Evaluation method of hand-arm vibration using high-speed camera

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Abstract
High-speed cameras are increasingly used in various fields of science and technology. Their usefulness is particularly appreciated during the analysis of rapidly changing physical phenomena. They also make it possible to study the oscillatory motion of objects. The article presents an attempt to use a high-speed camera to test vibrations occurring in the working environment. A proposal for a method of identifying and evaluating vibrations based on the analysis of the motion image of elements of hand tools obtained with the use of a high-speed camera was presented. The algorithm of the developed method was verified while working with typical hand tools. To compare the obtained results, the values of vibration acceleration obtained by means of a standard measurement system based on piezoelectric vibration transducers were used. The research also provided information on the limitations and conditions of using the high-speed camera for vibration testing in the work environment. The differences in the values of exposure to vibrations determined with the use of a high-speed camera and a standard measurement system show that the presented method of vibration identification and evaluation can be successfully used for vibration tests at workplaces.

Keywords: vibration, high-speed camera, research

1. Introduction

Increasingly used high-speed cameras allow for non-contact studies of the movement of various objects and their structures [1-15]. This allows you to replace standard measurement methods based on the use of sensors placed directly on the tested object with methods based on image analysis.

In many situations (e.g. the movement of very small elements or delicate structures) this is the only way to obtain information about the phenomena that are taking place. The use of non-contact techniques also affects the elimination of phenomena related to changes in the parameters of mechanical systems caused by placing additional masses of sensors in them. This has a direct impact on the accuracy of measurements of physical parameters of motion. Research conducted in many centers confirms the possibility of using non-contact techniques, including those based on the use of high-speed cameras, also in the field of measurement and analysis of mechanical vibrations [1-4, 7-10, 12-15]. However, this involves the need to solve problems concerned with the ensuring of correct work conditions of high-speed camera to obtain useful results. The most important of them are: the correct selection of optical components of the camera, the use of appropriate parameters for image capture, provide adequate lighting and ensuring a stable camera position during recording. An additional issue is the question of how the vibration measurements results obtained using a high-speed camera differ from the results obtained by classical methods. Until now, high-speed cameras have not been used to measure vibrations affecting an employee in a working environment. This way of measurement is not taken into account by the vibration test methods given in the relevant standards, e.g. [16, 17]. The use of high-speed cameras opens up new possibilities for analyzing the effects of vibrations on individual parts of the body of an employee operating tools and machines. The purpose of the presented research was to develop and check the hand-arm vibration test method using a high-speed camera.

2. Proposal of evaluation method of hand-arm vibration

The proposed method of identification of exposure to vibrations in the working environment using the image of the oscillatory motion of machine / tool elements is based on the analysis of the displacement time signal of a selected point (points) on the vibrating object recorded by a high-speed camera. The rules for selecting of measurement points and coordinate systems used during measurements in workplaces have been taken from the standard EN ISO 5349:2001 [16,17] for hand-arm vibration tests.

The displacement time signal of the observed point $s(t)$ is obtained as a result of the virtual or real marker tracking algorithm using Movias image analysis software. After double differentiating the displacement time signal, the vibration acceleration time signal $a(t)$ at the selected point is obtained (formula 1).

$$a(t) = \frac{d^2 s(t)}{dt^2}. \tag{1}$$

Then the spectrum of the vibration acceleration signal $a(f)$ is determined (formula 2).

$$a(f) = \int_{-\infty}^{+\infty} a(t) e^{-j2\pi f t}\, dt. \tag{2}$$

According to the EN ISO 5349 [16, 17] and EN ISO 8041 [18] standard for hand – arm vibration measurements correction filter W_h is used.

After correction the vibration acceleration spectrum $a(f)$ with the correction filter W_h, the corrected vibration acceleration spectrum $a_h(f)$ (formula 3) is obtained at a given measuring point.

$$a_h(f) = a(f) \cdot k_l(f) \tag{3}$$

$k_l(f_i)$ – correction coefficient, l – correction filter W_h, f – frequency.

Due to the correction characteristics of W_h, (high attenuation for frequency components over 600 Hz) the range of analyzed vibration frequencies was limited to 1000 Hz.

By using an operation analogous to integration (formula 4), a corrected total value of vibration acceleration is obtained a_h.

$$a_h = \sqrt{\sum_{f=f1}^{f2} a_h^2\,(f)} \tag{4}$$

f1 – lower limit frequency of the analyzed range, *f2* – upper limit frequency of the analyzed range.

The value of daily exposure to hand-arm vibration is determined from formula (5):

$$A(8) = \sqrt{\frac{1}{T_0}\sum_{i=0}^{n}(a_{hv,i}^2 \cdot t_i)} \tag{5}$$

$$a_{hv,i} = \sqrt{a_{hx,i}^2 + a_{hy,i}^2 + a_{hz,i}^2}\ ,\ \mathrm{m/s^2}$$

$a_{hv,i}$ – value of the sum of vibration acceleration vector for the *i*-th operation carried out by the worker exposed to hand-arm vibration, m/s^2, *i* – number of operation carried out by the worker exposed to hand-arm vibration, *n* – total number of operations carried out by the worker exposed to hand-arm vibration, t_p – duration of the *i*-th operation, min, T_0 = 8h (480 min).

The presented assumptions was based on the determination of vibration acceleration due to the possibility of reference the obtained results directly to the limit values set out in applicable law. (However, it is possible to adapt the method in which instead of vibration acceleration, can be used velocity, displacement or energy of vibration.)

The proposal of the evaluation method of hand-arm vibration using high-speed camera has been developed taking into account also results of pre-tests covering the selection of optics, recording parameters and lighting. The algorithm of the method is presented on the diagram in Figure 1. The method is implemented in three subsequent phases:

1. The first phase (blue blocks in the algorithm diagram) involves determining test conditions such as location, number of measuring points and choosing the type of marker (physical or virtual). Because the accuracy of measurements, better results with subsequent tracking of measurement movement points are obtained when the physical marker is selected. In the first phase, preparatory activities for image recording are also performed, such as the selection of recording parameters (recording speed – frame rate depending on the frequency range of the analyzed vibrations, resolution, shutter speed value, recording time) and optical elements cooperating with the camera. The choice of focal length of the lens or the decision to use teleconverters and / or intermediate rings depend primarily on the distance between the camera and the moving object. Indirectly, the optical set used and the recording parameters chosen are related to the selection of lighting, which is an equally important element during image recording. When using long focal length lenses and recording at high speeds it is necessary to use very strong continuous light sources.

2. The recording of the oscillatory motion image and preparation of data for analysis (yellow blocks in the algorithm diagram) are implemented in the second phase of the algorithm. It includes the recording of video images, e.g. using the Photron FASTCAM Viewer software in a format that allows subsequent analysis and tracking of the oscillatory movement of selected measuring points using the MoviasNeo 2D v. 2.54 software. When tracking the movement of measuring points, the highest accuracy was obtained when using the spline function for interpolation. In this method, the coefficients of interpolating polynomials are determined in such a way as to ensure at points not only the interpolation function but also its derivatives. This is important for later double differentiating the obtained time signal of the displacement of the measuring point.

   The correlation coefficient value should not be less than 0.95 during the entire tracking operation of the measuring points. The best tracking results (especially with fast-changing signals) were obtained with the number of prediction points being limited to 1.

The second phase of the algorithm also includes choosing the right conversion factor value, which is equivalent to calibrating a classic measuring system using a reference source. The conversion factor value has a direct impact on the results of quantitative analysis.

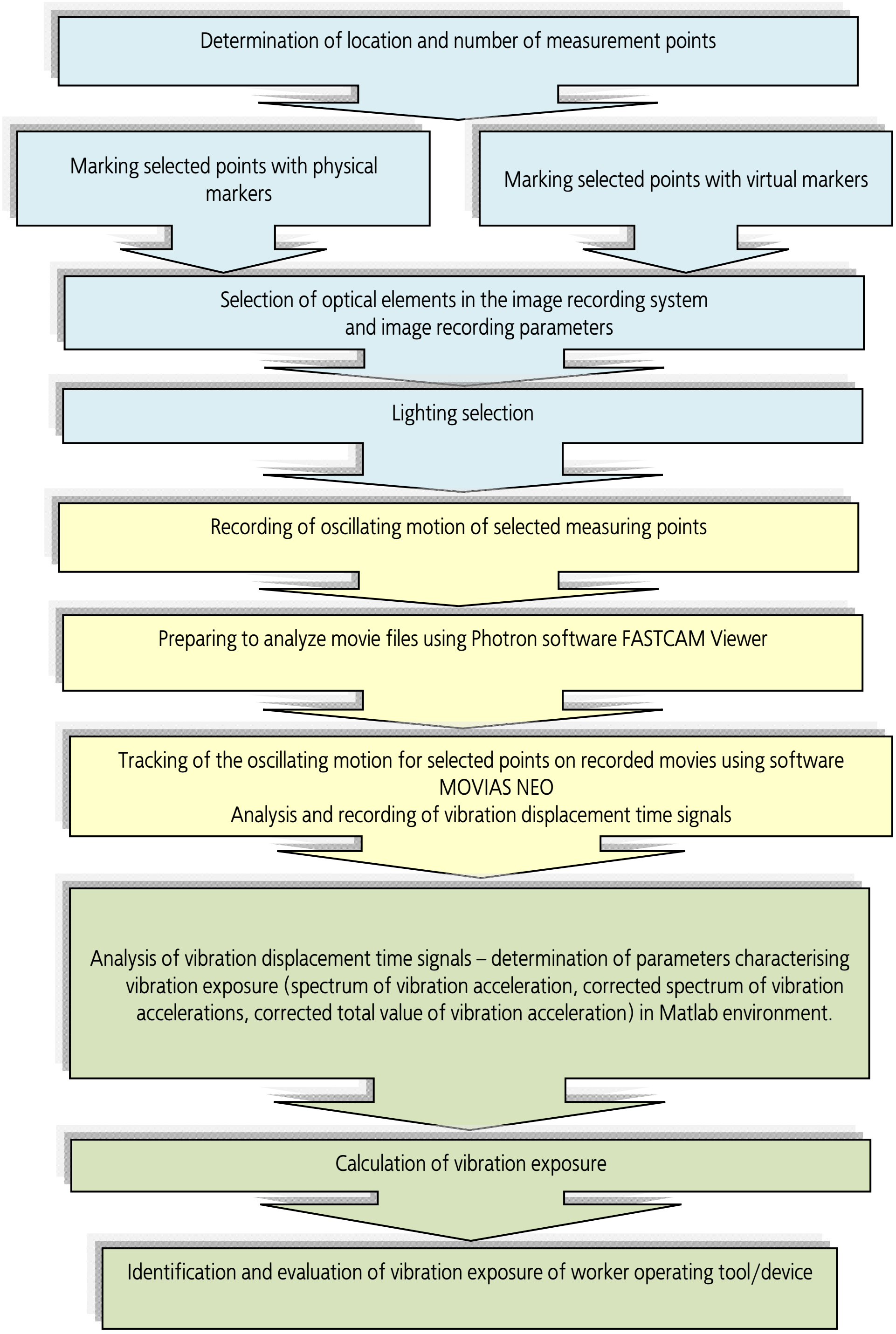

Figure 1. Algorithm diagram for identifying employee exposure vibrations in working environment based on the analysis of the oscillatory movement of machine / tool elements

3. The third phase of the method algorithm (green blocks in the algorithm scheme) contains data analysis and calculations. By double differentiating the time signals of vibration displacement

by using CFC (Channel Frequency Class) filters, vibration acceleration time signals are obtained. On their basis, uncorrected and corrected spectra of vibration accelerations are determined;

a calibration correction is also made taking into account the reference values of the reference vibration source. The corrected vibration acceleration spectrum is used to calculate the total vibration acceleration values.

The analyzes and calculations are repeated for each measuring direction X, Y, Z and then after taking into account the exposure time, the daily (or short-term) vibration exposure is determined according to the standard EN – ISO 5349. Based on it, identification and assessment of vibration exposure of the operator operating the tested tool / device is carried out.

3. Verification research

The performed verification tests of developed method consisted in the simultaneous recording and analysis of vibration signals using two measuring systems differing in the method of vibration detection:

- reference system: B&K 4393V piezoelectric vibration transducers with B&K NEXUS 2692-14 preamplifier and B&K Pulse multi-analyzer system; the vibration transducer has the following main technical parameters:
  - type of transducer: charge (DeltaShear),
  - frequency range: 0.1 ÷ 16500 Hz,
  - sensitivity: 0.316 pC / ms^2,
  - eight: 2.4 g;
- high-speed camera Photron FASTCAM SA1.1; during camera image recording, the TAMRON 18-400 mm F / 3.5-6.3 Di II VC HLD lens was used (with the KENKO 2x TELEPLUS PRO 300DGX teleconverter and 68 mm MeiKe intermediate rings); the following values of record parameters were used:
  - frame rate: 2000 frames / s,
  - resolution: 1024 pixels x 1024 pixels,
  - shutter speed value: 1 / frame,
  - record duration: 16.7 s,
  - video recording format: AVI.

Selected values were determined by 32 GB memory size of the camera and desired duration of recording. According to the sampling theorem frame rate 2000 fps should ensure correct analysis of recorded images of measurement object in frequency range from ~0 Hz up to 1000 Hz. A 1 mm diameter circular graphic marker was used to mark the measuring points. The Quadralite Atlas LED 60W continuous light lamps and LED torch Bailong T808 CREE XM-L were used for lighting. For measurements using reference system standard procedure was used (based on the EN ISO 5349:2001).

For measurements using high-speed camera the calculations were carried out on the basis of the obtained time signals of vibration displacement of measurement points. Then acceleration time signals were determined. On the base of these signals the frequency characteristics of vibration acceleration, total corrected (W_h characteristic) vibration acceleration values were calculated.

3.1. Measurement results

Simultaneous measurements of the vibration parameters using two mesuring systems were carried out for ten hand tools (vibration sources) applied successively. The measurements have been performed on the handles of the selected tools, during typical operations for each of the tools An example of measuring point location, orientation of the coordinate system and the transucer attachment method is ilustrated on the Figure 2.

Figure 2. An example of measuring point location, orientation of the coordinate system and the transucer attachment method during high-speed camera recording

The calculation results of corrected values of vibration acceleration a_h in three directions (X, Y, Z) and vector sum values a_{hv}, as well as difference between results from two measuring systems are presented in Table 1. In the tables, the reference measuring system is marked as *Pulse* and high-speed camera as *Camera*.

Table 1. Corrected values of vibration acceleration a_h and vector sum values a_{hv} for selected hand tools

Measurement object	Component	a_h, ms[2]		Difference [%]	Vector sum value a_{hv}, ms[2]		Difference [%]
		Pulse	Camera		Pulse	Camera	
Pneumatic wrench I	X	3.92	3.40	13.4	6.90	6.88	0.3
	Y	1.27	1.32	4.3			
	Z	5.54	5.84	5.1			
Pneumatic wrench II	X	6.06	6.17	1.9	6.68	6.75	1.0
	Y	1.85	1.78	3.5			
	Z	2.14	2.07	3.3			
Brushcutter Kawasaki TH34	X	3.89	3.80	2.5	7.19	6.96	3.1
	Y	3.18	3.42	6.8			
	Z	5.13	4.74	7.7			
Electric scissors Hecht 655	X	5.49	5.48	**0.2**	5.79	5.73	1.0
	Y	1.32	1.26	4.9			
	Z	1.30	1.13	13.2			
Electric Saw FPCS1800A	X	2.67	2.99	10.8	3.12	3.31	**5.7**
	Y	1.08	0.93	**14.4**			
	Z	1.19	1.07	10.5			
Combustion Saw Stihl 025 (front handle)	X	8.73	8.47	2.9	13.15	12.88	2.1
	Y	9.24	9.11	1.4			
	Z	3.39	3.31	2.4			
Combustion saw Stihl 025 (rear handle)	X	10.02	10.00	**0.2**	21.64	22.78	5.0
	Y	12.59	14.19	11.3			
	Z	14.19	14.75	3.7			
Saw for plastics Bosch GSG 300	X	2.09	1.93	7.7	2.40	2.27	5.5
	Y	0.80	0.80	0.9			
	Z	0.86	0.88	2.5			
Oscillating grinder CMI C-SS 200	X	7.08	7.07	**0.2**	7.19	7.19	**0.1**
	Y	0.47	0.48	0.6			
	Z	1.14	1.23	7.1			
Cordless screwdriver Makita DF347D	X	4.28	4.37	2.1	4.47	4.59	2.5
	Y	0.90	1.04	13.1			
	Z	0.92	0.91	1.3			
Jigsaw machine Bosch GST 150BCE	X	3.81	3.73	2.0	6.92	6.99	1.1
	Y	4.65	4.63	0.6			
	Z	3.42	3.79	9.8			

3.2. Evaluation results and discussion

Analyzing the results from Table 1, it can be stated that the values of corrected vibration acceleration directional components obtained using the high-speed camera and the reference system do not differ by more than 14.4%. In 23 cases out of 30 these differences are less than 8%. Even more favorable results were obtained when comparing the corrected vector sums: in all cases, the differences did not exceed 5.7%.

The achieved compatibility of results is greater than in tests by E. Bressel, G. Smith and D. Nash [3] carried out for several selected frequencies (29 Hz, 34 Hz, 39 Hz, 44 Hz, 49 Hz, 53 Hz) of vibration. The biggest differences obtained in them amounted to over 50%. Because piezoelectric transducer was then attached to the human tissue, the conditions of the tests may raise some doubts.

As an element of statistical analysis of presented results, the correlation coefficient was calculated for examined vibration parameters. Values in Table 2 show good compatibility of the results obtained with the developed method and obtained of using the reference standard measuring system.

Table 2. Correlation coefficient for corrected acceleraion values obtained using two meauring systems

Analyzed parameter	a_h	a_{hv}
Correlation coefficient value	0.9965	0.9988

The presented comparison results show that the test results obtained with the use of high-speed camera are reliable and can be used in assessing exposure to vibration.

Daily vibration exposures were determined based on calculated values of corrected vibration acceleration and vector sums. During the daily exposure determination, a total exposure time to vibration during a work shift was 4 hours. For exposure assessment, daily limit value for hand-arm vibration exposure 2.8 m/s^2 used in Poland (given in the ordinance of the Minister of Family, Labor and Social Policy of 12 June 2018 on the highest permissible concentrations and intensities of factors harmful to health in the working environment, Journal Of Laws of 2018, item 1286) has been applied. Determined using reference measuring system and high-speed camera values of daily exposures for operators of selected hand tools as well as evaluation results obtained using standard method and presented developed method contains the Table 3.

Table 3. Daily vibration exposure and evaluation results obtained using reference measuring system and developed method

Measurement object	Daily vibration exposure A(8), m/s^2		Difference [%]	Exposure	
	Pulse	Camera		Pulse	Camera
Pneumatic wrench I	4.88	4.86	0.3	high	high
Pneumatic wrench II	4.72	4.77	1.0	high	high
Brushcutter Kawasaki TH34	5.08	4.92	3.2	high	high
Electric scissorsHecht 655	4.09	4.05	1.0	high	high
Electric Saw FPCS1800A	2.21	2.34	5.7	medium	medium
Combustion Saw Stihl 025	15.30	16.11	5.0	high	high
Saw for plastics Bosch GSG 300	1.70	1.61	5.4	medium	medium
Oscillating grinder CMI C-SS 200	5.08	5.08	0.0	high	high
Cordless screwdriver Makita DF347D	3.16	3.25	2.6	high	high
Jigsaw Machine Bosch GST 150BCE	4.89	4.94	1.0	high	high

Based on the obtained results, it can be concluded that full compatibility of exposure assessments carried out based on the developed method of identification and using the standardized method has been achieved.

The results summarized in the table 3 show that at 4 hours of exposure, out of 10 tools tested, 8 of them cause high vibration exposure to worker. Only in two cases this exposure was moderate. This means that of the 10 tools tested, only 2 tools allow their safe use for 4 hours during a work shift.

4. Conclusions

Tests performed using a high-speed camera allow obtaining the same or very similar results to those obtained with the use of classic measurement systems. The test results confirmed the possibility of use of high-speed camera for research of low frequency vibration even at low displacements. It can be assumed that by using higher frame rates it will be possible to obtain similar results also at higher frequencies (i.e. up to 1000-1500 Hz).

Due to the need for a high zoom of the measuring point image, the use of a camera to analyze vibration is limited to situations where movement occurs within the range of the frame. At frequencies above 50-70 Hz, with amplitudes of *nm*, it may not be sufficient to use classic lenses and other optical elements (teleconverters, intermediate rings). The analysis of oscillatory motion recorded in the range of 2-3 pixels has no substantive justification. The proper operation of the camera is associated with ensuring adequate stabilization of its position, which significantly hinders its use in motion.

The results of verification tests show that the presented method of vibration identification and assessment, after taking into account the described limitations, can be successfully used for research vibration in the working environment.

The main advantage of vibration testing using a high-speed camera is the ability to obtain additional information about the phenomena observed during vibration generation and their impact on other mechanical systems, often without the need for further identification, analysis and interpretation. The dynamic development of the production technology of image recording devices, microprocessors, new generation computer memories and techniques based on image recognition and analysis allows us to predict that the use of high-speed cameras also for vibration analysis will be ever wider.

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