In situ testing of rail damages in accordance with Industry 4.0

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Abstract. The railway is a very important segment of the public transport and therefore its part of the critical infrastructure system. The speed of the trains depends on the rail conditions. The state of the rails needs continuous control to determine the train speed and continuous traffic and transport. The goal of the Industry 4.0 is to build a smart industry and industrial environment [1]. Part of this smart system is the traffic and the transportation on road and railway too. The continuous railway transportation needs quality railroads and trains. The rails have complex load during their lifetime. In this research, we wanted to find a test method and innovate an experimental setup for the continuous state control of rails. In our work, we wanted to find a relationship between propagations of the rail surface damage and the loads. Also based on failure propagation rules we wanted innovate a special installation for in situ monitoring the process of the rail surface damage, predict the defects and crack propagations. This work is in accordance with the aim of the Industry 4.0.

1. Introduction

Nowadays the railway transport innovation is very important part of the engineering profession in Hungary and in the world. When we talk about railroad, we can separate the problems in two parts, one is the rail substrate and the other is the rail material. Nowadays for rail we usually use hot rolled rail steel in pearlite microstructure. Based on the knowledge of the wear process we know that the chemical composition and the microstructure are also relevant parameters. We also know the correlation between the wear resistance and the hardness, which depends on the heat-treating process in case of steels [2].

We focused in this article on the load of the wheel rail contact and the surface of the rail (Rolling Contact Fatigue; RCF) [3, 4]. We studied the Hertzian stress between the wheel and rail surface that depend on the surface roughness and surface failure. The stress depends on the real contact surface area and the size of the contact surface depends on the size of the failure. This theory can help us understand the causes of the surface cracks propagation and the damage process. These surface failures limit the train’s maximum useable speed. The rail surface quality control is very important to assure the continuous traffic in railway system and prognosticate the maintenance time of the railroad. By monitoring the surface failure, we get the real rail quality data from which, we can calculate the real Hertzian stress, and based on those results we can determine the useable train speed on the measured rail parts (GPS coordinates). This information is very important for the next trains that are using the same railroad. The railway transport is a member of the critical infrastructure, which means
we cannot transport the measured data by a traditional device, so it needs a safe way for the data transfer. It is required to use a safe data transfer device, which transfers the data processing results like determined usable maximal speed value attached with the GPS coordinates of the used trains.

2. Wheel-Rails Contact

Between the wheel and rail, we can find a rolling and sliding contact that increase wear and fatigue behaviour. The value of the contact surfaces size very important because the Hertzian stress depends on the size of the contact area. In the literature, we found different models for the train wheel and rail contact [3-5]. In our project, we used a modified model for the wheel-rail contact [3]. The used model is the roller-roller contact in case of railway (shown the Fig. 1.).

![Figure 1. Wheel rail contact on base of Hertz model [3]](image)

The maximum Hertzian stress in case of roller-roller contact model equation (1), where $p$ is the average contact stress [N/mm$^2$], $Z$ is the wheel load [kN], contact surface area (ellipse) [mm$^2$], $2a$ contact ellipse long axis [mm], $2b$ contact ellipse short axis [mm] (Fig. 2.):

$$
\sigma = \frac{3}{2} \frac{Z}{A} = \frac{3}{2} \frac{Z}{\pi ab} \left[ \frac{kN}{mm^2} \right]
$$

(1)

![Figure 2. Hertz’s stress model in case of wheel rail contact [3]](image)

The Hertz stress calculation gives an adequate result in case of regular roller-roller geometry contact [6]. If we suppose any surface failure, crack, roughness error or other geometrical problem we need to
modify the introduced equation. The real contact surface size is smaller than the calculated. The real Hertzian stress $\sigma_{real}$ we can determine by equation (2) when $e [\text{mm}^2]$ is the size of surface failure area.

$$\sigma_{real} = \frac{3}{2} \frac{Z}{(\pi ab) - e} [\text{kN/mm}^2]$$

The determination of the real Hertzian stress is very important because based on this result we can predict the rail lifetime and the defects propagations. The failure is detected with our device by visual testing, which is supported by a rapid camera and then it evaluates the failure size ($e$) by an imaging system.

![Figure 3. Elliptical wheel-rail contact area and the failure size on the surface](image)

Fig. 3. shows a welded joint failure, a cracked defect and some deformation on the rail. Cause of the welding joint defect the Hertzian stress is extremely high in this part of the rail. It is assumable, that the high Hertzian stress caused the detected failures (cracks, plastic deformation) in the roller-roller contact area.

3. Surface visual testing

The failure size measuring is the key of our project’s success. The origin of the word diagnostic is the Greek diagnostics word, which means distinguish or identify. In rail diagnostics, we define the traditional visual inspection and the instrumental inspections and tests. The non-destructive testing methods usage is the way to assure the safe railway transportation. The diagnostic investigation means geometrical and material inspection. Nowadays the modern technology offers new material and geometrical testing methods. We built our device based on the surface geometry testing. On whole railway network (rail and parts of railroad) needs the continuous inspection [7-9]. Based on an adequate and successful monitoring system the railway transport can work safely and economically and it can predict the recovery works.

3.1. Monitoring by camera system

In our monitoring system, we needed to use high-speed camera because of the train speed [10]. That way we can take photos of the whole surface systematically. These pictures will contain the surface failures. Also for every picture, we need to attach a GPS coordinate. To custom this process, we need clear and clean rail surface.

3.2. Analysis of surface data

This imaging system is able to evaluate the failure size and based on that value the computer process based on the modified equation (2) calculate the real-time Hertzian stress. From the Hertzian stress value it can indicate the dangerous failures (and it’s GPS location) and calculate a train speed limitation for the dangerous rail part or send an alarm sign [11, 12].
The data analysis processed by mathematical processing software, based on the data classified and the used modified Hertz stress model.

4. Investigated monitoring system

Fig. 4 shows the innovated monitoring system. The data transfer and the monitored rail local coordinates (GPS) registration is also very important part of our device.

![Innovated monitoring system](image)

**Figure 4.** Innovated monitoring system

4.1. Classification of data and transfer type

**Data classification**

*Primer data:* The visual inspection gives numerous unprocessed data these are the primer data. It accumulates stores and transfers them in an adequate way for analysis [13]. To store temporary numerous data, we use a high-speed reader-writer puffer [14].

*Seconder data:* The storage and transfer of the local coordinate data (identify the tested rail segment) attached with the rail surface primer data have to be together [15, 16]. We use for these data the seconder data designation [17-19]. It is required to store and transfer the different origins and types involved data (data fusion).

**Transfer types**

The different data is classified in three different classes based on of the failure priority and the defect size.

*Critical data:* These are the measured critical sized failures data. These values are over the limit. They require a direct, real time transfer of this data to support the safety of the railway traffic. The critical data transferred immediately by GSM-R system to the datacentre.

*Important data:* These data are from the measured important, but not critical defect sizes. The measuring device saves these data and while it is near the station, it transferred to the station server by a radio transfer system. From the station server to the datacentre the data transfer to the cloud supported by optical or cable network.

*General data:* These are the data of the measured defects under critical or important limit size. These data are saved in the device memory and transferred to the data centre with radio transfer system when the device is arrives to the train terminal. These data are the bases of the prediction for the GPS coordinate identified railroad repair works.
4.2. Data critical infrastructure protection
The electronics information protection to support the transfer safety and the final point network protection is required to assure the measured and analysed data moving to the data centre and back transferring to the users. The execution of the data transfer required with accordance observing of the information safety rules in case of railway because this part of the state economy is a member of the critical infrastructure.
Nowadays cyber-attacks serially happen again the on critical infrastructure members which manifested that importance of the protecting them. The information safety rules adherence is required, to guarantee the safety operation of the introduced monitoring system.

5. Conclusion
In our work, we wanted to construct a monitoring system to support the safe and controlled railway infrastructure. We focused on one of the most important and difficult problem of the railroad defect detection. In the present traditional visual inspection used to detect the railroad surface defects that are outworn. We proposed a new complex monitoring system that is able to detect the failures and after the data analysis, our system can control the railway traffic system with a safe data transfer and protected from the cyber-attacks.

a) Railroads have failures on the surface. The railroad metal has mechanical properties and wears resistance. The surface load capacity is determined by the metal properties. The load is not constant in the railway system. Based on the wheel-rail contact model the Hertzian stress is determinable by the known Hertz equation. Because of the surface defect the real Hertzian stress can be much higher than the calculated from the contact stress model conception. To evaluate the real stress, it needed to modify the Hertz equation and decrease the contact surface size by the failure size. We proposed a modified equation that is the basis of our monitoring system data analysis.

b) The continuous surface visual inspection is realizable by the proposed monitoring system. The detected failure size data attached with the location coordinates and data classification transferred by a safe data transport way. Our system localises, detects and saves the railroad failures with local coordinates (GPS). The data transferring is done in a safe way to protect the system against cyber-attacks.

c) The innovated monitoring system realized in accordance with Industry 4.0.

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