Fiber-optic Bragg Sensors for the Rail Applications

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***Abstract*—The publication describes the use of fiber-optic sensors in the rail applications. We created a measuring system and sensor based on the fiber Bragg gratings (FBG). The basic tracked parameters of vehicles are detection and speed. The proposed system was tested in the real tram traffic. The system is characterized by a detection capability of 100 %, speed measurement is characterized by an absolute error of + - 3 kph. Sensors can be connected to existing city fiber networks. Information could be remotely processing because the spectral evaluation of sensors is not limited by the output power of the radiation source.**

***Index Terms*—Bragg grating, rail monitoring, optic fiber sensor**

I. Introduction

This publication describes the use of fiber-optic technology and its practical testing in urban tramway traffic. Comparison of the proposed solution with today's known functional solutions or patent writings from the field of fiber-optics shows that none of the systems is primarily designed as a source of information and traffic control signals, respectively for measuring partial parameters such as detection or speed of the rail vehicles. In essence, they are always diagnostic and tracking systems. However, some research and development organization dedicated to this area such as Polytechnika Hongkong, ZG Optique, Frauscher, ESIN Group, Hanning and Kahl, etc. [1]. Among the publications outputs focused on fiber-optic technology can be included distributed systems for measuring mechanical stress. The essence of measurement is the measurement of the Brillouin frequencies. These frequencies are dependent on the mechanical stress of the fiber and at the same time on its thermal stress. The result is a spatial specification of stresses along the length of the rail track [2-6]. Optical sensors and active infrared sensors work on the principle of transmitting and receiving optical beams (laser or infrared) between two reference points (consisting of a transmitter and a receiver). In case of placing two sensors at a defined distance, the speed of passing vehicles can also be analyzed [7-8]. The most widely used fiber-optic applications in rail transport include the use of Bragg's grilles. The mass of the train shows a significant deformation that acts on the rail tracks, the track sleeper or other elements that serve to hold the rail. This force generates the deformation stress that decomposes in the rail and causes places with expansion, neutral state or compression. Some experimental results verifying the use of Bragg sensors in train transport are described in the publications [9-16]. Verification within the tram traffic is provided in this article.

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II. Fiber Bragg Grating

Optical fibers are used primarily for telecommunication applications. Recently, optical fibers have been to be used in sensory applications too. A large group of fiber-optic sensors represents one-point Bragg gratings. Bragg grating is formed by the periodic change of refractive index in core optical fiber. This periodic change is written by UV laser into photosensitive optical fiber doped with germanium. Structure of Bragg grating reflects narrow spectral band and other wavelengths are transmitted. The Central wavelength of the reflected spectral band is called Bragg wavelength λ_B and is given by the equation:

$$\lambda_B = 2n_{eff}\Lambda, \tag{1}$$

where n_{eff} is an effective refractive index of Bragg grating structure, and Λ is a period of refractive index changes in core optical fiber. Structure of Bragg grating is shown in "Fig. 1."

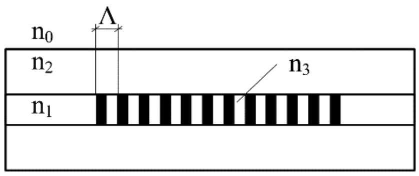

Figure 1. Structure of Bragg grating in core optical fiber.

The period of refractive index changes and effective refractive index depend on temperature change and deformation effect by the following equation:

$$\frac{\Delta\lambda}{\lambda_0} = k\varepsilon + (\alpha_\Lambda + \alpha_n)\Delta T, \tag{2}$$

where $\Delta\lambda$ is change of Bragg wavelength, k is the deformational coefficient, α_n is the optical temperature coefficient, α_Λ is the coefficient of thermal expansion, ΔT

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is the temperature change and ε presents applied deformation. [17]

The Bragg gratings have a temperature sensitivity of 10.35 pm/°C and a strain sensitivity of 1.21 pm/μstrain at a wavelength of 1550 nm. To increase the temperature sensitivity, the Bragg grilles are encapsulated in materials having a higher thermal expansion than the siliceous glass itself. In the case of a capillary steel tube, the temperature sensitivity was increased to 21.3 pm/ ℃, with the metallized tube 28.3 pm/ ℃ and with the organic polymer tube up to 137.6 pm/ ℃ [18-22].

III. Experimental Setup

For a better understanding and analysis of the distributed forces, a self-analysis was carried out, verifying the distribution or the effect of the deformation forces on the rail. We implemented a strain gauges sensors with resolution at the level of 1 μstrain, please see Fig. 2. The rail was strained within a press machine with a maximum load of 360 kN. The level of deformation forces, expressed in units of μstrain within the various strain gauges sensor positions, is shown in the "Fig. 3."

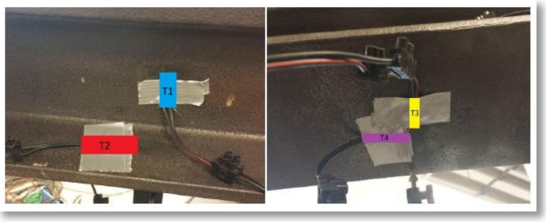

Figure 2. Location of the strain gauges: on the stand (T1) at the bottom of the longitudinal T2, at the bottom of the rail transversely (T3) and longitudinally (T4).

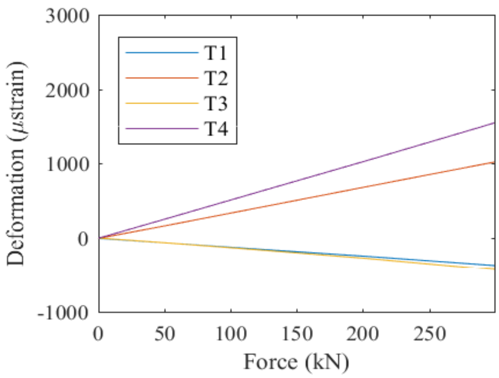

Figure 3. Level of deformation forces within the different strain gauges sensor positions.

Verified were the best positions or places for the location of the sensors, which had the most deforming effects. Because implementation on the bottom of the rail is problematic and from a real point of view it would be a very complicated solution, a place marked T3 was chosen as the starting point.

Implementation of Bragg sensors on the rail is shown in "Fig. 4." To measure the speed, the sensors were identically implemented at a distance of 10 m from each other. The sensors were attached with two-component adhesive.

Figure 4. Implemented FBG sensors on the rail.

A. Vehicle Detection

On the basis of the results described above, a series of measurements in the real tram traffic was carried out. Practical measurements of tram detection were conducted in the town Ostrava, more precisely in the part of Dubina and Hrabuvka after agreement and training by the transport company, which ensures the operation of tram cars.

A series of 13 measuring days was carried out after within 6-hour interval. The typical course of the recorded vehicle passage is shown in "Fig. 5." This is a filtered waveform showing the load on the first axle of the vehicle.

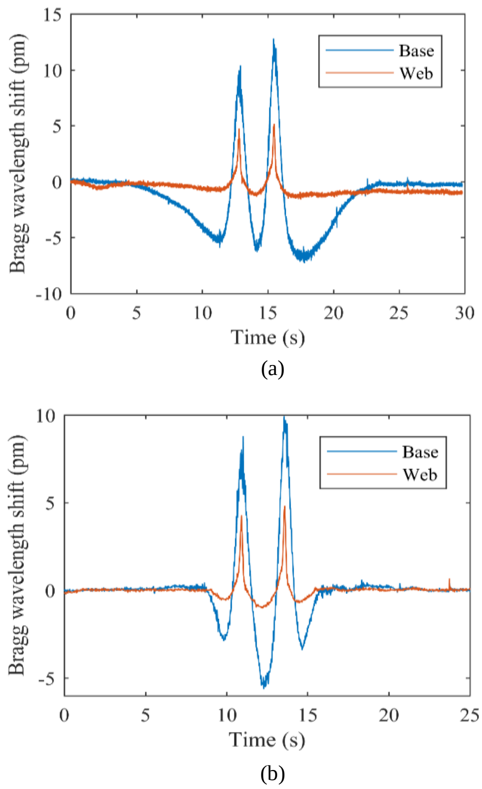

Figure 5. Typical course of recorded vehicle passage (a) without compensating of temperature influence (b) after compensating of temperature influence.

Table I takes into account the experiments performed within all measurement days. It can be seen that the detection of the vehicle was 100 % in the all measurement days. This is due to the big mass of the vehicles in the order of units to tens of tons.

TABLE I. SUMMARY OF VEHICLE DETECTION

Measuring day	Number of passes (-)	Detection rate (%)
1.	136	100
2.	142	100
3.	141	100
4.	159	100
5.	139	100
6.	154	100
7.	68	100
8.	76	100
9.	162	100
10.	155	100
11.	139	100
12.	143	100
13.	127	100

B. *Vehicle Speed Measurement*

Practical measurements of tram speed measurements were conducted also in the town Ostrava, more precisely in the part of Poruba and Pustkovec after agreement and training by the transport company, which ensures the operation of tram cars.

A series of 13 measuring days was carried out after within 4-hour interval. The typical course of the vehicle speed is shown in “Fig. 6.” This is a filtered waveform showing the load on the first axle of the vehicle.

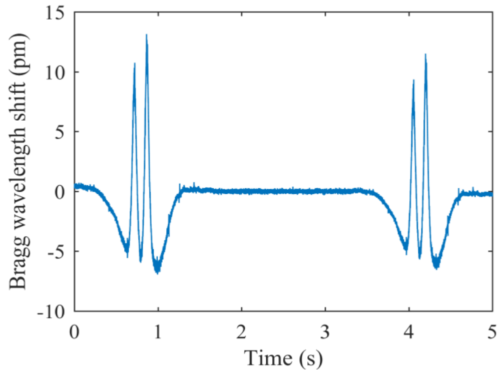

Figure 6. A typical course of the vehicle speed.

Vehicle speed was determined based on the known length, i.e. the location of the sensors apart and by the time span of the passage of the vehicle, see the relationship:

$$v = \frac{s}{t}, \tag{3}$$

where s is distance between sensors and t is time passing between the sensors.

Table II takes into account the experiments performed on all measurement days. It is obvious that the speed measurement is characterized by an absolute error of ± 3 kph.

TABLE II. SUMMARY OF VEHICLE SPEED MEASUREMENT

Measuring day	Number of passes (-)	Absolute error (kph)
1.	112	0.58
2.	123	2.18
3.	113	1.64
4.	137	1.33
5.	123	1.75
6.	127	2.56
7.	52	1.57
8.	63	0.01
9.	154	1.66
10.	142	1.36
11.	128	1.21
12.	124	2.21
13.	114	0.10

IV. CONCLUSION

This article describes the use of smart fiber-optic Bragg sensors in tram traffic. The system is characterized by a detection capability of 100 %, speed measurement is characterized by an absolute error of ± 3 kph. Fiber-optic sensors can be considered between smart sensors for several reasons. Many quantities can be analyzed and measured simultaneously (speed, detection, track deflection, direction, weight, etc.) using only two sensors. Sensors can be connected to existing city fiber networks. Information could be remotely processing because the spectral evaluation of sensors is not limited by the output power of the radiation source.

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