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FIBER OPTIC PHASE-BASED SENSOR FOR DETECTION OF AXLES AND WHEELS OF TRAM VEHICLES

This paper presents a novelty approach to usage of the fiber-optic phase-based sensor in railway transportation. We designed and tested the real deployment of this sensor working on the principle of light interferences within optical fibers. The proposed construction of the sensor allowed to increase the sensitivity and thanks to this can be detected and calculated individual axles and wheels of tram vehicles. We performed long-time period measurements (April to September 2019) in diverse climatic conditions, including measurements of 642 tram passages (several different construction types) in real urban traffic. The detection accuracy level was slightly above 99.4 %.

Keywords: *vehicle transport, fiber-optic, sensor, interferometric sensor, Mach-Zehnder*

1 Introduction

In order to maintain the safety of railway operation (tram or train), it's necessary to know the exact position and number of carriages within a rail vehicle. Nowadays, wheel detectors or axle counters are used for this purpose. They are characterized by relatively old technology methods with gradual descending reliability. Since these methods do not meet the contemporary criteria, many research teams try to find alternative approaches. One of them - fiber-optic sensors - seems to be a potential solution.

Research cooperation between the Faculty of Electrical Engineering and Computer Science (Czech Republic) and Faculty of Operation and Economics of Transport and Communications (Slovakia) has brought several interesting research outputs in this field [1-4]. This paper directly follows and extends our previously published study [2] in which we present interferometric sensor primarily used for tram vehicle detection, as well as for detection of frequencies generated during trams passage. We point out the ability to detect individual tram axles. Since the sensor sensitivity was originally not created for the detection of wheels and axles, the detection veracity was low (less than 50 %). Figure 1 shows the comparison of the tram (the same type of tram) passage detection obtained through the sensor described in the paper [2] and via the same sensor [2] in another day (individual axles cannot be identified).

It can be seen that the sensitivity of the sensor is not sufficient, and influences like the weather (the stronger wind is sufficient) can cause those individual axles cannot be detected with a high success rate.

In the traffic industry, fiber-optic sensors represent an alternative monitoring technique used to analyze basic parameters such as vehicle detection, traffic density, speed measuring or even vehicle weighing. The main advantage of these sensor types lies in their small size and weight. If suitable materials are used, the sensors are resistant to electromagnetic interference (EMI). They also offer a possibility of remote measuring evaluation (place of measurement is separated from the place of evaluation) with regards to the power of radiation source and attenuation of a connected optical fiber (between the sensor and evaluating unit). The telecommunication sector has brought significant development of optical fiber components and items of which most can be used for sensor applications. Therefore, the final price of the proposed sensor system is admissible.

2 State-of-the-art

In this section, we provide an overview of sensor types oriented to railway transportation. Monitoring of the track occupation was the primary task of sensor deployment in this sector. The classic approach uses track circuits and operates on the principle of separated parts of track division (so-called blocks). When a train is passing via the block, a circuit is created between the

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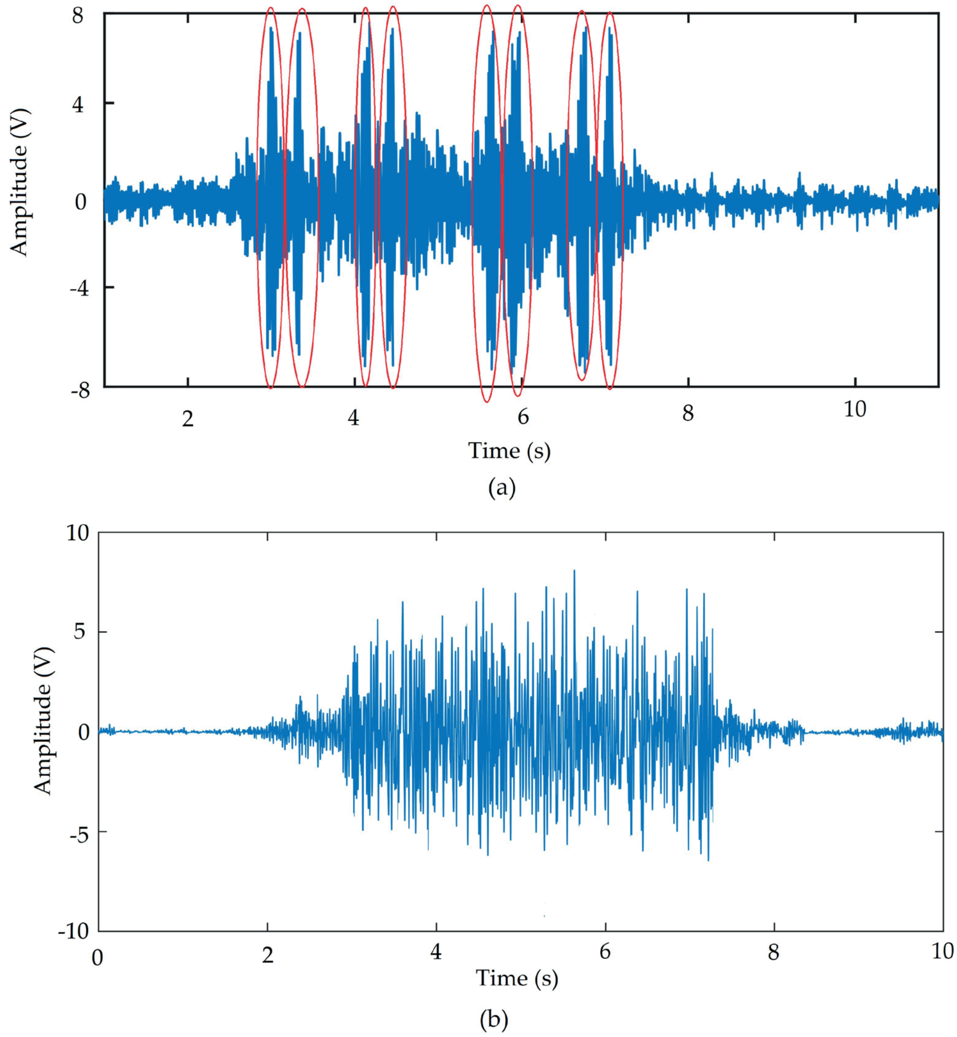


Figure 1 *Comparison of tram vehicle detection; (a) successful tram axles detection described and presented in paper [2], (b) results from another day recorded by the same sensor presented in paper [2] (individual axles cannot be identified)*

rails, which leads to recognition of the train within the block [5-7].

Another solution is based on wheel detectors or axle counters that require the flange for contact connection. This system is typically used not only for train identification, but also for detection of speed and direction [8-10]. The Light Detection and Ranging (LIDAR) instrument (installed close to the rails) emits rapid laser signal (thousands of pulses per second) and gathers signals bouncing back from obstacles. This tool can measure the train speed, the curvature of the track or the train position [11-14]. The European Train Control System (ETCS) is a current signaling and controlling system. Transceiver Eurobalise is installed between rails of each track. This element transmits information to the train, and it is energized by the power from the train antenna [12-14].

Only a few published papers have focused on the usage of fiber-optic interferometric sensors for traffic applications so far. An interesting study is presented in [15], in which the authors show measurements from a fiber-optic interferometer to detect trains in the Prague subway system. The measuring arm of the interferometer was fixed on the glass pad, and the authors proclaimed that they reached a higher sensitivity level. The research papers [16-17] proposed a system based on 5three-armed Mach-Zehnder interferometer consisting of one or more passive fiber trackside sensors and x86 family of instruction set architecture microprocessor. The system is able to measure traffic density within the rail transportation. In a study [18], a research team led by professor Li used fiber-optic Michelson interferometer for tram detection. With a total of 1435 passages in a selected tram, they obtained a 100 % success ratio. Paper [19] deals with an acoustic fiber-optic sensor for monitoring of the railway network from an extensive distance grounded on an interferometric connection. The paper [20] pointed out the use of a fiber-optic interferometer for the perimetric applications. The authors created a sensor based on the Mach-Zehnder interferometer to detect vibration response generated by people moving around the sensor. According to the authors, sensor can be useful for traffic density monitoring, but it has not been tested in real situations yet.

A notable contribution was presented by the paper [21]. Its authors used the interferometric sensor for the

***Table 1** Summary of the basic parameters of the mentioned fiber-optic sensors*

Type of sensor	Frequency range (Hz)	Size (mm)	Weight (kg)	Price ($) Sensor
Actual	4-160	400 x 350 x 95	1.4	350
from paper [2]	2-100	500 x 500 x 130	3	500

utilization of road information, such as vehicle type or its speed. Optical fiber had been fixed on the road surface, and in order to increase the sensitivity, an optical Fabry-Perot (F-P) fiber interference was selected. None of the above-mentioned publications is primarily focused on the detection of individual axles or wheels of tram vehicles with regard to fiber-optic technology.

Our paper proposes innovative interferometric sensor based on Mach-Zehnder two-armed interferometer, when by the specific construction of measuring and reference arms, storing both couplers, and innovative design changes of the sensor measuring part led to increased sensibility in such a level that individual axles of tram vehicles could be detected with high accuracy of more than 99 %. Sensor functionality was performed by a long measurement period lasted for 17 days in various climate conditions, observing 642 tram vehicle passages in real urban traffic of Ostrava city (Radvanice street, Czech Republic). As shown in the results below, the success rate of the detection of individual axles was 99.46 % regardless of the type, weight, and length of the tram vehicle.

Below we present the basic parameters of the proposed interferometric sensor in Table 1. This table shows the comparison of construction parameters and total prices. Our novel proposed sensor has a higher frequency range while having a smaller size and less weight than the sensor mentioned in paper [2]. Also, the price is lower due to changes in sensor design (the price is calculated based on the choice of individual components that were purchased individually).

3. Methods

3.1 Fiber-optic interferometry background

The interferometric sensors are based on the well-known physical phenomenon called interference. The practical output of this paper lies in a two-arm interferometer that allows detecting superpositions of two waves that have traversed various distances while having different phases. We distinguish three basic parameters which can influence the result phase changes according to the Equation (1):

$$\Delta\varphi = 2\pi\frac{n}{\lambda}\delta L + 2\pi\frac{L}{\lambda}\delta n - 2\pi nL\Big(\frac{1}{\lambda^2}\Big)\delta\lambda\,. \qquad (1)$$

Based on the above, wave phase $\Delta\varphi$ change depends on the length of L path, as well as on refractive index n and wavelength λ. As for the Equation 1, its first and second parts describe phase changes in measuring arm, while the third part explains phase changes caused by the source of radiation.

The following equations are related to the Mach-Zehnder type interferometer (hereinafter referred to as M-Z). The input intensity of the M-Z type interferometer that has been used is specified by the Equation 2, and it is related to an electrical current that uses the optical sensor also known as a photodetector.

$$I = 2I_0\Big\{1 + \cos\Big[\frac{2\pi}{\lambda}n(L_1 - L_2)\Big]\Big\}, \qquad (2)$$

where L_1 and L_2 represent the length of measuring and reference arm of the proposed sensor. The expected signal (caused by the passing tram vehicles generating low vibration frequency response ω) on the output of the photodetector can be expressed by Equation 3:

$$i = \varepsilon \times I_0\alpha\cos(\varphi_d + \varphi_s \times \sin\omega t), \qquad (3)$$

where ε represents the sensitivity of the photodetector, I_0 represents the medium signal value, α represents losses (primarily caused by the instability of the light polarization) on the interferometer, φ_d represents the changing phase shift, φ_s is the duration of the amplitude, and ω represents a low vibration frequency response applied to the measurement arm of interferometer [22-24].

3.2 Proposed interferometric sensor and evaluation part

Figure 2 shows a diagram scheme of the proposed interferometric system. Used 3 Hz high-pass filter (HP) was used to filter out the DC (direct current) and low frequencies (temperature influences). Diagram scheme further consist of photodetector PbSe (photoconductive lead selenide photodetector), DFB (Distributed Feedback) laser (LD) with central wavelength 1550 nm and output power of 10 mW, and an A/D (Analog/Digital) converter (type NI-USB 6210 measuring device by National Instruments with sampling frequency 500 S/s).

The published results derived from our papers [1-4] served as a basis to design a part of the sensor. In these papers were tested various covering and damping materials for reference arm, as well as different fiber protection, and suitable forms of photodetectors and lasers. Innovative aspects in this paper related to the proposed sensor include:

1. Storing of the measuring (spiral) and reference fiber (spiral).
2. Storing of both couplers.

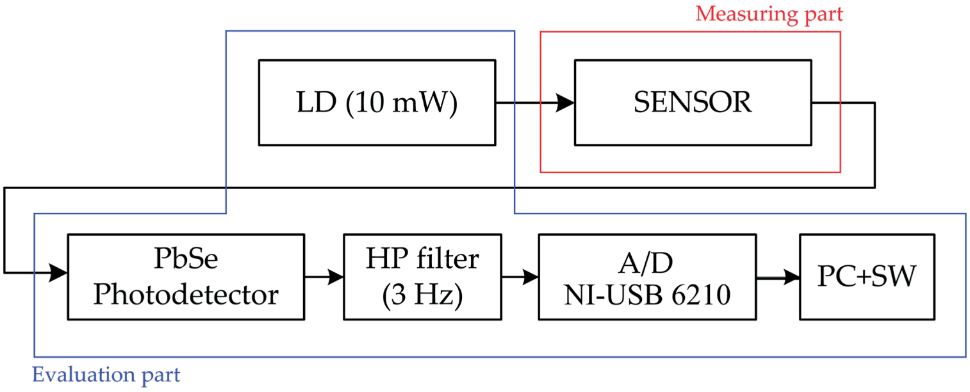
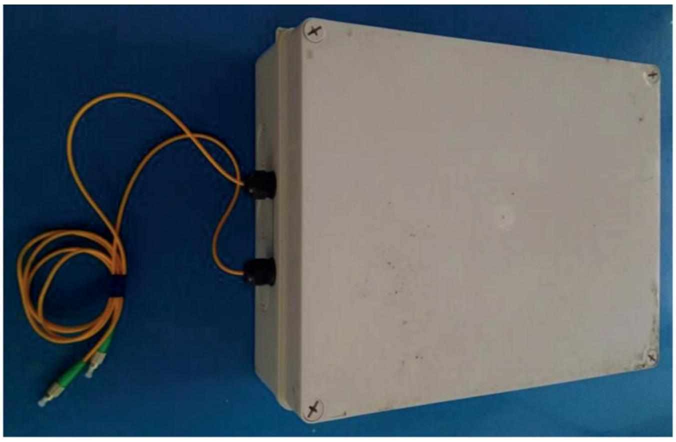
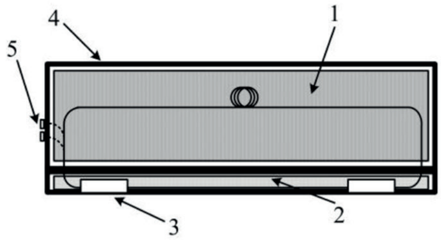


Figure 2 *A diagram scheme of the proposed interferometric system*



a)



b)

Figure 3 *a) A photo of the proposed interferometric sensor; b) diagram scheme of the proposed interferometric sensor Numeric signs explanation: 1. Reference part (height 8.5 cm), 2. Measuring part (height 1 cm), 3. Both couplers, 4. Protective PVC waterproof box, 5. I/O interface (FC/APC connectors).*

3. Modified length of measuring and reference arm to 3.5 m.
4. Complete encapsulation of the measuring part into one cm high epoxy resin layer.
5. Removing the glass pad (resonator) that was part of the measuring section [2] - now the measuring arm is stored on a 1 mm thin PVC (polyvinylchloride) layer (based on the laboratory measurements), from which the waterproof protective box is made.

Applying of this construction design solution allowed us to reach such a level of sensor sensitivity increase, that even simple two-arm interferometer could detect individual tram vehicle axles (including tram wheels). In our design model, we chose classic telecommunication fibers of G.653 type. The input and output interface was created by screwing connectors FC/APC that secured fixed connection and minimal attenuation. Based on the previous research [4] and [16], we decided to use optical couplers with a coupling ratio of 1:1 (tolerance +/- 5 %). The prototype was covered with a waterproof box. A software application has been developed and enhanced [2] for processing and visualization of the measured data within the LabVIEW environment (National Instruments, Austin, TX, USA). The application loads raw signal from the measuring card, the next step is processing part (filtering of signal to eliminate the noise is included), the final output is a tram passage recording as depicted in Figure 6 and 7 in time and frequency domain. A prototype of the created interferometric sensor is shown in Figure 3.

The most significant construction change was the creation of separate segments for both measuring and reference parts, with both couplers being moved into the measuring part. This solution helped us to achieve higher phase differences between the measuring and reference arms of the interferometer. Measuring part was completely encapsulated into a 1 cm high layer made from epoxy resin, which resulted in maintaining the optimal ratio of Young's modulus of elasticity and density, as well as effective transmission of vibration-acoustic response induced by tram vehicle passage via the measurement fiber.

4 Experimental measurement

The experimental measurement took place in the peripheral part of Ostrava city (Radvanice), where we had official approval to conducted real measurements. The measurements were performed under the various climatic conditions (measurement period lasted from April to September 2019). Figure 4 shows the measurement

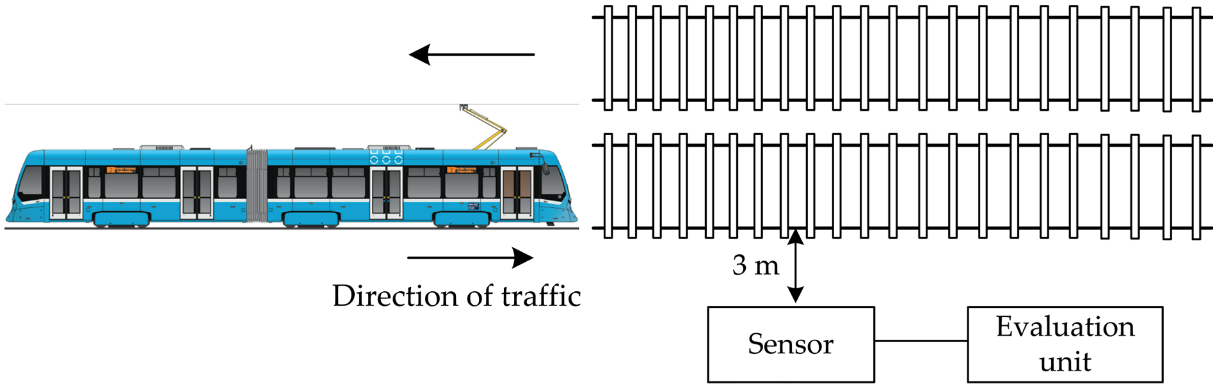
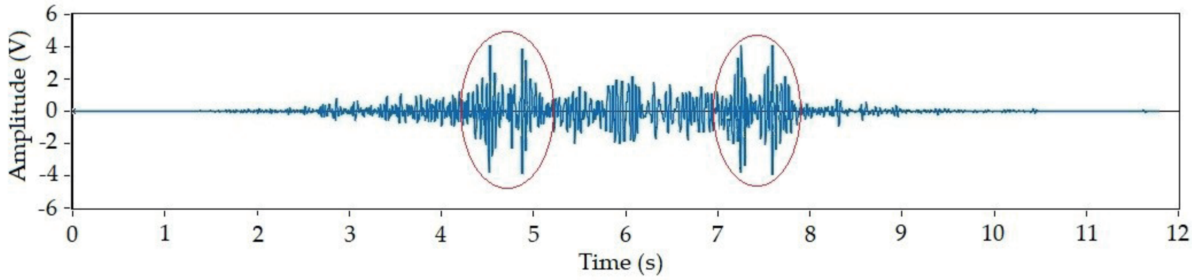


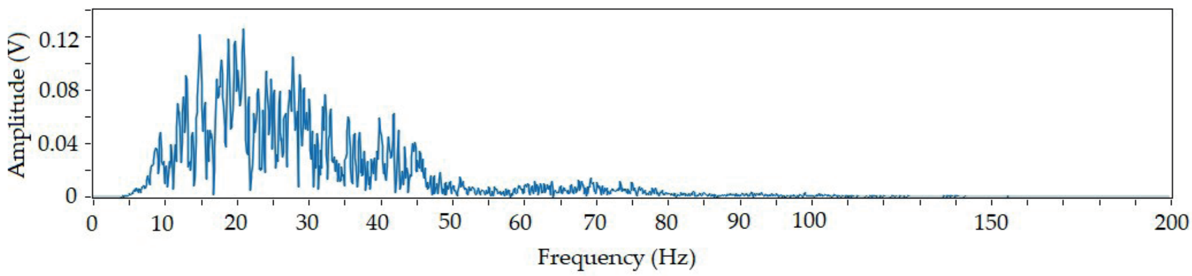
Figure 4 *A diagram scheme of measuring situation*

a) *b)* *c)*

Figure 5 *Tram vehicles photos were taken during the measuring process (the red circle labels the position of the sensor)*



a)



b)

Figure 6 *Recording of passage for tram vehicle with two axles, respective 4 wheels (type Vario LFR);*
a) time record b) frequency record

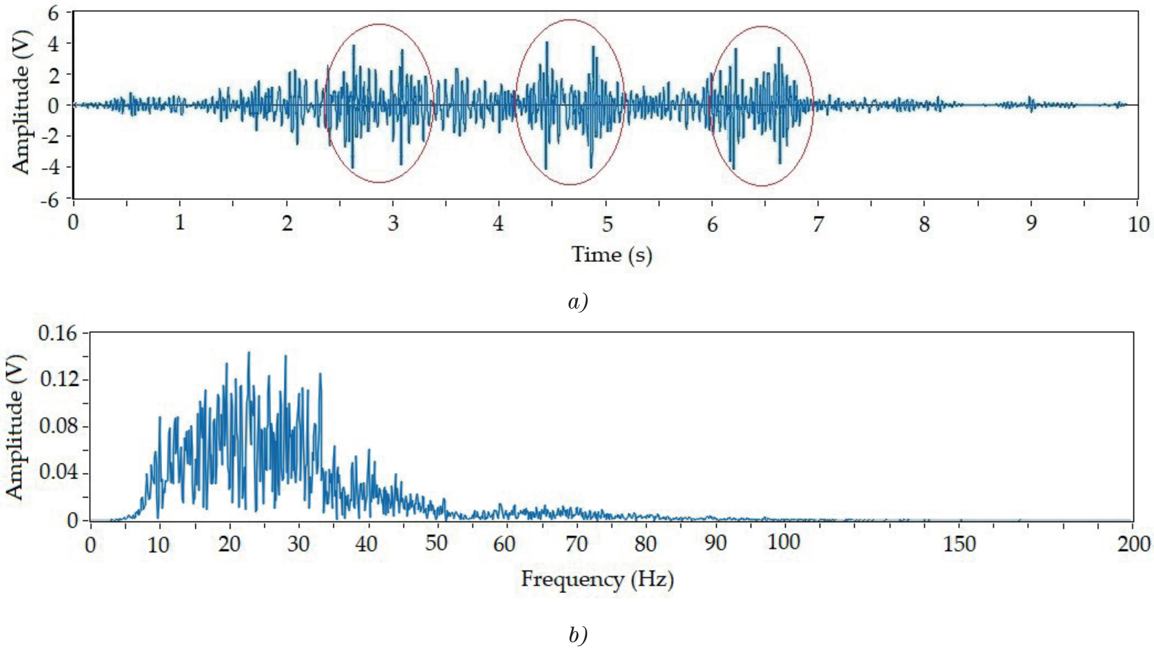


Figure 7 *Passage recording for tram vehicle with 3 axles / 6 wheels (type Stadler Tango NF2); a) time record b) frequency record*

scheme. Tram vehicles speed was reaching 40 - 75 kph (in accordance with the infrastructure limits). Distance between the sensor and the rail foot was set to 3 m. This parameter had been defined as a minimum value for safety operation by Czech technical standard (see CSN 31 1500, second edition) [25]. Three types of tram vehicles operated on this testing path, namely Vario LFR (a), Stadler Tango NF2(b) and Inekon 2001 TRIO (c) with 2 or 3 axles (4 or 6 wheels). Figure 5 shows real photos of these tram vehicles taken during the measurement period. Measurements were performed on the rail closer to the sensor, as depicted in Figure 4.

The interferometric sensor is placed on the left bottom (red labelled), 3 m from the rail foot (Figure 4). During all measurements, the individual types of tram and the number of wagons were calculated manually (reference), detailed information about the tram axles and wheels is freely accessible in [26]. The detection was considered successful when the sensor detected not only axles but also the number of wheels for each axle.

Figure 6 (a) shows an example of the time recording of passage for tram vehicle with 2 axles (4 wheels). The X-axis represents the time (s), Y-axis reflects the voltage amplitude (V), and it is directly proportional to light intensity caught by the used photodetector. Individual maxima (red labelled) indicate the axles (number of wheels) of the individual tram vehicles. Figure 6 (b) shows the measured frequency spectrum for individual tram vehicles, and its values correspond with the standard published in [27].

This standard defines the frequency range which can be generated by rail vehicles during their passage, as presented in paper [2]. In this case, X-axis represents the frequency (Hz) and Y-axis represents the voltage amplitude (V).

Figure 7 (a) shows an example of the time recording of passage for tram vehicle with 3 axles (6 wheels). The graph shows 3 groups with 6 individual maxima, each one corresponding to 1 wheel. Figure 7(b) depicts the measured frequency spectrum that corresponds with the values presented by the technical standard in [27].

It is obvious that our proposed sensor is able to detect individual axles and wheels with sufficient accuracy (please see summary in Table 2). The individual maxima (Figure 6 and Figure 7) correspond with the number of wheels. Table 2 summarizes the measurement results, measurement dates, as well as the weather conditions (we defined 4 basic types: sunny, cloudy, windy and rainy), further Number of passes (-) of trams, Wrong detection (-) and Detection success (%).

5 Discussion

While performing the measurements, we identified certain limitations. If tram vehicles meet at the measurement point (passing in the opposite direction), sensor does not have to distinguish individual axles successfully. This case happened only two times during the whole measurement period. In case of bad weather (heavy rain and windy), from the obtained signal, we were not able to recognize the individual axles. This also happened two times. Since the testing was done from April to September, we did not have a chance to test the sensor in winter conditions. We plan to continue with the data collection and prepare our system for adaptation in low temperatures and snow cover, which is going to be the primary task of our next study.

Given the fact that the proposed sensor consists of conventional fibers and FC/APC connectors, it could be

***Table 2** Summary of realized measurements*

Day / Month / Weather	Number of Passes (-)	Wrong Detection (-)	Detection Success (%)
1 / April / cloudy	38	0	100
2 / April / windy	41	0	100
3 / April / sunny	36	0	100
4 / May / rainy	44	2	99.12
5 / May / rainy	28	0	100
6 / May / sunny	17	0	100
7 / June / cloudy	29	0	100
8 / June / sunny	47	1	99.53
9 / July / sunny	53	0	100
10 / July / sunny	25	0	100
11 / July / sunny	36	0	100
12/August / cloudy	39	0	100
13 / August / sunny	43	0	100
14 / August / sunny	52	0	100
15 / September / rainy	56	0	100
16 / September / windy	31	1	99.69
17 / September / windy	27	0	100
Summary	642	4	99.37

connected to dark telecommunication fibers along the rail infrastructures. Measurements evaluation could be performed remotely (laboratory tested distance was up to 2 km), the main limitation here would primarily be related to the fiber type for interconnection between the sensor and evaluation unit, and also to the power of radiation source. The improved sensitivity to axle detection is significantly higher in comparison to the sensitivity presented in our previously published paper [2]. Innovative construction led to an increase in the frequency range, but also to weight, size and price reduction. Another important advantage of our solution is that the system does not require installation into the rails (in comparison to other conventional systems [5-7]). During the measurements, we had to observe the minimum distance of 3 m from the rail according to [25], but a higher sensitivity of the sensor can be expected if the sensor will be placed closer to the rail.

Our future plans include the detection of flat wheels because this is the current and discussed topic. Flat wheels can cause travellers' discomfort and damages to tram axles [28-29].

The sensor has been tested in tram traffic; we assume that it will be possible to use it in classic train traffic (it is problematic to obtain a permission for measurement). Also, this will be one of the primary tasks of our next study.

6 Conclusion

This paper deals with the alternative usage of fiber-optic technology in the public transportation sector, especially for the detection of axles and individual wheels of tram vehicles. We have proposed an interferometric phase-based Mach-Zehnder sensor which works on the principle of light interferences within optical fibers. We performed real deployment based on the measuring of 642 tram vehicles during the long-time period of April - September 2019 in different climatic conditions. The successful detection rate of axles and wheels reached above 99 %. Characteristic features of the proposed solution are low price, practical construction, as well as the possibility to evaluate remotely information thanks to the connection via dark optical fibers located alongside the rail infrastructures.

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