

Vibration identification of the roadheader cutting head using high-speed cameras

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Abstract. Vibrations of the roadheader cutting head were measured by means of two methods during the cutting performed on the test set-up created at the Faculty of Mining and Geology at the Silesian University of Technology. The first of them included installing accelerometers on the roadheader boom near the cutting heads. In the second one, a photogrammetric kit was used, major components of which were high-speed cameras connected with TEMA Motion 3D software used for movement analysis. Based on the motion recorded in videos, the cutting head movement trajectories were delineated, with their velocity and acceleration determined. This article presents a photogrammetric method, as well as selected results of the comparative analysis of cutting head vibrations using both methods when cutting simultaneously with two cutting heads, with the boom inclination perpendicular to the floor.

1 Introduction

High-speed cameras settled in for good in the field of scientific research and industry. They are popular in military applications [1], on production lines or in crash tests. However, measurement techniques based on recording events with high-speed cameras have also been more and more popular in other fields of industry and science [2–11] thanks to the constantly improved imaging and image analysis techniques. Undoubtedly, they have many advantages, but also carry certain disadvantages. The use of high-speed cameras is not always justified or it might not produce the expected results [12].

In the objects of limited accessibility due to structural or safety reasons, the use of high-speed cameras seems to be a highly beneficial solution. However, there is a basic requirement to be met for the applicability of this measurement technique. The studied object or its interesting component must be visible for the camera or cameras. An extensive range of cameras, lenses, lights and computer software dedicated to this type of devices offers high customisability in terms of configuring the equipment of the test set-up depending on particular metrological needs.

In underground mining, the photogrammetric measurement technique, especially using high-speed cameras, has not been used much so far. In the Department of Mining Mechanization and Robotisation of the Silesian University of Technology, mining machines, *i.e.* scraper conveyors [13, 14] and a roadheader [15], were tested in laboratory conditions. This article presents selected roadheader test results with

respect to the analysis of movement and vibrations of its main components in operation.

2 Test set-up

The test set-up with an R-130 roadheader (manufactured by FAMUR S.A.) was created as part of the scientific research programme "Controlling the Movement of Roadheader Cutting Heads to Decrease Energy Consumption and Dynamic Loads" of the Faculty of Mining and Geology at the Silesian University of Technology, co-financed by the National Centre for Research and Development. One of the components of the extended measurement system, attached to the studied roadheader, is the system of accelerometers installed in the selected structural nodes of the machine [16]. They were responsible for measuring vibration acceleration in three mutually perpendicular directions at the boom end, near the cutting heads. To link the dynamic load and vibrations of the roadheader with the cutting process, the boom inclination angles, parallel and perpendicular to the floor, are monitored. To determine the trends of those angles' values, draw-wire sensors were installed on the actuator of the boom rising mechanism and on the roadheader turntable. The results of the measurements made using those sensors while cutting were confronted with the results of measurements from the photogrammetric method.

The photogrammetric measurement system (Fig. 1) used during the discussed experimental tests is composed of two high-speed cameras (1), control and recording station (2), as well as an appropriate light (3). Using two synchronised cameras made it possible to

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analyse the machine movement in the three-dimensional space. The movement reconstruction is based on the photogrammetric space intersection. The location of the traced points in space is determined based on two rays from that point, creating its image on photos made from two different positions [17]. A prerequisite for obtaining correct measurement results based on the image from two cameras is to place them appropriately, keeping the correct angle between the optical axes of the cameras. Frames of every camera must cover the same area (Fig. 2). Because of the size of the captured object (roadheader turntable, boom with cutting heads and the cement and sand block), and also because of the need to protect the cameras from dust created when cutting, the cameras were placed about 8 m from the roadheader.

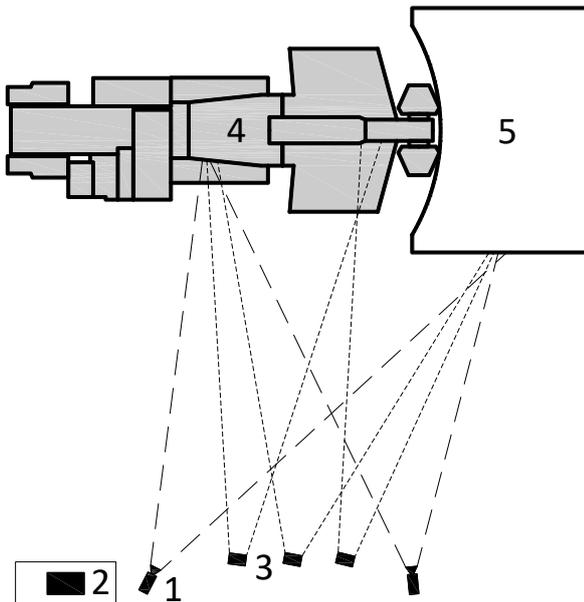


Fig. 1. Layout of the photogrammetric measurement system components in the test set-up: 1 — high-speed cameras, 2 — camera operation station, 3 — lighting, 4 — roadheader, 5 — cement and sand block.

An important factor affecting the quality of the recorded video material is suitable lighting. It determines *e.g.* the ability to obtain the contrast ratio required for the digital analysis of an image. The exposure time of a single video frame was 2×10^{-5} s, as required to avoid the blurring effect (image blurring caused the movement). This means that despite high optical sensitivity of the cameras, the ultra-short recording times for particular video frames required very strong light. High recording frequency, reaching 500 Hz here, also required non-pulsating light. The said conditions are met by dedicated LED light panels with their light directed at the observed objects.

To identify the movement and vibrations of the roadheader boom using photogrammetric measurements, it was necessary to adapt the test set-up as appropriate. To determine the location and orientation in the space of the objects recorded in the videos, it was necessary to film at least three stationary reference points. During image processing, they were used to create coordinate systems where the movement of the studied object was

analysed. For practical reasons, it is best when the points are situated on the same plane. For that purpose, quadrant markers attached to the cement and sand block were used at the test set-up. As a result, the location of selected points on the observed objects was determined unanimously. Such markers are best recognised by applications for movement analysis. Identical markers were also placed on the roadheader's boom and turntable.

The cutting process of the cement and sand block was filmed in 13-second shots at the test set-up prepared accordingly. This was the maximum time allowed by the integrated memory of high-speed cameras at the assumed recording frequency (500 Hz).

In the example presented in this article, the cutting process was carried out with the boom moving perpendicular to the floor, downwards. Cutting was done simultaneously with two cutting heads. In the standard technology of cutting the head face surface in the roadway or tunnel with the boom-type roadheader, this is used when moving on to the next cut parallel to the floor. However, it can also be perceived as the main work movement *e.g.* when cutting coal mine roadways [18].

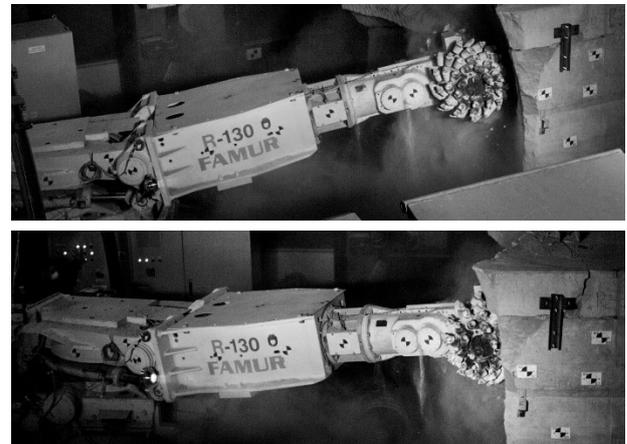


Fig. 2. Image of the shot area from the left and right camera.

3 Compilation and analysis of measurement data

TEMA Motion 3D software was used to analyse the movement. Once the videos were imported to the software, markers were defined (Fig. 3), and the location and spatial orientation of the coordinate system were determined. Correction factors for lens distortion were introduced to eliminate the image curvature and the changes of location of the analysed measurement points were traced on consecutive frames of the recorded videos. Marker coordinates (x, y, z), obtained as a result of said operations, were exported to the spreadsheet and then transposed to the XYZ stationary coordinate system of the station where X- and Y-axes are situated on the floor plane, Y-axis is parallel to the longitudinal axis of the roadheader and is directed towards the cement and sand block, while Z axis is directed upwards (Fig. 4). The transformations were carried out to determine the boom inclination angles parallel (α_H) and perpendicular (α_V) to the floor. The angles were derived from the coordinates of the markers placed on the boom with

known geometry. Trends of boom angles inclination parallel and perpendicular to the floor, determined in this way, were compared with the trends of boom inclination angles obtained from measurement systems installed on the roadheader (draw-line sensors) (see Fig. 5 and 6).



Fig. 3. A frame from the interface of the image analysis software called TEMA Motion 3D — view of markers placed on the boom and the cement and sand block.

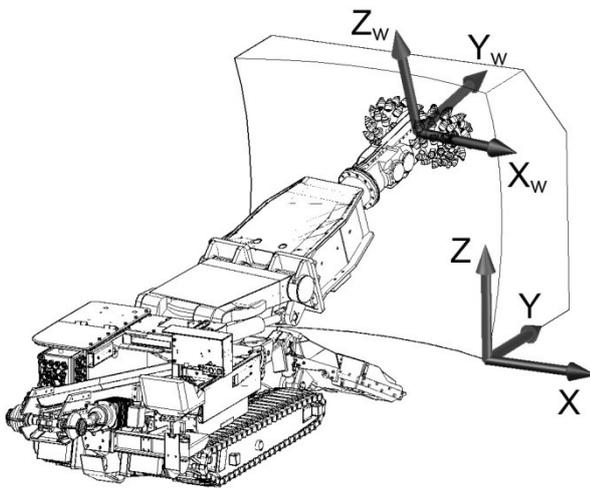


Fig. 4. Coordinate systems orientation —stationary— related to the cement and sand block cut (XYZ) and moving —related to the roadheader boom (XWYWZW).

The value of the boom inclination angle parallel to the floor α_H is approximately constant, while the value of boom inclination angle perpendicular to the floor α_V decreases. This results from the way of cutting the cement and sand block surface downwards. The trend line for the above-mentioned angles obtained using both methods analysed here is highly similar, though for the photogrammetric method they are shifted upwards by about $0.3^\circ \div 1^\circ$. The observed higher vibration amplitude in the trend of boom inclination angles perpendicular and parallel to the floor, obtained from the photogrammetric measurement, results from the fact that the measurement is made in a stationary XYZ reference system. The absence of any clear pulses in the trend obtained from draw-wire sensors is caused, on the other hand, by the fact that the said sensors were installed between the

roadheader turntable and the boom (system for measuring α_V angle) and between the roadheader turntable and the body (system for measuring α_H angle). This means the sensors measured angles in a moving reference system related with the roadheader turntable and the body, as appropriate.

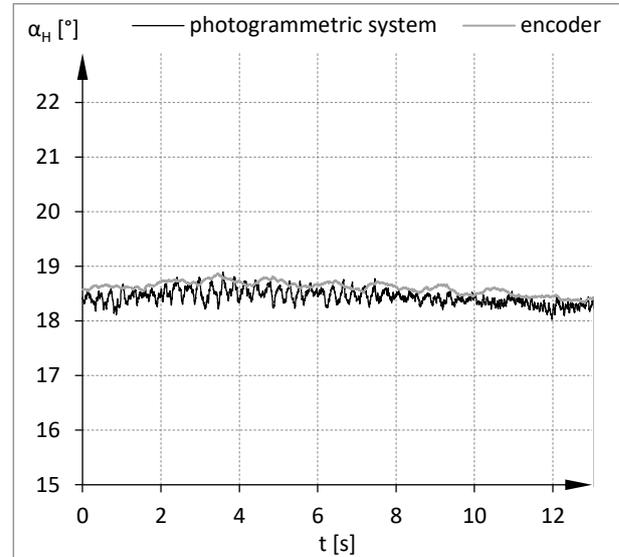


Fig. 5. Trend of the boom inclination angle parallel to the floor, recorded with two methods: the draw-wire sensor (gray line) and the photogrammetric system (black line).

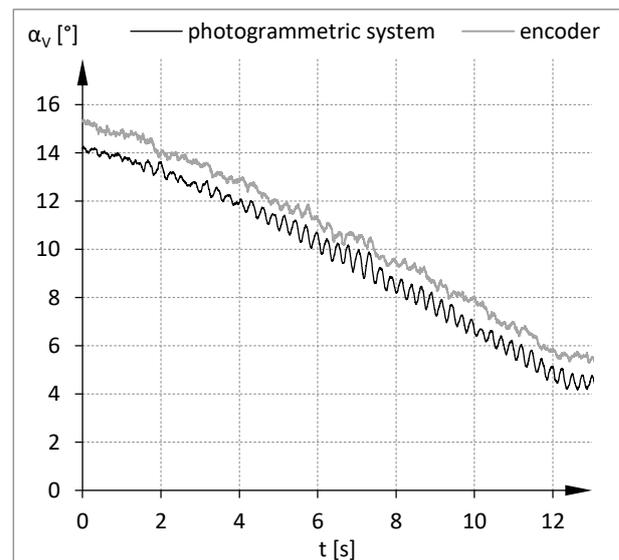


Fig. 6. Trend of the boom inclination angle perpendicular to the floor, recorded with two methods: the draw-wire sensor (gray line) and the photogrammetric system (black line).

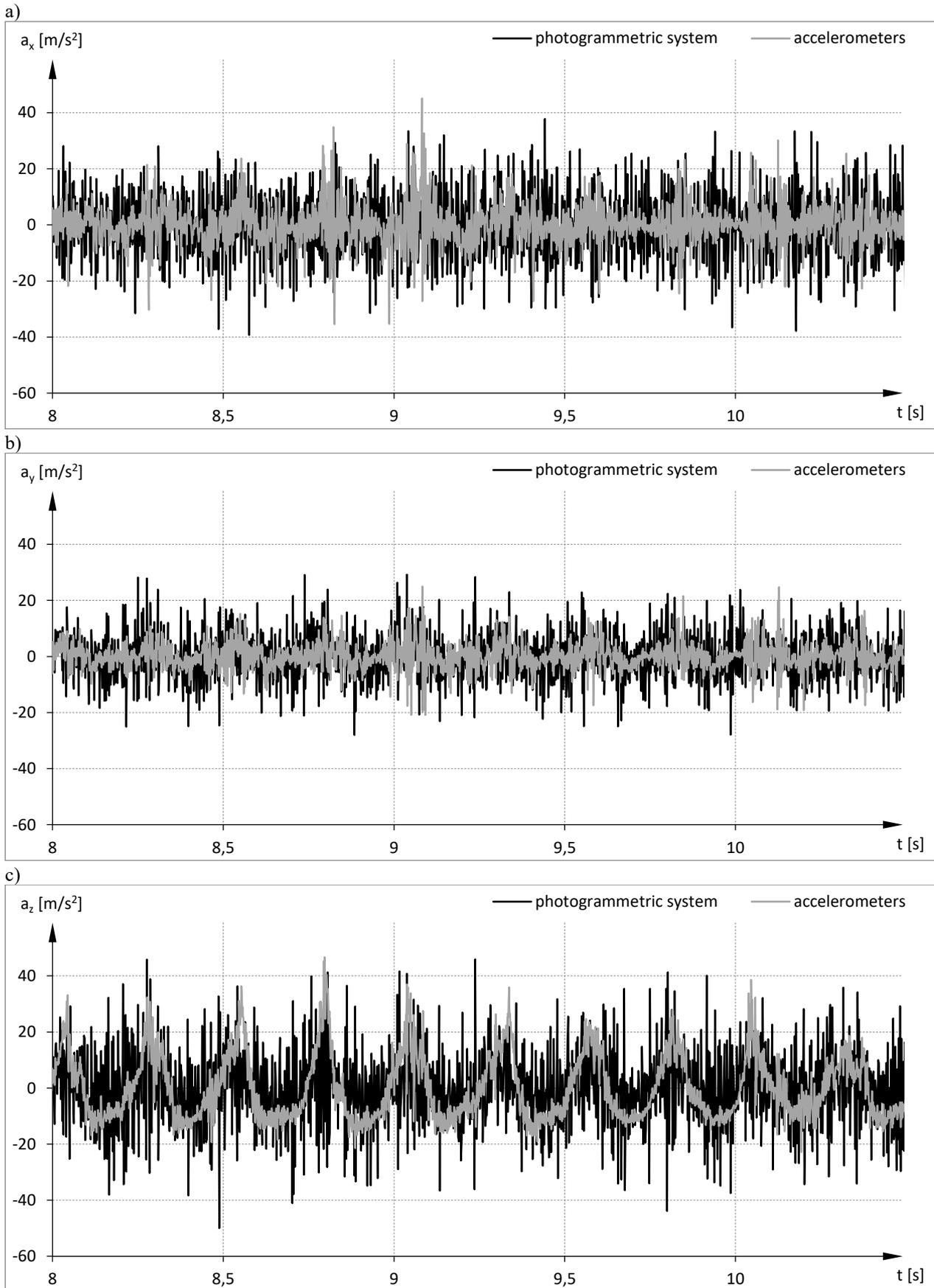


Fig. 7. Trends of vibration accelerations for cutting heads: a) in the direction of XW axis, b) in the direction of YW axis, c) in the direction of ZW axis.

Because of the high amounts of dust created in the course of cutting and due to the rotary movement of the cutting heads, the direct observation of the cutting head location is very difficult. This is why the momentary cutting heads' location (the point where their axes of rotation cross the longitudinal axis of the boom) was determined from the current location of W1 and W2 markers (Fig. 3) placed on the boom. Next, the components of the velocity and acceleration towards the axis of the stationary XYZ coordinate system were determined, calculating the time derivatives for the components of such shifts. Accelerometers installed on the boom measure the vibration acceleration components in the direction of the axes of the moving $X_wY_wZ_w$ coordinate system related to the boom where X_w axis is parallel to the cutting head axis of rotation, Y_w axis is parallel to the boom axis and Z_w axis is directed upwards. To compare the trends obtained from the two methods, the acceleration vectors determined based on the photogrammetric measurements were transposed into the $X_wY_wZ_w$ coordinate system (Fig. 4).

The trends for the acceleration components in the direction of the $X_wY_wZ_w$ coordinate system for both measurement methods are compared in Figure 7. They display high similarity, with clearly visible periodicity both for trends obtained from the accelerometers and from the photogrammetric methods, and a similar variability range for vibration accelerations obtained from the two methods. However, for photogrammetric measurements there is a distinctively high share of high-frequency components. This is confirmed by the spectral analysis of the analysed dynamic characteristics, and is a direct consequence of the time derivatives of the cutting head shift trends in time, giving the velocity trends and, further on, vibration acceleration values at a given point. The derivation process increases the share of the measurement noises in the output signal [19]. To verify the consistency of trends in both measurement methods, they were subject to FFT analysis (Fig. 8). For frequencies up to 50 Hz, three components with the frequency of 3.5 Hz, 7 Hz and 17 Hz are clearly visible in the trends of vibration accelerations obtained from the photogrammetry. The said components are also visible in the spectrum of vibration accelerations recorded by the accelerometers.

4 Summary

The vibration measurement method by means of the photogrammetric system, based on two high-speed cameras, presented in this article, is a tool for the observation of fast-changing phenomena, including the determination of time trends for shifts, velocity and acceleration of vibrations in a 3D space for various objects or their characteristic points. It is a convenient alternative to direct methods of movement measurement and analysis based on sensors attached to the analysed object, inserted in the measuring paths of the measurement and the recording system. An important advantage of optical measurement methods is their negligible interference with the structure of the studied object, limited, in fact, to placing markers, with the size and shape recognisable by the software designed for

analysing recorded images, on its surface. Here, the measurement is remote (contactless), therefore, the system is not exposed to the direct impact of factors likely to damage it, accompanying the machine operation or resulting from the monitored process or phenomenon.

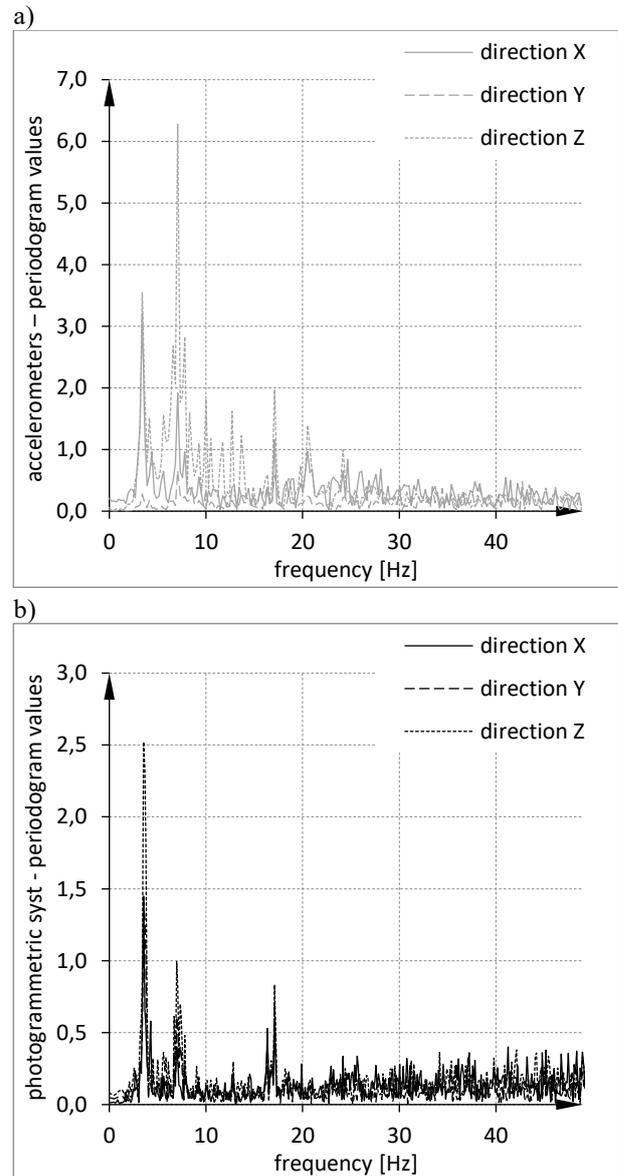


Fig. 8. Amplitude and frequency spectrum of vibration accelerations: a) measurement with accelerometers, b) determined based on trends obtained from the photogrammetric system.

Due to the measurement carried out using optical methods and (high-speed) cameras, this solution, however, requires appropriate environmental conditions for the measurement to be taken. This refers, primarily, to the air transparency, its humidity and temperature, as well as the amount of light. Such measurements must be preceded by an in-depth analysis to select the size of the field of vision and the geometry of the test set-up (camera location and position), determining the resolution of this measurement method, range, uncertainty and the ability to achieve a stereoscopic result, which all constitute the grounds for the 3D

analysis. This determines the choice of necessary equipment, including the selection of camera lenses.

High price and sensitivity of cameras to the environmental factors make the industrial application of similar measurement systems, especially in mining, highly limited. For underground mine sites, this is also connected with the need to meet specific safety requirements (e.g. intrinsic safety), necessitating the application of extra covers and an airtight housing. The limited space of mine sites also determines the possibility of locating the cameras as appropriate in relation to the studied object (machine) to obtain the required field of vision. Optical methods are great for laboratory applications, including heavy-duty work machines. An example of such use of the measurement system based on high-speed cameras is experimental studies of R-130 roadheader presented in this work.

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