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Proposed approach for direct rail state monitoring with distributed acoustic sensing DAS

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ABSTRACT: Railways are one of the fundamental modes of transportation, dating back centuries. They allow for the movement of people and goods across hundreds and thousands of kilometres. Such a large system relies on precise timing and excellent organization. Any incident or failure can result in losses amounting to millions of euros and cause unacceptable delays. Monitoring the condition of the railway is necessary to ensure safety and system effectiveness, but it is challenging due to the long distances that need to be monitored. Conventional sensors can provide high-quality data, but they do not offer a complete picture of the railway's state, and local defects can be overlooked. A great solution for railway monitoring is DAS. A fibre optic sensor integrated with the structure can be used to obtain information about strain and vibration, with a fine resolution of even down to 1 metre, over tens of kilometres of track. Installing the sensor in the railway substructures can be challenging and exposes the sensor to potential damage. Another approach discussed in the article is to attach the sensor directly to the rail. Long sections of track can be covered with monitoring within a few hours using automated machine, enabling direct measurement of the rail's condition. This paper presents the results of such installation, showing the potential of synergizing monolithic distributed fibre optic sensors with DAS technology to increase the safety and reliability of rail transport.

KEY WORDS: rail, railway, DAS, strain-rate, monolithic sensors, dynamic measurement.

1 INTRODUCTION

Research presented in the paper is mostly driven by the goal of improvement of safety in railway transport. We live in the times when due to galloping climate changes, sustainable ways of transportation, like railways may be one of the key ways of slowing down the global temperature from increasing [1]. However, there are challenges that have to be overcome to increase sustainability level of rail transport. The development is eagerly promoted due to its considerably lower emission rates than other modes of transportation. However, greenhouse gas emission is not the only environmental threat coming from transport industry. Another factors worth consideration are noise pollution and direct threats to wild animals [1]. Rail tracks run through the whole countries and continents. Their paths all possible zones, cities, wildlands and rural areas. The span between the stations reaches tens of kilometres', which makes it extra-ordinarily difficult to control and limit threats. Additionally, railway structures are prone to experience local damages due to deterioration. During the operation time, railways are exposed to harsh weather conditions, rapid temperature changes, uneven substrate settlement and massive vertical loads of passing trains. Exposition to such conditions may cause change of the track geometry. Damaged tracks may influence not only comfort of the passengers but also their safety. In most extreme case the train may fall of the track. Such an accident may be a huge environmental or urban catastrophe. Fixing is difficult, slows down or even completely blocks other trains and causes large costs and labour consumption [2, 3].

Following risks may be significantly limited or even completely avoided by proper monitoring the railway. Effective solution for such an application is Distributed Acoustic Sensing (DAS). The DAS technology is subpart of the Distributed Fibre Optic Sensing (DFOS). All the DFOS technologies utilise optical fibre as an array of sensors. Sensing device - optical interrogator - divides the fibre into set of aligned segments. As a result of the measurement, each segment (gauge) is represented as a discrete data point in result array. Value of each data point is a mean value of a measured physical quantity in all the points located in specific gauge [4, 5]. The DAS interrogators divide the fibre into dense set of overlapping channels (gauges) providing full continuity of the measurement along the fibre path. The distributed nature of this sensing technique allows continuous recording with multiscale grid of virtual unit gauges. Virtual placement of the gauges allows free manipulation on their arrangement without necessity of rearranging the setup. All the changes can be introduced by proper tuning of the interrogators [6,7]. Crucial part of system designing is proper placement and installation of the sensor. Industrial practice is to install the sensor in the trackside or to use already installed telecom cables [8, 9]. Installation of the sensors in the ballast layers of the railway may be challenging due to the complexity of the structure, traffic and law regulations. Moreover, such installation method requires placing additional cable duct which disturbs strain transfer mechanism. Another unfavorable phenomenon occurring in soil mechanic is non-elastic behavior of gravel ballast layers. Rocky, non-expansive soils as gravel used for sub-track construction do not transfer tensile forces. In such configuration only vibrations can be measured. More comprehensive solution is to attach the sensors directly to the track. This way system can measure direct strain of the element to give more information about the actual track condition [10]. Nevertheless, DAS interrogators have limited dynamic range.

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Strong, high amplitude vibration may lead to saturation effect occurrence. This may lead to the substantial data loss [11]. Correct configuration of interrogator settings and adoption of sensor properties is crucial for proper operation of the measurement system. In this paper, authors propose the solution for direct rail track monitoring, allowing dynamic measurements of high-speed trains, passing with velocity of up to 250km/h, alongside with the long-term static strain measurements. The solution was tested during full-scale field experimental sessions, proving the feasibility and correctness of such an approach.

2 DISTRIBUTED ACOUSTIC SENSING PRINCIPLES

2.1 *Rayleigh backscattering application in DAS*

Rayleigh backscattering can be effectively used for precise strain and temperature measurements in both silica and polymer fibres. Two main approaches of Rayleigh phenomenon can be distinguished: Optical Time-Domain Reflectometry (OTDR) and Optical Frequency Domain Reflectometry (OFDR). OTDR-based measurements are usually much faster and can be performed on significantly longer sections of the fibre than OFDR [12]. DAS interrogators operate on OTDR combined with phase control coherency (φ-COTDR) in order to deliver high-quality information about the rate of the strain change (strain-rate), along the fibre. Distribution of the reflected light intensity in the fibre for COTDR is random.

Regardless this randomness nature of the signal, it varies harmonically, as shown in Fig. 1. This way, with application of phase control approach, the phase information can be revealed. Whereas the phase angle is directly proportional to the strain change along the fibre axis [13], creating the opportunities for practical applications in civil engineering and geotechnics.

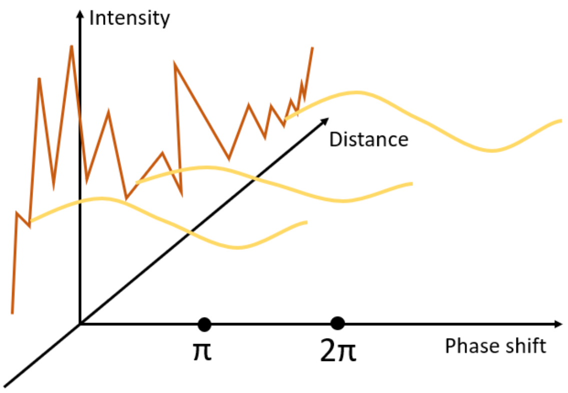

Figure 1. Intensity changes are irregular along distance but harmonic along phase shift axis [13].

2.2 *Dynamic range of DAS interrogators*

Dynamic range of acoustic sensing device (interrogator) is the magnitude of the strain change between two time samples that can be accurately unwrapped. Due to harmonic behavior of the intensity, only certain magnitude of strain change can be measured accurately. Because of that, DAS interrogators differentiate the strain in time domain in order to obtain strain-rate, using the following equation:

$$\frac{\mu\varepsilon}{s} = \frac{\partial\mu\varepsilon}{\partial t} \tag{1}$$

where $\frac{\mu\varepsilon}{s}$ is strain rate given in microstrains (με) per second and $\frac{\partial\mu\varepsilon}{\partial t}$ is a derivative of strain in time-domain.

Use of strain-rate allows to measure wider range of strain by measuring small changes and then stitching them together, by phase unwrapping in order to obtain whole picture, as shown in Fig. 2 [13].

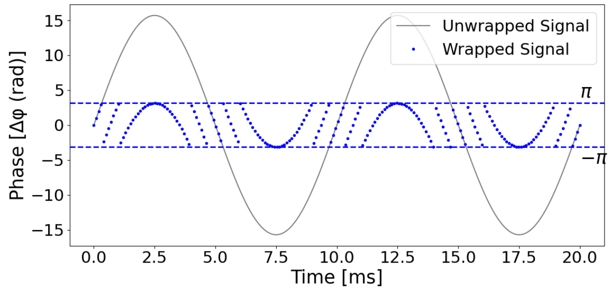

Figure 2. Wrapped and unwrapped differential phase.

As the value of the strain change can be both positive and negative, the dynamic range of any DAS interrogator is limited between <- π ; π >. Return signal is always within this range, even if the input strain in the time *dt* would move outside the limit [14].

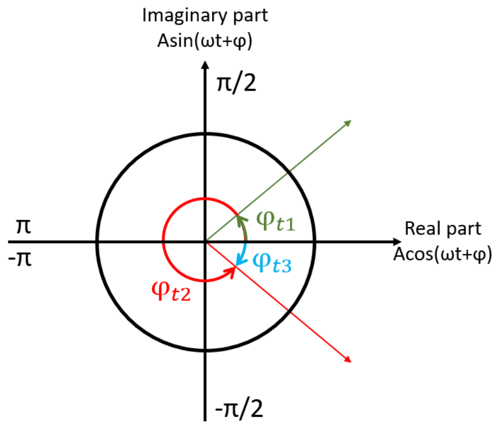

Figure 3. Phase angle change in complex coordinate system.

The phase angle change between the two following samples should not exceed |π|. If so, φ_{t2} is non-distinguishable from φ_{t3}. The exceeding the limit due to the high vibration amplitude during recording is being called saturation effect. Dynamic range can be improved with higher sampling resolution or shorter gauge length. Due to higher sampling frequency, time distance *dt* is shorten, allowing to observe the events of higher dynamics (higher amplitude change in time). Shortening the gauge length limits the part of the fibre from which energy is being acquired (averaged) from.

Exact effect of the gauge length value can be observed in the relation between the angle phase shift and strain [15]:

$$d\varphi = \frac{4\pi G\zeta}{\lambda}\varepsilon \tag{2}$$

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Where dφ is a phase angle shift, G is gauge length, ζ is opto-elastic scaling factor, λ is the operational optical wavelength in vacuum and ε is the strain. Based on the equation (2), we can conclude that the relation between gauge length and phase angle shift is linearly proportional.

3 PROPOSED APPROACH FOR DAS-BASED DIRECT RAIL TRACK STATE MONITORING

3.1 System design

The system in question was deployed on a railway line in south-central Poland to monitor its technical condition and enable the maximum speed of trains to be increased to 250 km/h.

A key objective of the system was to enable multiple fibre optic measurement techniques using a single sensor, making it adaptable to various sensing methods beyond just DAS. This flexibility allows to use other interrogation schemes simultaneously (including for example Brillouin-based strain sensing DSS and Raman-based temperature sensing DTS). In the designed system, it was decided to install two sensors on the side surface of the rail web (Figure 4) in order to add Distributed Displacement Sensing (DSS) functionalities to the system. Knowing the spacing between the sensors, measuring strain distributions over the entire length and assuming relevant boundary conditions, both local curvatures and vertical displacements (shape changes) can be calculated.

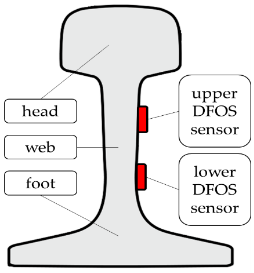

Figure 4. Cross-section of rail with sensors' location.

The sensor integrated into the system is an adjusted version of the EpsilonFlat – the monolithic solution from Nerve-Sensors family. Unlike the standard EpsilonFlat, which utilises two sensing fibres, this modified version employs four fibres, as shown in Figure 5. Table 1 summarises selected mechanical properties of the sensor.

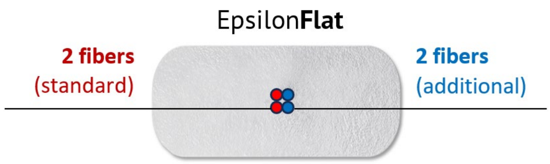

Figure 5. Cross-section of the sensor used in the system.

Table 1. Selected mechanical parameters of the EpsilonFlat

Parameter	Value
Strain range	±4%
Elastic modulus	3 GPa
Bending radius	100 mm

The monolithic core of the sensor, coupled with its flat cross-section, ensures the best possible strain transfer mechanism, resulting in precise and high-quality readings [16]. Low elastic modulus of the sensor itself combined with the elastic glue causes minimal, negligible influence of the sensor on the mechanical parameters of the rail. This design effectively captures and transmits strains with minimal distortion, guaranteeing the accuracy and reliability required for monitoring the rail's performance over time.

Additional fibres within the sensor cross-section allowed for the world-unique approach in system configuration. his adjustment enhances the sensor's versatility, providing additional configuration possibilities to meet the unique challenges of the project. Sensors were delivered on site in 50 m long sections. Two fibres were spliced together creating one long loop to be measured with long-distance interrogators. However, two additional fibres allow for connection of high-spatial resolution interrogators to scan shorter sections with higher precision, if necessary (Figure 6). Is shows, that various measurement devices do not have to compete with each other, but can be used synergistically to expand the diagnostic capabilities of the entire system. While maintaining high-resolution data acquisition capabilities, it is also possible to offer a cost-effective and versatile solution for large-scale monitoring applications.

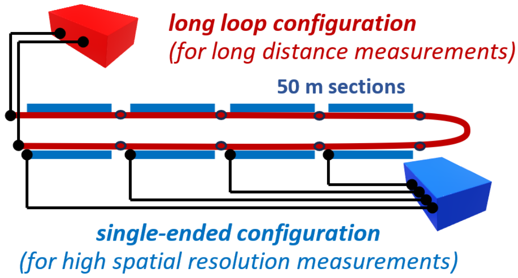

Figure 6. Scheme of the measurement path.

The sensors were arranged in a 2 x 250-metre-long loop, featuring two continuous sensing paths and independent, shorter 50-metre-long sections. Every 50 metres, the sensor paths passed through connection wells, where the necessary connections were made – Figure 7.

Figure 7. Connections between segments of the sensors during installation and the view of the protective well.

This configuration ensured that the system maintained optimal functionality across the entire loop, allowing for continuous monitoring while facilitating easy maintenance and troubleshooting through strategically placed connection points. The segmentation of the fibres into shorter paths also enhanced the flexibility of the system, accommodating long-distance spans without compromising signal integrity or performance.

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Chosen arrangement allowed simultaneous acquisition of dynamic and static measurement data.

3.2 Sensor installation

The installation of the sensor required initial pre-sanding of the rail's side, aimed at achieving proper grip. The goal was to exfoliate only a thin layer of loose corrosion, ensuring minimal impact on the rail's mechanical parameters. This effect was successfully achieved using a water under pressure, a method that provided the necessary surface preparation without compromising the rail's integrity. The selection of materials for the bonding process was critical to the success of the installation. High durability, a low elastic modulus, excellent corrosion resistance, and strong adhesion were essential to ensure the sensor’s secure attachment. To meet these requirements, epoxy-based adhesives were employed for gluing the sensor to the rail. The selection of the glue was preceded by research into various solutions in the laboratory.

To guarantee precision and time effectiveness of the installation, a specialised piece of equipment was designed and developed specifically for this project (Figure 8). The cart system utilises electric motors and pneumatic glue dispensers to ensure an even and consistent application of adhesive. The electric motors power the movement of the carts, enabling precise control over the positioning and alignment during installation.

Figure 8. Semi-automatic rail cart used for sensors’ effective installation along the rail.

This technology allows for a highly efficient, repeatable, and controlled gluing process, contributing to the overall success and reliability of the sensor installation. Before the final application within the operate railway line, the solution was tested on an experimental section of the rail (Figure 9) to better understand on-site challenges and minimise the risk of errors. The success of the installation in Poland allowed for the commercialisation of the cart in Germany and UK.

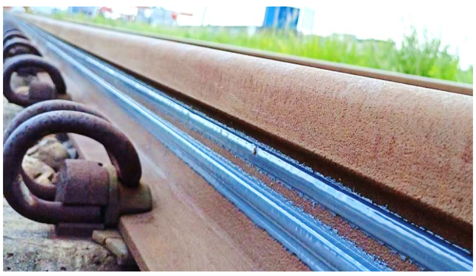

Figure 9. EpsilonFlats after test installation.

The combination of innovative installation technology, high-quality materials, and specially designed sensors resulted in a gluing speed of up to 120 metres per hour. This makes the approach an excellent solution for km-long sections, where conventional manual bonding is very difficult, if not impossible to achieve. In the current project, the total length of 2,200 metres of sensors was installed directly to the rail surface.

3.3 Spatial survey

Chosen configuration of the sensing path, despite of multiple benefits, is also connected with some challenges. Complicated layout requires the proper selection of the active sensing segments (excluding loops, patchcords and pigtails) within the whole optical path. DAS-based interrogators usually operate on spatial resolutions of not less than 1 m. In this scale, it is challenging to clearly distinguish the measurement part of the fibre from the connecting part.

The proposed solution to the problem was to use pigtails (connecting cables between the segments) with different fibre properties, causing the clear differences in the Brillouin signal. To make a detailed documentation of the sensing path, the hybrid Rayleigh & Brillouin interrogator Neubrex NBX-7031 (Figure 10) was used with its backscattering-based mode.

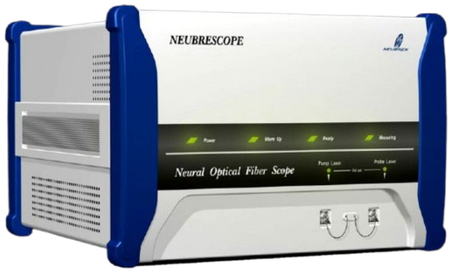

Figure 10. Neubrex NBX-7031 hybrid interrogator.

Brillouin backscattering allows direct fibre parameters identification without necessity of providing reference reading. The Brillouin shift, quantity linearly connected with absolute strain of the fibre [17], allows to clearly distinguish between the measurement sections glued to the rail and free connecting patchcords. – Figure 11.

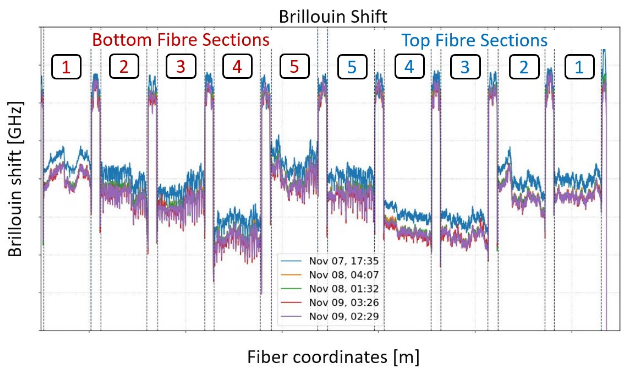

Figure 11. Brillouin Shift measurement results.

Brillouin survey provided very precise information about the exact length of the measurement path components. Proper tuning of the optical device reflection coefficient *ROI=1.468*

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with the coefficient used in DAS interrogator resulted in 1:1 translation of measurement path between the fibres. In the cases where standard methods for spatial surveying may be not efficient enough, shown approach is an ideal solution for self-survey of the sensor.

3.4 Used DAS interrogator and measurement settings

Observing a highly dynamic event, such as the high-speed passage of a train, demands both the highest possible sampling frequency and the shortest achievable gauge length. Achieving this balance is crucial for capturing rapid changes in strain distribution along the fibre optic sensor. There are multiple ways to enhance gauge length, both at the sensor and interrogator levels. For example, one approach involves implementing weak Fibre Bragg Gratings (weak-FBGs) along the entire fibre, which can improve spatial resolution and measurement precision. However, this method is often costly and not universally compatible with all interrogator devices, making it less practical for certain applications. Alternatively, gauge length optimisation can be achieved through advanced signal processing techniques and the use of appropriate interrogation technology.

In the project, the Febus A1 DAS interrogator (Figure 12) was deployed – a device that utilises Phase-Sensitive Coherent Optical Time-Domain Reflectometry (φ-COTDR) to enhance reading quality. Unlike the classical DAS approach, where the injected light pulse is a simple impulse, the Febus A1 leverages optimised coding and signal processing algorithms to improve sensitivity and spatial resolution. This advanced approach ensures reliable interrogation over fibre optic paths exceeding 100 km, while mitigating the risks of signal fading and significant Signal-to-Noise Ratio (SNR) degradation.

Figure 12. FEBUS A1 interrogator.

A key advantage of φ-COTDR in the Febus A1 is its ability to achieve a gauge length as short as 1 metre, a spatial resolution that is typically unattainable with standard interrogators. Conventional DAS systems often struggle to maintain short gauge lengths due to limitations in pulse-based interrogation methods, which can lead to reduced spatial resolution and increased noise. By employing optimized signal processing, the system effectively enhances precision without compromising signal integrity. This feature is particularly valuable for applications requiring highly localised strain and vibration measurements, such as high-speed train monitoring, where detecting rapid structural changes with fine spatial granularity is crucial. This makes the device a perfect choice for railway dynamic monitoring.

For the in-situ testing, it was decided to measure the dynamic passages of the trains using combination of the parameters summarised in the below table.

Table 2. Used DAS acquisition parameters.

Parameter	Value
Gauge length	2 m
Sampling frequency	40 kHz
Channel (gauge) spacing	20 cm

3.5 Methodology of the experiment

To evaluate the performance of the monitoring system in a real-world high-speed scenario, an experiment was conducted using a Pendolino ED250 train. The location of the measurement section was a long, mostly straight section of the railway track. During the experiment, multiple train passages were recorded under varying speeds to assess the system's capability in detecting and analysing strain signals associated with different train dynamics. To minimise the influence of temperature fluctuations on the readings and provide maximally stable conditions, all DAS measurements were conducted at night. The railway traffic was suspended for the duration of the experiment, ensuring an undisturbed testing environment. The measurement crew maintained constant communication with train operators to ensure that the train traveled at the predefined speeds. A total of four test runs were performed at velocities of 200, 220, 240, and 250 km/h within a single night. The time interval between consecutive passages was determined by the necessary stopping, reversing, and re-accelerating of the train to the target speed, with a minimum of 45 minutes between the runs. This ensured that the rails had sufficient time to fully stabilise after each passage, preventing residual strain effects from influencing subsequent measurements. As a reference technique, heavy-duty accelerometers with dynamic range of 50 G and frequency range from 5 to 2000 Hz were employed.

4 RESULTS AND PROCESSING

4.1 Raw data: strain-rates

The raw data recorded by the device is a strain-rate array (Figure 13) at discrete points located in the centers of predefined gauges. Each discrete value represents an average of the rate of strain change along the single gauge length. As the fibre is interrogated as whole, initial processing (or post-processing) has to be introduced in order to cut-out measurement sections from the entire path.

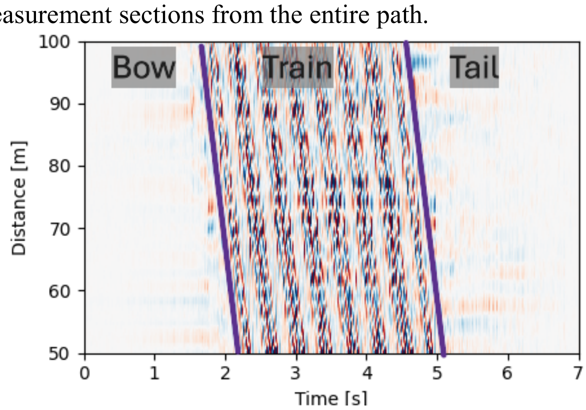

Figure 13. Example strain-rates recorded by the bottom sensor during train passage with 250 km/h speed.

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A recorded image provides high-quality insights into dynamic processes existing in the railway structure during high-speed train passage. Three main zones of the signal may be distinguished. In the bow-zone, a para-seismic wave travelling through the rail may be observed. In the main part of the signal – the train-zone – signal is complex. Eight skew lines on the map represents the moments in time where the wheel bogies of the train were in specific locations along the rail. Number of the lines correspond with number of the bogies. Empty spaces between the lines represents the spans of every carriage between the subsequent bogies. Last zone of the signal is a zone o tail waves, the ones lasting in the structure for some time after the train passage [18]. Overall check at the signal allows to assume that used acquisition parameters, combined with dedicated monolithic-core of fibre optic sensors, resulted with non-saturated, high-quality signal, recorded in extra-ordinary proximity to the strong vibration source.

4.2 Spectral analysis

Distributed Acoustic Sensing can be used as a network of virtual, unit-like channels, each functioning akin to a geophone, measuring strain or displacement at various points along the fibre-optic sensor. The system output can thus be understood as an array of time-series recorded by specific virtual gauges positioned along the fibre, capturing the strain dynamics of the monitored structure. Due to this nature of the signal, any method of classical digital signal processing is valid, allowing for a wide range of analytical techniques to be applied to the DAS data.

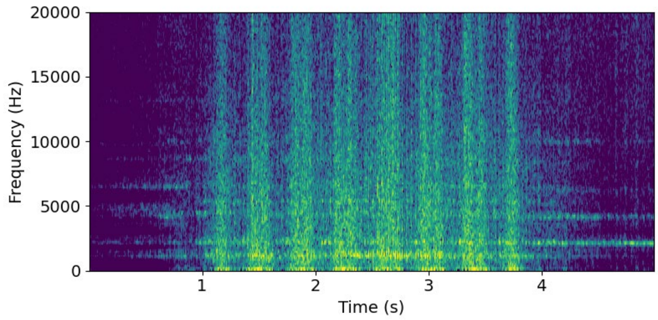

Figure 14. Spectrogram of the single time-series of strain-rate recorded in the middle of measurable section.

The example data presented in Fig. 14 clearly reflects the direct influence of train passage, with distinct frequency components corresponding to the mechanical events. Notably, the spectrogram reveals a predominant contribution from low-frequency waves. This phenomenon is likely linked, inter alia, to a rapid rise in temperature within the rail due to its loading by the passing train, coupled with a relatively slow heat dissipation rate from the rail. The thermal effects associated with the train passage thus become embedded in the strain measurements, manifesting as low-frequency trends.

Given the dynamic nature of the observed event, the authors opted to mitigate the influence of these thermal effects by applying a low-cut Butterworth filter of the third order. The chosen cut-off frequency of 5 Hz serves to effectively attenuate the low-frequency components, which are primarily attributable to temperature-induced strain. This filtering step not only reduces the trend-like behaviour often observed in the integrated strain signal but also compensates for the confounding effects of temperature variations, enabling a clearer view of the mechanical strain caused by the train passage.

This approach illustrates how DAS measurements supported with proper sensors, can be refined to focus on the relevant mechanical signals, removing the thermal noise that may otherwise obscure the true nature of the event under study. While reference measurements using accelerometers were also employed, it is worth noting that these sensors primarily capture signals from 5 Hz and above, aligning with the chosen filtering approach but playing a less central role in addressing the low-frequency thermal effects observed in the strain data.

Deeper understanding of the signal can be achieved by application of the Frequency Band Energy (FBE) analysis. This approach allows for comparison between energy levels in specific frequency bands. The energy E of the discrete, finite-time signal, denoted as x is sum of the signal's absolute value square in proper time t boundaries (3).

$$E = \int_{t1}^{t2} |x(t)|^2 dt \quad (3)$$

Since the total energy remains conserved between the two domains, it is possible to analyse the distribution of the energy across different frequency components by examining the squared magnitudes of the Fourier coefficients. Hence, by summing the squared magnitudes of a specific portion of the Fast Fourier Transform (FFT) coefficients, denoted as X, one can determine the energy contained within a particular frequency f band [19] using equation (4).

$$FBE = \sum_{f_{min}}^{f_{max}} \sum |X(t)|^2 \quad (4)$$

From the Distributed Acoustic Sensing (DAS) perspective, such a method provides the capability to monitor the occurrence of different frequencies along the entire fibre length and provide neat visualisation. This ability is particularly valuable for analysing dynamic changes in the recorded signal and distinguishing specific patterns based on their spectral characteristics. By integrating this approach with the Short-Time Fourier Transform (STFT), it becomes possible to not only categorise signals by their frequency components but also track their temporal evolution, offering deeper insight into underlying phenomena.

In the presented research, the authors conducted STFT analysis twice, utilising two distinct window lengths to maximise the level of detail in signal examination. The first calculation employed a longer window, consisting of 8129 samples – chosen as the eightfold multiple of 1024 – which was specifically applied to the first six bands corresponding to the lowest frequencies. This selection was made to enhance frequency resolution in the low-frequency domain, where finer spectral details are often crucial for accurate interpretation. For the remaining higher-frequency bands, a window of 1024 samples was determined to provide optimal results, balancing time and frequency resolution to ensure a comprehensive and precise analysis of the recorded signal.

Presented results of FBE were calculated from the signal after low-cut filtration introduced previously.

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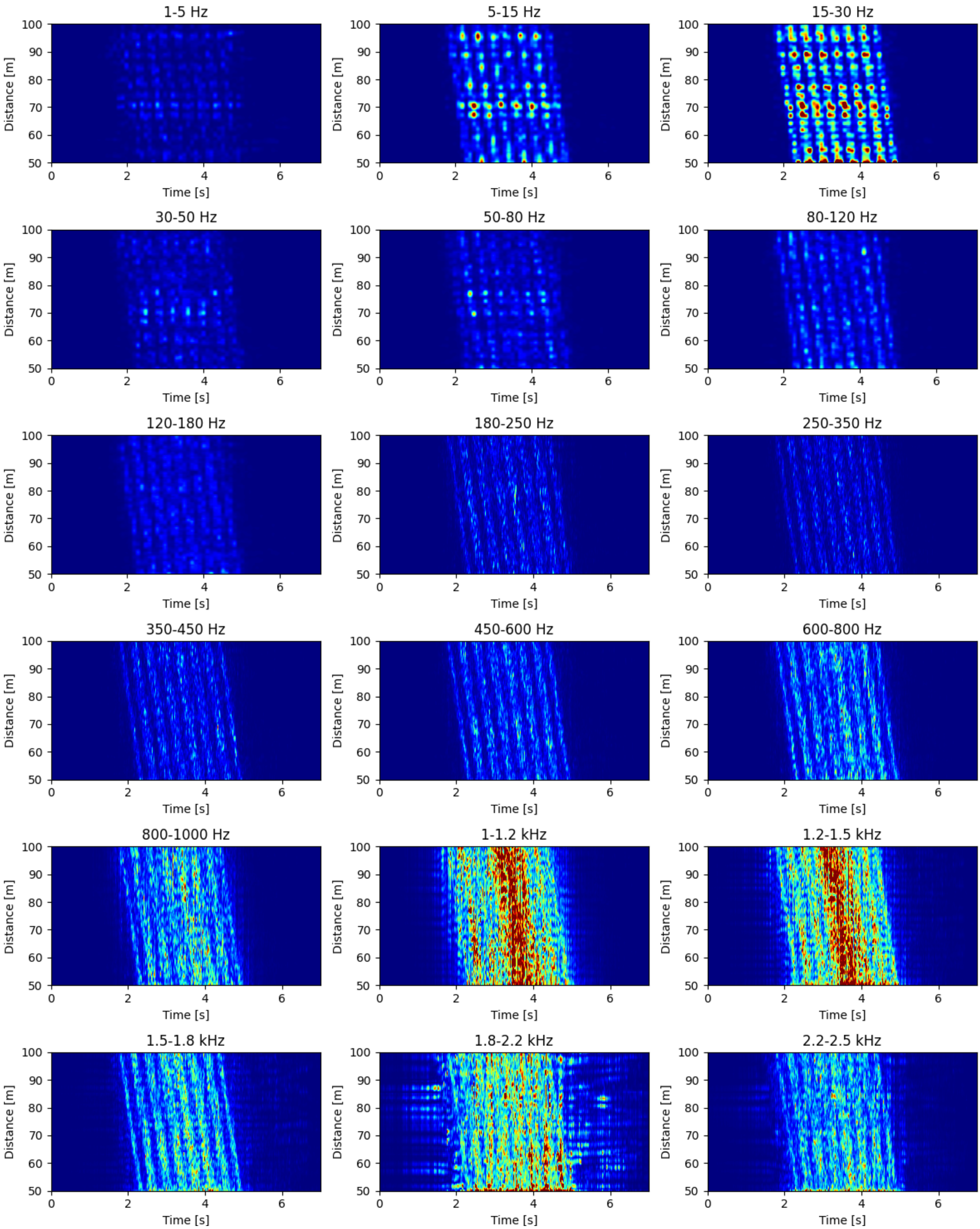

Figure 15. Comparison of energy levels within specific frequency bands.

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When a train travels along the track, various phenomena generate acoustic noise in addition to mechanical changes. The primary sources of this noise include the train's machinery, braking system, and, most significantly, the interaction between the wheels and the rail. Most of these acoustic noises are concentrated at frequencies above 500 Hz [20].

However, noise-induced mechanical vibrations consist of low-amplitude waves with high attenuation, meaning they do not significantly affect the mechanical state of the rail. The authors empirically analysed the entire frequency spectrum and determined that the range of <0; 2.5> kHz is the most relevant, either due to its contribution to overall strain rates or the information it carries. The frequency bands for calculation were selected to maximise information and comparability while ensuring proper coverage within the chosen range. Since energy levels decrease across subsequent bands, the bands were gradually widened to maintain sufficient values for comparison.

The data exhibits a clear pattern, showing that the majority of the signal is concentrated in the low-frequency range, up to 50 Hz. Higher frequencies, up to 600 Hz, contain relatively low energy. A significant portion of the signal consists of acoustic noise. Above 600 Hz, the energy level progressively increases, peaking between 1.1 kHz and 1.5 kHz. In this range, a highly visible noise band appears, particularly around the third and fourth carriages. According to the technical documentation of the Pendolino ED250, this high-noise area corresponds to the placement of traction transformers within the train. These findings highlight the direct relationship between onboard equipment and noise influence on the measurements. Noise-carrying frequency bands in this case are clearly separated from the valuable parts of the signal. With this informations authors decided to apply additional Butterworth low-pass filter of the 3rd order, with cut-off frequency of 1kHz.

Characteristics of the FBE maps allow assumption that wide frequency distribution is connected with wide frequency range of an event rather than with saturation effect occurrence.

4.3 Spectral coherence check

To ensure high-quality measurements, the fibre signal must not be saturated. To verify that clipping due to exceeding the dynamic range does not occur, spectral coherence between collocated channels should be calculated. Authors estimated spectral coherence by the following equation:

$$\gamma^2(f) = \frac{|G_{xy}(f)|^2}{G_{xx}(f)G_{yy}(f)} \quad (5)$$

where G_{xy}(f) is the cross-spectral power density, and G_{xx}(f) and G_{yy}(f) are the spectral power densities of either signal. High coherence ($\gamma^2 \approx 1$) signifies a strong correlation between DAS signals with synchronous recording, while low coherence suggests a weaker correlation or the possible presence of noise caused by signal clipping (saturation) [11].

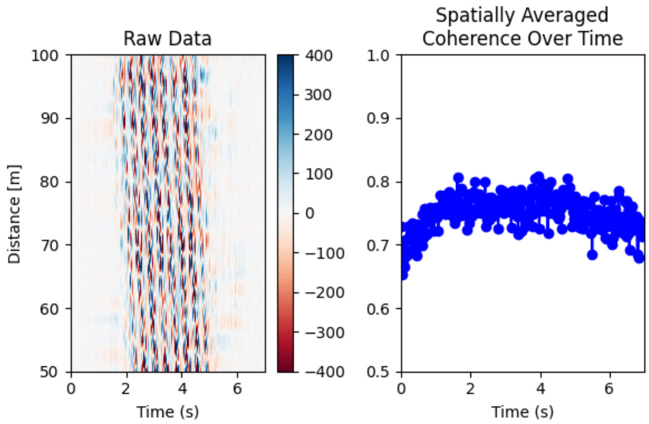

Figure 16. Side by side comparison of the raw strain rate (left) with the calculated signal spectral coherence (right).

Spectral coherence had been calculated between all the following DAS channels with window length of 10^3 samples and presented in Fig. 16. Values on the diagram represent spatial mean coherence from each set of windows. Results show high spectral coherence, mostly > 0.7. High magnitude of spectral coherence between adjacent channels indicates that signal has not been saturated.

4.4 Strain-change and reference check

All DAS interrogators measure the strain change in time. If properly recorded, the strain-rate signal can be integrated over time to reconstruct the train change – a quantity that is more intuitive from engineering perspective and easier interpreted in comparison to direct strain rate signal. Moreover, when considering the Bernoulli hypothesis – which assumes that plane sections remain plane and perpendicular to the neutral axis after deformation – it follows that vertical displacements and longitudinal strains are intrinsically linked.

In the case of steel rails with expected very small displacements (< 1.5 mm), this assumption is especially valid, also due to the high stiffness of the steel and its homogeneity. Consequently, accelerometer measurements, which capture vertical motion, can serve as a reliable reference for strain-based calculations. This interrelation reinforces the validity of using accelerometer data to compare with DAS measurements.

Accelerations *a* measured by accelerometers were integrated twice in time *t* to obtain vertical displacements in specific points.

$$d(t) = \iint a(t)dt \quad (6)$$

As the quantities to be compared are known to be proportional, but exact coefficient of proportion is unknown, only the tendencies were compared. For that sake, values has been normalised and presented in Figure 17.

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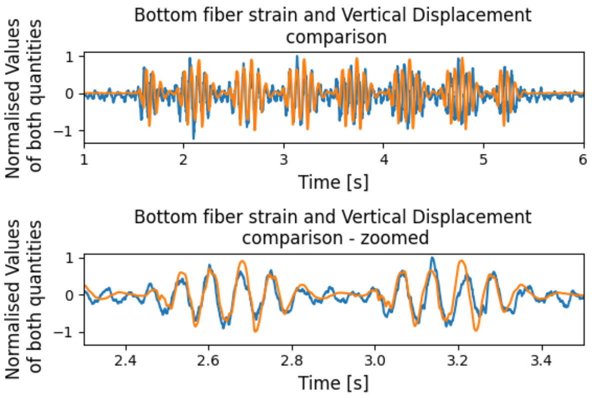

Figure 17. Comparison of DAS-measured strains (blue) with displacements from accelerometers (orange).

The compared data clearly show the expected correlation. Since the sensor is positioned in the bottom zone of the rail, its strain behaviour reflects its location relative to the neutral axis of the rail. In a downward displacement of the rail, the bottom sensors experience positive strain (tension). Conversely, during upward displacement, the same sensors are compressed, resulting in negative strain.

5 CONCLUSION

The study briefly discussed in the article demonstrates a robust approach for direct rail state monitoring using Distributed Acoustic Sensing (DAS) and specially designed monolithic sensors. By directly attaching the sensors to the rail surface, the system is capable of simultaneously capturing both dynamic and static strain data over very long distances using various types of interrogators, including those with high spatial resolution. Experimental results from high-speed train passages validate that the measured strain signals align with classical beam theory: fibres located at the bottom of the rail exhibit positive (tensile) strain during downward displacement and negative (compressive) strain during upward displacement. Furthermore, advanced signal processing techniques, including spectral analysis and energy band evaluations, effectively isolated the mechanical strain effects from thermal influences, thereby ensuring reliable data assessment and interpretation. The innovative semi-automatic installation method significantly enhanced deployment speed and consistency, making the solution both scalable and cost-effective. Overall, the proposed DAS-based monitoring system offers a promising tool for real-time railway infrastructure assessment, leading to improved safety, optimised maintenance strategies, and enhanced operational reliability in rail transportation.

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