Measurements of Vibration Using a High-Speed Camera – Comparative Tests

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Abstract

In the technical diagnostics and monitoring of high dynamic processes high-speed cameras are getting wider application. Recorded images sequence analysis of an object position makes possible to study also the oscillating movement. In this paper results of some exploratory research of test vibration signals are presented. The aim of the study was to examine the possibility of applying high-speed camera to vibration measurements in the frequency range up to 1000 Hz. The performed tests consisted in the simultaneous registration and analysis of vibration test signals using 4 alternative measuring systems. and then the determination of the frequency characteristics of vibration acceleration, total corrected (Wh characteristics) and uncorrected vibration acceleration values. The results of recorded image analyses of oscillating movement were compared with results of vibration acceleration measurements obtained using laser and piezoelectric transducers. Vibration acceleration spectra, the uncorrected and corrected (Wh characteristics) total vibration acceleration values were determined. Based on the achieved results, some limitations and conditions for the application of the high-speed camera used for vibration analyses have been identified. The test results confirmed the possibility of use of high-speed camera for research of low frequency vibration even at low displacements.

Keywords: vibration, high-speed camera, comparative research

1. Introduction

Application of standard vibration measurement methods based on the use of common vibration transducers sometimes can be difficult or impossible. In many cases, the mounting of vibration transducers forces a change in way of the device operation or work condition. This influents on the measurement results and vibration assessment carried out on the basis of this results. In such cases very often non contact measurements are good (or only one) solutions. Application of high-speed camera in various fields of science [1-15], shows the potential possibilities for its use also e.g. in the field of machine monitoring or the vibration evaluation [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 registration. 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.

2. Research methodology

The performed tests consisted in the simultaneous registration of vibration test signals using 4 alternative measuring systems and then the determination of the frequency characteristics of vibration acceleration, total corrected (Wh characteristics) and uncorrected vibration acceleration values. The calculations were carried out on the basis of the obtained time signals of vibration acceleration.

Four measuring systems differing in the method of detection and registration of vibration signals were used in the tests:

- B&K 4371V piezoelectric vibration transducer with B&K NEXUS 2692-14 preamplifier and B&K Pulse multi-analyzer system,
- Polytec PDV100 doppler laser transducer with B&K Pulse multi-analyzer system,
- B&K 4371V piezoelectric vibration transducer with National Instruments NI USB-6363 data acquisition card,
- high-speed camera Photron FASTCAM SA1.1.

The type 4371V B&K vibration transducer has the following main technical parameters: type: charge (DeltaShear), frequency range: 0.1 ÷ 12600 Hz, sensitivity: 1 pC / ms2, weight: 11 g.

The Polytec PDV100 doppler laser transducer allows non-contact vibration measurement in the frequency range from 0 Hz to 22 kHz from a distance of 0.2 m to 30 m. It has three measuring ranges of vibration velocity: 20 mm/s, 100 mm/s, 500 mm/s.

The NI USB-6363 measurement card enabled setting the same signal recording parameters from a B&K 4371V type vibration transducer as when recording with a high-speed camera.

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). On the basis of pretests results 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.

Selected values were determined by 32 GB memory size of the camera and desired duration of registration. According to the sampling theorem frame rate 2000 fps should ensure correct analysis of recorded images of measurement object in frequency range : ~0 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.

The RFT 11076 vibration exciter, signal generator B&K 1054 and the Behringer power amplifier were used to generate test signals. The RFT 11076 vibration exciter is not equipped with a cooling fan; this ensures no distortions at low signal levels.

In Figure 1 measuring systems during calibration using the MMF VC21D calibrator are shown.

Figure 1. Measuring systems during calibration

During multi-point calibration: 1 m/s^2, 16 Hz; 1 m/s^2, 40 Hz; 2 m/s^2, 80 Hz; 5 m/s^2, 159 Hz; none of the systems showed faultless linearity. However, the differences between the individual points did not exceed 5% of the reference value.

For the research have been used 6 test vibration signals:

- Signal 1 – narrow-band noise, centre frequency: 16 Hz, band width: 31.6 Hz,
- Signal 2 – narrow-band noise, centre frequency: 160 Hz, band width: 31.6 Hz,
- Signal 3 – narrow-band noise, centre frequency: 320 Hz, band width: 31.6 Hz,
- Signal 4 – narrow-band noise, centre frequency: 640 Hz, band width: 31.6 Hz,
- Signal 5 – narrow-band noise, centre frequency: 920 Hz, band width: 31.6 Hz,
- Signal 6 – filtered white noise, frequency range: from 2 Hz to 2000 Hz.

The value of the ambient temperature during the test was within the range: from 20 to 22 ° C and the relative humidity in the range: from 36 % to 45 %.

3. Results

Simultaneous measurements of the vibration acceleration with all four measuring systems were carried out for six test signals applied successively.

In the case of measurements using a high-speed camera, the vibration acceleration signal was obtained by twice differentiating the vibration displacement signal. Vibration velocity signal from the laser transducer was differentiated once. In the case of measuring systems with the piezoelectric transducer, vibration acceleration signals were recorded directly. For the measuring system with the NI USB-6363 data acquisition card, the signal analyzes were carried out based also on the recorded vibration acceleration signals. All recorded signals were analyzed with a resolution of 1 Hz in the frequency range of 1 Hz - 1000 Hz. Analyzes of the oscillation motion images of the measuring point were carried out using the MoviasNeo 2D v. 2.54 software. The method of spline functions was used for interpolation. When tracking the movement of measuring points, the correlation coefficient value was not less than 0.95.

The determined frequency characteristics of vibration acceleration are presented in Figures 2 - 7. Table 1a contains the results of identifying frequency components obtained using four measuring systems, and Table 1b contains the results of statistical calculations. Based on the determined vibration acceleration spectra, the uncorrected and corrected (Wh characteristics) total vibration acceleration values were calculated. The obtained values are summarized in Table 2a and the results of statistical calculations in Table 2b.
Although statistical calculations were carried out for a series of only four elements, they are helpful in analyzing the measurement results.

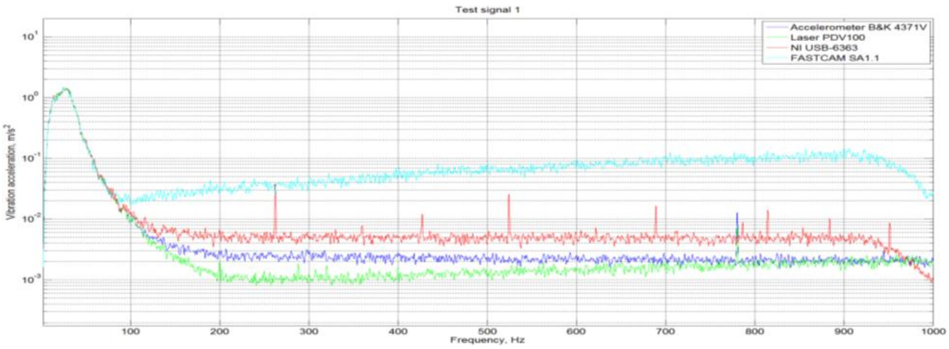

Figure 2. The vibration acceleration spectrum of the test signal 1 determined using: accelerometer B&K 4371V, laser transducer PDV100, I/O Device NI USB – 6363, high-speed camera FASTCAM SA 1.1.

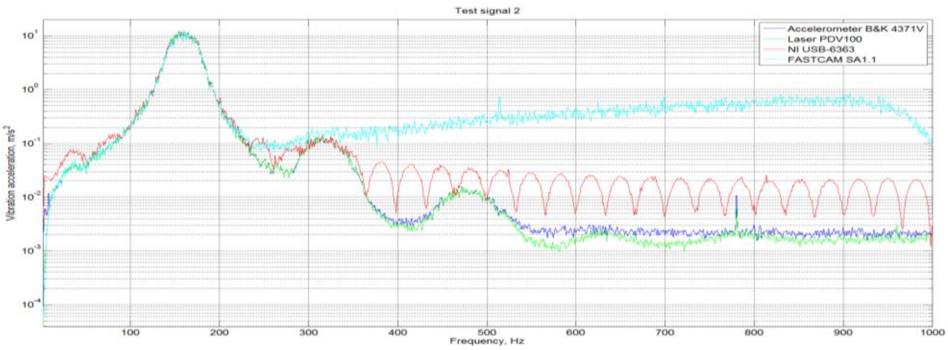

Figure 3. The vibration acceleration spectrum of the test signal 2 determined using: accelerometer B&K 4371V, laser transducer PDV100, I/O Device NI USB – 6363, high-speed camera FASTCAM SA 1.1.

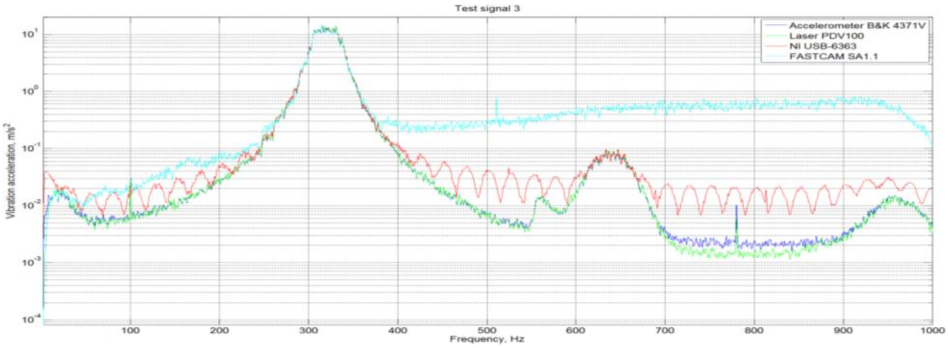

Figure 4. The vibration acceleration spectrum of the test signal 3 determined using: accelerometer B&K 4371V, laser transducer PDV100, I/O Device NI USB – 6363, high-speed camera FASTCAM SA 1.1.

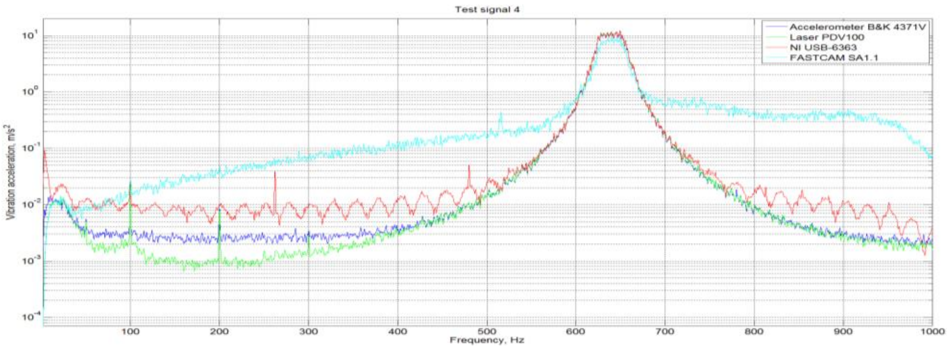

Figure 5. The vibration acceleration spectrum of the test signal 4 determined using: accelerometer B&K 4371V, laser transducer PDV100, I/O Device NI USB – 6363, high-speed camera FASTCAM SA 1.1.

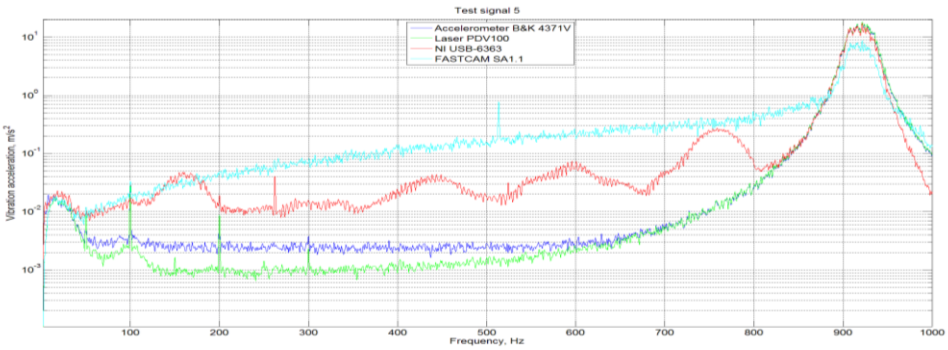

Figure 6. The vibration acceleration spectrum of the test signal 5 determined using: accelerometer B&K 4371V, laser transducer PDV100, I/O Device NI USB – 6363, high-speed camera FASTCAM SA 1.1.

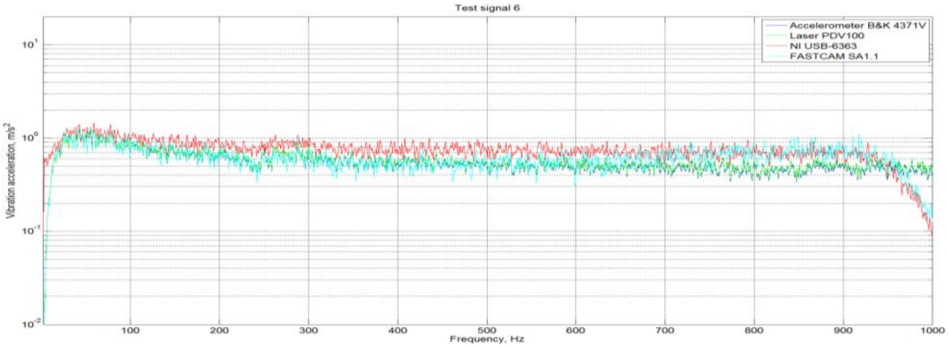

Figure 7. The vibration acceleration spectrum of the test signal 6 determined using: accelerometer B&K 4371V, laser transducer PDV100, I/O Device NI USB – 6363, high-speed camera FASTCAM SA 1.1.

Table 1a. Vibration acceleration and frequency values of dominant component for test signals

Test signal	Vibration acceleration value of dominant component, m/s^2				Frequency value of dominant component, Hz			
	B&K 4371V	LASER PDV 100	NI USB - 6363	FAST CAM SA 1.1	B&K 4371V	LASER PDV 100	NI USB - 6363	FAST CAM SA 1.1
Signal 1	1.49	1.49	1.47	1.50	24.69	24.69	25.00	24.69
Signal 2	12.07	12.26	12.18	11.96	155.00	155.00	154.69	154.38
Signal 3	14.15	14.46	14.37	14.23	315.00	315.00	315.00	315.00
Signal 4	11.77	12.13	12.31	9.37	650.00	650.00	650.00	650.00
Signal 5	17.74	18.29	17.36	8.83	921.88	921.88	921.88	921.88
Signal 6	1.26	1.28	1.46	1.29	55.31	55.31	59.38	55.31

Table 1b. Vibration acceleration and frequency values of dominant component for test signals - results of statistical calculations

Test signal	Vibration acceleration value of frequency dominant component				Frequency of dominant component			
	Mean m/s^2	Standard deviation	Median m/s^2	Coefficient of variation %	Mean Hz	Standard deviation	Median Hz	Coefficient of variation %
Signal 1	1.49	0.01	1.49	0.8	24.77	0.16	24.69	0.6
Signal 2	12.12	0.13	12.13	1.1	154.77	0.30	154.84	0.2
Signal 3	14.30	0.14	14.30	1.0	315.00	0.00	315.00	0.0
Signal 4	11.39	1.37	11.95	12.0	650.00	0.00	650.00	0.0
Signal 5	15.56	4.50	17.55	28.9	921.88	0.00	921.88	0.0
Signal 6	1.32	0.09	1.29	6.9	56.33	2.03	55.31	3.6

Table 2a. Total weighted and unweighted values of vibration acceleration for test signals

Test signal	Vibration acceleration, m/s^2							
	Unweighted values				Weighted values (W_h filter)			
	B&K 4371V	LASER PDV 100	NI USB - 6363	FASTCAM SA 1.1	B&K 4371V	LASER PDV 100	NI USB - 6363	FASTCAM SA 1.1
Signal 1	5.53	5.53	5.62	5.90	3.79	3.78	3.84	3.79
Signal 2	53.58	54.43	52.30	52.37	5.44	5.52	5.31	5.21
Signal 3	63.21	64.59	63.27	62.34	3.14	3.20	3.14	3.06
Signal 4	54.52	56.15	55.75	42.56	1.31	1.35	1.35	1.02
Signal 5	74.40	76.69	69.05	36.56	1.14	1.18	1.07	0.58
Signal 6	21.06	21.70	22.75	18.91	3.30	3.31	4.16	3.37

Table 2b. Total weighted and unweighted values of vibration acceleration for test signals - results of statistical calculations

Test signal	Unweighted values of vibration acceleration				Weighted values of vibration acceleration (W_h filter)			
	Mean m/s^2	Standard deviation	Median m/s^2	Coefficient of variation %	Mean m/s^2	Standard deviation	Median m/s^2	Coefficient of variation %
Signal 1	5.64	0.18	5.57	3.2	3.80	0.03	3.79	0.7
Signal 2	53.17	1.02	52.97	1.9	5.37	0.14	5.37	2.6
Signal 3	63.35	0.93	63.24	1.5	3.13	0.06	3.14	1.9
Signal 4	52.24	6.49	55.13	12.4	1.26	0.16	1.33	12.6
Signal 5	64.17	18.68	71.72	29.1	0.99	0.28	1.11	28.3
Signal 6	21.10	1.62	21.38	7.7	3.53	0.42	3.34	11.8

4. Discussion

After analyzing the obtained results, the following observations were formulated:

- In the frequency range of generated signals, a big similarity of time signals was observed for test signals 1, 2, 3, 6 (Fig. 1, 2, 3, 6) obtained with all four systems. Good but lower time signal compliance occurred for test signals 4 and 5 (Fig. 4 and 5) in the case of time signals obtained using a measuring system with a high-speed camera. This may mean that the camera registers amplitudes of components with frequencies above 700 Hz with less accuracy.
- In the frequency range 950 Hz - 1000 Hz for test signal 6 (Fig. 6), the decrease in compatibility of time signals obtained on the basis of signal analysis from the measuring system with the NI USB-6363 data acquisition card and obtained using a high-speed camera in comparison with signals from systems containing the PULSE system is caused by 2 kHz sampling rate.

- At low signal levels, the noise recorded by the NI USB-6363 card was greater than for systems with the PULSE system (Fig. 1 - 6).
- The time signals obtained using measuring systems with a piezoelectric vibration transducer are the result of analyzes of recorded vibration acceleration time series. The time signals obtained with the use of a measuring system with a laser transducer already required differentiation, because the system registered vibration velocity signals. Single differentiation did not introduce significant signal distortions compared to signals obtained using a piezoelectric transducer with the PULSE system (the double differentiation tested already caused significant distortions).
- Except in the case of test signal 6 (Fig. 6) and in the frequency range up to approx. 200 Hz for signals 2, 3, 4, 5 (Fig. 2 - 5), the largest background levels occurred for the measuring system with the high-speed camera (Fig. 1 - 5). However, additional tests carried out showed that large differences in background levels obtained using image analysis from the camera compared to levels obtained in other systems are not the result of inaccurate tracking of the measuring point movement. The time signals of vibration displacements of the measuring point obtained as a result of image analysis, required two differentiations. Visible large background levels are the result of imperfect algorithms used to integrate / differentiate real time signals. This was confirmed by analyzes carried out both in the Movias software and in standard signal analyzers (analog and digital).
- The highest background levels for test signals 2, 3, 4, 5, 6 in the low frequency range, ie up to approx. 50 Hz (and up to approx. 180 Hz for test signal 5) occurred for the measuring system with the NI USB-6363 data acquisition card.
- The results of identification of the dominant frequency component based on the time signals obtained for all applied measuring systems and all test signals were consistent (Table 1a). The coefficient of variation for determining the dominant frequency component did not exceed 3.6 % (Table 1b). Higher values of the coefficient of variation occurred for the amplitude of the identified dominant component for test signals 4 and 5 (12 % and 28.9 % in Table 1b, respectively). This is the result of noticeably smaller values of vibration acceleration for a measuring system with the high-speed camera (Table 1a).
- The highest compatibility of the dominant component amplitude values for all measuring systems was obtained for test signal 1 (coefficient of variation 0.8% in Table 1b). This means that at frequencies below about 70 Hz, all the measuring systems used allow for identical results. The achieved compatibility of results is greater than in tests by Bressel, E., Smith, G., Nash, D. [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.
- A similar effect was observed in the calculation of the vibration acceleration weighted total values of the test signals (Table 2a). The highest compatibility of values for all measuring systems was obtained for test signal 1 (coefficient of variation 0.7 % in Table 2b).

- For unweighted total values of vibration acceleration (Table 2a), the highest compatibility of values for all measuring systems was obtained for test signal 3 (coefficient of variation 1.5 % in Table 2b).
- The highest values of the coefficient of variation for unweighted and weighted total values of vibration acceleration occurred in the case of test signal 5 (29.1 % and 28.3 % in Table 2b, respectively). It is also the result of obtained smaller values of vibration acceleration for a measuring system with the high-speed camera (Table 2a).

5. 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 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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