Postprint of: Judek S., Skibicki J., Visual method for detecting critical damage in railway contact strips, MEASUREMENT SCIENCE & TECHNOLOGY, Vol. 29, No. 5 (2018), pp. 1-8

# Visual method for detecting critical damage in railway contact strips

**S Judek[1], J Skibicki[1]**

[1] Gdansk University of Technology, Faculty of Electrical and Control Engineering, str. Gabriela Narutowicza 11/12, 80-233 Gdansk, Poland

E-mail: slawomir.judek@edu.pg.pl

**Summary.** Ensuring an uninterrupted supply of power in the electric traction is vital for the safety of this important transport system. For this purpose, monitoring and diagnostics of the technical condition of the vehicle's power supply elements are becoming increasingly common. The paper presents a new visual method for detecting contact strip damage, based on measurement and analysis of the movement of the overhead contact line (OCL) wire. A measurement system configuration with a 2D camera was proposed. The experimental method has shown that contact strips damage can be detected by transverse displacement signal analysis. It has been proven that the velocity signal numerically established on that basis has a comparable level in the case of identical damage, regardless of its location on the surface of the contact strip. The proposed method belongs to the group of contact-less measurements, so it does not require interference with the structure of the catenary network nor the mounting of sensors in its vicinity. Measurement of displacements of the contact wire in two-dimensional space makes it possible to combine the functions of existing diagnostic stands assessing the correctness of the mean contact force control adjustment of the current collector with the elements of the contact strip diagnostics, which involves detecting their damage which may result in overhead contact line rupture.

Keywords: condition-based maintenance, current collector, fault identifications, vision system, railway transportation

## 1. Introduction – subject of the analysis

Electric rail vehicles are most often powered from the overhead contact line via a current collector mounted on the roof. As ensuring redundant power supply in the electric railway traction is economically unjustified, appropriate collection of energy by the vehicle is crucial for the reliability and safety of this transport system. For example, based on an analysis of the causes of OCL damage for DB, SNCF and Trenitalia in 2004, it was shown that 915 train stops occurred due to contact wire rupture, resulting in 443 thousand minutes of delay (Tanarro and Fuerte, 2011). This indicates the significant importance and role of diagnostic systems, especially as this data also includes high-speed trains and modern infrastructure.

At present, it is a typical practice to evaluate technical condition of current collectors by using preventive methods. This is usually done manually in rolling stock depots during periodical vehicle inspections. As a consequence, inspection of current collectors is time-consuming, imprecise, cost-ineffective and its results in many aspects depend on the diligence and subjective assessment of the staff. The characteristic feature of the preventive method is that, during the interval between inspections, an inoperative current collector can contribute to the occurrence of OCL faults.
An alternative approach is to monitor the technical condition. The implementation of this method of on-line monitoring under operating conditions is currently one of the most dynamic directions of development in the methodology of evaluating the technical condition of current collectors (Daadbin et al., 2012; Jardine et al., 2006; Judek and Jarzebowicz, 2014; Karwowski et al., 2016; Schöbel and Maly, 2012).
The elements which are in direct contact with the overhead contact line are usually carbon contact strips. During the vehicle movement, the strips slide along the contact wire. Therefore, they are exposed to wear and damage. In order to ensure a uniform wear of the strips, a structural shift of the contact wire and the support wire from the track axis at the support point of the overhead catenary construction is used in the catenary network - the so-called stager. A worn and damaged contact strips are shown in Fig. 1.

a)

b)

Fig. 1. Carbon contact strip: a) normal wear and tear, b) critical damage

Excessively worn and damaged contact strips should be detected as soon as possible and replaced. Otherwise, they may contribute to the deterioration of the current collection quality and increase the wear of the contact wire. In the event of damage to the strips, characterized by a significant loss of contact material, the contact wire may become stuck at the site of damage, which, in adverse conditions, may even lead to the rupture of the OCL. Assuming that the local operating conditions and the extent of damage to the strip do not rupture the OCL, as a result of the abnormal dynamic cooperation of these two elements of the vehicle's power supply additional vertical and transverse component forces will appear. In consequence, in addition to the normally occurring vertical component, the horizontal component of the displacement of the contact wire will appear.
There are numerous systems for detecting critically damaged contact strips. Current collectors may be equipped with systems for diagnosing damage to the contact strips. The methods based on pneumatic automatic dropping devices and sensors mounted directly in the strip are shown in (Bocciolone et al., 2013; Steimel, 2014; Schröder et al., 2017). Their functioning depends on the fact that when the contact strip is seriously damaged, the collector automatically move down and therefore the risk of damage to the overhead contact line is eliminated. Due to the progressive opening up of national rail transport markets and in the light of increasingly widespread interoperability, this would require unification of the solutions used, which is practically impossible on a large scale.
A different approach regarding the diagnostics of the technical condition of contact strips consists in the implementation of automated inspection stands at selected locations of the railway line. In this type

of solution one can distinguish two groups, based on the implementation method. The first one requires significant interference in the infrastructure of the railway line. (Usuda et al. 2011) proposed a way of detecting contact strip damage using an indirect method, by measuring the vertical accelerations of overhead contact line wire caused by improper co-operation of the OCL and the current collector. This requires the installation of accelerometers directly on the contact wire, which involves high installation costs. It is also necessary to exclude a section of the railway line from traffic for both assembly and service purposes. The sensors used require a DC voltage power supply of several, or even about a dozen of volts. The measurement signal is also low-voltage in its character. This requires ensuring galvanic separation from the catenary network voltage, which varies from 1.5 kV DC to 25 kV AC, depending on the standard used. The increasingly popular wireless sensor networks (WSN) require converting the measurement signal to data sent through radio access network. Due to the fact that, under typical operating conditions, currents from several hundred to a single kilo ampere are collected from the catenary, it is very important to ensure that the ICT network is not affected by electromagnetic disturbances. (Koyama et al. 2016) proposed a solution eliminating the need to install sensors on the wires of the OCL. They indicated that the interaction of the chipping strip with the contact line causes additional component forces in the direction transverse to the track axis. They showed that the use of strain gauges installed in the OCL support elements - the so-called registration arms - allows for measuring these component forces and identifying the damaged strips on their basis. Despite the lack of direct contact of the sensors with contact wire, the method of powering and acquisition of the measuring signal is still troublesome, especially in case of failure of insulators or occurrence of over-voltages. In addition, the proposed diagnostic algorithm requires the installation of strain gauges at three successive support points of OCL. The typical distance between the support in the electric traction is about 50–70 m. Therefore, supplying power to the measuring systems, as well as distributing and/or synchronizing the measurement data is problematic.

The second group of solutions does not require the assembly of measuring system elements which would interfere with the catenary network infrastructure. (Karwowski et al. 2016) indicated the possibility of diagnosing the technical condition of a current collector via non-contact distance measurement using laser rangefinders. The described diagnostic system could be used to detect damaged strips, as described by (Usuda et al. 2011), but it would require further expansion and development of additional data-processing algorithms. An important group of methods for identifying contact strips damage are visual systems. Solutions of this kind are used in diagnostics of overhead contact line, current collectors and their dynamic interaction (Borromeo et al., 2006, Cho and Park, 2016). A solution which utilizes two cameras is shown in (Hamey et al. 2007). The proposed algorithm allows for estimation of wear and detection of selected contact strips damage. The authors indicate an 80% efficiency of the system. However, no details on the methodology used for acquisition and processing of measurement signals nor accuracy information have been provided. (Skibicki 2018) and (Skibicki and Bartłomiejczyk 2017) have shown that 2D imaging in catenary applications allows for obtaining information on displacement in two axes with a measurement uncertainty at the level of a few millimetres or even better. This is an alternative to laser measurement. A development of 2D visual methods is laser 3D scanning. (Judek and Jarzebowicz 2014, 2015) described a monitoring and diagnostic system for contact strips, which allows for wear assessment, and indicated the possibility of detecting damage not only to step-shaped chipping. The proposed method, although more sensitive, requires more complex signal processing algorithms.

## 2. The measurement method

The proposed new method for measuring contact wire displacements is based on a fast 2D imaging camera and advanced image analysis. The principle of functioning of the measurement method is presented in Fig. 2.

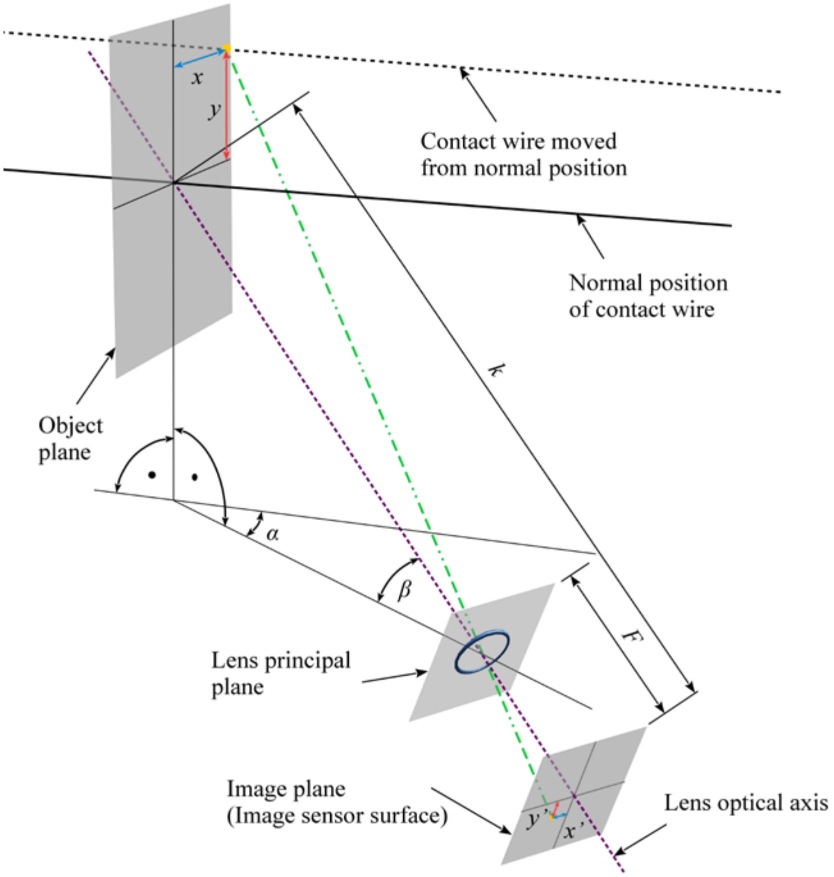



Fig. 2. Method for measurement of contact wire displacements – principle of operation, where: *x*, *y* – displacement of the contact wire in the horizontal and vertical axis respectively; *x'*, *y'* – displacement of the image on the camera matrix in the horizontal and vertical axis respectively, *k* – distance between the central point of the object plane and the image plane, *F* – distance between the main plane of the lens and the camera matrix (plane of the image); *α* – angle between the vertical plane in which the contact wire lies and the vertical plane in which the optical axis of the lens lies; *β* – angle of inclination of the optical axis of the lens in relation to the horizontal one.

The camera observes the contact wire with its characteristic measuring point. The displacement of the contact wire from the initial position will cause the displacement of the image of the measurement point on the image sensor of the camera. By measuring this displacement and knowing the geometric configuration of the test stand, the extent of displacement of the contact wire in the horizontal and vertical axis can be calculated. For the spatial configuration shown in Fig. 2, the displacement in the horizontal axis *x* can be expressed as:

$$x = \frac{(x-F)\cdot x'\cdot \cos\beta}{\cos\alpha\cdot(F\cdot\cos\beta - y'\cdot\sin\beta) - x'\cdot\sin\alpha} \tag{1}$$

Respectively, for the vertical axis *y*:

$$y = \frac{(k-F)\cdot(y' + x'\cdot\sin\beta\cdot\tan\alpha)}{F\cdot\cos\beta - y'\cdot\sin\beta - x'\cdot\tan\alpha} \tag{2}$$

The distance *F* between the plane of the camera sensor and the main plane of the lens depends on the focal length of the lens *f* and the distance of the object from the camera sensor *k* . It is provided by the relation:

$$F = \frac{k - \sqrt{k^2 - 4\cdot k\cdot f}}{2} \tag{3}$$

where: *f* – focal length of the lens.

In turn, the focal length of the lens depends on the current focus setting, that is, on the scale of the projection and it is provided by the relation:

$$f = \frac{k}{2+\frac{z'}{z}+\frac{z}{z'}} \tag{4}$$

where: $z'$ - image size of the object on the camera sensor; $z$ - the dimension of an object placed at a distance $k$ with the correct focus setting.
The recorded image is subjected to advanced processing in LabView, so that a scaled measurement result can be obtained from the $x'$ and $y'$ position of the image and the relations (1) and (2).

## 3. Experimental setup

On the basis of the theoretical assumptions of the measurement method, a laboratory test stand has been developed, the diagram of which is shown in Fig. 3.

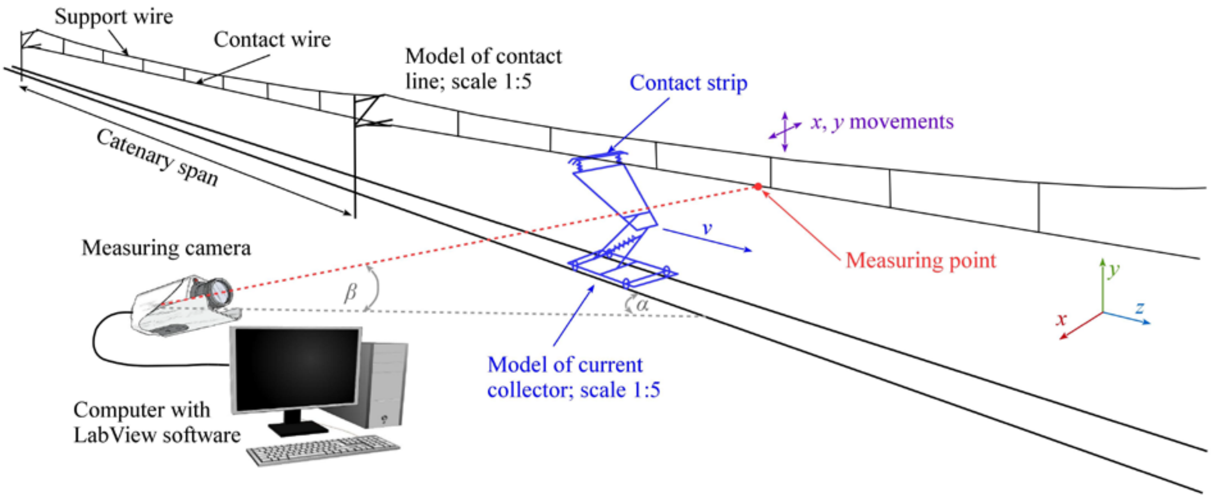



Fig. 3. Diagram of measurement test stand

The stand consists of a 1:5 scale overhead contact line section, with a length equalling two suspension spans. A bogie with a single-arm current collector, also in the 1:5 scale, moves around the stand. The measuring point has been set at half the length of one of the spans of the OCL section. A Basler acA 2040-180kc camera, with the following parameters, was used for the measurements:

- sensor resolution: 2046x2046 px (4 Mpix);
- sensor size: 11.26x11.26 mm;
- maximum recording speed: 180 fps.

The Sonnar 4/300 lens is attached to the camera, the focal length of which is determined in accordance with the relation (4) and amounts to: $f$ = 302.36 ± 0.15 mm (all results in this paper are given with standard uncertainty). Other characteristic values resulting from the spatial configuration of the stand are:

- distance $k$ = 3075.46 ± 0,87 mm;
- distance $F$ = 339.93 ± 0.19 mm;
- angle $\alpha$ = 42.507 ± 0.038º;
- angle $\beta$ = 16.000 ± 0.064º.

The measuring instruments listed in the table were used to determine the value of indirect measurements.

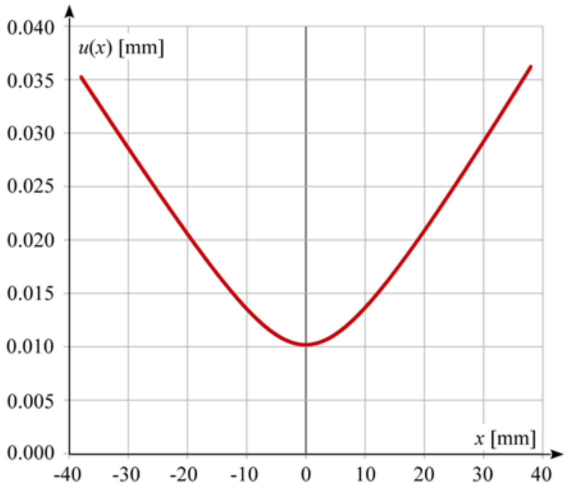
Table 1. List of measuring instruments used for indirect measurements

| No. | Name of the instrument | Standard uncertainty | Purpose |
|---|---|---|---|
| 1. | The Basler acA 2040-180 kc camera with the Sonnar 4/300 lens | u($x$') = 0.94 μm<br>u($y$') = 1.1 μm* | Measurement of the object's image position $x$' and $y$' on the sensor;<br>Indirect measurement of distance $F$ |
| 2. | BOSCH GLM 80 Professional laser rangefinder | 0.87 mm | Measurement of distance $k$;<br>Indirect measurement of angle $\alpha$;<br>Indirect measurement of distance $F$ |
| 3. | FWP MADb 400 calliper | 0.029 mm | Indirect measurement of distance $F$ |
| 4. | ACS-080-2-SC00-HE2-2W inclinometer | 0.067° | Indirect measurement of angle $\beta$;<br>Indirect measurement of angle $\alpha$; |

* values determined experimentally based on standard deviation of stochastic scatter of a series of 10000 measurements made for a stationary test stand.

The measuring range of the contact wire displacement achieved for the data presented above is ± 38 mm from the initial position in both the horizontal and vertical axes. The measurement uncertainty depends on the displacement value relative to the initial point and is shown in Fig. 4.

a) b)



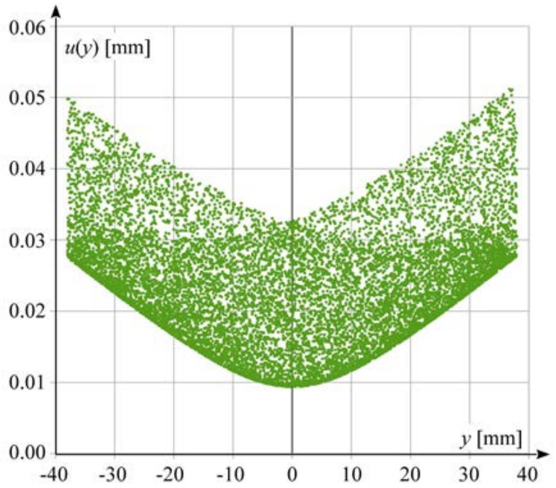




Fig. 4. Standard uncertainties of measurement of OCL contact wire displacement; where: a) uncertainty of measurement in horizontal axis $x$ , b) uncertainty of measurement in vertical axis $y$

## 4. Results

As part of the measurements, the recording of the contact wire displacements caused by the interaction of the current collector, for a contact strip in good condition and a mechanically damaged strip was performed as shown in Fig. 5.

a)

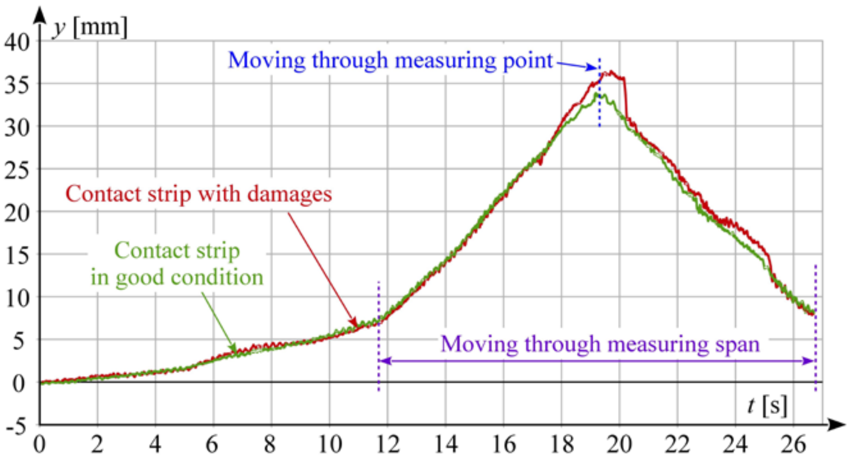
b)


Fig. 5. Contact strips in a model current collector, where: a) contact strip in good conditions; b) artificially damaged contact strip

Modelled artificial damage (Fig. 5b) reflects the type of critical damage, where the contact wire may be hooked, which in consequence may lead to OCL break. Minor damage, e.g. chipping, which will not result in the contact wire being hooked and pulled out, will not be detected by the discussed method due to the lack of a signal which can be used to detect them.

The rides of the bogie with the current collector were performed at a speed of $v$ = 0.5 m/s, which, taking into account the scale of the stand, corresponds to the speed of 2.5 m/s (9 km/h) of a full-size vehicle. The results of the measurements of the horizontal and vertical axis displacements of the wire are shown in Fig. 6.

a)




b)

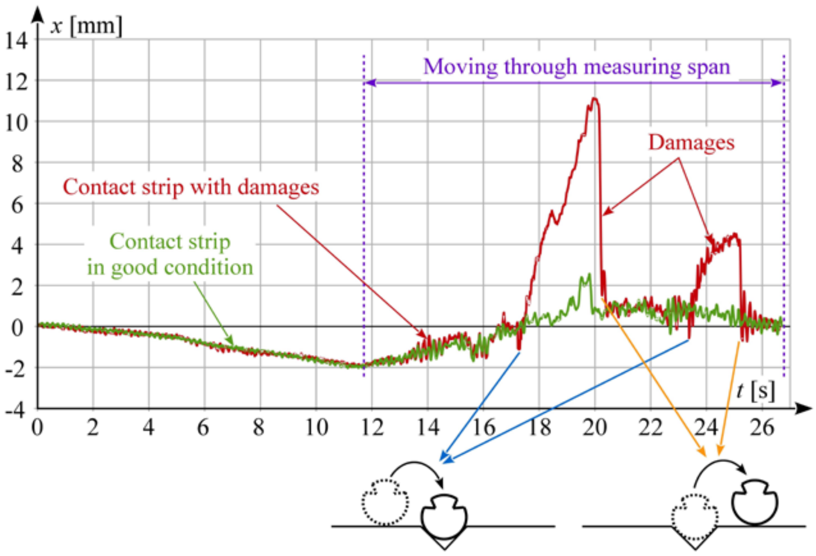



Fig. 6. Results of measurements of contact wire displacements, where: a) displacements in vertical axis $y$ ($t$); b) displacements in horizontal axis $x$ ($t$)

During the passage through the measurement span, the vertical lift of the contact wire caused by the pressure force of the current collector exerted on the overhead contact line is visible (see Fig. 6a). The course of the wire displacements in the horizontal axis $x(t)$ clearly shows the movement of the wire caused by contact strip damage. The groove, the dimensions of which are comparable to the diameter of the wire, results in it being pulled in the lateral direction, which lasts until the horizontal force induced by this deformation makes the wire exit the groove.
At the moment when the wire exits the groove, it rapidly returns to its normal position, which is the one which occurs when the collector strip is in good condition. The level of the lateral displacement signal, with the same level of contact strip damage, depends on the location of this damage. A stronger signal occurs when the wire becomes hooked near the center of the suspension span, i.e. near the measurement point. In such a case, the displacement will be much larger than when the wire is drawn closer to the suspension points. This shows that it is not possible to determine the critical lateral displacement value which could be considered as a detection signal, indicating potentially dangerous damage to the contact strip.
To achieve this unambiguous detection criterion, the resulting course of displacement was subjected to a differentiation procedure, which resulted in the course of the horizontal velocity of the contact wire, as shown in Fig. 7.

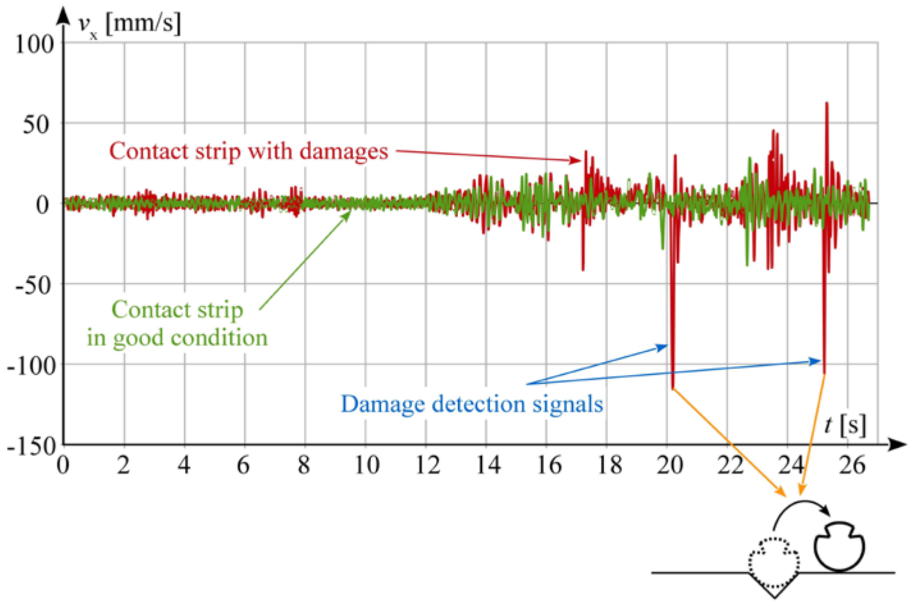



Fig. 7. Course of horizontal velocity of contact wire

Fig. 7 shows that the value of the contact wire velocity in the horizontal axis, when these movements are caused by contact strip damage, is practically the same, regardless of the location of the impact of the damage on the contact wire. The speed signal may therefore be considered as a detection criterion of damage to the contact strip, the level of which threatens the safety of traffic and poses a risk of OCL rupture.
At the time when the collector moves on the adjacent suspension span preceding the measuring span (time from 0 to approx. 12 s), slight displacements of the contact wire at the measurement point, caused by the lifting of the wire on the preceding span are visible. This lift induces the rotary movement of the registration arm at the point of suspension, as shown in Fig. 8.

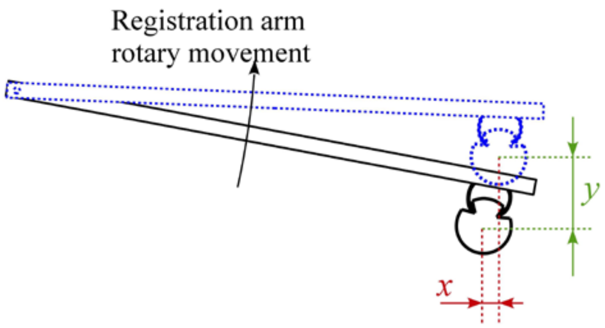



Fig. 8. Wire displacement caused by rotary movement of registration arm at suspension point of OCL together with its components, horizontal *x* and vertical *y*

The rotary movement of the registration arm translates into the displacement of the wire at the measuring point in the *x* and *y* axes.

Displacements in the vertical axis for the good and the damaged contact strips also vary slightly, but these differences are so negligible that they cannot be the basis for an unequivocal assessment of the occurrence of contact strip damage.

It should be mentioned that laboratory tests have been carried out at low speed. However, the obtained results are similar to those presented by (Usuda et al. 2011) for the object on a scale of 1:1 at a similar speed. It should therefore be presumed that, at higher speeds, the proposed measurement method will also produce results similar to those presented in the article mentioned above. However, it requires experimental research, the implementation of which is planned.

Another issue which will need to be taken into account during measurements in real conditions are environmental factors, such as wind or ground vibrations caused by a passing vehicle. As regards the influence of wind on the measurement results, it can be stated on the basis of (Song et al., 2017) that the nature of the contact wire displacements induced by wind is different from the displacements caused by critical damage to the contact strips. However, confirmation of this requires experimental research. The effect of ground vibrations caused by a passing vehicle can be reduced by increasing the distance between the camera and the measuring point. As shown in (Skibicki 2018), measurements from a large distance are possible while maintaining high measurement accuracy.

## 5. Conclusions

The method of detecting damaged current collector contact strips proposed in the article is a novel solution, allowing for a significant improvement of the diagnostic process. Thanks to the measurement of contact wire displacements in two-dimensional space, it is possible to combine the functions of the existing diagnostic systems assessing the correctness of the static force adjustment of the collector with the elements of the contact strip diagnostic elements, which involves detecting their damage, which may result in overhead contact line rupture. Such detection was hitherto very difficult to accomplish due to the problematic definition of the diagnostic signal which informed about the collector damage. The currently used methods required either using a significant number of sensors e.g. accelerometers or strain gauges on the catenary or the use of 3D laser scanning technology. The latter yielded measurement results which would later require complex analysis Thanks to remote measurement, the proposed method does not require interference with the structure of the OCL nor the mounting of sensors in its vicinity. This is a great advantage of the discussed method, as there are no problems related to the power supply, galvanic separation of sensors from the traction network or transmission of the measurement signal. Also, service works related to operating the system do not require closing the track or turning off the OCL supply. The low level of uncertainty and the high accuracy of the obtained measurement results should also be taken into consideration.

The disadvantage of the method is the need for very precise positioning of the test stand and, what is characteristic for all visual methods, the sensitivity to external lighting.

The tests were carried out at a relatively slow speed of movement of the current collector, so further research will concern the impact of speed on the measurement results. This will allow for a more accurate recognition of the method and will be a preparation for an experiment on a full-scale object.

References

Bocciolone, M., Bucca, G., Collina, A., Comolli, L., 2013. Pantograph–catenary monitoring by means of fibre Bragg grating sensors: Results from tests in an underground line. Mech. Syst. Signal Process. 41, 226–238. doi:10.1016/j.ymssp.2013.06.030

Borromeo, S., Aparicio, J.L., Martinez, P.M., 2006. MEDES: Contact wire wear measuring system used by the Spanish National Railway (RENFE). Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit 217, 167–175. https://doi.org/10.1243/095440903769012876

Cho, C.J., Park, Y., 2016. New Monitoring Technologies for Overhead Contact Line at 400 km·h −1. Engineering 2, 360–365. https://doi.org/10.1016/J.ENG.2016.03.016

Daadbin, A., Rosinski, J., Smurthwaite, D., 2012. Online monitoring of essential components helps urban transport management and increases the safety of rail transport. pp. 541–552. doi:10.2495/UT120461

Hamey, L.G.C., Watkins, T., Yen, S.W.T., 2007. Pancam: In-Service Inspection of Locomotive Pantographs. IEEE, pp. 493–499. doi:10.1109/DICTA.2007.4426837

Jardine, A.K.S., Lin, D., Banjevic, D., 2006. A review on machinery diagnostics and prognostics implementing condition-based maintenance. Mech. Syst. Signal Process. 20, 1483–1510. doi:10.1016/j.ymssp.2005.09.012

Judek, S., Jarzebowicz, L., 2014. Algorithm for automatic wear estimation of railway contact strips based on 3D scanning results. IEEE, pp. 724–729. doi:10.1109/ICEPE.2014.6970004

Judek, S., Jarzebowicz, L., 2015. Wavelet Transform-Based Approach to Defect Identification in Railway Carbon Contact Strips. Elektron. Ir Elektrotechnika 21. doi:10.5755/j01.eee.21.6.13755

Karwowski, K., Mizan, M., Karkosiński, D., 2016. Monitoring of current collectors on the railway line. Transport 1–9. doi:10.3846/16484142.2016.1144222

Koyama, T., Usuda, T., Kawasaki, K., Nakamura, K., Kawamura, T., 2016. Methods for Detecting Pantograph Defects Using Sensors Installed on Contact Lines. Q. Rep. RTRI 57, 207–212. doi:10.2219/rtriqr.57.3_207

Maly, T., Schweinzer, H., Rumpler, M., 2004. Advances in train monitoring by networked checkpoints. IEEE, pp. 339–342. doi:10.1109/WFCS.2004.1377741

Schöbel, A., Maly, T., 2012. Operational fault states in railways. Eur. Transp. Res. Rev. 4, 107–113. doi:10.1007/s12544-011-0068-z

Schröder, K., Rothhardt, M., Ecke, W., Richter, U., Sonntag, A., Bartelt, H., 2017. Fibre optic sensing system for monitoring of current collectors and overhead contact lines of railways. J. Sens. Sens. Syst. 6, 77–85. doi:10.5194/jsss-6-77-2017

Skibicki, J., 2018. The issue of uncertainty of visual measurement techniques for long distance measurements based on the example of applying electric traction elements in diagnostics and monitoring. Measurement 113, 10–21. doi:10.1016/j.measurement.2017.08.033

Skibicki, J., Bartłomiejczyk, M., 2017. Analysis of measurement uncertainty for contact-less method used to measure the position of catenary contact wire, performed with the use of Monte Carlo method. Measurement 97, 203–217. doi:10.1016/j.measurement.2016.11.008

Song, Y., Liu, Z., Duan, F., Lu, X., Wang, H., 2017. Study on Wind-Induced Vibration Behavior of Railway Catenary in Spatial Stochastic Wind Field Based on Nonlinear Finite Element Procedure. J. Vib. Acoust. 140, 011010. https://doi.org/10.1115/1.4037521

Steimel, A., 2014. Electric traction - motive power and energy supply: basics and practical experience, 2nd edition. ed. DIV, Deutscher Industrieverlag, München.

Tanarro, F., Fuerte, V., 2011. OHMS - Real-time analysis of the pantograph catenary interaction to reduce maintenance costs. IET, p. 5A2-5A2. doi:10.1049/cp.2011.0600

Usuda, T., Ikeda, M., Yamashita, Y., 2011. Method for Detecting Step-shaped Wear on Contact Strips by Measuring Catenary Vibration. Q. Rep. RTRI 52, 237–243. doi:10.2219/rtriqr.52.237