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TENTATIVE IMPLEMENTATION OF ON-LINE DIAGNOSTICS OF ELECTRIC MULTI-UNIT PANTOGRAPH IN LITHUANIAN RAILWAYS

Summary. The task of modern diagnostics of electric rail vehicles is to determine on-line the technical condition of the contact of the rolling stock's pantographs with the catenary wire. The quality of electrical current collection and the wear rate of the pantograph completely depends on the pantograph/wire dynamic interaction. The article discusses the possibilities of installing and using modern diagnostic tools for electric multi-unit pantographs on the electrified lines of the Lithuanian Railways (LTG). In order to increase the efficiency of servicing pantographs and reduce costs, the maintenance of pantographs is being improved based on data from monitoring their technical condition. The criteria for detecting (recognizing) damage to the pantograph and the parameters of damage signals have been determined. The trial drives were carried out using the vibration measurement device made by "LTG Infra" specialists. The interaction dynamics of the pantograph and catenary wire during multi-unit driving process was investigated. A malfunction – the exceeded impact of the pantograph on the network wire – was detected on the "Vilnius-Kaunas" railway section. Finally, conclusions and plans for future applied research are presented.

1. INTRODUCTION

Electrification of railways is the most important direction of technical progress in the modernization of the railway transport sector in order substantially to reduce its contribution in GHG. After replacing thermal traction with electric power, environmental pollution is drastically reduced, the speed of passenger trains and the mass of freight trains are increased. Railway specialists call the process of adapting a track section to electric traction the term "electrification". In practice, it has been proven that the throughput of electrified railway lines is at least 20% higher and energy consumption is up to 5% lower compared to thermal traction. This is very important in densely populated areas where high pollution limits the use of thermal traction. Using electric locomotives as a less complex machine than a locomotive reduces the operating costs of locomotives, and due to higher train speeds, a smaller rolling stock is also sufficient. It has been proven that operating costs are almost 20% lower when using electric locomotives at higher traffic volumes than using thermal locomotives.

The electrification system of railway lines consists of electricity generation sources, transmission network and consumption devices. After adapting the section to electric traction and using it densely, infrastructure maintenance problems are encountered. It is especially relevant to properly and periodically maintain the most important parts of the electric traction equipment, which are vital to the entire electric traction system, that is, those that are of great importance for the continuous operation of the entire system. One such place is the monitoring and maintenance of the technical condition of the pantograph. It is relevant and very important, because the electric motors of the multi-units receive power through the pantograph. Electricity is supplied to the train engines even at high train speeds, so mechanical dynamic effects inevitably lead to damage to the pantograph. This happens when the train

moves at high speeds, as well as due to friction and other reasons: meteorological phenomena, changes in the terrain of the railway track, geometric parameters of the railway track (curves, slopes), etc. i.e. A regular inspection is required to determine the condition of the pantograph [1]. It is particularly difficult because it is performed only at a certain periodicity and only visually, i.e. by physically climbing onto the roof of the train and thereby identifying violations. This maintenance requires both a certain infrastructure and suitable facilities. Depots must have pantograph inspection places, which must be able to disconnect a certain section of the contact network from the voltage, so that service personnel can safely perform pantograph inspection and repair work.

The main line of Lithuanian Railways "Vilnius–Klaipėda" is being rapidly electrified. In addition, the modern rail line "Rail Baltica" is being intensively built from Kaunas to Latvia, which will run electric rolling stock. Thus, there is a huge challenge of monitoring the interaction between catenary wire and pantograph [2]. The rolling stock current receivers and power supply network system receives high dynamic loads, so their operation and maintenance are a sensitive dilemma for the Lithuanian railway company. Receivers that supply electric power to rolling stock via AC lines are called pantographs.

It should be noted that the quality of electricity collection and the intensity of wear of the current collector are highly dependent on the dynamic of the pantograph/wire interaction [3]. Under the influence of vibration or other external factors (e.g. wind, snow, frozen wire) some parts of the pantograph and catenary systems are damaged. After certain damage cycles, cracks are formed in the parts that grow to complete mechanical disintegration. At present, the most commonly used pantograph maintenance method in railway depots is visual inspection (inspection), which is effective only in case of obvious pantograph faults. Pantographs are damaged by two types of damage: wear and tear, which pose a serious threat to the continuity and safety of train traffic. In order to improve the efficiency of pantograph maintenance and reduce costs, it is necessary to improve the technical maintenance organization and planning based on real-time monitoring data. Currently only two railway sections are electrified in Lithuania: "Vilnius–Kaunas" and "Vilnius-Trakai". Electrification works are still being carried out on the third stretch "Vilnius–Klaipėda", so the electrified railway network is still unwell developed in our country and only visual inspection methods are used to detect pantograph faults. In order to implement automated diagnostic solutions, it is necessary to analyze how these problems are solved in foreign countries that have a well-developed network of electrified railway lines and large fleets of electric rolling stock.

The need and speed of implementation of catenary and pantograph technical condition diagnostic systems is growing rapidly, but non-destructive testing still remains an aspirational innovation in the fields of science and industry [4, 5]. One of the areas of application of the image recording equipment is a device for determining damage to rolling stock pantographs, which records parameters using photo equipment [6]. In Denmark, at a certain point of the electrified section, there is a set of various diagnostic devices that reproduce the gauges of the train. A block containing a camera, its holding arm and a sensor laser module is attached to the top of the diagnostic device structure. A general view of the construction of the pantograph condition monitoring system is presented in Fig. 1.

A similar study was conducted in Turkey [7]. The test differs in the methods of image recording and processing of the obtained material, when the parameters are recorded using video equipment. The scheme of pantograph diagnostic image material processing is presented in Fig. 2.

In this case, the filming camera is mounted on the roof of the electric vehicle and the lens is aimed at the pantograph and contact wire. The material captured in real time is sent to a computer, where the information is processed by an anomaly detection algorithm. The method makes it possible to capture parameters similar to the previously mentioned method: pantograph tilt angle deviation and slide reaction force, support thicknesses, their wear, cracks and manifested erosion and surface temperature. In this way, it is possible to expand the range of parameters, so wear, cracks and sparking of the contact wire are additionally monitored. The accuracy of the method allows processing cracks with an error of ± 0.1 mm, pantograph tilt deviation and contact wire fluctuations – an error of ± 5 mm. The accuracy of the other previously mentioned parameters complies with the BS EN 50317 standard [2]. An analogous study was carried out by scientists of the Institute of Electrical and Electronics Engineers of Turkey, who monitored the dynamic parameters of the pantograph and contact wire in real time [8].

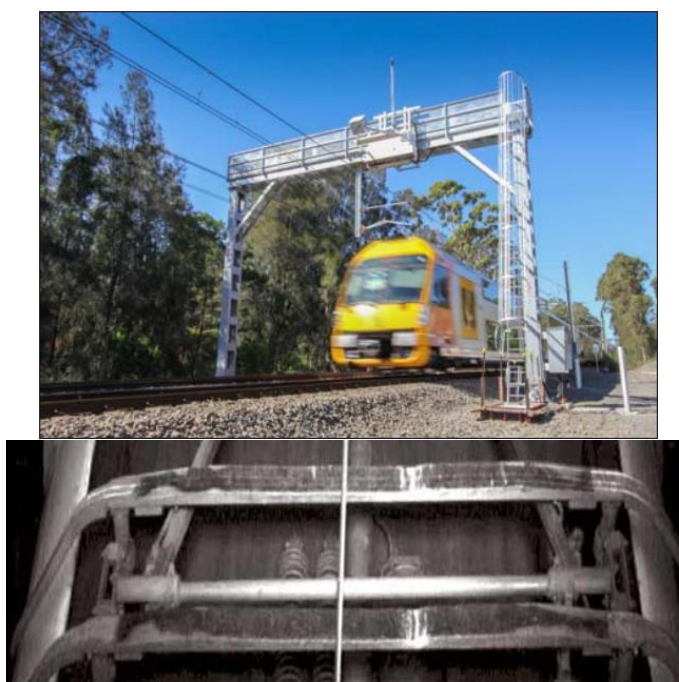


Fig. 1. Construction of the pantograph condition monitoring system [5]

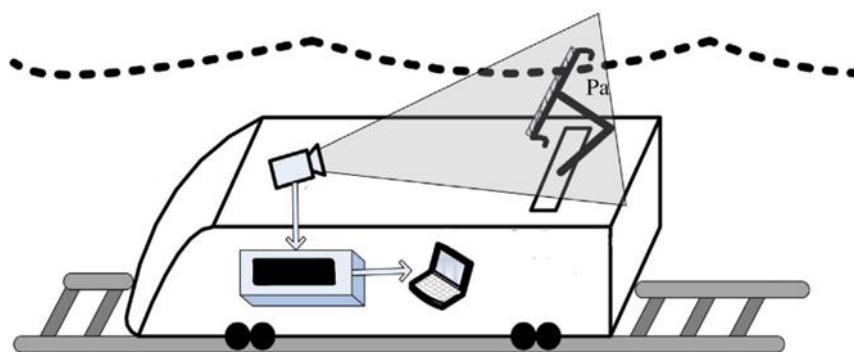


Fig. 2. The view of layout of pantograph diagnostic video monitoring devices [6]

The fault detection algorithm developed by the researchers tracked the contact suitability of both systems in the three pantograph zones, thus increasing the effectiveness of fault detection. Japanese researchers, improving previous studies and in order to obtain more accurate results, used three cameras in their study [9]. This research method obtained the best and most accurate damage detection results from all the previously mentioned studies.

Another group of Portuguese researchers concentrates on signal processing, detecting damage to the pantograph surface due to improper interaction with the contact wire [10]. In the implementation of practical research, various structural solutions are tested, since a piezoelectric accelerometer is used, which has structural and inductive limitations. In the course of the signal processing research, an attempt is made to attach the sensor to the support of the contact network through additional fastening elements, and the connection to the contact network itself is made through insulated wires. Fig. 3 shows the construction diagram of piezoelectric sensors.

Such a sensor mounting solution is made in order to move the sensor away from the induction zone at a suitable distance. The signal of mechanical vibrations is extracted, which is processed by different mathematical models and the general form of the result is output with the estimated values that show the wear level of the pantograph in operation. Expanding the research on the use of sensors in diagnosing the correct contact between the pantograph and the electrical network, a study conducted in Switzerland revealed that optical fiber sensors can be used to achieve this goal [12]. In the operation of electric multi-units in the presence of high electromagnetic fields, high-voltage optical fiber sensors have an advantage

over other sensors, which are resistant to various temperature regimes, high voltage and electromagnetic field [11]. These sensors are mounted on the contact edges of the pantograph in two places and record the contact force with the contact wire in real time. An extended study showed that the new temperature compensation method is more effective than the traditional one [13]. This study was based on the use of temperature-compensating optical sensors that doubled the vibration frequencies of the pantograph during the study.

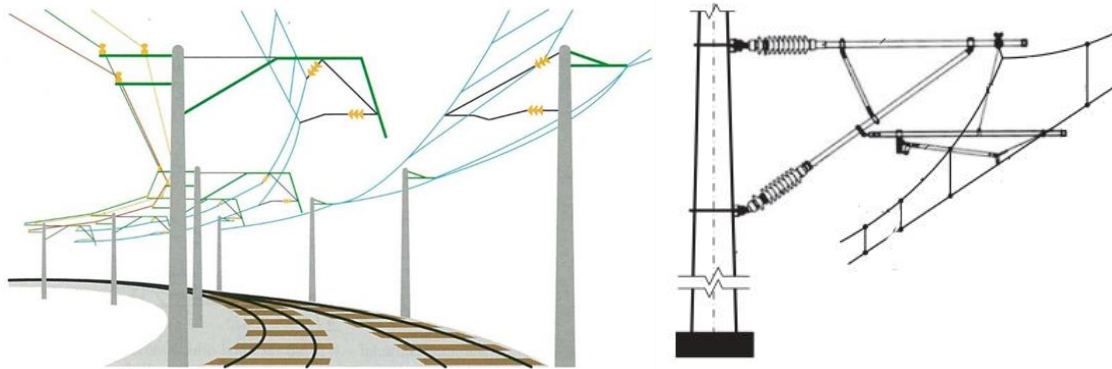


Fig. 3. Mounting structure of piezoelectric accelerometers [11]

The contact network is a complex set of technical devices and systems in an electrified railway section, which is subject to strict and individual requirements depending on the specific conditions of the operated region, which determine structural solutions and usage characteristics [14, 15]. The catenary must ensure proper contact between the pantographs of the rolling stock and the contact wire under various climatic conditions and the maximum permissible speed, for example in the case of strong wind, there is a possible "wave" of the catenary, which in the studied study showed that this phenomenon increases the probability of damage by 13.2% [16]. Also, the contact network must ensure uniform wear of the contact inserts of electric multi-unit and railcar pantographs on the entire contact surface. In order to prevent backlash and malfunctions of individual parts of the network, a compensation system is applied, thanks to which it is possible to change the tension of the contact wire, adjust the position with respect to the road axis (usually applied in the case of icing), reducing the influence of the previously mentioned "ripple", etc. The contact wire must meet the standard requirements: in stations and intermediate stations, the wires of the contact network above the rail head must be at least 5750 mm, and at crossings – at least 6000 mm. In exceptional cases, this distance can be reduced to 5675 mm, according to the EN 50122-1 standard [17], on tracks where rolling stock parking is not foreseen, as well as at intermediate stations. The wear and sparking of the contact wire that occurs has a negative impact on the infrastructure and electric multi-units, so periodic inspection of the contact network is necessary. Electrified sections stretch for hundreds of kilometers, making it a difficult and time-consuming inspection. In this case, pantograph diagnostic equipment (image processing or sensor methods) is used to process the recorded data (improper support reaction force, surface temperature, cracks, stains, etc.) and determine the condition of the contact wire.

2. METHODOLOGY OF WIRE-PANTOGRAPH CONTACT MEASURING TECHNOLOGIES

When developing a diagnostic system, it is very important to analyze the signals that reveal the condition of the object. These are often acoustic signals reflecting changes in mechanical vibrations, chemical processes, electric currents or electromagnetic fields. Obviously, when the electric multi-unit runs and the pantograph sweeps over the catenary, this sweeping process will cause some noise in the environment and mechanical vibrations in the catenary mounting system. The resulting wear of the pantograph and the change in the shape of the contact surface cause additional vibrations characteristic

of the damage, and the sparking caused by the deterioration of the contact is also heard and reflected in the general signal of mechanical vibrations of the contact network.

The mechanical vibrations of the catenary wire are mainly affected by the vibrations caused by the contact with the pantograph alone. Electromagnetic field measurement would be suitable for identifying contact network sparking, but some potentially dangerous defects that have appeared on the surface of the pantograph do not affect the electrical contact and do not spark for some time [18]. Methods based on the electromagnetic principle are not suitable for detecting such damage. At the same time, it should be noted that due to the large traction currents and electromagnetic fields formed around the point of contact between the traction pantograph and the contact network, it would be complicated to properly apply the electrical parameters measurement system. Methods should be used to obtain the defect signal of the analyzed pantograph, which would be as little affected by electromagnetic fields as possible.

For these reasons, catenary vibration signal would be most suitable for pantograph diagnostic signal. In this case, it is possible to develop the concept of a stationary diagnostic system, which would study the vibrations of the contact network at a selected point during the passage of the train. The mechanical vibrations caused by the train's pantograph would be captured by vibration sensors, digitized and analyzed to identify the condition of the pantograph of a passing train.

The planned tested piezoelectric sensors are suitable for pantograph damage detection. These sensors convert one form of energy into another and are widely used for measurements. Piezo sensors convert vibrations into an electrical signal. When faced with mechanical shocks, piezoelectric transducers generate a sufficient electric discharge that changes the direction of arrangement of molecules in liquid crystals. The electrical signal, electrical voltage, or electrical charge generated by the sensor is proportional to the magnitude of the force acting on it or the displacement of the oscillations. The sensor generates an electrical signal, which can be further mathematically processed by means of mathematical analysis.

Signal analysis can be performed based on calculated statistical parameters such as maximum amplitude, kurtosis, root mean square (RMS), standard deviation, Crest Factor, etc. The characteristic characterizing the strength of the vibration is the amplitude of the signal $x(n)$. For estimating the level of short-term shocks, the maximum amplitude is valuable, which is easy to calculate using the equation:

$$\text{Peak} = \max(|x(n)|) \quad (1)$$

Absolute data values are searched to avoid missing negative values. Maximum amplitude values show only the highest levels reached - the impact duration and energy are not taken into account. Therefore, it is better suited for detecting infrastructure faults than for assessing the condition of pantographs.

The most important amplitude measure that describes vibration levels is the root mean square value (RMS). This is the second central moment of the signal. The *RMS* value evaluates the changes in the curve over time and therefore provides information about the strength of the vibration – how much energy is stored in the vibration (expressed in g or m/s²). In the presence of defects, the vibrations are amplified and the increased *RMS* values identify or detect the occurrence of the damage. *RMS* is calculated by the formula:

$$RMS = \sqrt{\left(\frac{1}{N}\right) \sum_{n=1}^N ((x(n))^2)}; \quad (2)$$

where: N – number of read data.

To estimate the size of the errors, the qualitative error between the mean square value and the standard deviation σ is calculated as:

$$\frac{RMS - \sigma}{RMS} \cdot 100. \quad (3)$$

A *Crest Factor* is the *RMS* proportion of the maximum amplitude and acceleration:

$$\text{Crest Factor} = \frac{\max(|x(n)|)}{RMS}. \quad (4)$$

A proportion is a dimensionless quantity and is therefore used to compare data. The *Crest Factor* is sensitive to transient increases in amplitude that are too short to affect the overall *RMS* magnitude. Thus, comparing the values of the ridge coefficients of a clean and damaged pantograph, it is possible to

observe the deterioration of the condition. By observing trends in this size over time, the ridge ratio could be an indicator of early wear. Unfortunately, due to amplitude errors (in case of mismatches between data acquisition frequency or filters), this quantity is not reliable enough for monitoring the pantograph condition.

Asymmetry is the 3rd centered moment of the probability density function. Its value is zero when the function is symmetric, and it acquires a large value in the case of asymmetric functions. Typically, skewness is normalized by dividing by the degree of the corresponding standard deviation. It can be expressed by the formula:

$$Asymetric = \frac{\frac{1}{N} \sum_{n=1}^N (x(n) - \bar{x})^3}{\sigma^3}. \quad (5)$$

The extremum is the fourth moment of the probability density function. It is a dimensionless quantity used to detect significant peaks in the vibration signal in the time domain. Extremity effectively amplifies isolated signal peaks, so its value is greater for sharper signal peaks (especially in pulsed signals). The extremity is normalized by dividing by the degree of the corresponding standard deviation:

$$Ekstremum = \frac{\frac{1}{N} \sum_{n=1}^N (x(n) - \bar{x})^4}{\sigma^4}. \quad (6)$$

The measured vibrations are usually rich in extraneous noise and resonant frequencies that distort the results obtained during the analysis. For this reason, it is important to properly prepare the data for processing. Fourier transforms assume that the signal is periodic and consists of an integer number of periods. Unfortunately, most of the time the measured signal is not composed of an integer number of periods, so frequencies from the incomplete period distort the signal. As described by the scientists of the National Instruments Corporation [19], this phenomenon, when the energy of one frequency leaks into other frequencies during the Fourier transformation, is called spectral leakage. This effect can be reduced by using the windowing method, which reduces the amplitude of discontinuities at the boundaries of each finite sequence of acquired data. Windowing consists of multiplying the time record by a window of finite length, the amplitude of which smoothly and gradually changes towards zero at the edges. A continuous waveform without any sharp transitions is achieved. There are various window functions that can be selected depending on the type of signal being studied. For example, for stationary signals, the most commonly used windows are: rectangular, Hann, Kaiser-Bessel and flat top. Commonly, in the general case (95%). A Hann window is sufficient because it has adequate frequency resolution and reduces spectral “leakage”.

3. TESTING OF WIRE AND PANTOGRAPH INTERACTION MEASUREMENT DEVICE

The measuring device for research was developed by the representatives of the quality and safety department of the "LTG Infra" company, which is suitable for monitoring the interaction between the pantograph and the catenary cable. During the research, a vibration measuring sensor was used – an accelerometer for measuring acceleration. A vibrating physical body (sensor) gains momentum along a certain axis, it becomes force-dependent. Thus, accelerometers are designed in such a way as to measure the force acting on a body of known mass along a certain axis. The type of device used in the study is a digital accelerometer ADXL345, as this device provides the ability to measure forces in several directions, such as X, Y and Z axes. As the pantograph moves along with the multi-unit in a certain direction, the accelerometer records gentle vibrations caused by pantograph vibration, improper contact wire tension, and small irregularities in the rails. When the pantograph is subjected to higher loads (catenary impact, large tilts to the sides, sudden descent), the readings of the accelerometers fluctuate significantly on a higher scale due to sudden changes in acceleration. The stronger the force acting on the body, the faster the body's velocity changes. Not only the modulus of the velocity changes, but also the direction, and the change in velocity per unit time is acceleration. So, the stronger the acting force, the greater the acceleration of the body. When the train is running on smooth tracks, the pantograph moving at high-speed experiences a shock from the contact wire, in this case, the force acting on the pantograph will change slightly. Meanwhile, the vertical force due to gravity increases sharply,

influencing the accelerometer readings along the Z axis. Thus, the acceleration measured along the Z axis will reach 0.5·g and more depending on the impact force. On the basis of such readings of the device, it is assumed that the pantograph is affected by tensioning inaccuracies of the contact wire or other faults characteristic of the pantograph.

A global positioning system (GPS) and the accelerometer was at the same time. It is a high-precision satellite radionavigation system that provides information about the position of objects in space (3D), their speed, direction and distance traveled, distances to selected points, and the exact time of the location at a given moment. The use of the NEO-6M-0-001 device in the study is based on the fact that when integrating GPS with a triaxial accelerometer, one of the axes of the accelerometer coincides with the main longitudinal axis. Then all measurement data are transformed into a uniform coordinate system. Transformed coordinates are projected onto the axis system using a rotation matrix. These calculated parameters are then used to detect instantaneous accelerations in a three-dimensional axis system. Also, GPS data is used to process accelerometer readings and convert them into a visual anomaly detection system that displays it on a road map.

Both devices were placed in a metal box, which was not characterized by large dimensions, since the latest technologies allow to significantly reduce the dimensions of the devices. The case is 101 mm long, 76 mm wide, and only 23 mm high. A lithium-ion power battery was also installed inside. Battery and a voltage converter supply the most important data gathering and sending devices. This power device supplied the devices with electrical power for about 48 h. A sensor device for receiving data. ARM family microcontroller STM32F100RB is used for partial data processing. The box is attached to the pantograph frame thanks to a magnet. The advantage of the design of the test device is that the test measurement is not affected by environmental factors. The devices inside the metal box are completely protected from rain, snow and other natural effects. The box and the positioning of the devices inside it are shown in Fig. 4.

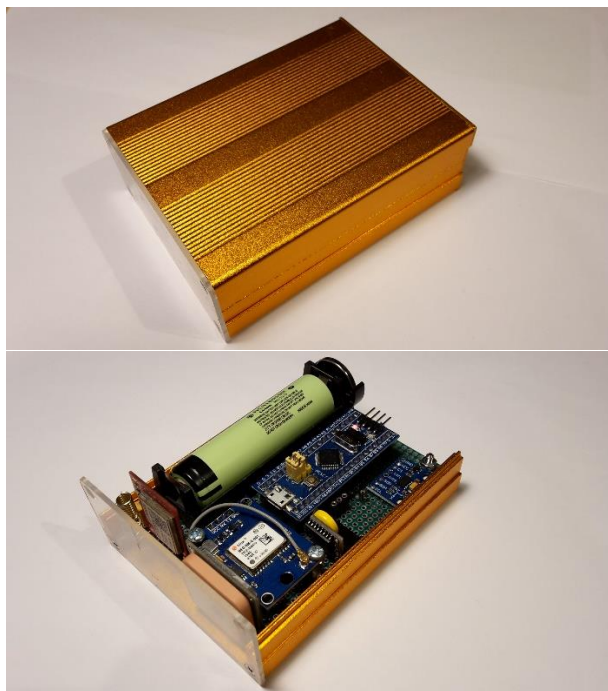


Fig. 4. Protective box for measuring device and components of device

Microcontroller STM32F100RB used data converter. By monitoring the data parameters, it was observed that the data ranges from 0.5·g units to 1.5·g units. The graph of the real data during the movement of the electric multi-unit when the pantograph experiences shocks (when the maximum peak of the amplitude exceeds the limit of 1.5·g) is presented in Fig. 5. The data is displayed along 3 axes, each of which captures different forces acting on the pantograph. The box is installed on the pantograph so that the axes of the accelerometer are: X axis – AX – perpendicular to the direction of pantograph

movement, Y axis of the accelerometer – AY – coincides with the direction of movement of the pantograph, and Z axis of the accelerometer – AZ – vertical. The data on the AX axis show the braking/deceleration of the pantograph, the readings on the Y axis capture the lateral oscillations, and the data on the AZ axis reflect the unevenness (roughness) of the catenary or improper wire tension.

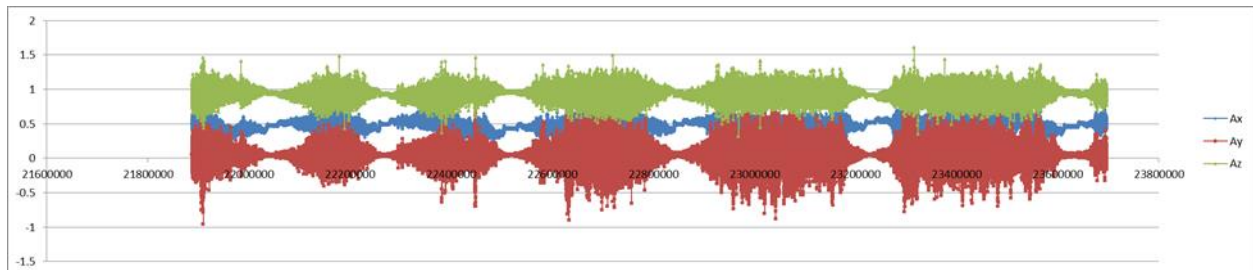


Fig. 5. Pantograph vibration graph

After receiving the primary vibration signal data, it is analyzed in the smart signal monitoring system of the accelerometer. After analyzing that the data ranges from 0.5-g units to 1.5-g acceleration units, a report is generated. Accelerometer readings are displayed in the report when vibrations exceed the 1.5-g limit. Exceeding the set limit indicates the capture of the previously selected parameter to monitor. In this way, the hit received is determined. The increased shock recorded in the pantograph vibration frequency diagram is shown in Fig. 6.

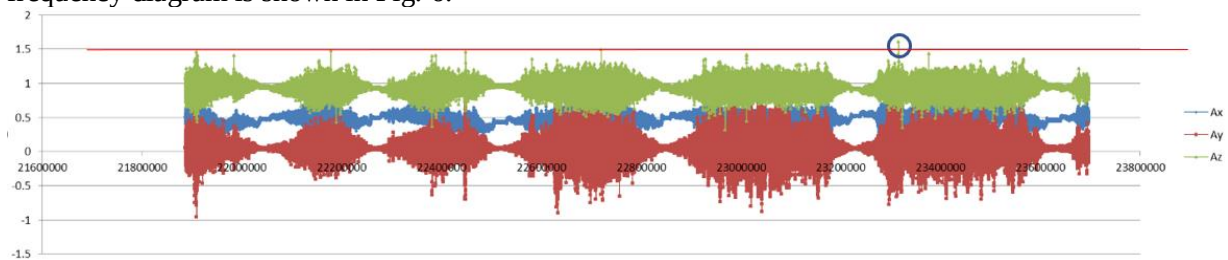


Fig. 6. Recorded the exceeded impact of the pantograph in the vibration frequency diagram

The interface between the GPS system and the accelerometer system allows additional data to be captured, which provides an opportunity to analyze the situation more broadly. "U-blox 3D ADR" integrated system technology is designed to supplement the navigation system so that it works in tunnels, large underground sites, surrounded by large buildings, where the GPS signal is too weak. It is also classified as inertial, but it also includes additional measuring tools. The system uses a Kalman filter for data synthesis. Since it is an inertial navigation system, the error increases with distance traveled. The product of this technology is a chip, it connects to the accelerometer microcontroller, receives data from the accelerometer sensor and sends the position data to the navigation system. In the navigation system, data is displayed on the railway section when the limit set by the vibration signal is exceeded, i.e. a shot is recorded. Fig. 7 shows the geographical place, on which the impact of pantograph / wire contact interaction determined on the "Vilnius-Kaunas" railway section.

During the study, data is collected from the sensor to a personal computer. The ADXL345 accelerometer has an integrated memory management system with a 32-level FIFO (method of storing elements in a data structure), thanks to which the burden on the main microcontroller can be reduced. Measurement data for X, Y and Z axes are stored in FIFO levels. Data collection is terminated when all FIFO 32 levels are filled. Thanks to the transmitter integrated in the GPS module and the interface between other devices, the accumulated data are stored in the cloud, thus freeing the cache of FIFO levels for further measurements.

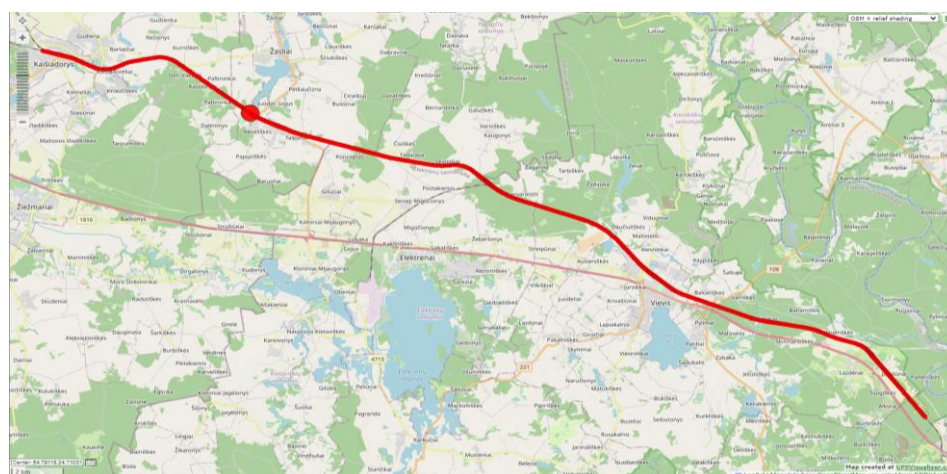


Fig. 7. The place of impact of pantograph and contact wire interaction detected on “Vilnius–Kaunas” railway section

4. CONCLUSIONS

Analysis of contact network vibration signals recorded by a piezoelectric sensor is quite appropriate for the multi-unit pantograph diagnostics. After examining a set of possible signal transformation algorithms, it was found that the spectrum autocorrelation function is the most suited for evaluating the classification features of the pantograph-induced vibrations signal. The code described in the Python program works while has been improved by removing noise filtering inaccuracies. In order to develop data processing, it is needed to obtain a larger (sufficient) set of impact signals and vibration signals in case of pantograph damage. After detecting a pantograph damage, a comparative analysis of frequency spectra is applied, when the frequency spectra are examined at different stages and signs of the pantograph's technical state (pantograph without damage; a damage starts forming/occurring; and pantograph with damage).

In the course of further research, it is planned further to apply the FFT method to process the obtained multi-unit pantograph vibration signals, to apply microphones to determine the acoustic signals emitted by the of the pantograph/wire contact. The purpose of the application is to extract informational features of the pantograph fault signal, on the basis of which it would be possible to distinguish between different signals. Also, to select a signal transformation algorithm that allows to properly assess the signs of vibration impact signals caused by pantographs, when damage occurs when the frequency limit values are exceeded.

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