with a 10 m gauge length, which was the standard configuration during the campaign and forms the baseline for comparison. To investigate the influence of gauge length, a second configuration with 2 m gauge length was also tested.

Figure 3-8 shows the averaged PSDs for all train pass-bys recorded over one day with the 2 m configuration. The FO response again remains limited to frequencies below ~25 Hz, with no clear extension of usable frequency content compared to the 10 m results shown previously (e.g. Figure 3-3 and Figure 3-5). In both configurations the accelerometer spectra extend up to ~60 Hz, while the FO spectra consistently capture only the lower part of the frequency range.

Detailed PSD averages for SPR(A), ICM, and VIRM train types under the 2 m gauge length configuration are provided in Power Spectral Density signals. These confirm that the limitation to low frequencies is consistent across train categories.

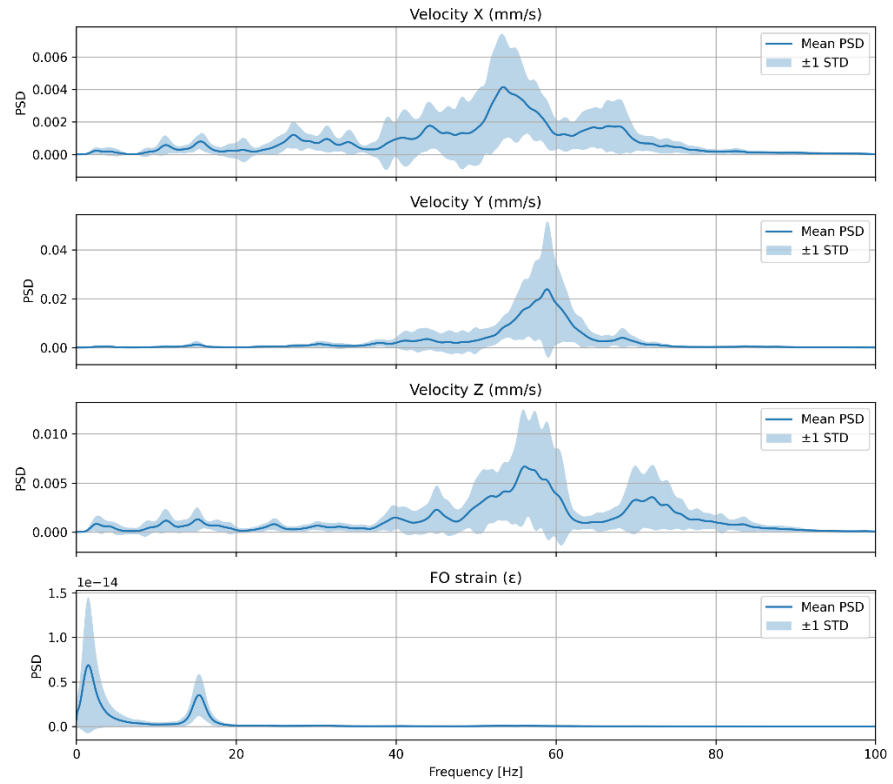


Figure 3-8 Average PSD signal from the accelerometers and fibre optics for all train types available including freight trains, measured between 26/08/2024 and 27/08/2024 in Holten with a gauge length of 2 m.

3.5 Other site fibre optics measurements

FO measurements from additional campaigns were also reviewed to confirm broader patterns. At Wierden (2024), FO data were collected with an OptaSense interrogator. A representative example is shown in Figure 3-9, where FO time series and PSDs again show vibration content limited to frequencies below ~25 Hz.

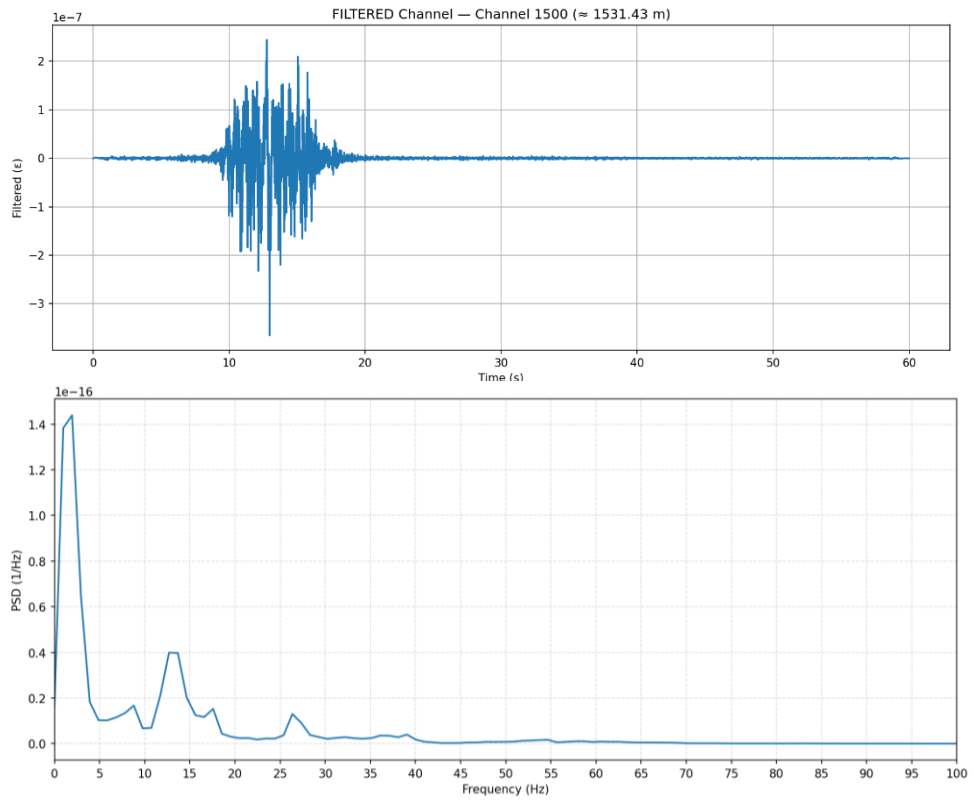


Figure 3-9 Strain timeseries (top) and PSD signal (bottom) of a single train pass-by, measured in Wierden with a gauge length of 10 m and filtered with a bandpass 1 – 100 Hz.

4 Discussion

The comparisons between fibre optic (FO) and accelerometer measurements at Holten (2024) and Culemborg (2020) provide a consistent picture of the capabilities and limitations of distributed acoustic sensing (DAS) for railway-induced vibration monitoring. The discussion below synthesises the main findings from the case studies.

4.1 Agreement at low frequencies

Across all datasets and train types, FO and accelerometer measurements show good agreement in the lower frequency range (0–25 Hz). The bogie-related frequencies (10–20 Hz) are clearly identifiable in both methods, and band-pass filtering of accelerometer signals to the 1–20 Hz range highlights this correspondence. At Culemborg, similar agreement is observed when using accelerometers located further from the track, where natural attenuation of higher frequencies produces spectra comparable to FO. This indicates that DAS provides reliable information on the dominant low-frequency vibration content induced by train pass-bys.

4.2 Loss of high frequency content

A consistent finding at both sites is the absence of high-frequency information in the FO records. Accelerometer spectra extend to ~60–75 Hz, with peaks often associated with sleeper pass-by frequencies, whereas FO spectra show little to no content above ~25 Hz. Attempts to recover high-frequency signals through data augmentation did not yield meaningful improvements. This limitation is therefore intrinsic to the DAS measurement principle under the configurations used.

4.3 Effect of the gauge length and frequency response

Gauge length is a key parameter in DAS because it controls the spatial averaging applied to the fibre signal. In Holten, FO data were acquired with both 10 m and 2 m gauge lengths. Across both configurations, the FO spectra remained limited to frequencies below ~25 Hz, with no clear extension of usable frequency content. The 2 m configuration preserved slightly more energy at intermediate frequencies but did not recover the full high-frequency content observed by accelerometers.

To further interpret the observed frequency response, theoretical calculations were made for characteristic train–track elements. Two SPR(A) train pass-bys at Holten, with speeds of 100 and 135 km/h, were analysed. The characteristic frequencies were calculated using Equations (1) and (2), where v is the train speed, d is the spacing of a structural element, and t the associated pass-by time:

$$t = d/v \quad (\text{Eq. 1}), \quad fs = 1/t \quad (\text{Eq. 2})$$

With d the characteristic length of the system and t the time that the train takes to pass the characteristic length.

Table 4-1 presents the theoretical frequencies for sleepers, bogie wheelbase, and bogie-to-bogie distances. The corresponding measured responses are shown in Figure 4-1.

Table 4-1 Frequency response for different train and rail elements at two different SPR(A) train speeds.

Element	distance (m)	Speed	Speed
		100 km/h	135 km/h
		28 m/s	38 m/s
Sleepers	0.6	46 Hz	63 Hz
Bogie wheelbase	2.5	11Hz	15 Hz
Bogie to bogie	18	2 Hz	2 Hz

In the velocity spectra, the sleeper-passing frequencies (46–63 Hz) are clearly identifiable, whereas they are absent from the FO spectra, except for a weak partial response at 100 km/h. For the bogie wheelbase spacing (11–15 Hz), both accelerometer and FO spectra show peaks in agreement with the theoretical values.

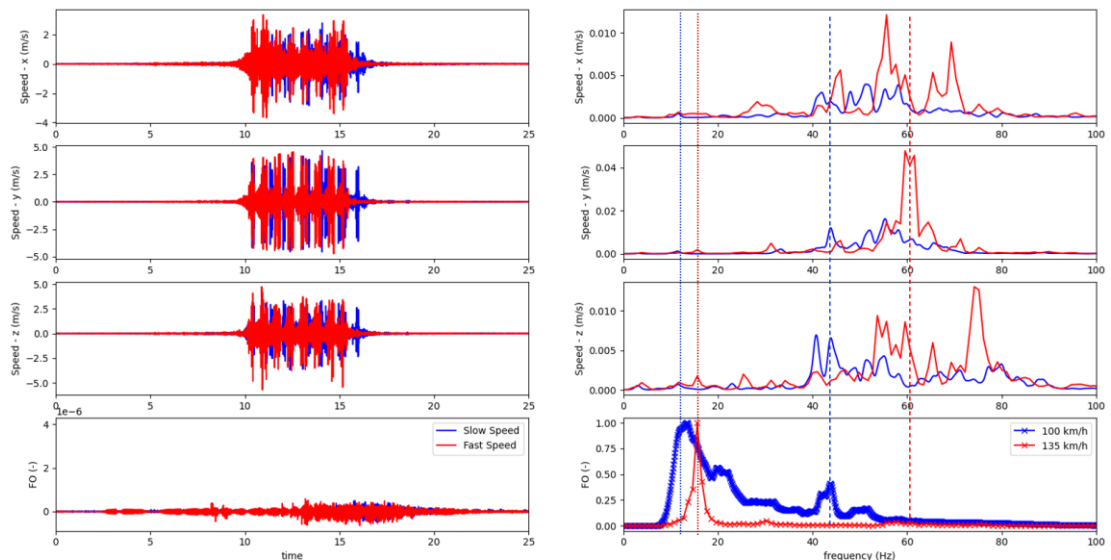


Figure 4-1 Pass-by vibration timeseries (left) and PSD signal (right) in the accelerometers and fibre optics at Holten for two SPR(A) train types traveling at 100 km/h (blue) and 135 km/h (red).

Figure 4-2 presents a simple synthetic moving-load experiment designed to illustrate how the gauge length affects the frequency content of FO measurements. The input signal does not come from real data but from a toy-vehicle model in which a set of axles travel at constant speed along the fibre, each producing a clean sinusoidal load as it passes.

When the raw signal is averaged over the fibre to mimic gauge length, high-frequency peaks are progressively attenuated (Figure 4-2). With 2 m gauge length, the ~50–60 Hz peak is partially preserved, while with 10 m it is strongly suppressed and the spectrum is dominated by lower frequencies. This behaviour reflects the role of gauge length as a spatial low-pass filter. It has been elaborated theoretically in Appendix C.

Recent literature (Milne, et al., 2025) supports this interpretation, showing that DAS gauge length imposes a trade-off between spatial resolution and noise performance for quasi-static measurements. Shorter gauge lengths improve recovery of short wave-length (high wave-number) strain variations but increase noise levels, while longer gauge lengths provide cleaner signals at the expense of frequency detail. For moving vibration sources such as trains, this spatial filtering translates into attenuation of the corresponding high-frequency content of the signal. The present field and synthetic results are consistent with this understanding: reliable low-frequency capture up to ~20–25 Hz, but loss of sleeper-passing peaks above ~40 Hz under the tested configurations.

In addition to gauge length and interrogator configuration, the degree of coupling between the cable and surrounding soil, the cable's mechanical construction, the interrogator methodologies and others are likely to influence the frequency response. For example poor coupling or stiff cable sheaths can further attenuate high-frequency motion transfer to the fibre.

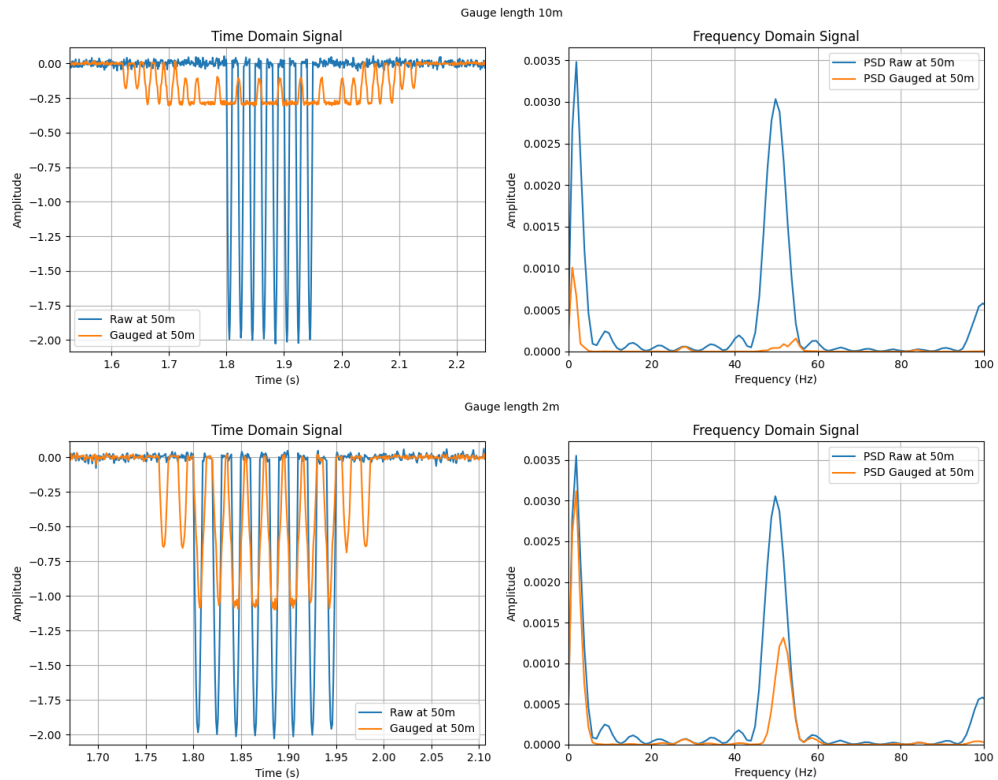


Figure 4-2 Synthetic moving load signal to illustrate the effect of the gauge length as a spatial low-pass filter. On top the averaging with a gauge length of 10 m and at the bottom with a gauge length of 2 m.

4.4 Noise characteristics

Noise analyses at Holten indicate that FO background signals contain a peak around 16 Hz, with amplitudes 4–5 orders of magnitude lower than train-induced signals. While this background is not significant compared to the train responses, it illustrates the presence of low-level system or environmental noise within the FO recordings. No systematic noise analysis was available for the accelerometer datasets, so direct comparison of noise floors could not be made.

4.5 Consistency across sites and interrogators

The results from Holten and Culemborg, despite differences in site conditions, sensor layouts, and interrogators (OptaSense at Holten, Silixa at Culemborg), are remarkably consistent. Both confirm reliable FO performance at low frequencies, limited response at higher frequencies, and stable behaviour across train types.

In addition to interrogator configuration, the installation conditions of the dark fibres themselves may also influence the recorded response. Differences such as cables installed directly in the soil versus cables placed within ducts can alter soil coupling and thereby affect the transmission of higher frequencies or even introduce unexpected artefacts. These installation effects have not yet been systematically characterised but may provide part of the explanation for the high-frequency loss and other anomalies observed at certain sites.

5 Implications and next steps

The findings discussed in Chapter 4 demonstrate that DAS, under current configurations, can reliably capture the low-frequency components (≤ 25 Hz) of train-induced vibrations, but fails to resolve the higher-frequency range (> 25 Hz). This limitation is primarily governed by the gauge length and the inherent spatial averaging of the fibre-optic measurement principle. Despite this, the technique demonstrates consistent low-frequency performance across sites and interrogators, confirming its potential for continuous, spatially dense vibration monitoring along the railway.

Building on this understanding, the following sections outline how these insights translate into practical implications for the relationship between FO and traditional sensors (Section 5.1) and into recommendations for further work, particularly the development of machine-learning approaches to bridge the two measurement domains (Section 5.2).

5.1 Relation between FO and traditional measurements techniques

The comparison of fibre optic (FO) and accelerometer measurements at Holten (2024) and Culemborg (2020) demonstrates that FO can reliably reproduce the low-frequency part of the vibration spectrum. In the range up to approximately 20–25 Hz, FO and accelerometer spectra show close correspondence, with bogie-related frequencies (~ 11 – 15 Hz) consistently identifiable in both methods. This confirms that DAS is a suitable tool for capturing the dominant low-frequency components of railway-induced ground vibrations at embankments.

Above 25 Hz, however, FO measurements show strong attenuation due to the effect of gauge length averaging. As a result, characteristic high-frequency features such as the sleeper-passing frequency (~ 50 – 60 Hz depending on train speed) are absent from FO data. Accelerometers therefore remain indispensable for applications that depend on high-frequency resolution.

If the FO will be used for continuous inspection of changes in track quality or level of environmental vibrations, the limitation of bandwidth is equal to a limitation of (wave-)length of the inspected phenomena. With the highest train speed of e.g. 140 km/h ($= 39$ m/s) and a frequency limit of 20 Hz, the inspected length is limited to $2 \cdot 39 / 20 = 4$ m. The factor 2 is required from Nyquist-Shannon theory.

This means that FO and accelerometers provide complementary information. Further exploration of gauge length settings, interrogator configurations, and signal processing options is needed to determine whether FO can be extended to capture higher-frequency components or whether its applicability will remain limited to the low-frequency range.

5.2 Recommendation for next steps

The measurement results make clear that FO and accelerometers provide complementary information: FO reliably captures the low-frequency range, while accelerometers retain the high-frequency detail. The next step is therefore to build on this complementarity by developing machine-learning (ML) models that link FO signals to conventional vibration metrics. This also aligns with the final objective of Activity 5: exploring whether FO measurements can be translated into parameters traditionally obtained from accelerometers.

The initial focus will be on predicting peak ground velocity (PGV), a robust and widely used descriptor of soil vibration. FO data will provide the dense input signals, and accelerometer-derived PGV values will serve as reference outputs for model training and validation.

A key consideration is that PGV is strongly influenced by high-frequency components—precisely the part of the spectrum that FO tends to attenuate. Direct PGV prediction from FO may therefore underestimate vibration amplitudes, especially close to the track. To address this, the modelling framework will explicitly consider both the full PGV and a low-pass-filtered PGV derived from band-limited accelerometer data. Comparing these will clarify how much of the PGV information lies within the FO-resolvable frequency range and whether a band-limited PGV proxy is a more appropriate prediction target.

Although FO is limited in capturing high-frequency content, an ML approach remains worthwhile. Data-driven models may uncover relationships between FO and accelerometer responses that are not immediately visible in the spectral comparisons. To support this, the feature set will include not only FO strain but also train type, speed, axle configuration, direction, soil conditions, track characteristics, and track-sensor distance. This broader context may help compensate for the loss of explicit high-frequency detail in the FO signals.

The modelling will proceed stepwise. The first stage will use gradient-boosted decision trees (XGBoost) to predict PGV for individual train pass-bys, establishing an interpretable baseline. Once this foundation is in place, the work can expand to predicting frequency-domain features and, at later stages, to approximate reconstruction of vibration time signals. All training and validation datasets will be generated through the Python pipeline developed in Activity 5 to ensure consistent preprocessing and data structuring.

6 Conclusions and recommendations

The comparison of fibre optic (FO) and accelerometer measurements at Holten (2024) and Culemborg (2020) demonstrates that FO reproduces low-frequency vibrations ($\leq 20\text{--}25$ Hz) with good reliability, including bogie-related frequencies. This establishes FO as a consistent tool for monitoring the dominant components of railway-induced ground vibrations.

At higher frequencies (> 25 Hz), FO showed strong attenuation under the tested configurations, and characteristic peaks such as the sleeper-passing frequency were not resolved. However, it cannot yet be concluded that this limitation is intrinsic to FO. Further investigation of gauge length, interrogator configuration, and processing options is needed to determine whether higher-frequency content can be captured under alternative settings.

The practical implication is that FO and accelerometers should currently be regarded as complementary. FO provides continuous, spatially dense coverage of low-frequency vibrations along the track, while accelerometers offer detailed high-frequency information at discrete points.

It should be emphasised that the conclusions drawn in this study are based on a specific interrogator configuration, gauge length, and installation setup. The findings therefore reflect the performance of one particular combination of measurement system and soil conditions. Further work is needed to understand how results may vary under different interrogator types, configurations, and processing methods, as well as the effects of cable–soil interaction, cable construction, and installation quality.

In particular, the installation conditions of the fibres such as: direct burial versus installation inside protective ducts, may strongly influence coupling quality. These differences can lead not only to site-to-site variability but also to measurable loss of high-frequency content and other unexpected behaviours in the recorded train responses.

A systematic comparison across alternative fibre types and coupling conditions and installation methods is essential to generalise the present conclusions and add to the understanding all the vibration phenomenon observed in the measurements.

Based on these findings, it is recommended to proceed with the development of machine learning models linking FO signals to conventional vibration metrics. The first objective will be the prediction of peak ground velocity (PGV) using gradient-boosted decision trees (XGBoost). This baseline will test the feasibility of FO-accelerator translation, with the potential to expand to frequency-domain features and more complex outputs in subsequent stages. Additional metadata such as train type, speed, soil conditions, and sensor location will be incorporated to strengthen predictive capability.

If successful, this approach will extend the value of existing dark fibre networks into a scalable monitoring tool for railway infrastructure.

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7 Funding and disclaimer

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A Power Spectral Density signals

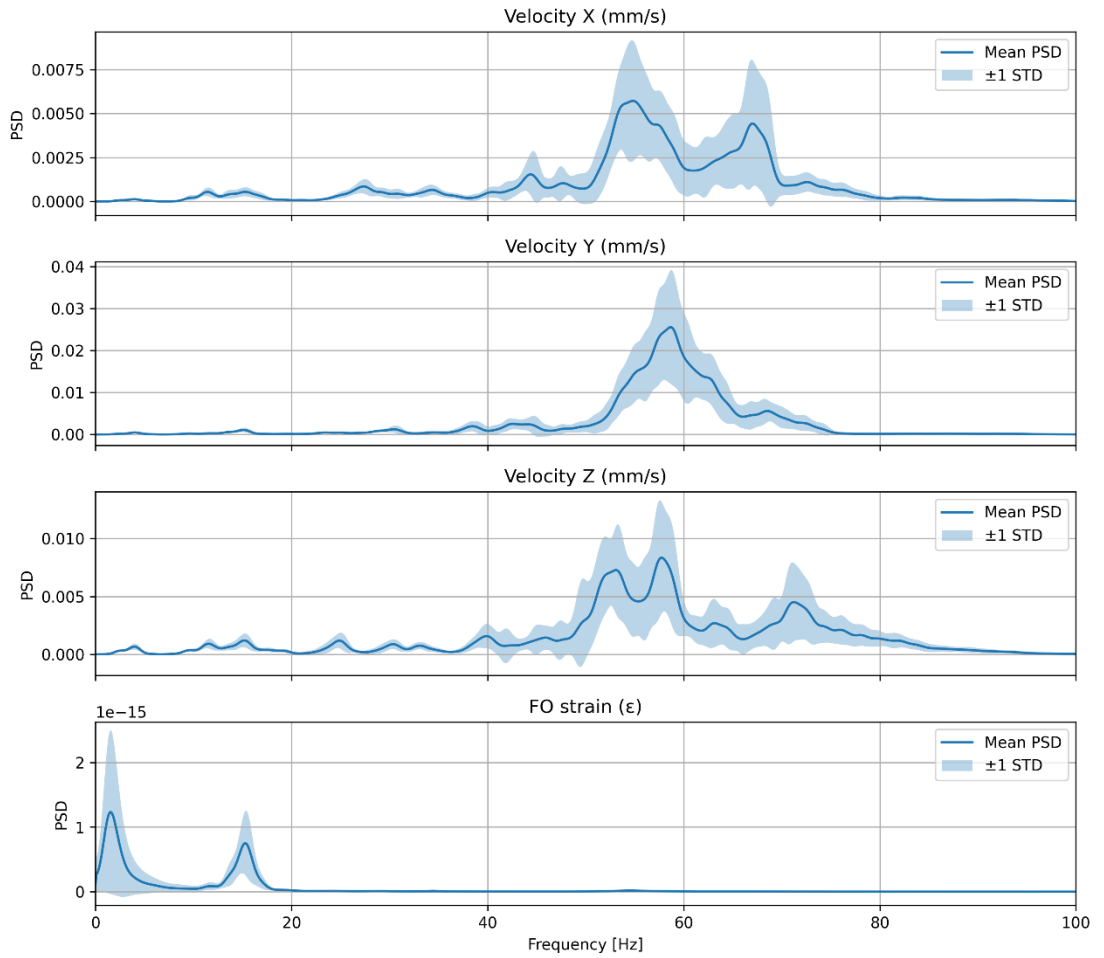


Figure A.1 Average PSD signal from the accelerometers and fibre optics for the ICM train type measured between 29/08/2024 and 31/08/2024 in Holten with a gauge length of 10 m.

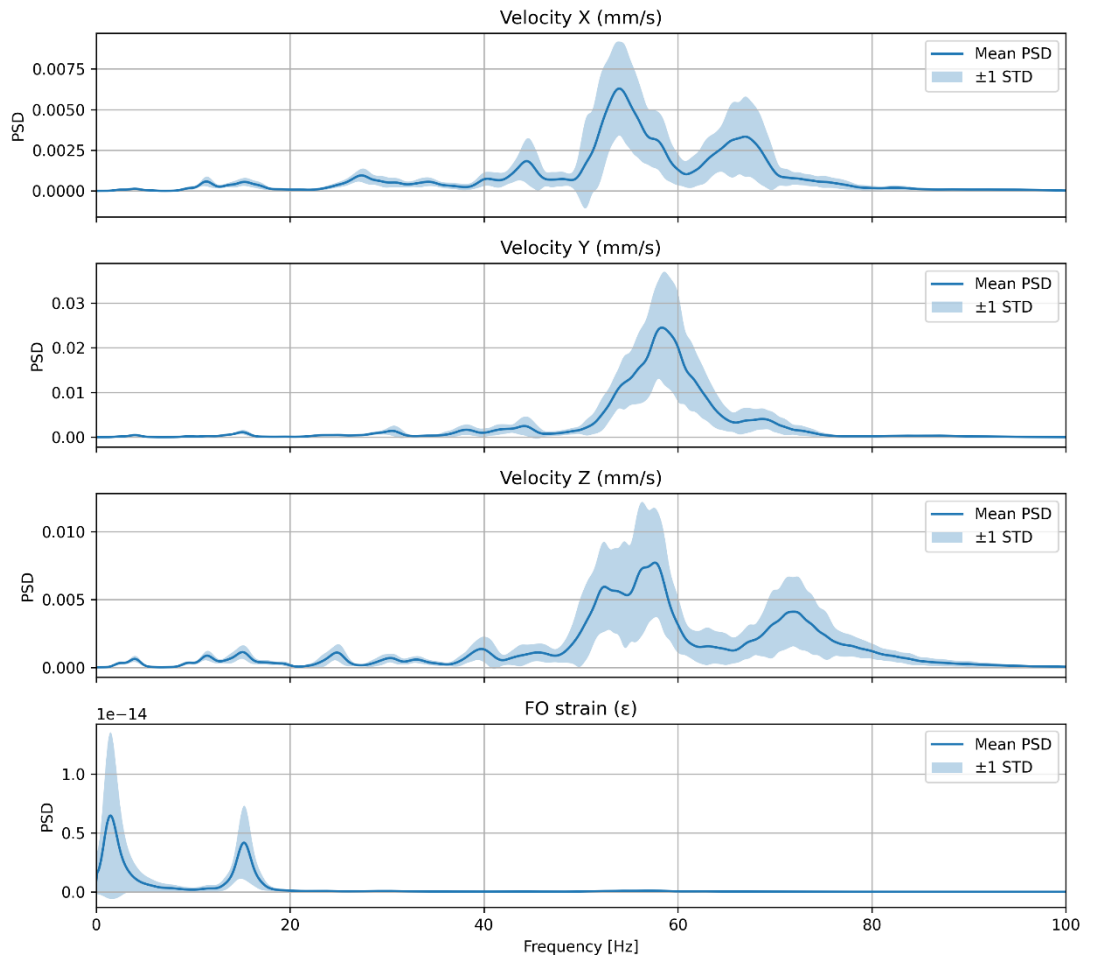


Figure A.2 Average PSD signal from the accelerometers and fibre optics for the ICM train type measured between 26/08/2024 and 29/08/2024 in Holten with a gauge length of 2 m.

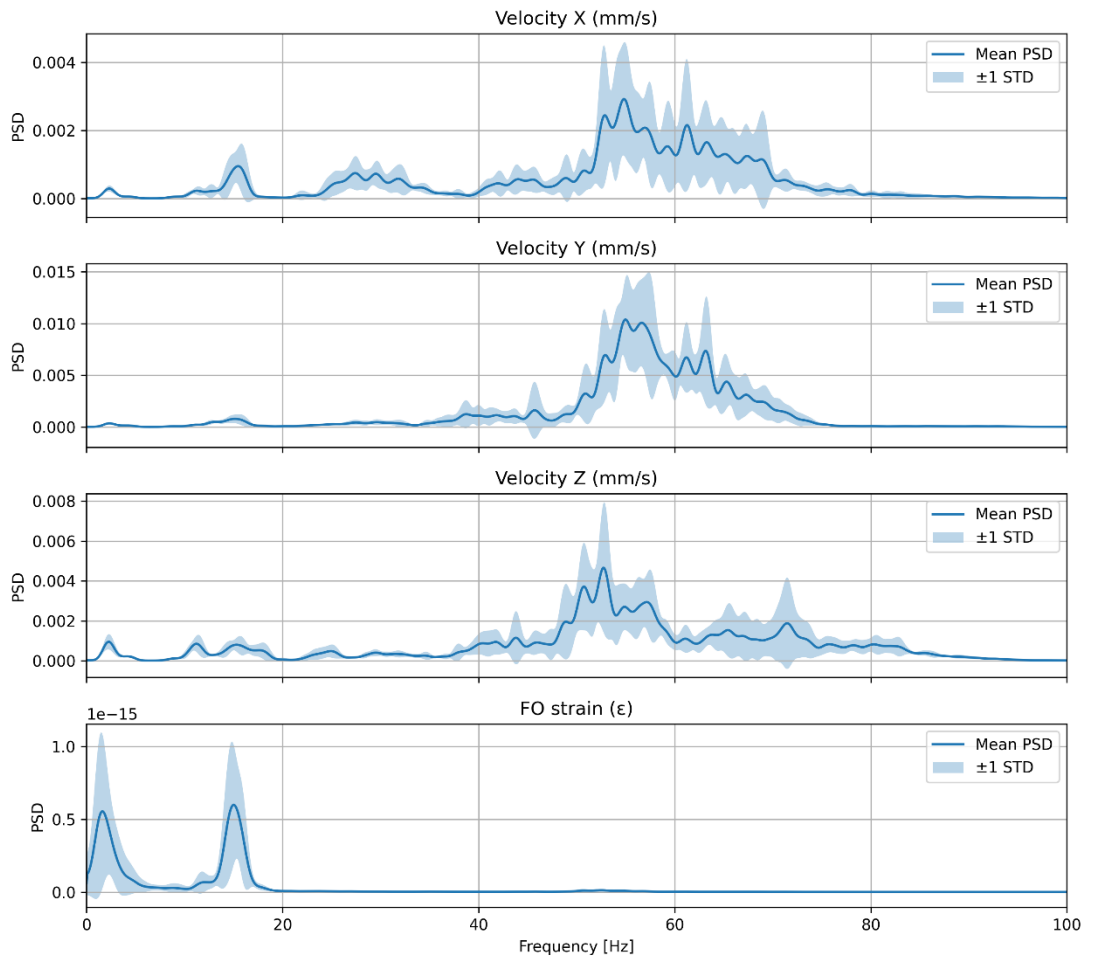


Figure A.3 Average PSD signal from the accelerometers and fibre optics for the SPR(A) train type measured between 29/08/2024 and 31/08/2024 in Holten with a gauge length of 10 m.

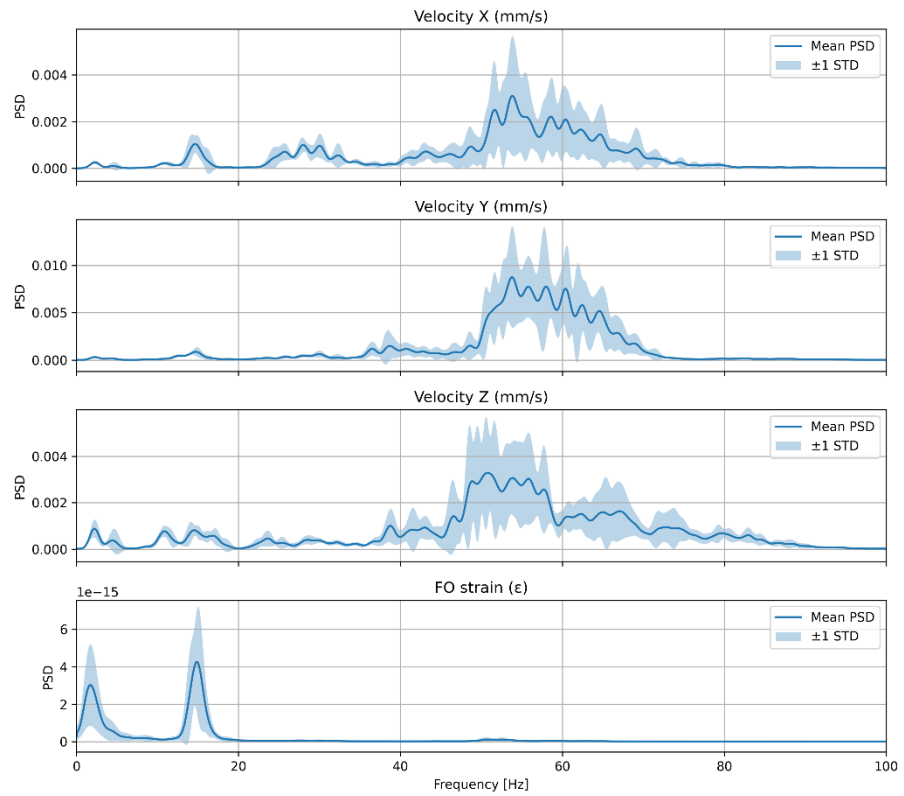


Figure A.4 Average PSD signal from the accelerometers and fibre optics for the SPR(A) train type measured between 26/08/2024 and 29/08/2024 in Holten with a gauge length of 2 m.

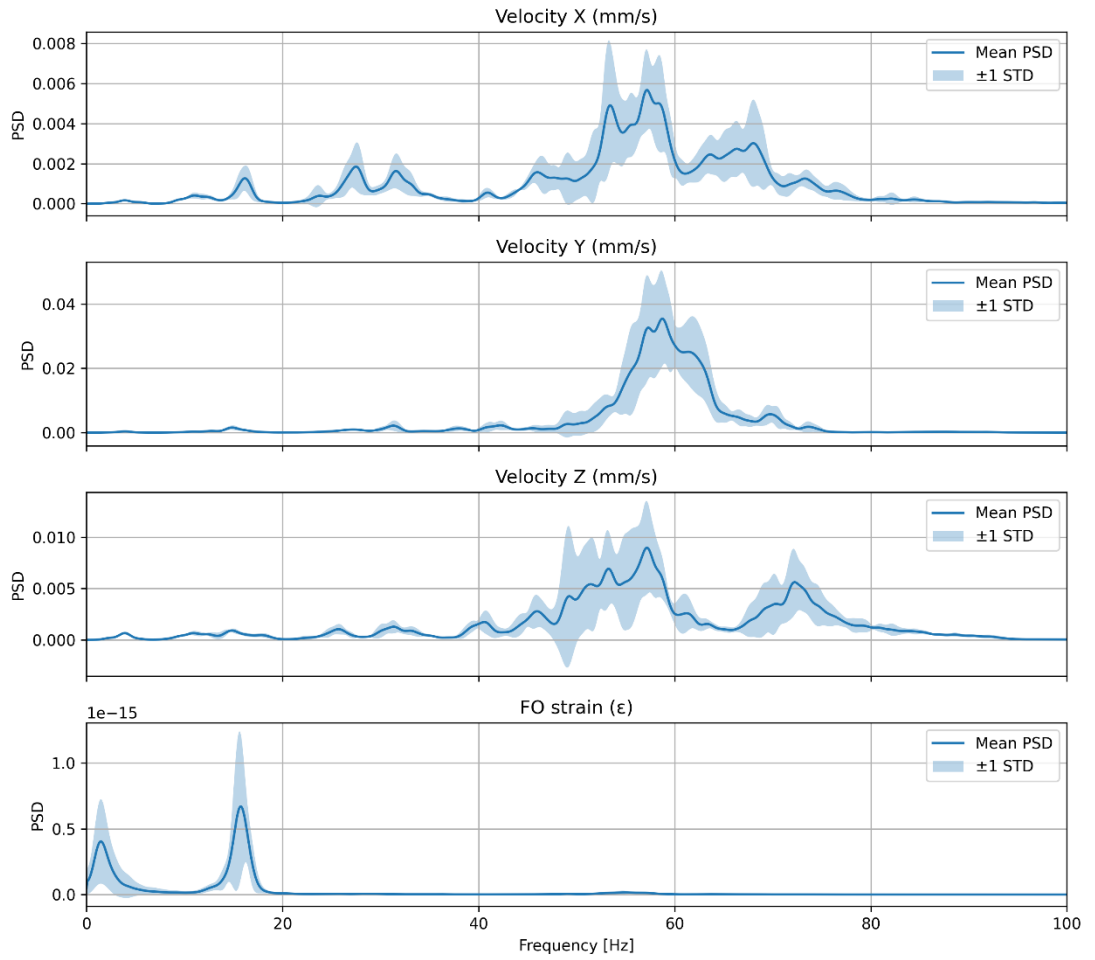


Figure A.5 Average PSD signal from the accelerometers and fibre optics for the VIRM train type measured between 29/08/2024 and 31/08/2024 in Holten with a gauge length of 10 m.

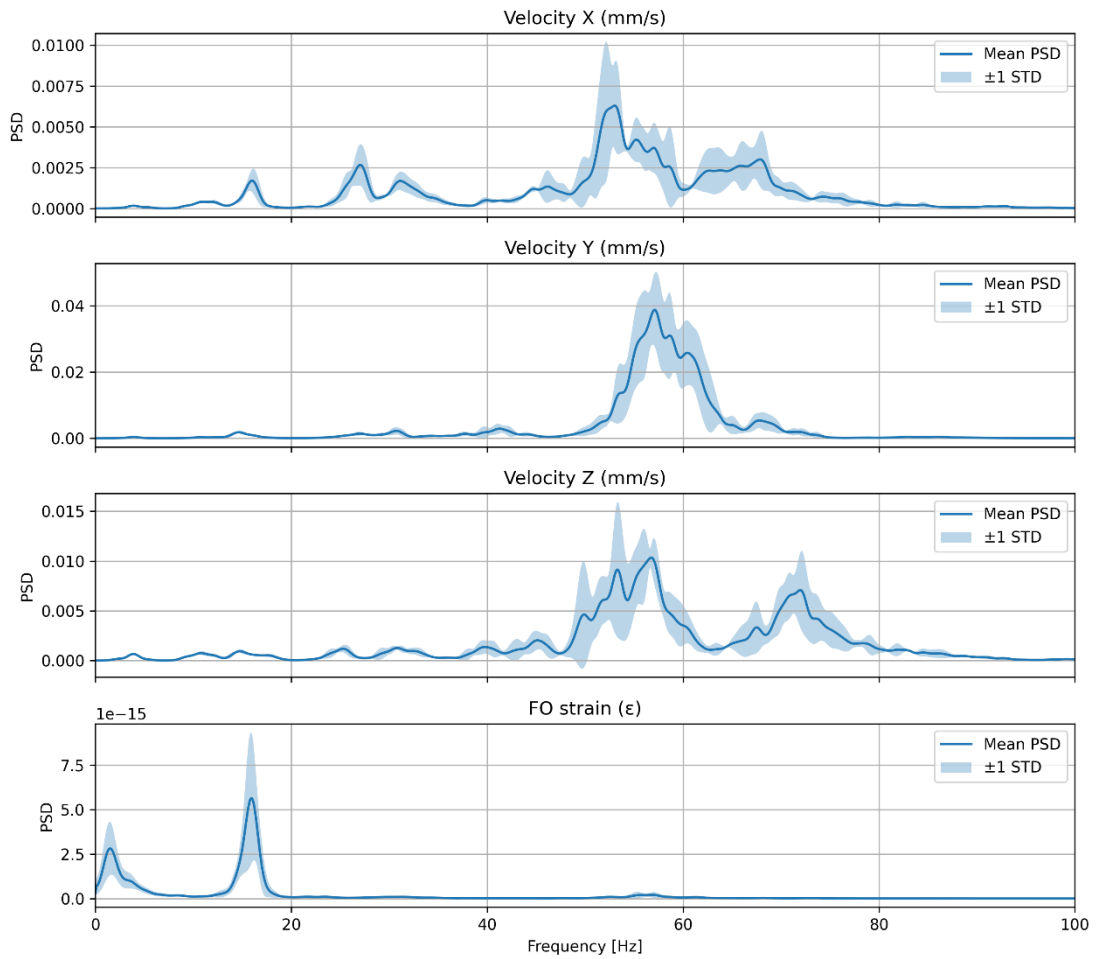


Figure A.6 Average PSD signal from the accelerometers and fibre optics for the VIRM train type measured between 26/08/2024 and 29/08/2024 in Holten with a gauge length of 2 m.

B Holten signal attenuation with distance from the track

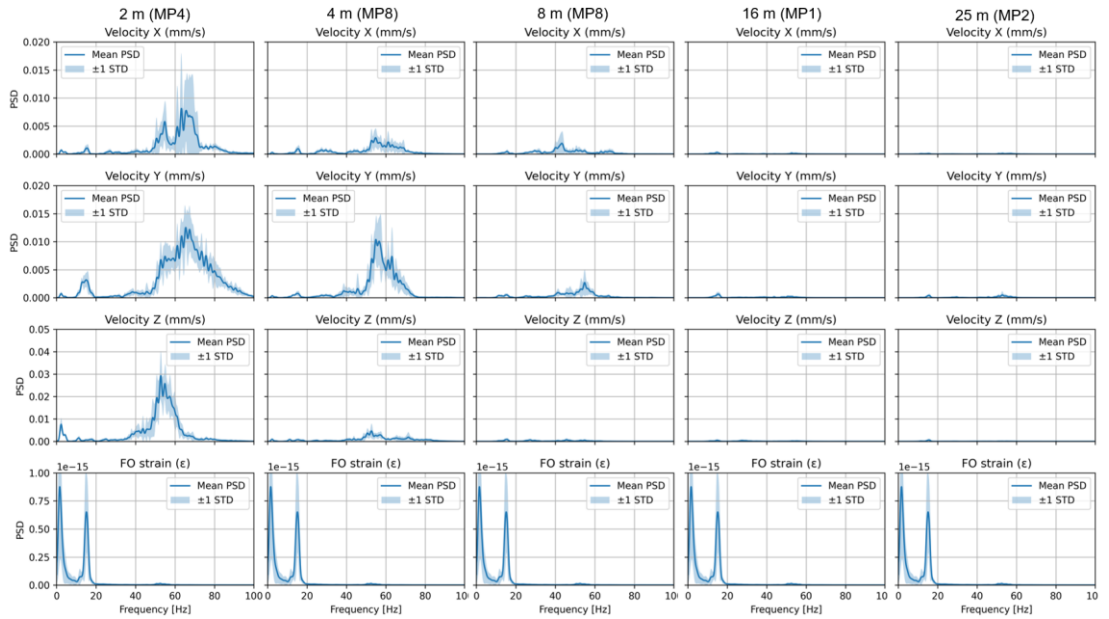


Figure B.1 Attenuation of the accelerometers signal as a function of the distance from the track. Signals measured from 29/08/2024 to 31/08/2024 in Holten for SPR(A) train types.

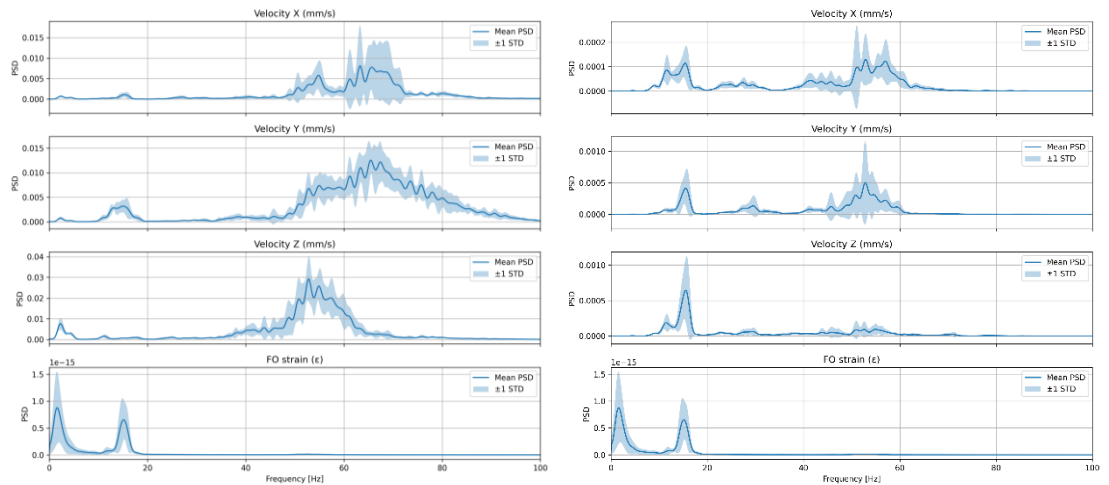


Figure B.2 Detailed comparison between the accelerometers closest (left) and most distant (right) from the track in Holten to illustrate the attenuation of the higher frequencies with distance.

C Theoretical frequency response

For a harmonic plane wave that propagates parallel with the FO, the response of a measurement with given gauge length can be calculated theoretically. The strain that is derived from the difference in displacement in two points with a distance equal to the gauge length is derived. Figure C.1 shows the calculated strain in the FO for a harmonic wave with amplitude 1 mm/s as a function of frequency of the wave. The result depends on the wave speed. At low frequency the theoretical value is found. For a wave with 10 Hz and wave speed 100 m/s a zero is observed. At the frequency, the wavelength is equal to the gauge length. This is two times the Nyquist frequency. For higher frequencies the sensitivity of this device reduces quickly.

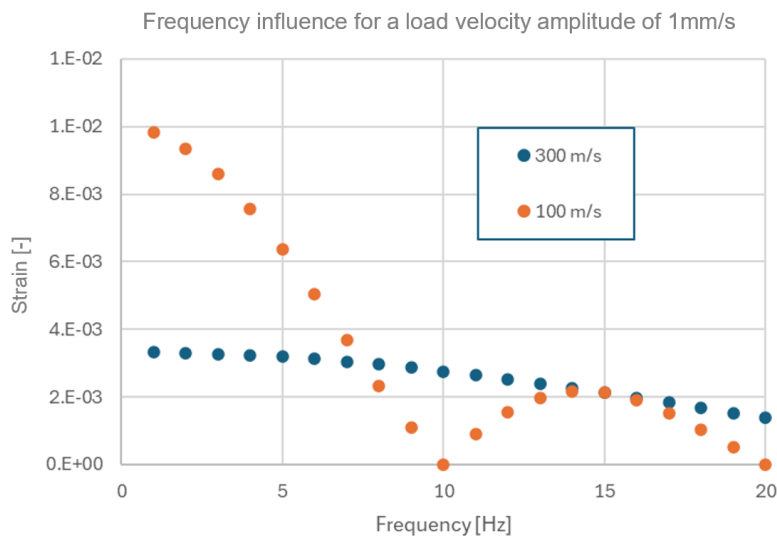


Figure C.1 Influence of frequency on measured strain for harmonic wave with wave speed 100 m/s and 300 m/s (note unit strain is mm/m).

For a gauge length of 2 m, the first zero in the sensitivity curve will be found at a wavelength a 2 m thus (for a wave speed of 100 m) at 50 Hz. This theoretical result is not observed in the field measurements. This might be due to the fact that at these higher frequencies; the soil cable interaction hinders the transfer from the soil to the fibre optics. This might depend on the type of cable in the soil.

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