Diagnostics of operational wear in hybrid load-carrying cables

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Abstract. Along with the development of lifting devices, the new hybrid load-carrying cables were introduced to the market. The solutions of this type covered both, steel ropes of circular section and belts being a hybrid combination of many steel ropes potted with plastic coating into a single flat friction belt. Such design of ropes as compared to the traditional round steel ropes enabled to reduce the drive wheel diameter while maintaining frictional contact conditions and required ratio of the drive wheel and load-carrying cable diameters that is at least 40. Despite the above-mentioned advantages, a research issue that is of interest but so far has not been fully investigated is the process of wear of the hybrid load-carrying cables and evaluation of the technical condition of ropes being the load-carrying elements in the applied solutions, especially during the long-term operation. This article presents the possibilities of applying the magnetic method for evaluation of the technical condition of steel ropes being the load-carrying element of hybrid belts. The authors have presented their solution of the measuring head for magnetic testing of the load-carrying hybrid cables, elaborated by the team of employees of the Department of Machine Engineering and Transport at University of Science and Technology in Cracow, that enables the quantitative assessment of the hybrid load-carrying cable wear.

1. Introduction
The constant development of methods and means of technical diagnostics is required to ensure the appropriate level of safe operation of machines, devices, and technical objects. Currently, the process of diagnostics covers all modern technical facilities, while the older facilities functioning in the industry are being adopted to the changing regulations. The parameters that are subject to continuous diagnostics have been presented in Figure 1. The purpose of this paper was to develop the method procedure and the measuring equipment that will enable to find the location of damages and determine the technical condition of hybrid load-carrying cables.

In the publication [1], the author described his own-invented method of monitoring the elongation of lift load-carrying ropes during the actual time. He proposed that monitoring should be assured using several magnetic sensors and markers placed on the ropes, on the sections that are not in permanent contact with the friction wheel. Due to constant loading, their length changes with the operation time. In the author’s opinion, the evaluation of the rope elongation change should be based on the read-out of the distance between the markers. In the conference materials [2], the authors presented the method of magnetic metal memory (MMM) for monitoring the technical condition of the hoisting machine during the actual time. The application of this method allowed the authors to passively observe the magnetic field changes and the occurring magnetic and mechanical effects for touch-free monitoring of critical
components of the mining machines. Based on the example of the hoisting machine shaft, the authors discussed the diagnostics problem, the theoretical basis of magnetic and mechanical effects allowing for the impact of the magnetic field of the electric motor, the magnetic metal memory method, and the expected diagnostics symptoms. In the article [3], the authors focused on the issues related to the monitoring of the load-carrying ropes through magnetometric sensors intended for determination of the relation between the number of bends of the steel rope and the value of its magnetic field induction. The authors related the obtained results to the ropes operated in the actual facilities, which allowed determining their stress and condition. The method procedure developed by the authors enabled to state that the value of magnetic induction in the rope being bent changes after each subsequent bend, which in turn made it possible to evaluate the number of bends of the rope concerning its service life. In the publication [2], the authors present the possibilities of applying the magnetic method for evaluation of the technical condition of steel ropes in the area of their ends in the conical holders. In the publications [4,5] the authors discuss the issue of the energetic effectiveness evaluation of the passenger lifts. They present the discrepancies resulting from different standards of computing the energetic effectiveness of such materials handling facilities, resulting mainly from the accepted various algorithms and subjectivity of assumptions that should be made for the calculations. They pay attention to a significant problem related to the theoretical nature of such computation that is far from the actual operational load of the object. They present their own-invented hardware solutions that enable the measurement of actual operational and energetic parameters of the lifts and, at the same time, propose their own-invented method for determination (computation) of the energetic effectiveness of the lifts. The studies related to the material removal processes and the modern construction materials are another area of interest connected with monitoring of the material surface condition. In the publication [6], the authors endeavour to observe and affect the process parameters while drilling, milling, or turning using the signals obtained while monitoring. In the publication [7], the authors proved that making the thin-wall cabin panels rigid affected the emitted sound level in the lift cabin, and thus the comfort of the travelling persons. In the publications [8,9], the authors made an attempt to describe the impact of the changing operating conditions of the lifting devices onto the wear process of the safety gear components that are subject to big loads during the emergency braking. In the publication [10], the author presented the results of his tests consisting in the evaluation of the lift braking path depending on the safety gear design. Based on the test, it was proved that, depending on the safety gear design, the generated braking path had different lengths, which directly affected the comfort of the travelling persons. In [11], the authors described the application of the methods of electron microscopy and X-ray spectroscopy with energy dispersion to obtain the non-metallic inclusion cracking mechanism and chemical composition data. During their research, they referred to the mechanisms that occurred in the 100-year-old bridge

Figure 1. Parameters subject to diagnostics in technical facilities.
structures. In the publication [12], the authors describe the application of monitoring for the manufacture of aluminium shafts by the cross-wedge rolling method. In the opinion of the authors, the described process preceded with the numerical simulations is feasible within the satisfactory ranges of the engineering parameters under tests.

As comes out from the presented available state-of-the-art publications, currently the monitoring process constitutes one of the major trends in the technique being liable not only for the development of the production technology but also for maintenance of the machines.

2. Hybrid load-carrying cables – state of the art

The hybrid load-carrying cables have been developed as a response to the following market demands:

- Reduced dimensions of the powerplants.
- Quieter and more reliable flexible connection drives.

Figure 2 shows the powerplants compared as regards the size a) in a traditional form, intended for mating the steel ropes with round section, and b) in a compact form, intended for mating the hybrid load-carrying cables. Further to the above, the load-carrying belts became the object of diagnostics; their exemplary construction has been shown in Figure 3 along with the round ropes in wrapping.

![Figure 2](image1.png)

**Figure 2.** Comparison of the lift powerplants: a) reducer of Sassi production, source: www.sassi.it, b) powerplant without reducer of OTIS make, source: www.otis.com.

![Figure 3](image2.png)

**Figure 3.** Steel and polyurethane load-carrying cable – 30 mm x 3 mm [13].

The exemplary belt presented in Figure 3 consists of 12 steel ropes, each having a diameter of 1.6 mm. Each rope consists of 7 strands composed of 7 wires, which gives 588 wires, each having a diameter of 0.18 mm in case of the 30 mm wide belt. For such a belt construction, the shear force is 36000 N. In the belt design, the adverse phenomenon of a rope twisting inside the belt structure was anticipated. That design was
made a non-outwinding one thanks to alternating positioning of cables wound clockwise and counterclockwise as a result of which the outwinding moments of particular ropes got reduced. The developed belt solution, apart from the concise structure obtained by the use of polyurethane warp, eliminates the need of preserving the load-carrying cables and increases friction between the load-carrying cable and the drive shaft. According to the information given by OTIS and ContiTech companies materials regarding the hybrid load-ropes, the flat shape makes the contact surface bigger, which also has a significant impact on the stress distribution. Despite many advantages, it is required to learn about the life processes, their nature, and speed of the load-carrying system component damage increments using the diagnostics devices of various types that enable to forecast the time and the possibility of further safe operation of devices and to anticipate the approximate time of their replacement due to excessively big wear.

3. Hybrid load-carrying cable – diagnostics issues

The most frequently applied method of the steel cable diagnostics is visual testing (VT) in accordance with the PN-EN ISO 9712 standard. However, in the case of the hybrid load-carrying cables, this method is possible only for the condition when the steel cable wires contained inside the load-carrying cable damage the polyurethane coating and are visible outside. Further to this, the full diagnostics of the hybrid load-carrying cables creates a problem, especially as regards the cracks that cannot be detected using the visual testing method. Figures 4 to 8 show the most frequent damages that may be diagnosed by the VT method. The damages shown in Figures 4 to 8 totally eliminate the load-carrying cable from its further operation.

![Figure 4](image1.png)

**Figure 4.** Deformation (bulge) of the coating [14].

![Figure 5](image2.png)

**Figure 5.** Imprints of ropes along the load-carrying cable [14].

![Figure 6](image3.png)

**Figure 6.** Ropes protruding out of the coating [14].

![Figure 7](image4.png)

**Figure 7.** Cracking of the polyurethane surface.

![Figure 8](image5.png)

**Figure 8.** Puncture of the polyurethane surface through the broken wires.
4. Hybrid load-carrying cable – magnetic head
The information provided in the available publications and the own experience in the scope of construction and operation of the hybrid load-carrying cables as well as the diagnostics of steel cables has led to the development of the prototype measuring head. The magnetic head is based on the principle of local magnetisation of the tested ferromagnetic structure with the permanent magnetic field and enables recording the changes of the stray field around the tested load-carrying cable. The magnetic circuit of the head, shown in Figure 9, is composed of a steel plate being the magnetic jumper on which the polarised strong permanent magnets (NdFeB) and the pole shoes are symmetrically seated. Each of the pole shoes shorts the magnets polarised in one direction [5]. The central area of the head is occupied by the induction sensors (measuring coils). The magnetic circuit is closed by the hybrid load-carrying cables that move over the pole shoes.

![Figure 9. The measuring head for measuring the hybrid load-carrying cables a) schematic diagram, b) application on an actual object.](image)
When the respectively high magnetic energy is ensured, it enables to locally magnetise the tested structure to the level above $B=1.4$ T. The so-called stray field “outgoing” beyond the tested structure emerges in the location of the hybrid belt damage. The magnetic field force lines are subject to deflection “omitting” the air gaps (metallic section loss locations, e.g. wire breaking, etc.). This fact affects the vector of stray flux over the damage location and the value of its radial component. A change of this parameter value in time is detected by the induction sensors and then converted onto the electromotive force of induction and is recorded by the recording unit. In order to test the entire length of the load-carrying cable and to induce SEM in the induction sensor, it is required to ensure the mutual movement of the head and the load-carrying cable. The relation defining the electromotive force value in accordance with Faraday’s law is as follows [15,16]:

$$SEM = \varepsilon = -\frac{d\phi_{Br}}{dt}$$  \hspace{1cm} (1)

where:
- $\varepsilon$ – electromotive force of induction,
- $\phi_{Br}$ – magnetic induction flux of stray field (radial component),
- $t$ – time.

Figure 10 shows the voltage signal recorded during the test performed on an actual facility on one of the load-carrying cables, over its entire length. The real-time measurement was conducted during the cabin travel at the speed of 0.4 m/s over the entire distance between the limit switches of the lift, which is approximately 30 m of the load-carrying cable length.

![Figure 10. Voltage signal recorded while testing over the entire length of the load-carrying cable.](image)

At the distance of 28 m from the original position that corresponds to the cabin position in the lower part of the lift shaft, there is a significant change in the recorded signal amplitude. Such a change is related to the magnetic field disturbance originating from a loss of the metallic section of the ropes under tests and breaking of the wires potted in the plastic wrap. During the visual inspection of this area, no protruding wires, deformation, or other damage of the external coating of the load-carrying cable was detected. In Figures 11 to 13, a portion of the signal having the highest recorded signal amplitude value was selected. Figures 11 to 13 present the results of the authors’ testing in this area, recorded during the subsequent measurements conducted annually within the period from 2017 till 2019. On the graphs showing the results from the subsequent years, we can see an increase in amplitude and a change in the recorded signal shape. This is the indication of the observed damage size changes that enlarge along with the operational process and are visible via the losses in the metallic section of the load-carrying cable tested. For example, the signal amplitudes close to 28.1 m in the analysed time interval increased by 193% (8.9 mV in 2017; by 15.7 mV, mV in 2018; by 17.2 mV in 2019) which may indicate the
increase in the number of broken wires in this location. Whereas in the area of 28.4 m, a signal was identified in which both amplitudes within the analysed period increased by 218% (5.9 mV in 2017; by 8.1 mV in 2018; by 12.9 mV in 2019) and the shape (signature) changed. This may indicate that the number of broken wires increased and the distance between the broken wires became bigger. In Figure 13 presents the results of tests conducted in 2019, additionally, a visible new signal originating from the next damage in this area is identified.

![Figure 11. Portion of recorded signal (2017).](image)

![Figure 12. Portion of recorded signal (2018).](image)

![Figure 13. Portion of recorded signal (2019).](image)
The presented results confirm the applied nature of the equipment described in this article. The tests of the same load-carrying cable performed in the subsequent years indicate the repeatability of detected defect locations and the possibility of assessing the increment of their extension.

5. Conclusions
The examination of the publications and the authors’ tests on the application of the prototype measuring head enabled to make the following conclusions:
- Complete monitoring of the technical condition of the hybrid load-carrying cables is possible only when applying the state-of-the-art diagnostic facilities.
- The load-carrying cable dimensions and the material deformation and wear can be determined by means of visual inspection.
- The visual inspection does not provide full information about the condition of the hybrid load-carrying cables, so it is required to determine the criteria for such facilities that may be based on the results of magnetic tests conducted with the use of the mentioned head.
- The use of the head whose operation is based on a change of electric parameters allows reaching the satisfactory qualitative and quantitative results.
- The use of the head within 3 years on a real facility allowed determining the progress of defect changes in the steel ropes.
- Timely diagnostics of the hybrid load-carrying cables allow limiting the uncontrolled downtime of the lifting devices.

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