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Analysis of cutting picks trajectory and cutterhead vibrations of roadheader with use of high-speed cameras

In order to identify the behavior of cutting picks during the process of mining with the use of a roadheader's cutterhead, an optic system has been employed. The main elements of the system were high-speed cameras. In conjunction with TEMA Motion 3D software (which is designed to analyze movement based on images registered in videos), this allowed for a detailed analysis of the trajectories of the boom, cutterheads, and cutting picks during the process of cutting. This article presents the process of conducting measurements as well as the results of a comparative analysis of the boom vibrations and movement trajectories of cutting picks on the cutterhead for selected cut types: progressive and degressive.

Key words: *high-speed camera, roadheader, transverse cutterheads, progressive cut, degressive cut, vibrations*

1. INTRODUCTION

From the point of view of a multi-pick cutterhead, defining the instantaneous position of cutting picks is essential for linking them with the forces generated during mining. Depending on the rotational speed of the cutterheads and boom extension speed, consecutive picks entering the cutting zone can make new cuts or fall into grooves made by previous picks [1]. Additionally, the modification of these parameters impacts the shape of the cross-section area of the cut [2–6]. An analysis of the load characteristics of picks (which is necessary for verifying the numerical model of a roadheader [7–10] and automatically control the parameters of the machine during mining [11]) requires the identification of the actual movement trajectories of the picks (where cutting, compression, and lateral forces are measured) and the roadheader vibrations (especially of its excavating system components). Using an external optical system of high-speed cameras (that are not a part of the machine) that is precise enough to define the position changes of the cutterheads and their picks is an alternative method to a direct measurement [12]. Taking into account the complex movement trajectory of the transverse cutterhead (where the picks move in a spiral motion over the torus surface during the cutting process, which is impacted by overlapping vibrations of the boom and the whole machine), using an optical measurement system to identify displacements of selected points on the boom and the roadheader cutterhead have proven to be the right solution.

2. TEST STATION

The measurements were conducted at a test station [13] at the Department of Mining Mechanization and Robotization of the Faculty of Mining and Geology at the Silesian University of Technology; this station was built as a part of the “Controlling the movement of roadheader cutterheads to decrease energy consumption and dynamic loads” research project co-financed by NCBiR (the National Center of Studies and Research).

In order to conduct optical measurements to define the movement of the cutterhead, the test station had to be additionally prepared (Fig. 1). One of the basic requirements for image analysis is the filming of fixed reference points used to positioncoordinate systems in space while moving with the object. The method used for measurement required that these reference points were situated on the same plane. Taking into account the conditions at the work station, the only solution to meet these requirements was to anchor a slab with quadrant markers to a concrete block. The slab was placed above the planned cuts.

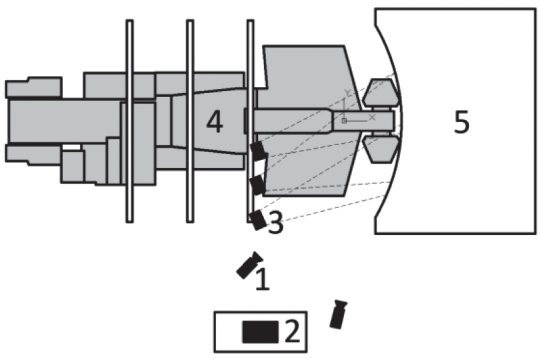

Fig. 1. Layout of components of optical measurement system at test station: 1 – cameras; 2 – camera operation station; 3 – lighting; 4 – roadheader; 5 – concrete block

Another condition required to conduct the analysis of the movement of objects in a 3D space is simultaneously filming them with two time-synchronized cameras placed in relation to the filmed objects in such a way that the angle between the optical axes is within the range defined for this measurement method. Therefore, the cameras were placed on tripods as widely apart as possible at the sides of the test station.

Just as important as the camera deployment around the test station is the appropriate lighting. Filming with the ultra-short registration times of each video frame requires a very bright and stable source of lighting (that does not pulse). For lighting the test station, special LED panels were used. They were placed on the arcs of mine roadway supports at the test station, and the light beams from each panel were directed in such a way as to concentrate the light at the place of measurement. The obtained light power enabled us to register the videos with a 1000 Hz frequency with the exposure time of a single video frame of 2×10^{-5} s. Such a short exposure time was required to avoid smudging (blurriness due to filmed-object movement) in the registered video.

The camera deployment around the test station and the use of proper lenses allowed us to frame the same area for both cameras, which included the end of the roadheader boom, the right cutterhead, the slab with markings, and the cutting area in the central part of the concrete block working face, approximately 1.5 m wide (Fig. 2).

a)
b)

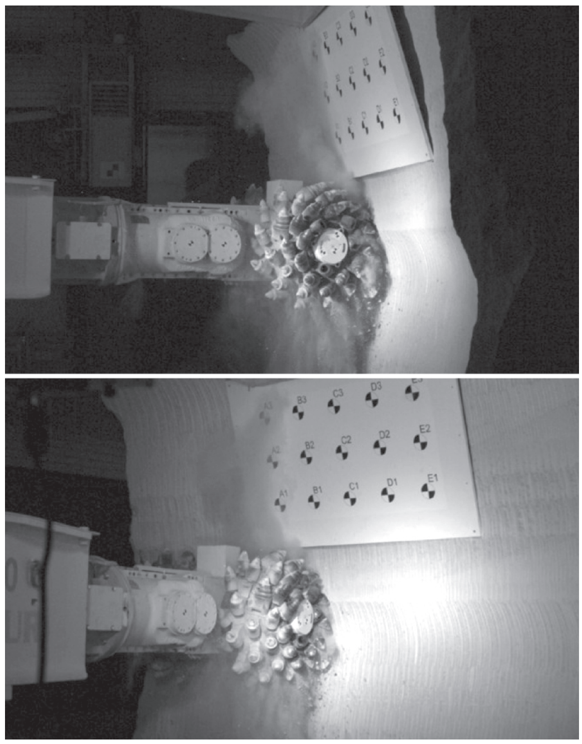

Fig. 2. View of area filmed by right (a) and left (b) cameras at test station during mining

In order to identify the movement of the cutterhead and boom, these objects also had to be equipped with markers so that the changes in their position could be clearly determined later during the analysis. In order to determine the changes of the boom position, two markers were attached to the reduction gear covers of the cutterhead drive. Whereas, in order to determine the movement trajectory of the cutterhead, three markers at its side cover were used due to the fact that the cutterhead also performs a rotary movement.

The mining process of the concrete block was filmed at the prepared test station in 5-second takes (this was the maximum time for the internal memory of the high-speed cameras). This length of time, depending on the rotational speed of the cutterheads, enabled us to register between three and five full revolutions of the cutterheads.

3. PROCESSING OF MEASUREMENT DATA

The movement analysis was conducted with the use of TEMA Motion 3D software. This included the determination of marker positions on the reference slab, boom, and cutterhead in the registered images as well as a determination of a spatial coordinate system common to both cameras, a determination of correction factors for lens distortion (in order to eliminate the curvature of images), and the tracking changes of the marker positions (Fig. 3) on consecutive frames of the registered videos.

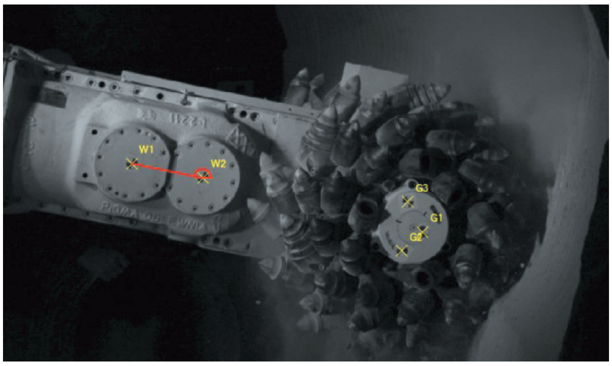

Fig. 3. Frame from software's interface to analyze TEMA Motion 3D image – virtual tracking points at boom and cutterhead

As a result of the conducted procedures, the x, y, and z coordinates of the markers on the reference slab and cutterhead (Fig. 4) as well as on the boom were obtained, reflecting their consecutive positions in their movement trajectory.

The coordinates of the points that determined the movement trajectory of the cutterhead set out in the TEMA Motion 3D software were exported. Later, they were matched with the coordinates of points that determined the cutting picks arrangement on the virtual model of the cutterhead obtained from a 3D scanner. The mutual correlation of the coordinate systems of the cutterhead model and cutterhead movement trajectory allowed us to determine the movement trajectory of the cutting picks on the cutterhead.

In the end, all movement trajectories were positioned on a Cartesian coordinate system related to the concrete block. The center of the system was located in the bottom right corner of the block. The "*y*" axis was directed into the concrete block, while the "*xz*" plane overlapped the plane of the concrete block's face (into which, the roadheader cutterheads were slumped), and the "*z*" axis was directed vertically.

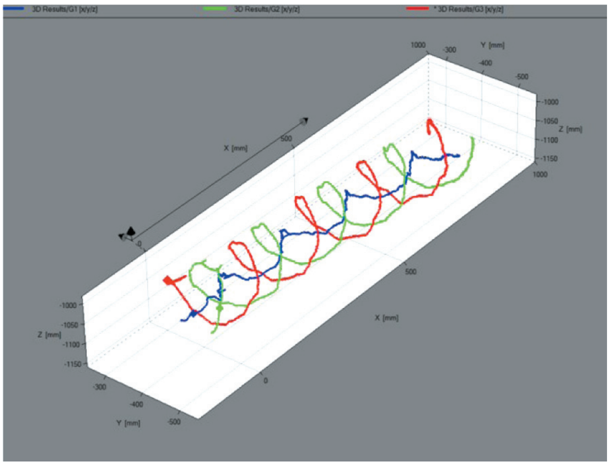

Fig. 4. Movement trajectories of cutterhead markers while performing one cut

Examples of the movement trajectories of the markers on the roadheader boom and the determined movement trajectories of the blades of three selected cutting picks are shown in Figure 5.

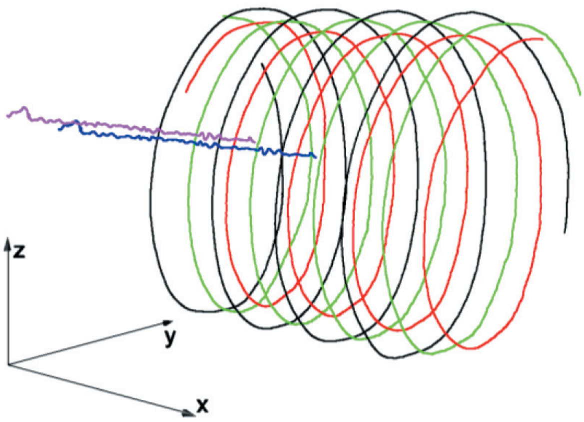

Fig. 5. Movement trajectories of markers on boom and three picks on cutterhead while performing one cut

During the analysis of the boom movement, the measurement error value was determined based on the time functions of the measured positions of the

W1 and W2 points on the boom and the determined distance between them (Fig. 6).

$$L_{w1w2} = \sqrt{(\Delta x_w)^2 + (\Delta y_w)^2 + (\Delta z_w)^2}$$
$$\Delta x_w = x_{w2} - x_{w1} \qquad (1)$$
$$\Delta y_w = y_{w2} - y_{w1}$$
$$\Delta z_w = z_{w2} - z_{w1}$$

where $x_{w1,\,w2}$, $y_{w1,\,w2}$, $z_{w1,\,w2}$ – the determined coordinates of points W1 and W2

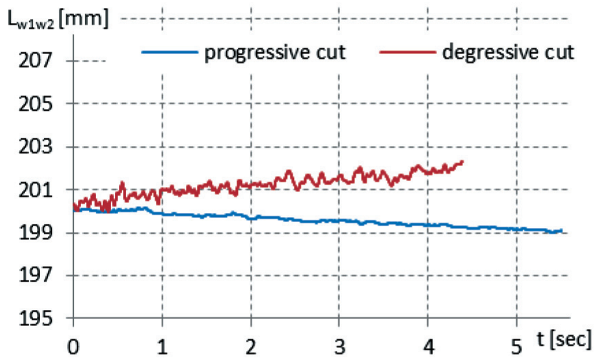

Fig. 6. Determining value of measurement error based on W1 and W2 point distance

The distance between the markers on the boom is 200 mm. The distance, which measured during the movement of the boom with the use of the optical camera system, changed by 2 mm, which translates to a measurement error of 1%. The errors were mainly caused by dust, the vibrations transmitted to the structure of the building in which the measurement was conducted, and by errors during the determination of lens-distortion correction. Due to the fact that the spatial position of the cutterhead was determined analytically based on the position of the W1 and W2 points, the results of the analysis presented in this article are affected by a similar error.

4. CUTTING PICKS MOVEMENT TRAJECTORIES AND BOOM VIBRATIONS

This article presents the selected results of the roadheader's boom vibration analysis and movement trajectories of the cutting picks on the cutterhead during progressive and degressive cutting with a cutterhead rotational speed of 44.8 rpm.

Progressive cuts are cuts where the cutting depth gradually increases – usually starting from a value of zero. In the case of a roadheader equipped with transverse cutterheads, these are usually created while mining the working face with the horizontal movements of the boom when the rock is excavated below the previously existing breach (Fig. 7). Due to the position of these cuts in relation to the previous cut, they are also called lower cuts.

On the other hand, degressive cuts are cuts where the pick starts cutting with a certain initial depth that is the maximum depth of a cut in most cases; then, the depth of the cut gradually decreases (Fig. 7). These cuts are created by raising the cutterheads and mining the layer of rock above the existing breach; hence, another name for these cuts is "upper cuts."

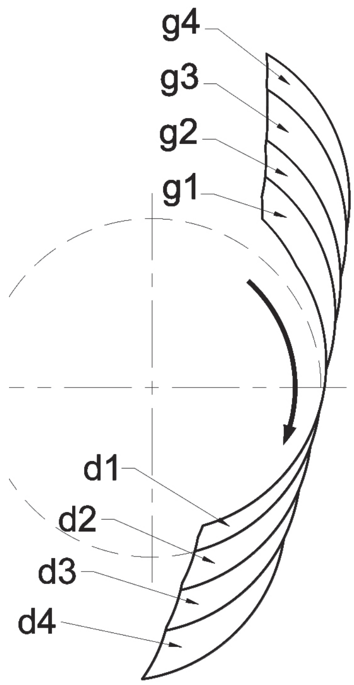

Fig. 7. Consecutive cuts performed by transverse cutterheads of the roadheader: d – lower (progressive), g – upper (degressive)

While extending the boom in the plane parallel to the thill, the picks on the transverse cutterhead theoretically move in a spiral motion over the surface of toruses. However, due to the vibrations of the boom caused by the mining process, these trajectories are distorted; this in turn results in differences between the theoretical and actual shapes of the cuts [14]. Figure 8 shows the determined actual movement trajectories of three picks in the coordinate system related to the cutterhead where the "*x*'" axis matches the theoretical cutterhead rotation axis. The black dashed lines in the figure form circles that are the projection of the theoretical movement trajectories of the selected picks. For the presented pick-movement trajectories, deviations toward the "y'" axis are significantly smaller than toward the "z'" axis.

$$z_i' = z_i - z_{gt}$$
$$y_i' = y_i \cdot \cos\alpha_{Hr} + x_i \cdot \sin\alpha_{Hr} - y_{gt} \tag{2}$$

where:

- x_i, y_i, z_i – designated coordinates of the tips of the conical tools in the accepted main coordinate system,
- y_{gt}, z_{gt} – theoretical coordinates of the position of the cutterhead resulting from the set parameters and boom movement,
- α_{Hr} – real boom extension angle in the plane parallel to the thill.

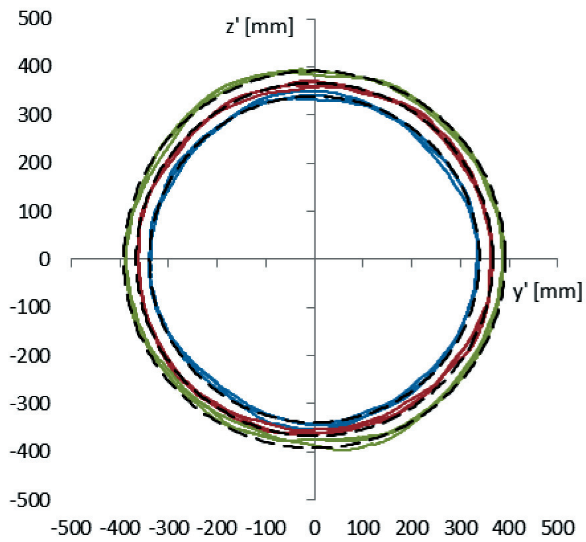

Fig. 8. Deviations of actual movement trajectories of cutting picks from theoretical trajectories caused by vibrations of cutterhead, presented in plane perpendicular to cutterhead rotation axis

Determination of the vibrations of the boom and its cutterhead based on the movement trajectories of the picks is difficult due to their rotation movement in relation to the cutterhead rotation axis. This is why the vibration analysis of the cutterhead was conducted based on the reference points positioned on the body of the boom.

The resultant position of the cutterhead in relation to its theoretical position in affected by the vibrations of the whole machine body and of the boom in relation to the body (instantaneous changes of the boom extension angle in planes that are perpendicular and parallel to the thill). The area of the video frames allowed us to determine the torsional vibrations of the boom and the resultant cutterhead vibrations during the mining process.

The progressive cut presented in this article was performed with a theoretically determined boom extension angle in the plane perpendicular to the thill of α_V = –12.78° and the degressive cut with an angle of α_V = –2.08°. In order to directly compare the intensity of the boom vibrations, these values were treated as a reference point equal to 0° (Fig. 9).

$$\Delta\alpha_V = \alpha_{Vr} - \alpha_{Vt} \tag{3}$$

where:

- α_{Vr} – real boom extension angle in the plane perpendicular to the thill,
- α_{Vt} – theoretical (given) boom extension angle in the plane perpendicular to the thill.

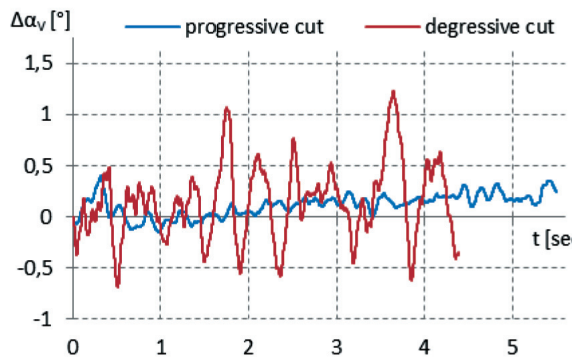

Fig. 9. Course of changes of boom extension angle in plane perpendicular to thill in relation to theoretical position

As seen from the presented characteristics, the amplitude of the angular displacements of the boom in the plane perpendicular to the thill while performing the degressive cut was even 3.5 times higher than with the progressive cut. In the case of the degressive cut, it reached up to 1.7°, while for the progressive cut – up to 0.5°. The displacements of the boom by the α_V angle caused by vibrations significantly affected the actual position of the cutterhead. Changing angle α_V by 1° in the case of the analyzed roadheader type causes a displacement of the cutter head in the plane perpendicular to the thill by 54 mm.

When mining horizontal layers, the extension angle of the boom in the plane perpendicular to thill α_V remains theoretically unchanged; however, the extension angle of the boom in the plane parallel to thill α_H changes, which is the result of the movement of the roadheader's turntable. In the presented examples, the boom was extended in the plane parallel to the thill with an average angular speed of ω_H = 0.06 rad/sec for the degressive cut and ω_H = 0.04 rad/sec for the progressive cut (Fig. 10).

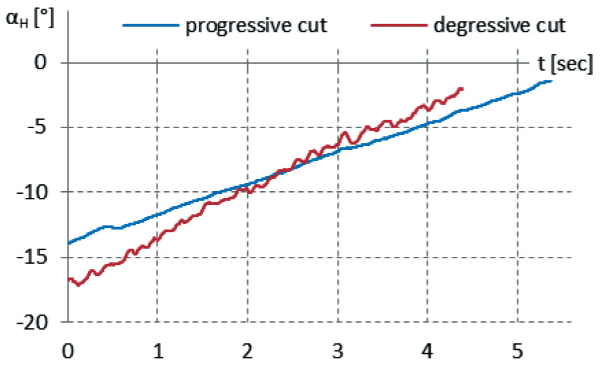

Fig. 10. Course of changes of boom extension angle in plane parallel to thill

In order to analyze the changes (vibrations) of extension angle α_H, the theoretical instantaneous values of this angle due to turntable movement were treated as reference points and were assigned a value of 0° (Fig. 11).

$$\Delta\alpha_H = \alpha_{Hr} - \alpha_{Ht} \tag{4}$$

where:

α_{Hr} – real boom extension angle in plane parallel to thill,

α_{Ht} – theoretical boom extension angle in plane parallel to thill.

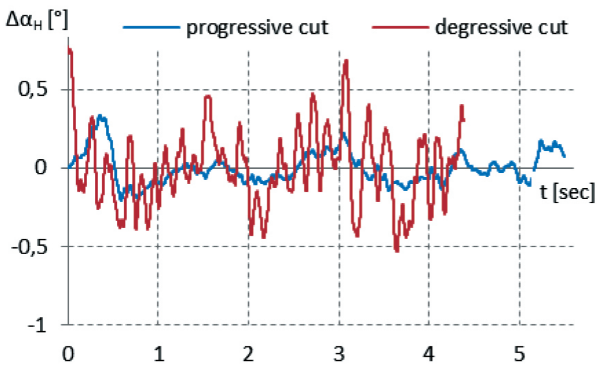

Fig. 11. Course of changes of boom extension angle in plane parallel to thill in relation to theoretical instantaneous position

For the degressive cut, the amplitude of the changes of extension angle α_H reached up to 1.2°, and for the progressive cut – up to 0.5°. Similarly, as with the vibrations in the vertical plane and in the case of the vibrations in the horizontal plane, the changes of extension angle α_H were much higher while performing the degressive cut than with the progressive cut. The difference was almost 2.5 times higher. From the perspective of guiding the cutterhead, the important fact is that a change of extension angle α_H by 1° in the roadheader used for the study caused the cutterhead to move in the plane parallel to the thill by 56.5–66.8 mm, depending on the assumed value of angle α_V.

The torsional vibrations of the boom presented in Figures 9 and 11 significantly influenced the actual position of the cutterhead in space in relation to the theoretical position.

The instantaneous resultants of the cutterhead displacements were analyzed separately in relation to each axis of the main Cartesian coordinate system related to the processed concrete block.

$$\begin{aligned} \Delta x &= x_{gr} - x_{gt} \\ \Delta y &= y_{gr} - y_{gt} \\ \Delta z &= z_{gr} - z_{gt} \end{aligned} \tag{5}$$

where:

x_{gr}, y_{gr}, z_{gr} – real coordinates of the position of the cutterhead,

x_{gt}, y_{gt}, z_{gt} – theoretical coordinates of the position of the cutterhead resulting from set parameters and boom movement.

The largest displacements of the cutterhead position were observed for the degressive cut in the vertical direction – "z" axis (Fig. 12). The amplitude of these displacements reached up to 58 mm. For the same direction, the amplitude of the displacements for the progressive cut had a maximum value of 30 mm; however, this was observed only at the beginning of the registered process (at 0.3 s in the measurement). After that, the amplitude of the displacements remained at a level of 15 mm.

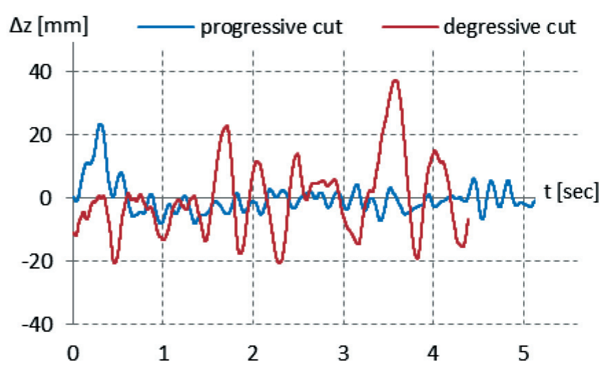

Fig. 12. Course of changes of cutterhead position along "z" axis perpendicular to thill in relation to theoretical instantaneous position

This was very much different for the change of the cutterhead position along the "x" axis. The deviations of the cutterhead from the theoretical position were significant for both the progressive and degressive cuts (Fig. 13). In the former case, the amplitude of the changes was up to 30 mm, and in the latter – up to 50 mm. In these cases, the period of the main changes of the cutterhead position along the "x" axis was similar or approximately equal to the period of the cutterhead's revolution.

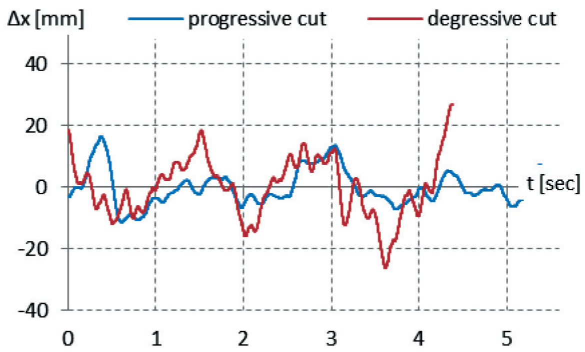

Fig. 13. Course of changes of cutterhead position along "x" axis parallel to thill and perpendicular to roadheader axis in relation to theoretical instantaneous position

The smallest displacement for the progressive and degressive cuts were observed in the direction of the "y" axis, which is the longitudinal axis of the roadheader (Fig. 14).

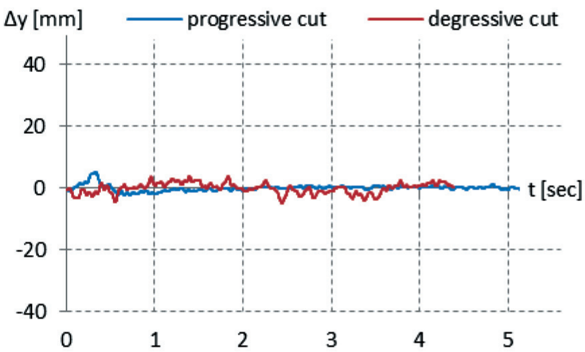

Fig. 14. Course of changes of cutterhead position along "y" axis parallel to thill and roadheader axis in relation to theoretical instantaneous position

The total deviation of the actual position of the cutterhead from the theoretical position derives from the sum of the displacement vectors in relation to a particular axis of the coordinate system.

$$\Delta R_{xyz} = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2} \tag{6}$$

Figure 15 shows thetheir comparison for the progressive and degressive cuts.

In the first case, the largest deviation of the cutterhead position from the theoretical position is 27 mm; however, it does not exceed 10 mm on average. In the second case, the maximum deviation of the cutterhead position was 45 mm for the degressive cut, with the average deviations remaining at a level of 20 mm.

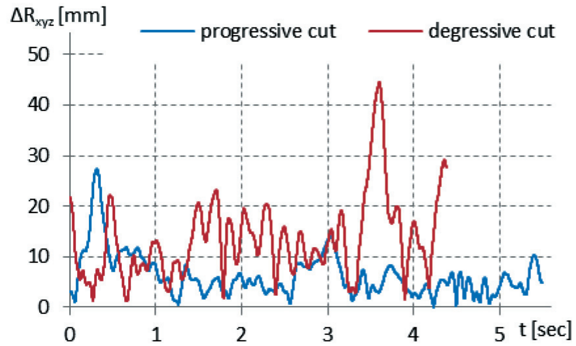

Fig. 15. Course of deviation changes of cutterhead actual position from theoretical position

5. SUMMARY

The boom and cutterhead vibrations identified during the course of the study are significant, and they cannot be omitted in the process of modeling the roadheader or when automatically controlling the parameters of the roadheader's excavation system during mining. Furthermore, the registered deviations of the cutterhead position from the set theoretical position are very often higher than the cutting depth of the picks on the cutterhead, which leads to the cutting picks being unable to reach the excavated rock or the cutting depth rising above the theoretical value. Thus, the strong vibrations of the cutterhead cause a significant increase in the work dynamics of the whole roadheader.

Using high-speed cameras for vibration measurements or determining the movement trajectories of objects is quite common in technical industries; however, it is an innovative solution in the mining industry. The main problems when using optical measurement systems are the high dust content, lack of sufficient space around the measured objects, and insufficient lighting. However, under laboratory conditions (such as in the Department of Mining Mechanization and Robotisation of the Silesian University of Technology), these obstacles can be overcome, and the optical measurement system with high-speed cameras proved to be a valuable tool in identifying the movements and vibrations of the components of the tested machine.

Acknowledgement

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