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LASER MEASUREMENT SYSTEM FOR THE DIAGNOSTICS OF MINE HOIST COMPONENTS

LASEROWY SYSTEM POMIAROWY DO DIAGNOSTYKI ELEMENTÓW GÓRNICZYCH WYCIĄGÓW SZYBOWYCH

This article discusses a completely new concept for the diagnostics of sheaves in rope hoisting equipment used in deep mining, where excavated material, consumables, and people are transported via shafts. Rope sheaves involve shafting, guide sheaves, and support rollers on which ropes reel in special grooves. Those grooves may be made directly in the material of the sheave rim or in a specially installed plastic liner. Those grooves are made in the appropriate dimensions. Any change to those dimensions is due to a number of phenomena that occur in life cycle processes and significantly affects the condition of ropes. Measurement of the geometrical parameters of rope grooves for diagnostic purposes provides information about the condition of the rope system and guidance on the appropriate corrective actions. This article presents a solution that permits continuous measurement of selected geometrical parameters of the grooves using a non-contact method of scanning sheave rims with a laser beam. The basic geometric parameters of grooves and sheave rims were defined. The system was shown to be useful in the determination of axial and radial run-out of rope sheaves.

Keywords: 3D visions systems, rope sheaves, diagnostics, hoisting equipment

Artykuł dotyczy zupełniej nowej koncepcji diagnostyki kół linowych maszyn wyciągowych stosowanych w górnictwie głębokim, w którym transport urobku, materiałów oraz ludzi prowadzony jest szybami. Koła linowe to pędnie linowe, koła kierujące i odciskowe, po których obtaczają się liny w specjalnie wykonanych rowkach. Rowki te mogą być wykonane bezpośrednio w materiale wieńca koła linowego lub w zamontowanej specjalnie tam wykładzinie z tworzyw sztucznych. Rowki te wykonane są w odpowiednich wymiarach. Zmiana tych wymiarów wynika z szeregu zjawisk, jakie zachodzą w procesach eksploatacji i znacząco wpływa na stan współpracujących lin. Pomiar parametrów geometrycznych rowków linowych w celach diagnostycznych daje informację o stanie układu linowego oraz dostarcza wskazówek dotyczących działań korygujących te wymiary. W artykule przedstawiono rozwiązanie

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pozwalające na ciągły pomiar wybranych parametrów geometrycznych rowków bezkontaktową metodą skanowania wieńców kół linowych wiązką promienia laserowego. Zdefiniowano podstawowe parametry geometryczne rowków i wieńców kół linowych. Wykazano przydatność systemu do wyznaczenia bicia osiowego i promieniowego kół linowych.

Słowa kluczowe: systemy wizyjne 3D, koła linowe, diagnostyka, maszyny wyciągowe

1. Introduction

All transport equipment operating in Polish mines are subject to mining regulations in order to ensure an adequate level of security during their lifetime. Most of the equipment was installed in the 70s and 80s. In later years, some of it was upgraded and is now in a satisfactory condition. Upgrades and repairs of equipment only prolong the lifetime, but do not always remove the causes and consequences of damage. In many cases, the wear of a component may be observed by using different methods to assess its condition, including mainly diagnostic methods.

Technical diagnostics is used not only to ensure safe operation of equipment, but it is also desirable from an economic point of view as it reduces operating costs, especially those unpredictable. In the case of large-scale goods and unitary products, high costs are generated by any damage leading to failure and warrant the use of non-destructive methods for diagnostic purposes. Because diagnostic studies have the effect of lowering total cost of operation, it is desirable to introduce new technologies and methods of assessment into the diagnostics of parts of machinery and equipment in order to improve safety and prolong their life.

Mine shaft hoists are rope transport systems which are important for the country's economy and which ensure energy security. In Poland, much of the electricity is sourced from hard coal (56.4 %) and brown coal (35.1 %) (data from the Central Statistical Office for the year 2012). Hoisting machines contain many components that need to be or should be examined in order to obtain empirical data to improve reliability. Typical components of mine hoists subject to an irreversible process of wear include ropes, sheaves, lining of driving and guiding sheaves, hoist vessels, hoist vessel guiding systems, etc. The topic of researching components of mine hoists has been raised on several occasions in various works (Wolny, 2011; Kowal, 2011). The operating parameters measured on real objects are in many cases used as empirical evidence for the upgrading and repair of equipment in service as well as for the design of new systems.

Safe operation depends on the condition of components such as:
– components which directly transfer loads,
– components which do not directly transfer loads, but have an impact on their wear.

The effectiveness of tests and operational reliability depend on the research methodology adopted. Components selected for testing should be the weakest links or the fastest-wearing parts in the system. Modern machinery and equipment are made with high strain on the material (reduced size and weight while increasing the loads, speed, acceleration, etc.). This leads to an acceleration of ageing and wearing processes. During operation, there are reaction forces in kinematics pairs originating from forces of the transmitted loads. Variable tensile stresses are created in rope systems, depending on the parameters and conditions of operation. During cooperation of components, abrasive, adhesion, fatigue and corrosion wear occurs. Many triggering factors affect such wear processes. Knowledge of the causes of damage is the basis for constructing the machine's reliability system. Variations in the wear of equipment are often referred to as the approximate value of parameter changes. Some parts of machinery have damage that is impossible to observe and which manifests itself only after reaching the limit condition. Damage is an important event that occurs in machinery and is, in a way, the source of creating reliable and efficient equipment. Damage can be classified as measurable (e.g. changes in geometry) and immeasurable (e.g. corrosion, decrease in fatigue life). The condition of machinery and equipment depends on the random distribution of triggering factors and their prerequisites. Damage in the process of operation is random and can be classified as shown in Fig. 1 (Żółtowski, 1996).

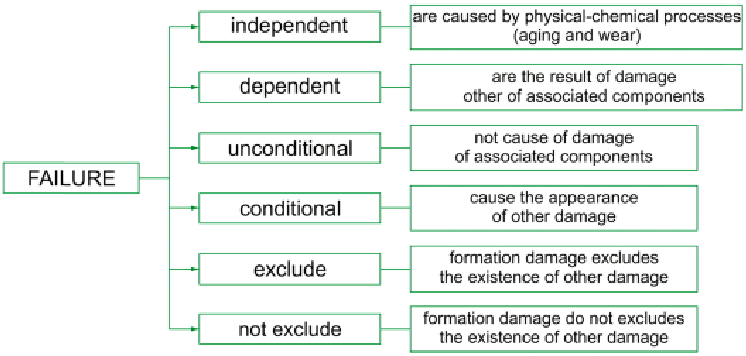

Fig. 1. Classification of damage in terms of random interactions of physical processes

The main task of technical diagnostics of equipment is to detect the risk of failure of the equipment. The condition can be evaluated on a continuous (monitoring of parameters) or temporary (testing) basis. On the basis of the recorded tendencies of changes in the monitored parameter, uptime can be predicted.

Choosing how to assess the equipment depends on its complexity and has an impact on the cost of diagnostics. The components to be diagnosed should provide information about the changes occurring in them during the operation process. The main objective of diagnostics is to discover the causes of damage, as determined by a set of specific characteristics, and to predict the development of that process. On the basis of measurable characteristics, one can determined the permissible (limit) wear parameters.

The remaining part of the paper presents an approach for assessing the conditions of a selected component of a hoisting machine. As an example, sheaves were selected. The method and the results of research were presented. The aim of the study was to determine the suitability of results obtained using the presented method for assessment of the conditions of tested components and their impact on other components cooperating with them.

2. Impact of the geometry of sheave grooves on cooperating components

In mine shaft hoists, in order to ensure an adequate coefficient of friction, adequate pressure, and adequate adhesion of the rope, sheaves have grooves. The shape of the grooves and/

or the use of appropriate materials for the lining of the sheave grooves has a major impact on the durability of ropes. Fig. 2 shows the effect of the geometry of a groove on the durability of a wire rope with spot and linear points of contact.

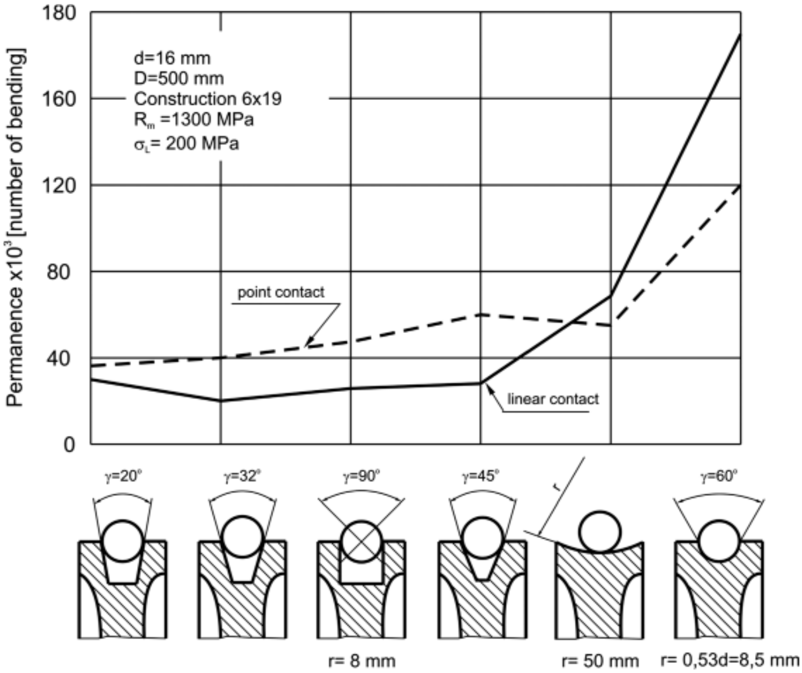

Fig. 2. Influence of groove geometry on the durability of wire rope with spot and linear points of contact between wires (Jemlich, 1985)

The above figure was prepared on the basis of practical experience, and it is one of the many confirmations of the design principle that the most optimal solution in terms of durability of ropes is to use a groove with the radius of 0.53 d (as measured in the axis of the effective diameter of the sheave). During operation of mine hoists, sheaves are subjected to variable loads. Between the guiding sheave and the drum of the hoisting machine, vibrations of high amplitude (catenary dynamics) are created in the rope. The variability of those lateral loads affects the wear of sheave grooves during operation. Also, changes in the assembly of sheaves and the bearing of the shaft or sheave axes can have a major impact on the wear processes of both the sheave groove and cooperating ropes. Another factor with a significant influence on wear is rope design in terms of their rigidity and the phenomenon known as rope twisting leading to uneven wearing out of the grooves. Those phenomena and the processes that determine them are as yet little explored (Nowacki & Tytko, 2011). This paper presents and describes the phenomenon of rope creep on the sheave, which causes abrasive wear of the lining, as shown in Fig. 3.

The next part presents the measurement methodology and method, which allows precise measurement of changes in the geometry of the sheave grooves.

Fig. 3. Uneven wearing of the groove lining in a driving sheave (Nowacki & Tytko, 2011)

3. Measurement method

The use of 3D vision systems for process tasks and for measurement and control is dynamically developed and gradually presented in academic papers (Kowal & Sioma 2009, 2010; Kowal et al., 2012; Olszyna et al., 2013). Those tasks may be performed at speeds of up to several thousand measurements per second (Gawlik et al., 2004; Kowal & Sioma 2009; Bednarczyk & Sioma, 2011). This paper discusses the issue of measuring the geometric parameters of sheaves and rollers used to guide the ropes and determine their radial (lateral) and axial (longitudinal) run-out. To perform the measurements, a properly prepared 3D vision system and structured light in the form of laser illumination were used. The measurement and evaluation of the parameters of a sheave is non-contact and is continuous around the entire circumference. Such arrangement allows the assessment of changes in selected parameters, such as the diameter of the rope groove during operation. To perform the measurement, appropriate vision system configuration and position of the system relative to the tested object should be designed.

The vision system was configured as shown in Fig. 4a. The laser beam illuminates the sheave at 90° in relation to its axis. The camera is set at a 45° angle with respect to the plane of the laser passing through the axis of rotation of the sheave. Measurement is made during rotation of the sheave. The camera records successive groove profiles on the sheave every 0.5° (Fig. 5a). This allows the recording of 720 profiles, from which a three-dimensional image of the surface of the groove around the entire circumference of the sheave is built (Fig. 5b).

Construction of a 3D vision system and determination of the resolution of the system requires selection of the following: optical system, camera resolution, geometry of the positioning of the camera and laser illumination, system calibration (Sioma, 2011). Those tasks need to be completed in order to build a three-dimensional image of a surface as shown in Fig. 5b. The image was then pre-processed in order to prepare it for measurement procedures. Their purpose is to remove interference that may inadvertently appear in the image and to prepare it for the measurements within a given range of tasks.

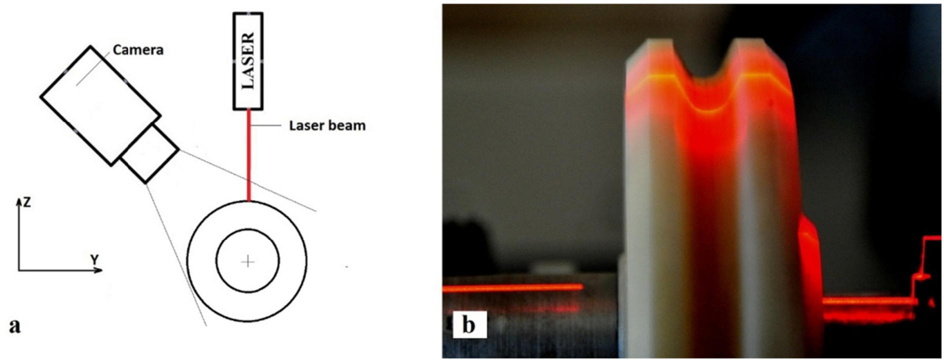

Fig. 4. Geometry of a 3D vision system (a) and view of sheave rim illuminated by laser (b)

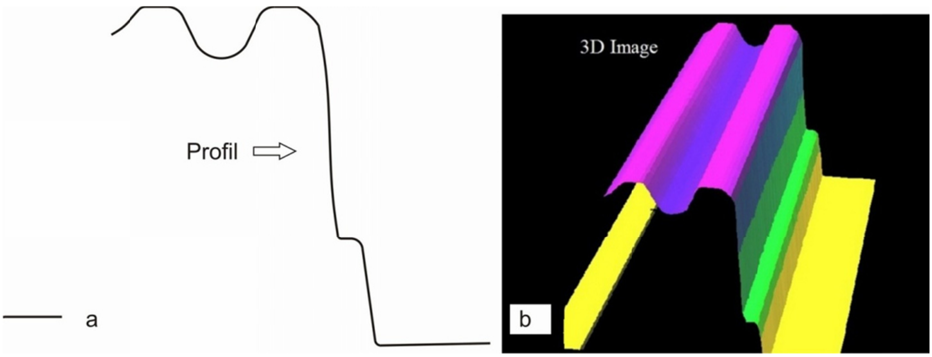

Fig. 5. Single height profile defining the shape of the sheave rim (a) and expanded view of sheave groove around the entire circumference (b)

4. Measurement results

Reference planes were defined in the image, and then measurement points were determined to allow:

- measurement of groove diameter (Δr),
- measurement of radial run-out on the body of the sheave,
- measurement of radial run-out in the groove of the sheave (Br),
- measurement of axial run-out on the body of the sheave,
- measurement of axial run-out in the groove of the sheave (Bo).

On each of the 720 profiles (Lp) describing the shape of the groove, a circle is marked out to define the shape of the bottom portion of the groove. This is the contact area with the sheave with which the line cooperates. That circle, inscribed in the profile, has a diameter determined from a set of points that form the image of a sheave groove. The value of the diameter measured this way is recorded in a database of measurement results. A view of a circle defined for one of the profiles and a three-dimensional shape of the groove is presented in Fig. 6.

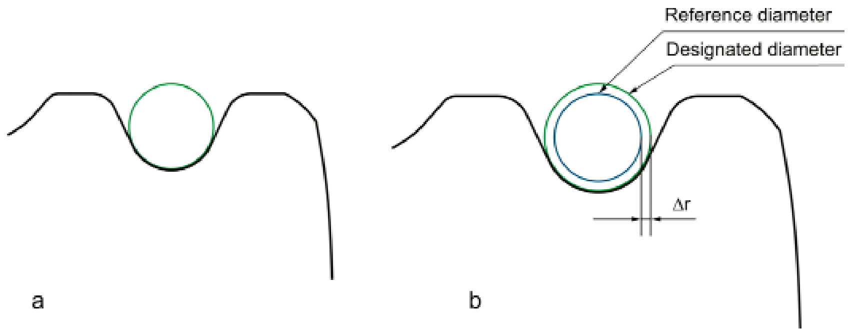

Fig. 6. Circle showing the diameter of sheave groove inscribed in the groove profile created by the vision system (a) and method of determining diameter deviations (b)

A circle with a so-called reference diameter, which is fixed for all the measurements performed, was adopted as the value of the diameter of sheave groove. Then, for each profile of the sheave rim, a circle inscribed in the groove profile was defined. Based on a comparison of the measured diameter and the reference diameter, deviation (the difference of the two values) was determined for each of the profiles. Based on that deviation, a diagram was prepared showing the changes in diameter (radius) around the entire circumference of the sheave rim. The diagram was prepared for 180 measurements (Lp) distributed uniformly over the circumference of the circle. The measurements were made with a resolution of 0.05 mm and scaled in the diagram to present changes in the diameter of the groove on the full circumference of the sheave.

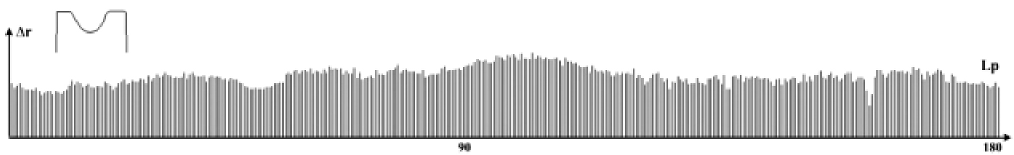

Fig. 7. Histogram of the distribution of changes in the diameter of rope groove around the entire circumference of the sheave rim

Also, measurements of radial and axial run-out were performed on the three-dimensional image. Those measurements were designed to examine the possibility of diagnosing sheave wear during operation. Radial run-out was assessed by measuring two characteristic points located on the circumference of the sheave. The first point, P1, was set on the body of the sheave where it does not cooperate with the rope. The second point, P2, was set inside the groove. Measurement of radial run-out at point P1 allows identification of damage associated with the fixing of the sheave onto the shaft or axis, e.g. in the form of damage to the bearing or incorrect sheave assembly. Point P2 enables observation of radial run-out in the groove, which may result from the cooperation between rope surface and groove surface. Those changes may indicate the presence of local mechanical damage. Location of P1 and P2 on the circumference of the sheave is presented in Fig. 8.

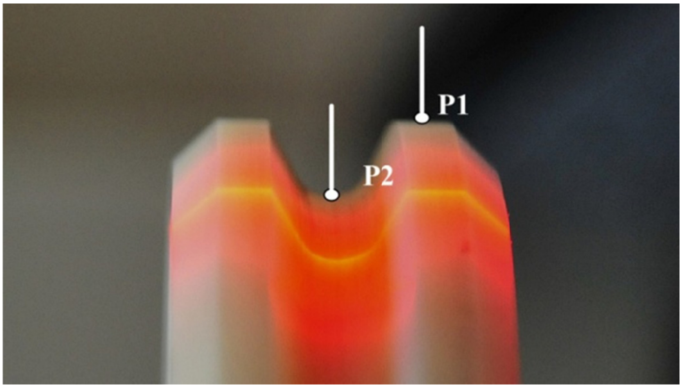

Fig. 8. Location of measurement points on the circumference of the sheave

Run-out measurement was performed in the following manner. For each of the measuring points, a constant measurement base for all measurements was defined. Then, for each of the profiles, the distance of P1 and P2 from the measurement base was determined, arriving at the value presented in the diagrams below. Due to the small size of the run-out, which averaged at about 1 mm, the measured values were scaled in order to plot those changes onto the entire circumference of the sheave. Analysis of run-out on the body of the sheave and inside the groove permits evaluation of the condition of the sheave and also identification of the causes of run-out on the sheave (Fig. 9). There may be two groups of reasons: related to the mounting of the sheave in the bearing and related to wear caused by various forms of rope vibration.

To measure axial run-out, also two reference points were set. Point P3 was located on the body of the sheave and point P4 was located within the groove. As before, run-out measurements at those points should allow determination of the run-out of both the sheave itself and the groove. Measurement at both points permits full identification of the size of run-out on the sheaves as a result of both cooperation with the rope as well as geometric changes related to the movement of

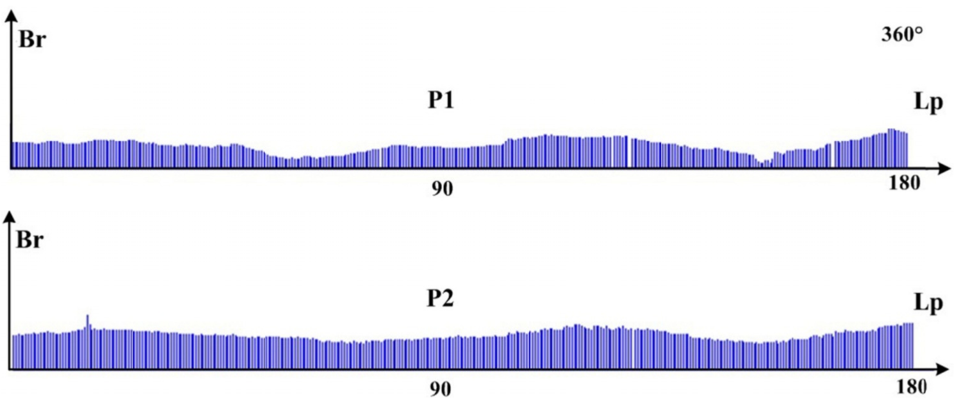

Fig. 9. Histogram of distribution of radial run-out based on 3D image of the sheave

the sheave. For points P3 and P4, a constant measurement base for all measurements was defined. Then, for each of the profiles, the distance of those points from the measurement base was determined, thus arriving at the run-out value presented in the relevant diagrams.

As a result of measurements at both points, P3 and P4, the following results of axial run-out measurement were obtained. The result was scaled to present the trend in the changes of run-out at the indicated measurement points.

As a result of measurements using a three-dimensional image of the rim of a sheave and its groove, an original proposal for using this technology for the analysis of sheave parameters during its operation has been developed. The results of measurements performed on a test bench confirm the possibility of continuous monitoring of a properly defined diameter of the groove of a sheave and the possibility of continuous monitoring of the run-out of sheaves, both axially and radially.

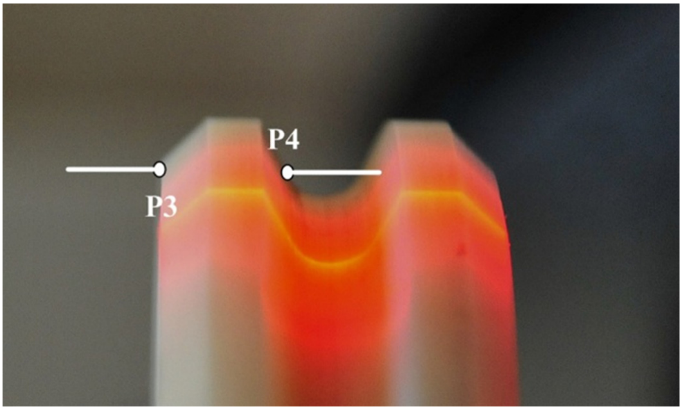

Fig. 10. Location of measurement points on the circumference of the circle for the purpose of determining axial run-out

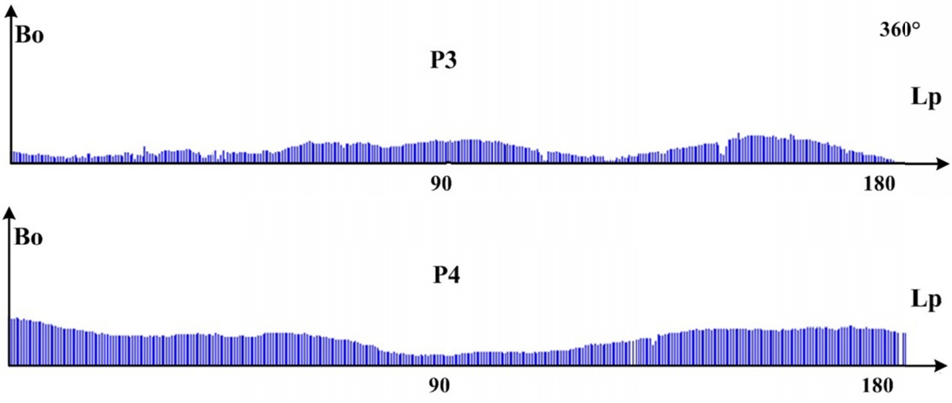

Fig. 11. Histogram of axial run-out from 3D sheave image as determined for the entire circumference of the sheave

5. Summary

The measurements and analyses lead to several conclusions.

1. The presented method of assessment of rope sheaves allows one to determine:
   - properly defined diameter of the groove of a rope sheave,
   - the size of radial run-out,
   - the size of axial run-out.
2. Selection of measurement points allows the measurement of run-out of both the sheave rim and the rope groove.
3. Measurements can be performed in real time, so the method can be part of a rope sheave monitoring system.

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