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ASSESSMENT OF THE CONDITION OF HOISTING ROPES BY MEASURING THEIR GEOMETRIC PARAMETERS IN A THREE-DIMENSIONAL IMAGE OF THEIR SURFACE

METODA OCENY STANU LIN WYCIĄGOWYCH POPRZEZ POMIAR PARAMETRÓW GEOMETRYCZNYCH NA TRÓJWYMIAROWYM OBRAZIE ICH POWIERZCHNI

This article discusses a vision method of measuring the geometric parameters of ropes and evaluating their wear based on measurements made in a three-dimensional projection of rope surface. The purposes of this method include assessment of the condition of all kinds of ropes working in the mining industry. The proposed method is novel, eliminates the shortcomings of previously used mandatory visual methods, removes their constraints, and is an important complement to magnetic methods. The article discusses the method of construction of a three-dimensional image based on mapping of the actual dimensions of the rope and on algorithms that allow determination of the parameters describing its basic geometrical dimensions and surface condition. The article discusses issues related to resolution of the vision system, resolution of laser beam analysis, and resolution relating to the measurement of the height profile on the surface of the rope. Based on the image constructed in such a way, measurements are presented in order to assess the dimensional parameters and surface defects in sample rope structures. Based on tests and analyses of the three-dimensional image, a range of inspection tasks using 3D vision systems is indicated.

Keywords: 3D vision systems, rope diagnostics, rope damage, rope modelling

Praca poświęcona jest omówieniu metody pomiaru parametrów geometrycznych lin i oceny ich zużycia metodą wizyjną na bazie pomiarów wykonywanych na trójwymiarowym rozwinięciu powierzchni liny. Metoda dedykowana jest między innymi do oceny stanu wszystkich rodzajów lin pracujących w górnictwie. Proponowana metoda jest nowatorska, eliminuje wady dotychczas stosowanych obligatoryjnych metod wizualnych, usuwa ich ograniczenia oraz stanowi istotne uzupełnienie metod magnetycznych. W pracy omówiono metodę budowy obrazu trójwymiarowego opartą na odwzorowywaniu rzeczywistych wymiarów liny oraz algorytmy umożliwiające wyznaczenie parametrów opisujących jej podstawowe wymiary geometryczne oraz stan powierzchni. W artykule omówiono zagadnienia związane z rozdzielczością

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systemu wizyjnego, rozdzielczością analizy wiązki laserowej oraz rozdzielczością związaną z realizacją pomiaru profilu wysokości na powierzchni liny. Na podstawie tak zbudowanego obrazu prezentowane są pomiary umożliwiające ocenę parametrów wymiarowych oraz wad powierzchni dla przykładowych konstrukcji lin. Na podstawie przeprowadzonych badań i analiz trójwymiarowego obrazu wskazany jest zakres zadań kontrolnych możliwych do realizacji przy wykorzystaniu systemów wizyjnych 3D.

Słowa kluczowe: Systemy wizyjne 3D, diagnostyka lin, uszkodzenia lin, modelowanie lin

1. Introduction

Assessment of the condition of all the ropes working in the mining industry is mandatory. The specific procedures for conducting such checks in the Polish mining industry are regulated by the relevant industry laws (*Regulation of the Minister of Economy...*, 2006). Similarly, in other countries. The group of approved methods includes both visual inspections and more detailed magnetic testing. The method presented herein allows transfer of the commonly used visual inspections from the group of qualitative methods to the group of quantitative methods. It also becomes possible to continuously monitor the condition of devices.

Automatic methods of inspection and damage detection are increasingly important for diagnosing the condition of process equipment in a variety of industries (Kwaśniewski, 2011). Rope diagnostics is especially important for devices which are used for the transport of people or which have an impact on the country's energy security, as in the case of mine hoists. Introduction of mandatory checks for numerous devices has also made safe operation dependent on the quality of technical condition assessment. In the case of visual inspection of ropes, there is always some risk of undetected damage to the rope, which can be dangerous. The method described below significantly reduces this risk.

Ropes are used in numerous rope transport devices, both in industry and in tourism and recreation. Ropes used in industrial devices are exposed to very difficult and different operating conditions. Sometimes, the defects and anomalies that appear in ropes are very small and difficult to detect even by experts experienced in diagnosing ropes. There is a search for newer methods of assessing the condition of both steel ropes and ropes made of modern materials (Kevlar ropes, ropes with plastic inserts, etc.). There are strict rules for testing steel ropes defined by law (*Regulation of the Minister of Economy...*, 2006) or recommended by manufacturers. The most common types of damage that occurs in ropes include wire cracks, wear, missing wires, corrosion, geometrical deformation or damage to the core. Some of those defects are easy to detect (wire cracks), while other are very hard to identify (corrosion, change in geometry) (Kwaśniewski, 2004). Figure 1 shows examples of damage that occurs during operation.

Visual inspections of steel ropes are one of the methods to detect defects. This method, which often involves checking the rope with a glove-protected or cleaning cloth-protected hand, exposes inspectors to some risk, such as injury caused by damage to the rope. Therefore, the test speed is not high and is 0.5 m/s on average. Nevertheless, it involves concentration and fatigue to the eye associated with the effort to detect the slightest damage on ropes, which in some cases have the total length of several kilometres.

This paper proposes a significant improvement to the above standard method by recording the image of rope surface around its entire circumference and length for later identification of selected geometrical parameters on a projected image. Visual examination of ropes allows detection of defects and damage by eyesight. Thorough examination and subsequent analysis and

Fig. 1. Example of clearly visible damage to the rope in the form of broken wire

interpretation of damage allows safe operation of rope devices. While working in equipment, ropes change their geometry, i.e. lay length of rope strands and diameter of the rope itself. Those changes are caused by bending and when the rope passes through shafting, vibration, and wear factors involving the loss of mass. The geometry of a rope has a considerable influence on its co-operation with other elements. Changes in the geometry of ropes are also caused by rotation around the axis as a result of untwisting torque (Nowacki & Tytko, 2009). This phenomenon may be the main reason for the development of defects and anomalies in the hoist rope during operation. How the rope works depends, to a large extent, on the device (Olszyna & Tytko, 2009). Changes to the mechanical and structural properties of ropes in the process of their operation is inevitable. By using appropriate methods of rope condition assessment, detection of certain forms of wear, and recommendations for further use, one can increase their durability. Measuring the diameter of a rope is the most widely used method to assess its geometrical parameters, but the instruments currently used do not allow reliable detection of locations of the lowest diameter on the rope, which may indicate disqualifying defects such as core damage. One of the motivations for research to explore new techniques for assessment of the technical condition of ropes is primarily the fact that the methods used currently to measure the diameter are inaccurate and do not offer the possibility of measuring lay length along the entire length of the rope. Also, it has not been clearly defined how to measure rope diameter so that this parameter could be used as a reference. The basic definition of rope diameter is the diameter of a circle as shown in Figure 2. Measured actual rope diameter is a key parameter for selecting ropes, associated components, etc.

Measurement with a vernier calliper with wider jaws allows such grasping of the rope that the jaws cling to the strands that lie directly opposite each other and the measurement is more accurate (Olszyna & Tytko, 2010). There is also the method of measuring rope diameter developed by Prof. Bittner from the Technical University in Vienna. It involves measurement of the circumference of a rope with a special ruler, which is wrapped around the rope, and its scale uses unit of length multiplied by π. This way you can directly determine the diameter of the rope. The ruler must be firmly tightened so that is becomes circular. This original way of measuring rope diameter, which is no longer in use, is shown in Figure 3.

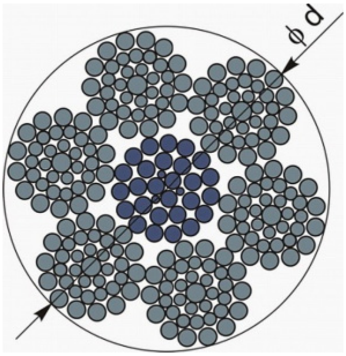
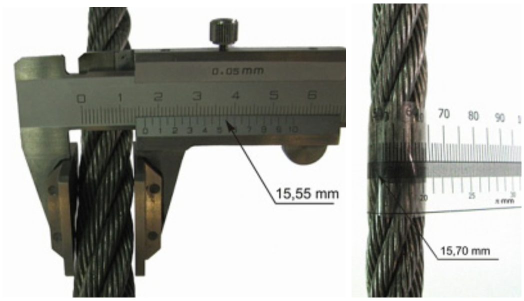


Fig. 2. Definition of the diameter of a twisted-pair cable



a) b)

Fig. 3. Methods of measuring rope diameter: a) – a vernier calliper, b) – a ruler with an appropriate scale which takes into account the number π

During a routine inspection and testing of ropes working in some devices, it is also very important to measure the second geometrical parameter, i.e. lay length of strands in the outer layer of the rope. This is important mainly in the case of mine hoisting ropes, which demonstrate a phenomenon known as twisting. Changing lay length informs about the untwisting torque, and this factor, leading to formation of contact and tangential stress in the wires, causes rapid fatigue wear. Changing length of the pitch as a result of twisting is always associated with a decrease of remaining fatigue life. The design of strand ropes makes it difficult and very time consuming to take an accurate measurement of the lay length using the current methods. A visible and measurable result of mining rope twisting is the constantly changing lay length, otherwise known as a change in the angle of twist of the strands in a rope (equivalent phenomena). Rope lay length, being the second fundamental geometrical parameter, is usually measured with a ruler, paper, chalk, grease or graphite or other support materials (Nowacki et al., 2008).

Measurements are usually made at selected locations throughout the length of the tested roped and using the chosen method. Figure 4 shows measurements of the lay length of a strand rope directly on the rope, using several methods.

Both the measurements of rope diameter and of lay length provide quantitative information on the state of the rope. Measurement of the above parameters is complicated by several side factors, which include: predisposition of the personnel performing the measurements and evaluation of the rope, lubrication of the rope, and intensity of illumination. Illumination of tested ropes in mining is, in most cases, artificial, which may contribute to human error. This relationship is shown in Figure 5. Increase in illumination intensity has an effect on the number of errors (Hlebowicz, 2002).

There is a justified need for finding new methods to be used in NDT of ropes to measure the geometric parameters and the condition of the surface of the rope. All ropes are withdrawn from service in accordance with specific acceptance criteria. For mining ropes, the decommissioning criteria are based on rope wear symptoms, which include broken wires, abrasions, deformation, etc. This work shows new possibilities of assessing the condition of ropes based on spatial visualization of rope surface. The method belongs to the group of indirect visual testing (VT) methods, which can be very useful in the commonly used visual and magnetic rope testing (MRT) methods.

a)

b)

c)

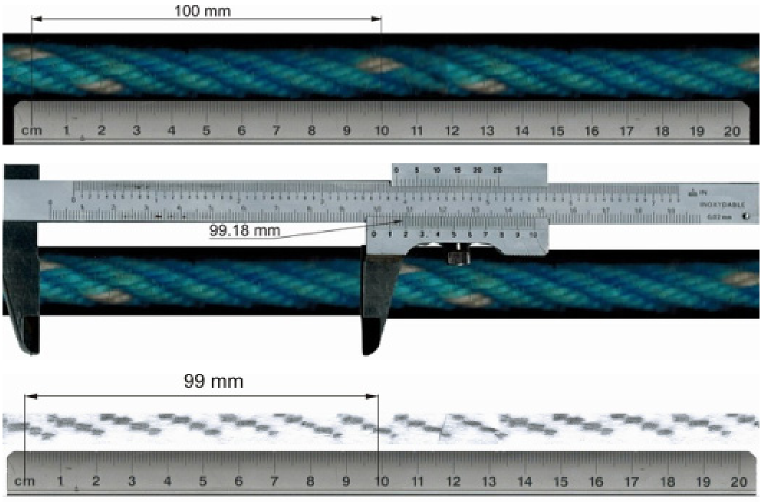


Fig. 4. Examples of measuring the lay length of a strand rope, where: a) measurement with a ruler b) measurement with a vernier calliper, c) measurement using a imprinted image on paper and, for example, graphite

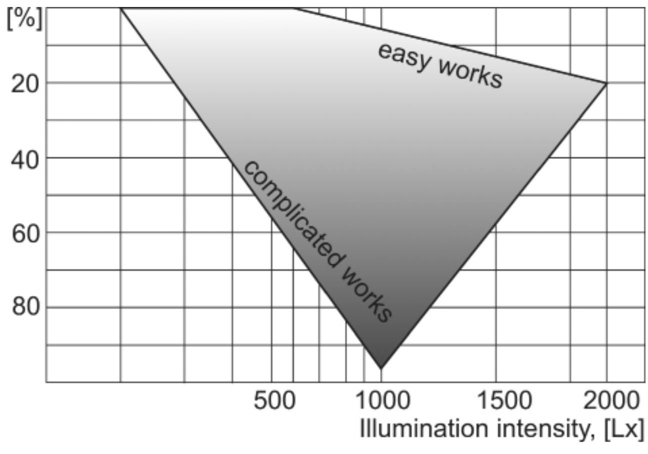


Fig. 5. Reducing the number of errors in visual assessment methods depends on illumination intensity

It can be an effective method to assess the technical condition of ropes which do not display any typical wear processes in the form of broken wires (Olszyna & Tytko, 2011). The method can be applied to ropes made of natural and synthetic fibres. Those ropes are becoming more widely used in many industries, including mining. Fibre ropes can now be assessed by visual inspection only. Therefore, it is necessary to search for new techniques for assessing fibre ropes.

2. Construction of a three-dimensional image of rope surface projection

Construction and configuration of three-dimensional vision systems allows matching the capabilities of the system to the measuring tasks performed by them (Gawlik et al., 2004; Kowal & Sioma, 2009; Bednarczyk & Sioma, 2011). The paper presents two methods for measuring the geometric parameters of ropes using a three-dimensional image of their surface obtained with a 3D vision system.

Measurement and evaluation of rope parameters should be carried out continuously along the entire length of the rope. This will enable assessment of the changeability in the determined parameters along the length of the rope and make it possible to assess changes in the selected parameters during operation of the rope. A three-dimensional image of the surface of a rope can be obtained by two methods (Tytko & Sioma, 2011). In the first method, a laser line illuminates the rope, and the laser line is set perpendicularly to the axis of the rope, as presented in Figure 6. The rope is scrolled through the measuring station along its axis, allowing determination of subsequent cross-sections and construction of a three-dimensional image of the surface of the illuminated part of the rope. For the adopted configuration of the station, one needs to determine resolution ΔX, ΔY, ΔZ in each of the three axes of the coordinate system of the station (Kowal & Sioma, 2010, 2012).

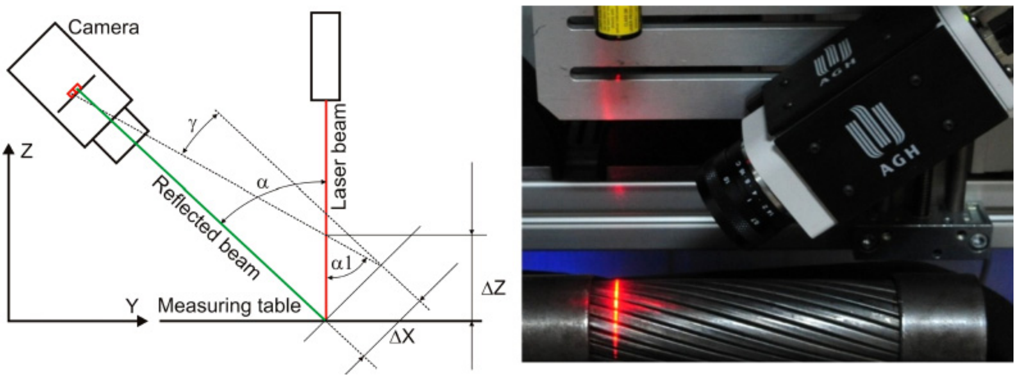


Fig. 6. Geometry of a 3D vision system and view of the laser line illuminating the rope

An image constructed in this configuration enables precise evaluation of the surface of the rope illuminated by the laser. A three-camera system allows assessment of the entire surface of the rope on the basis of three fragmentary images of its surface. It is extremely important in tasks involving inspection of damage to rope surface, in particular broken wires and abrasions on the surface of wires in the rope. Figure 7 presents an image of the surface of two types of ropes generated in the adopted system of alignment of the rope and a 3D vision system (Sioma, 2010).

The second method of generating an image of rope surface is such setting of laser line in relation to the rope so that it is parallel to the rope axis (Fig. 8). By rotating the measuring system around the rope, one gets a full three-dimensional image of the surface of the rope, which is its projection.

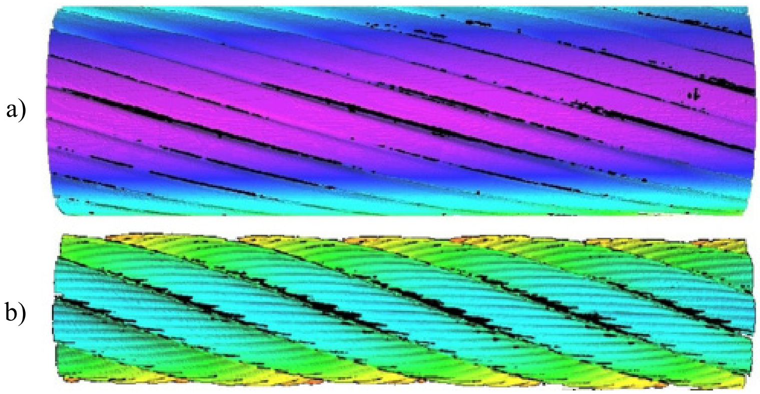


Fig. 7. 3D image of rope surface: a) – locked-wire rope with 23 “Z” wires
in the outer layer, b) – 8-strand rope

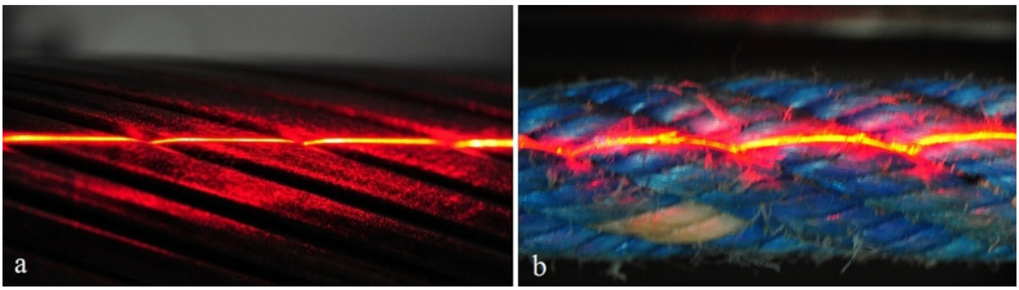


Fig. 8. Construction of a 3D image of rope surface: a) – locked-wire rope with 23 “Z” wires
in the outer layer, b) – 8-strand fiber rope

Figure 9 shows full images obtained by this method in the form of a full projection of rope surface. During full rotation around the rope 720 profiles were obtained. A projection of two ropes is presented: steel rope and fibre rope. A detailed image of the entire surface area covered by the measurement is shown on figure 9.

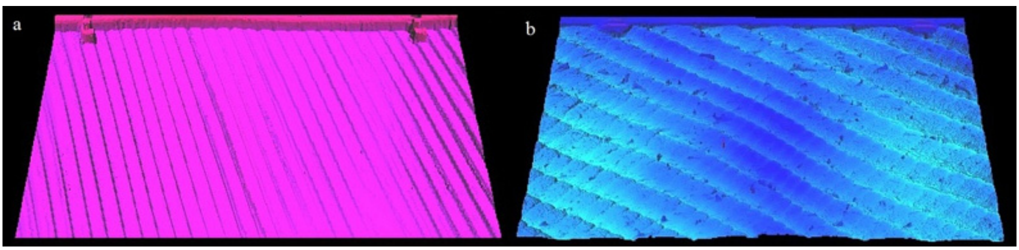


Fig. 9. 3D images of rope surface projections: a – locked-wire rope with 23 “Z” wires
in the outer layer, b – 8-strand fiber rope

3. Measuring lay length on a three-dimensional image of rope surface projection

A three-dimensional projection of the surface generated from a full rotation of the laser system around a 6-strand rope enables observation of the lay on all the strands making up the surface of the rope. Figure 10 presents a measurement of lay length taken simultaneously for two selected strands on the image of rope surface. By measuring lay length for all the strands shown in Figure 9, the average lay length was calculated. In this case, it is 100.04 [mm].

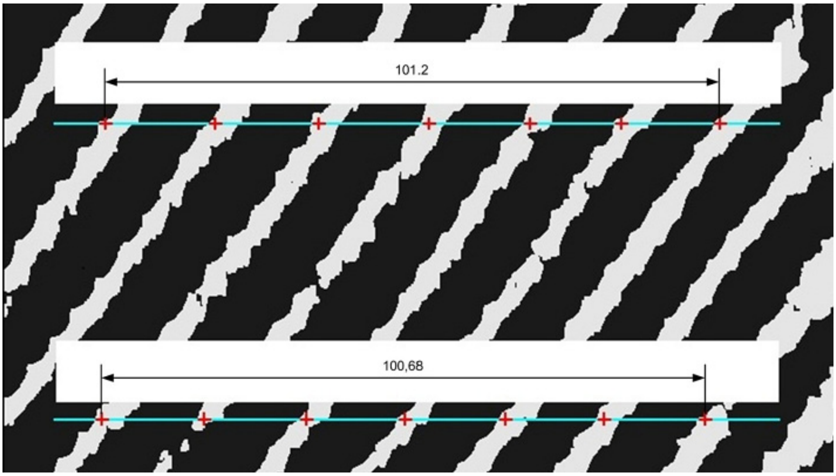


Fig. 10. Three-dimensional images of rope surface projections and method of determining lay length in two locations

In the image of rope projection, one can also observe local twisting of strands. This is evident in the form of straightness disorder visible as white areas in the valleys between the strands. This is shown in Figure 11. For selected strands, two control points were determined. A straight line was drawn between the points. This enabled evaluation of the deviation of the visible edge of the strand relative to that line. Local deviation of strand edge relative to the line indicates a local change of geometrical parameters. Those changes can be caused by a local change in diameter of the rope (bottlenecks, creases, etc.). Similarly, they can be caused by points of interruption or thickening of the rope core, which is one of the most dangerous types of damage, and very difficult to detect by other methods. Figure 11 shows the incompletely, as yet, identified diagnostic potential of the method.

In order to conduct proper imaging of the surface of different types of rope, the operating parameters of the vision system and the laser should be selected individually as regards the definition of FOV (Field of View) and laser power and mode of operation. Selection of the correct illumination is linked to the properties of the material as regards the absorption, reflection and scattering of a laser beam. Below is presented a rope made of highly permeable material,

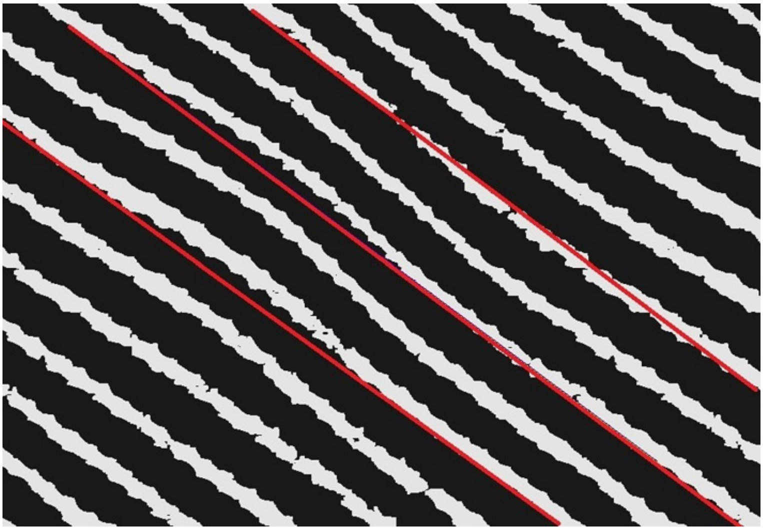


Fig. 11. Three-dimensional images of rope surface projections with a visible local disruption to the strand arrangement in the outer layer

for which a dedicated method of selection of laser parameters has been developed. Figure 12 shows the effect of combined scattering and absorption of laser light on the surface of the rope. The parameters were chosen so that the vision system shows the outline of the surface shown below in Figure 12.

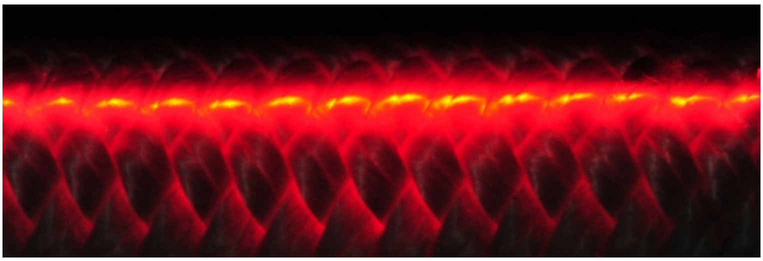


Fig. 12. Tightly-woven fibre rope

As a result of using a three-dimensional vision system, an image of the projection of the surface of a fibre rope was obtained. The rope diameter is 17 [mm]. The rope did not display typical pitch due to the fact that the rope is braided in its outer layer. Only the interlace was defined, which is the distance between successive 12 tucks in the weave, shown as a photograph of the surface in Figure 13.

Figure 14a shows the height profile of the surface of a rope at its axis, in the location presented in Figure 13 as segment AB. The profile shows a weave of the strands making up the surface of

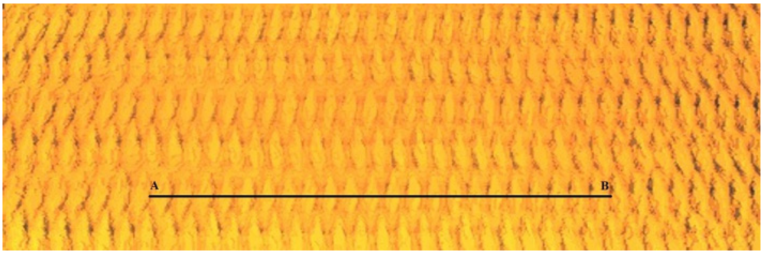


Fig. 13. Three-dimensional image of the surface of a multi-strand fibre rope

the rope. Figure 14b shows an analysis of the changes in profile heights carried out for selected profile points of the rope. The height of each of the strands was scaled in order to present relative height differences in the profile. Assessment of such a rope profile makes it possible to assess the quality of rope surface. It is also possible to detect surface deformations arising from the use of the rope and damage to fibres in the strands.

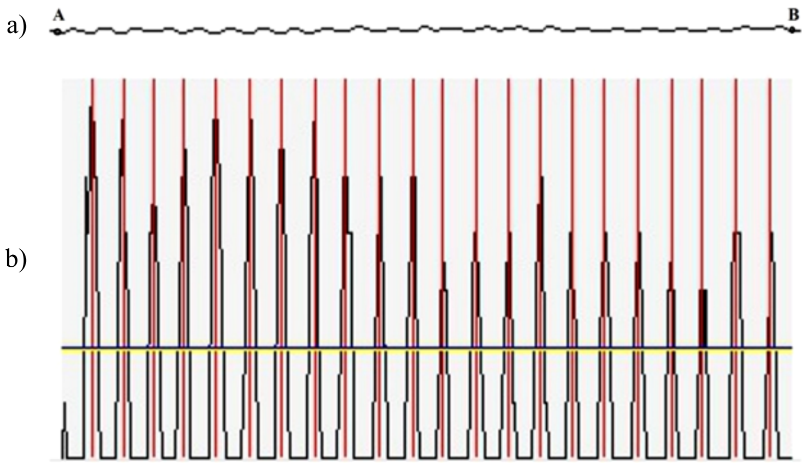


Fig. 14. Analysis of the profile of a fibre rope in segment AB (Fig. 13)

The distance between successive 12 tucks in the weave was measured using single-threshold binarization of a three-dimensional image. Due to the use of this operation, segmentation of the vertices of each of the strands illuminated by laser light was possible. As a result, an image resembling a collection of spots, which are the vertices of strands forming the surface of the rope, was obtained.

Visualization and measurement of the geometry of surface shown in Figure 15 concerns fibre ropes, which are not used in the Polish mining industry as hoisting ropes, but it shows the general diagnostic capabilities of the method as a visual testing (VT) method. As a result of image analysis, one can detect abrasions, deformations or indentations of single wires on rope

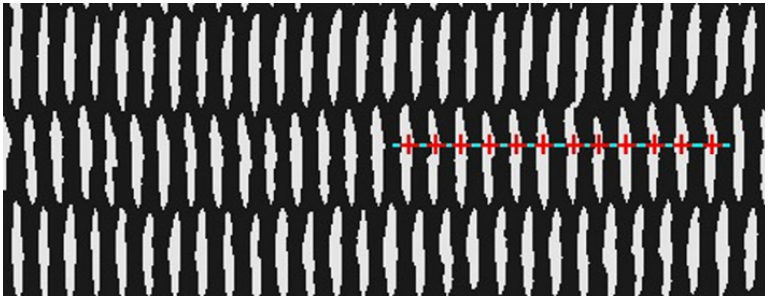


Fig. 15. Measurement of interlacing defined as the distance between successive 12 tucks in the weave

surface. The lack of diagnostic methods for this class of ropes translates into their non-use in the mining hoists. However, the trends observed with respect to rope hoists used in winches in marine mining show an increasing use of fibre ropes instead of steel cables. This is due to two of their fundamental properties: low density and corrosion resistance, at relatively low cost and strength comparable to steel ropes.

4. Summary

The above new methods of assessment of the surface of both steel and fibre ropes using a vision system allow one to draw several important specific conclusions:

- it is possible to create a digital image of the surface of a rope in the form of a full projection,
- the image of rope surface in the form of full projection permits identification and detection of various defects,
- the obtained images of rope surface allow determination of its diameter and pitch length of the weave,
- there is the possibility of creating algorithms enabling fast detection of damage to the surface of the rope,
- collection of research results in digital format (flash memory, HDD, etc.) makes it easy to restore the changes that occurred during the rope's life,
- results of measurements of the geometrical parameters of ropes obtained to date indicate that the developed vision system exceeds the accuracy of visual inspections carried out with traditional methods.

One can also formulate more general conclusions:

- the laboratory test results obtained so far indicate that there is the possibility of industrial application of vision systems to evaluate the technical condition of the surface of ropes and to measure their geometrical parameters such as diameter and pitch length,
- vision methods can be more than just an addition to the magnetic testing of ropes working in a variety of industries, including, in particular, in the mining industry.
- the method should be further developed, aiming at continuous monitoring of the condition of ropes.

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