JOURNAL OF CIVIL ENGINEERING, ENVIRONMENT AND ARCHITECTURE
JCEEA, 70, 2023, 51-64, DOI:10.7862/rb.2023.5

Natalia BRÓŻ[1]
Piotr NAZARKO[2]

CHALLENGES IN ASSESSING THE VIBRATIONS INFLUENCE ON PEOPLE IN BUILDINGS USING NON-CONTACT MEASUREMENTS

This research article presents a comparative analysis of vibration assessments in lecture halls to investigate their influence on people using contact (accelerometers) and non-contact (laser vibrometers) measurement techniques. The study aims to verify the accuracy and reliability of vibration analysis in relation to two approaches and determined physical parameters, i.e. acceleration amplitudes and vibration velocities. The intriguing fact was that none of the building users reported any perceived discomfort from vibrations, despite the determined parameters of the signal measured using a laser vibrometer indicating exceedance of permissible vibration amplitudes in several frequency bands. The conducted comparative analysis leads to the conclusion that the location of the laser head tripod on the vibrating floor introduces significant vibration amplification, which in turn may lead to an incorrect assessment of the impact of vibrations on people in buildings. The studies described in the article were carried out in accordance with the procedure contained in the Polish national standard PN-B-02171. The obtained results and the resulting conclusions are an important contribution to a better understanding of the advantages and limitations resulting from the use of non-contact measurements.

Keywords: vibration measurements, laser vibrometry, vibration influence on people in buildings, signal processing

1. Introduction

Buildings where people stay, whether temporarily or permanently, must satisfy specific standards regarding vibrational comfort determined by applicable regulations [1]. The acceptable level of vibration depends on the purpose of the rooms and the frequency of events that can cause discomfort. The most rigorous criteria apply to operating rooms and precision laboratories, while the highest levels of vibration are acceptable in places like workshops. Residential, office and school

[1]Corresponding author: Natalia Bróż, Rzeszów University of Technology, Department of Structural Mechanics, Powstanców Warszawy 12, 35-959 Rzeszów, Poland; tel. +48 17 865 1618; n.broz@prz.edu.pl, https://orcid.org/0000-0002-2719-7566.
[2]Piotr Nazarko, Rzeszow University of Technology, Department of Structural Mechanics, Powstanców Warszawy 12, 35-959 Rzeszów, Poland; tel. +48 17 865 1621; https://orcid.org/0000-0002-6135-2486.

rooms fall into the category where the impact of vibrations is moderate. It is worth noting that the human body is a highly sensitive instrument for perceiving vibrations, although how they are perceived and when they are experienced as discomfort is a very subjective feeling [2]. However, there are measurement procedures that aim to determine the frequency and level of vibrations that can negatively affect human health and well-being. This article presents the results of experimental studies conducted in one of the lecture halls at Rzeszow University of Technology, where it was observed that under certain circumstances vibrations from the floor slab and other equipment (such as podium, lectern, desk or microphones standing on them) can be distinctly noticed and felt by academic lecturers.

There are several methods for determining the impact of vibrations on people staying in buildings [3–5]. The Polish standard [1] provides for two procedures, which are based on measurements of vibration accelerations or their velocities. In both cases, these measurements can be carried out by attaching appropriate sensors to the tested element (contact method). Vibration velocities can also be measured using non-contact techniques, including laser vibrometry. These devices are characterized by high measurement accuracy, but the measurement itself is a challenge when the laser head tripod is placed on the floor where we intend to measure vibrations. This article presents the results of vibration analysis and their impact on people in buildings, along with a discussion of the impact of various factors on the obtained results (e.g. the impact of mounting the laser head, tripod spacing, vibration compensation). Two types of vibrometers were used in the experimental studies, and the obtained results were compared to measurements made using an acceleration sensor.

2. Scope and subject of research

2.1. Causes of building vibration

Buildings can experience vibrations from various sources. These vibrations can originate from ground-transmitted disturbances or from external acoustic disruptions. Additionally, internal sources within the structure can also contribute to these vibrations. Commonly, the vibrations felt in a building are transmitted through the ground, often resulting from nearby traffic, industrial activities like forging, or construction and demolition projects. Buildings can also experience vibrations from external factors such as wind or noise from heavy vehicles and intense aircraft sounds. While external sources are often recognized, internal sources, which can be just as significant, frequently go unnoticed. These internal vibrations can be categorized into two main types: mechanical and human-induced. In commercial settings, mechanical vibrations can arise from elevators, HVAC systems, and heavy-duty office equipment. In residential settings, household appliances like vacuum cleaners and washing machines, as well as actions like door slamming, can be sources of unwanted vibration excitation. Vibrations caused by human activities, such as walking, dancing, or even impulsive actions like jumping, are also common. Buildings with diverse functions can face unique challenges, especially when vibrations from one section affect more sensitive areas in another part of a building. For instance, it may concern a hospital with busy corridors close to occupied rooms [6].

In the case of the object subjected to testing, irregular vibrations where noticed in the room during classes, which could be observed on a desk or a microphone stand (Fig. 1), even without professional equipment. It was also observed that the vibrations do not come from the outside (i.e. from passing vehicles), but they are caused by internal dynamic action, mainly related to people walking in the corridor next to the room, as well as from people in this certain classroom.

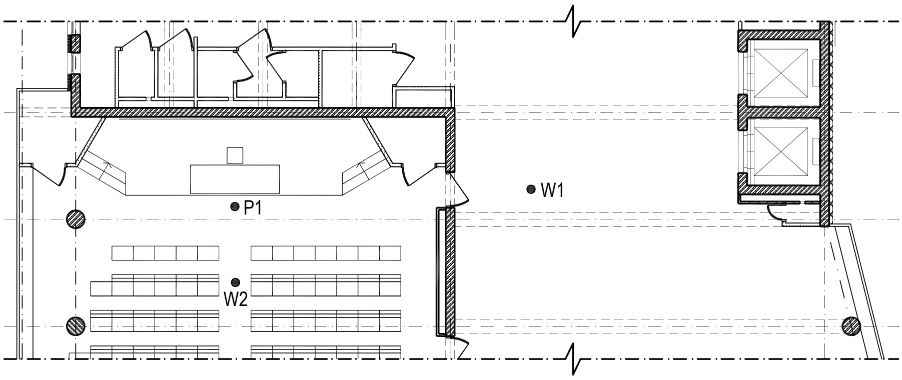

Fig. 1: Scheme of a studied lecture room with location of excitation (W1, W2) and measurement (P1) points.

The object of the research is one of the lecture halls (P.2) of the Rzeszow University of Technology located on the first floor of the P building at Poznanska Street in Rzeszow. This room has 188 seats for students. Some of them are designed in an amphitheater arrangement, i.e. with a slope of the floor to obtain better visibility. In this building, apart from teaching rooms, there are also dean's offices, laboratories and employee offices of the Faculty of Civil and Environmental Engineering and Architecture.

The floor structure consists of 40×40 cm beams spaced every 300 cm and a 10 cm thick combined reinforced concrete slab with finishing layers (Fig. 2). The total height of the floor is 16 cm (based on archival documentation). Inside the lecture hall, it is finished with PVC carpeting.

At the research planning stage, it was assumed that the measurement would take place at the P1 control point located on the floor in front of the teacher desk, while the vibrations themselves would be forced by rhythmic jumping (of one or more people) in the corridor at point W1 and inside the room, between the benches at point W2. Dynamic tests of pedestrian footbridges are carried out in a similar way. The schematic arrangement of the mentioned points and the layout of the lecture hall are shown in Fig. 1.

2.2. Measurment procedure and devices

The described situation concerns the passive reception of vibrations by a person who does not have a direct impact on the operation of the vibration sources. The Polish standard [1] specifies permissible vibration levels both in relation to the effective values of acceleration amplitudes and vibration velocities, calculated in 1/3-octave bands [7]. These values were calculated for events in which the duration of the assessed vibration parameter were greater than 0.2 of the peak value [8]

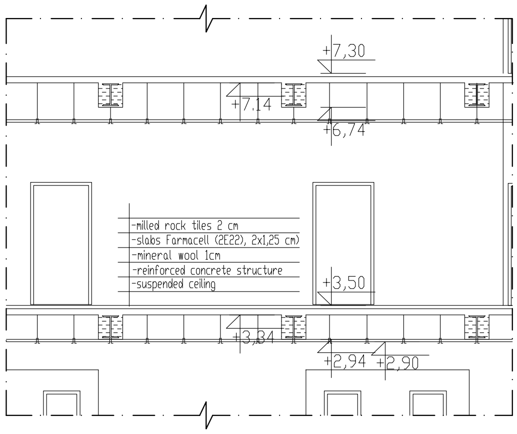

Fig. 2: Cross-section of the floor in the tested room.

after filtering the signal with a low-pass filter at a frequency of 120 Hz [1]. Next effective values of velocities and accelerations (Root-mean-square value, RMS) in selected frequency bands were calculated [9]. In the process of developing standard vibrograms admissible vibration level values $n = 4$ were assumed for rooms of the type Offices, schools and rooms of similar purpose and short-term vibrations with repeatability of more than 10 events per day (according to the table 3 of Polish standard [1]).

The standard test procedure involves carrying out measurements using wired acceleration or velocity sensors. In this research the LMS Scadas Mobile with Wilcoxon accelerometer (model 731-207, 10 V/g) were used for this purpose. The signals obtained in this manner served as the basis for developing standard acceleration vibrograms, simultaneously constituting a reference for the results obtained from velocity measurements carried out in a non-contact manner using laser vibrometry.

Vibrometers are devices that allow for highly sensitive, remote, and precise measurement of vibration velocities and displacements. These measurements can be conducted from substantial distances. This enables the monitoring of the dynamics of buildings, operating machinery, and critical production objects. The device consists of the following components:

- an advanced laser sensor with an integrated targeting system combined with a long-range interferometer,
- a controller, which converts the sensor's output signal into voltages monitoring velocity and displacement,
- a tripod with height adjustment,
- a computer with software package enabling data acquisition and preliminary data analysis.

In this research experiment a single-point Polytec RSV-150 laser vibrometer and a PSV-400 scanning laser heads were used for non-contact measurements of

a) b)

Fig. 3: Measurement devices and its position in the classroom: a) LMS Mobile and Polytec RSV-150, b) two laser heads (RSV-150 and PSV-400)

vibration velocity (Fig. 3). This device operates on nearly all surfaces, allows for remote access to distant areas, and is relatively user-friendly (compared to systems based on acceleration sensors). The principle of their operation uses the Doppler effect, which is why these devices are called Laser Doppler Vibrometers (LDV) [10].

The vibrometer software also allows to connect and simultaneously record signals from other devices, e.g. an acceleration sensor mounted on the laser head to compensate for its vibrations. This possibility was used in one of the stages of the experiments. All the most important vibrometer settings were collected in Table 1.

Table 1: Vibrometer settings

Settings	**PSV**	**RSV**
Junction Box	PSV-E-400-M4	VIB-E-220
Sample frequency	256 Hz	600 Hz
Sample time	32 s	25,6 s
Sample length	8192	15360
Resolution	3,91 ms	1,67 ms
Vertical range	5 V	10 V
Calibration factors	2e-3 $(m/s)/V$	2e-3 $(m/s)/V$
	0,9807 $(m/s^2)/V$	n/a

3. Experimental research

3.1. Contact and non-contact vibration measurements

At the first stage of the research the RSV vibrometer and the LMS system were used. For this purpose, an intermediate mass was placed on the floor (this results from technical recommendations for this type of measurements [11]) in front of the teacher desk. An acceleration sensor measuring vertical vibrations was placed on this mass, while the laser head was positioned above the measurement point P1 (Fig. 1). The vibrations were forced by rhythmic jumping of two people in the corridor adjacent to the room (point W1 in Fig. 1). Measurements were carried out in two configurations (also shown in Fig. 4):

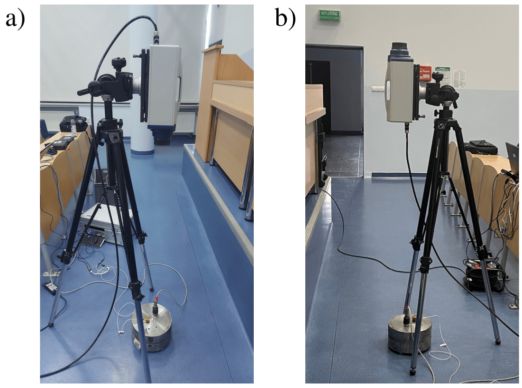

Fig. 4: Measurement schemes considered in the first stage of research (LMS system and Polytec RSV vibrometr): a) 1st configuration, b) 2nd configuration.

1. The laser beam directed downwards to measure vibration close to the acceleration sensor.

2. The laser beam directed upwards to measure the vibrations of the ceiling transmitted through the tripod legs in relation to a theoretically stationary ceiling.

Then, in relation to the recorded time signals of accelerations and vibration velocities, a standard procedure was carried out to determine the level of vibrations in relation to the permissible level of dynamic comfort specified in the standard [1]. The obtained in this way RMS values are shown in Fig. 5. The blue line indicates the permissible value for teaching rooms, the red line applies to rooms of the highest vibration comfort requirements (e.g. operating room; this is included for comparison purposes only). The horizontal axis shows the center frequencies of the bands specified in the standard, and the vertical axis shows the calculated effective vibration values. It can be seen, that in the case of measurements with an acceleration sensor (Fig. 4a), the permissible vibration values are not exceeded, but in the case of vibration velocity measurements using the RSV vibrometer, they are exceeded in the following three bands: 10, 12.5 and 16 Hz.

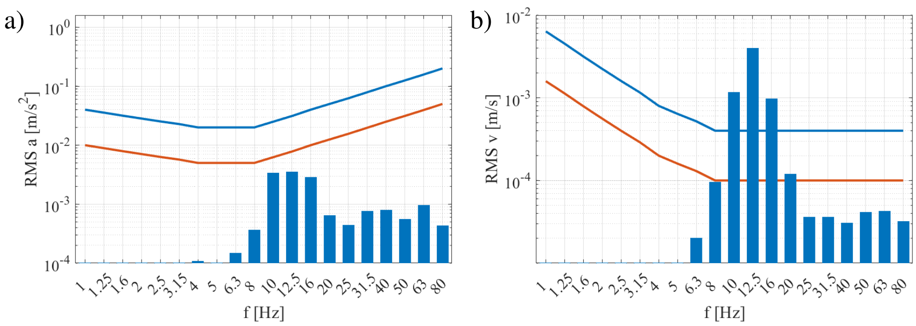

Fig. 5: RMS values of vibration amplitudes in relation to the measured physical quantities (scheme no. 1): a) acceleration, b) velocity

In the case of the second measurement configuration (Fig. 4b), the final results obtained were very similar (Fig. 6), even though the measurement was carried out to a stationary ceiling.

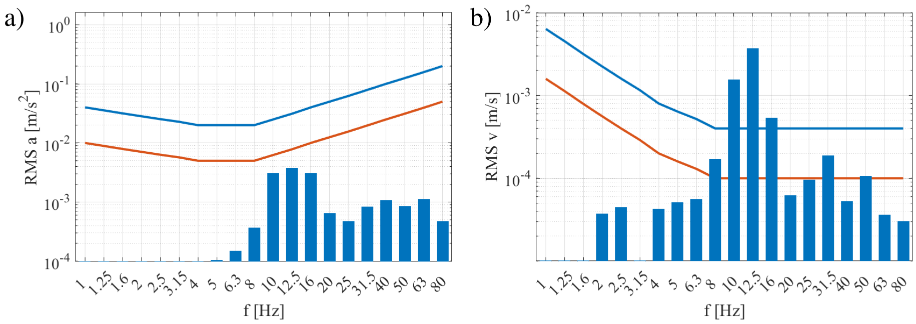

Fig. 6: RMS values of vibration amplitudes in relation to the measured physical quantities (scheme no. 2): a) acceleration, b) velocity

The conclusions can be drawn that the obtained results of a contact and non-contact measurement do not provide a clear answer whether the vibration level exceeds the permissible values or not. It was decided that it would be necessary to verify what may influence the exceeded permissible vibration level in the case of measurement using RSV laser vibrometer.

3.2. Comparison of two laser heads

In the second stage of the research, vibration measurements were carried out using two laser vibrometers: a single-point RSV-150 head and a PSV-400 scanning head (Fig. 3b). The aim was to compare the behavior of both vibrometers in the task of measuring vibrations of the ground on which the vibrometers are placed. Additionally, it was intended to analyze the influence of the tripod spacing width on the vibrations transmitted to the laser head. A contact sensor was placed on the laser heads, which allowed for simultaneous registration of vibration accelerations of the laser heads themselves.

For this purpose, a series of measurements were carried out in the following four configurations:

1. Head stands in both vibrometers (PSV, RSV) are set narrowly and relatively high, the accelerometer is placed on the PSV head, the excitation in the corridor at point W1 (Fig. 1).

2. The setting are the same as in case 1, but the excitation was located inside the room at point W2 (Fig. 1).

3. The stands of both vibrometers (PSV, RSV) are placed high, the accelerometer placed on the RSV head, the excitation was located inside the room at point W2 (Fig. 1).

4. PSV vibrometer stand set high, RSV stand set wide, the accelerometer is placed on the RSV head, the excitation was located inside the room at point W2 (Fig. 1).

a) b) c)

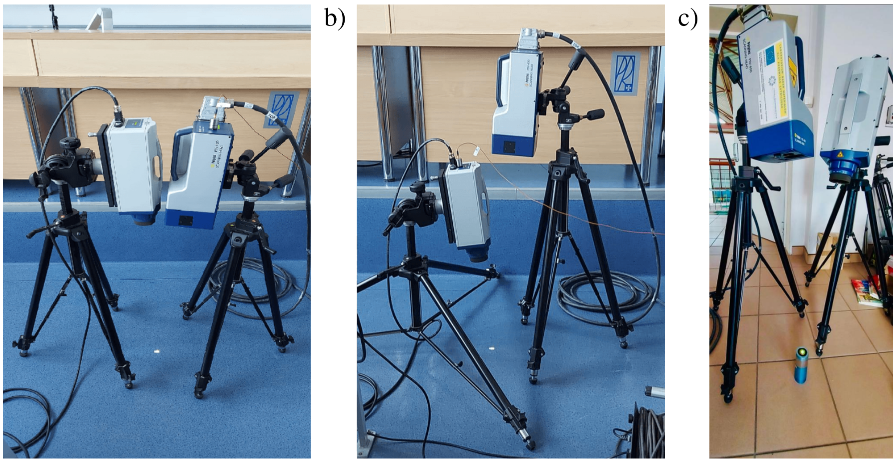

Fig. 7: Selected measurement schemes considered in the second stage of research: a) first and second configuration – head stands in both vibrometers are set narrowly and relatively high, b) fourth configuration – PSV vibrometer stand set high, RSV stand set wide, c) laboratory verification measurements using a sensor calibrator.)

The first, second and fourth configuration of the LDVs in the second stage of the research are shown in Fig. 7.

Figure 8 shows the measured vibration velocities by two vibrometers (PSV and RSV) in configuration no. 1 and 2 (see Fig. 7a). The first diagram (Fig. 8a) concerns the case when the vibration excitation was introduced in the corridor, in front of the lecture hall (at point W1), and the second (Fig. 8b) corresponds to the forcing introduced inside the room (at point W2).

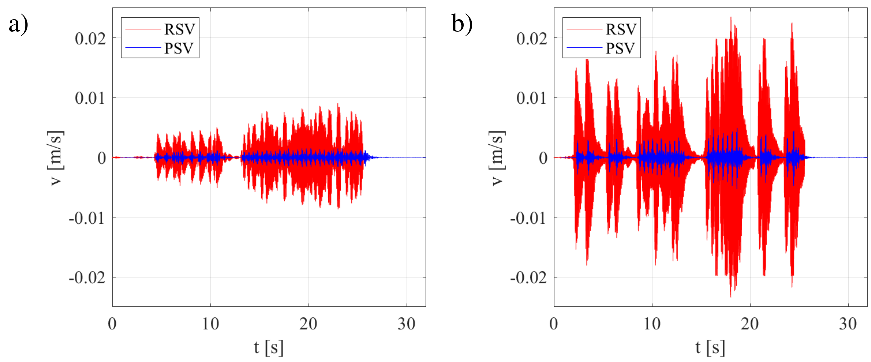

Fig. 8: RMS of velocities measured by the laser vibrometers RSV and PSV: a) configuration no. 1 – excitation at the corridor (point W1), b) configuration no. 2 – excitation inside the classroom (point W2)

Apart from clearly higher vibration amplitudes when excitation is located inside the room (closer to the measurement point P1), it can also be noticed that the vibration amplitudes measured by the laser head PSV are clearly smaller than in the case of the velocities measured by the laser head RSV (see Table 2). This was inexplicable because multiple verification of the settings of both vibrometers did not reveal any configuration errors in these devices that could cause such significant differences.

Table 2: Maximum amplitudes of vibration velocities (m/s) measured by the laser head PSV/RSV and a proportional coefficient

No.	PSV	RSV	Prop. coeff.
1	0.0016	0.0090	5.625
2	0.0053	0.0222	4.189

To exclude incorrect operation of the vibrometers, four measurement series were performed with respect to the vibrating sensor calibrator (PCB Piezotronics, $f = 79.8$ Hz, 1 g RMS; LDV configuration shown in Fig. 7c). The obtained vibration amplitudes (total maximum and dynamic amplitude) are shown in Table 3. The measurements results do not differ significantly. Only in case of maximum amplitudes their standard deviation with respect to the RSV vibrometer is 4.75 higher than for PSV. Based on this, it can be concluded that in the absence of ground vibrations, similar values of the measured vibration velocities were obtained from both vibrometers, therefore these devices operate properly.

Table 3: Amplitudes of vibration velocity $[m/s]$

	Max ampl.		Dynam. ampl.	
No.	PSV	RSV	PSV	RSV
1	0.0291	0.0291	0.0563	0.0565
2	0.0292	0.0292	0.0563	0.0563
3	0.0291	0.0292	0.0563	0.0564
4	0.0290	0.0285	0.0562	0.0553
Mean	0.0291	0.0290	0.0563	0.0561
Std$*10^{-4}$	0.787	**3.739**	0.521	0.563

When looking at both laser heads (Fig. 9), the only noticeable difference is the way they are mounted on the tripod. The RSV vibrometer has a plate that allows for precise positioning of the laser spot (it is a single-point measurement system, unlike the PSV scanning head). It is not rigidly connected to the head and when placed vertically, this may result in increasing the amplitudes of the measured vibration velocities.

a) b)

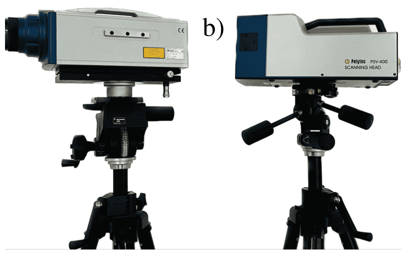

Fig. 9: Laser heads mounted on tripods: a) RSV-150, b) PSV-400

3.3. Analysis of the laser heads vibrations

In the next stage of the research, a quantitative analysis of the measured values was carried out due to the mounting of the laser heads on the tripod and the width of the tripod legs. Figure 10 shows a comparison of the vibration velocity signals with narrow (scheme 3) and wide (scheme 4, see Fig. 7b) positioning of the tripod legs in the case of measurements with the RSV laser head. As can be seen, the

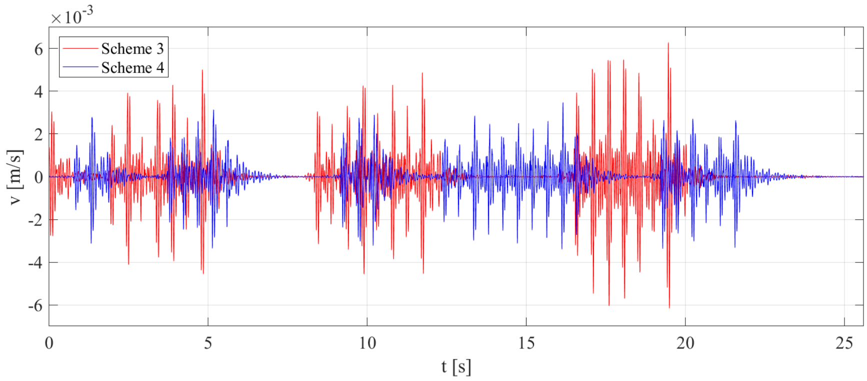

Fig. 10: Comparison of vibration velocity signals measured by the laser head RSV with narrow (3rd conf.) and wide (4th conf.) positioning of the tripod legs

vibration velocity amplitudes at a high tripod setting turned out to be larger. The quantitative data corresponding to the graph are summarized in Table 4. It can be seen that these values differ about 44% in a case of the maximum amplitudes for the vibration velocity.

Table 4: Maximum amplitudes of vibration velocities measured by the laser head RSV and accelerations measured by contact sensor

Scheme	Velocity $[m/s]$	Acceleration $[m/s^2]$
3	0.0063	0.2305
4	0.0035	0.1742
Prop. coeff.	0.56	0.76

In this task also accelerations were measured using one contact sensor placed on the laser head and connected to the junction box of the vibrometer. This allowed for simultaneous recording of both vibration velocities and accelerations. A comparison of selected acceleration time signals is shown in Fig. 11. The first two graphs show the accelerations measured on the PSV and RSV heads with a high stand spacing (Fig. 11a and 11b). These data come from different measurement series (configuration 2 and 3 described in the section 3.2), therefore the events on the time axis are not important, only the vibration amplitude levels on the vertical scale. Therefore, when comparing the maximum acceleration amplitudes ($A_{2,max} = 0.078\frac{m}{s^2}$, $A_{3,max} = 0.231\frac{m}{s^2}$), similar differences can be seen as in the case of the velocities presented in Fig. 8. In this case, the proportionality factor of accelerations was 2.96. This confirms previous conclusion, indicating that the way

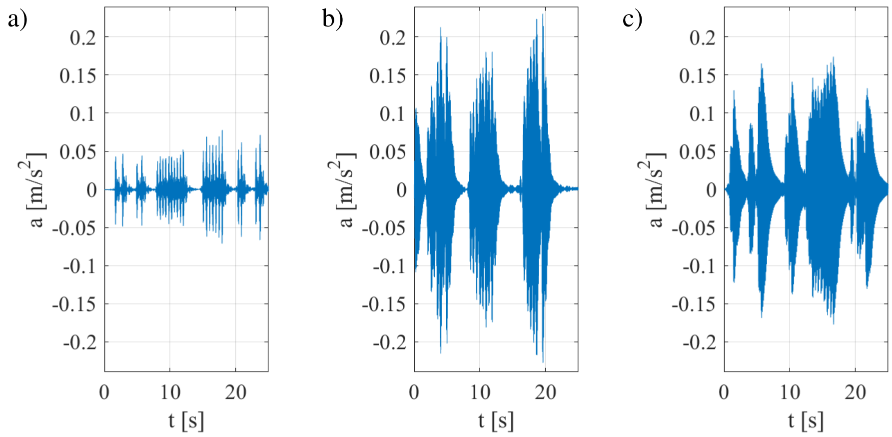

Fig. 11: Selected acceleration signals measured on the laser heads: a) PSV at high tripod position (2nd conf.), b) RSV at high tripod position (3rd conf.), c) RSV at wide tripod position (4th conf.)

the heads are mounted is the cause of discrepancies in measurements using laser heads placed directly on the vibrating floor.

It is also worth comparing the graphs presented in Fig. 11b and 11c, which concern the RSV laser head in a high and low tripod position. The data presented in Table 4 prove that wide spacing of the tripod legs resulted in a 24% reduction of the vibration acceleration level of the RSV laser head.

3.4. Vibration velocity compensation

The last stage of the research concerned the compensation of vibration velocities by integrating the previously discussed acceleration signals, which were measured with a contact sensor placed on each of the laser heads. Measurement directions of the sensor and the laser beam were the same. Numerical integration of signals was performed using the *cumtrapz* function in Matlab [12]. An example fragment of the original velocity signal measured by RSV laser head (velo.), the integrated signal (inte.) obtained from the acceleration sensor and their difference (diff.) are shown in Fig. 12.

A standard procedure [1] was carried out for both the original velocity signals measured by the vibrometer (velo.) and the compensated ones (diff.). The obtained results for the 1st configuration (see section 3.2) of the PSV vibrometer were shown in Fig. 13. It can be seen, that compensation of the signal did not result in a visible reduction of the effective values of vibration velocities. This is due to the fact that in this case the vibration velocity amplitudes obtained by integrating the acceleration signal were almost twice as large as the original signal measured by the vibrometer. After subtracting these signals, a similar level of amplitude was obtained as in the case of the original velocity signal. However the permissible values of the vibration comfort are only slightly exceeded at central frequency $f = 10$ Hz. There is 4.1e-4 when 4.0e-4 is allowed). The second highest value is at $f = 12.5$ Hz is equal to 3.8e-4, which is below 4.0e-4.

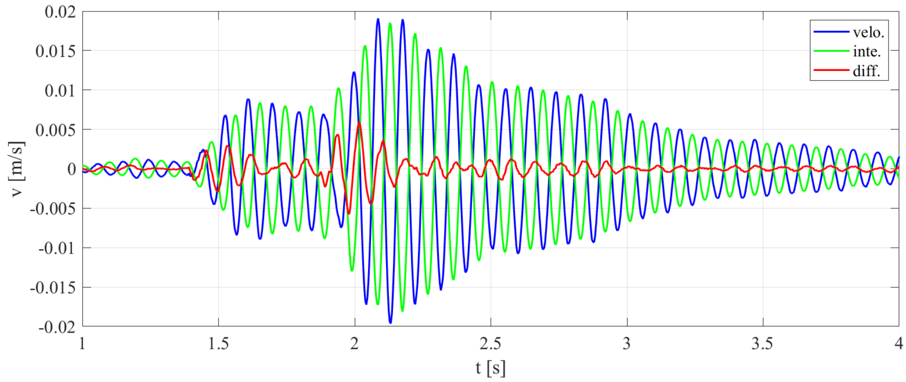

Fig. 12: A fragment of the signals: measured using the RSV laser head (velo.), integrated (inte.) based on the acceleration sensor and their difference (diff.)

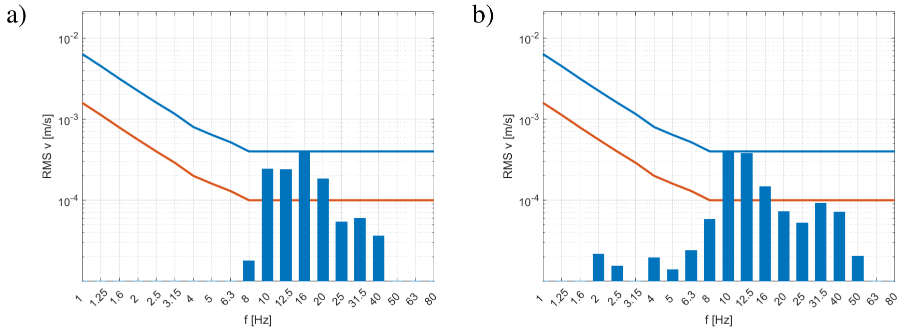

Fig. 13: Effective values of vibration velocities (PSV, 1st conf.): a) original signal, b) compensated signal

A similar analysis was also performed with respect to the velocity and acceleration signals measured in 4th configuration. The obtained results of effective velocity values were shown in Fig. 14. In this case, the achieved reduction in

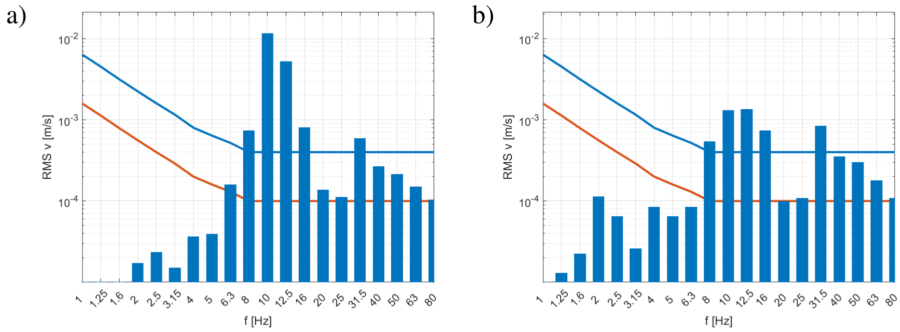

Fig. 14: Effective values of vibration velocities (RSV, 4th config.): a) original signal, b) compensated signal

vibration levels is clearly visible, although permissible vibration levels are still exceeded in few frequency bands.

4. Summary and conclusions

Despite numerous attempts, it was not possible to obtain similar results based on the contact and non-contact measurements. For this reason, further research in this area is needed to recognize that measurements using a vibrometer can be considered reliable in the event of significant vibrations of the base on which it is placed.

Smaller vibrations of the laser heads occurred when a wide spacing of tripod legs was used. It was confirmed by both measured values: vibration velocity and acceleration. The method of mounting the RSV head has a significant impact on the obtained vibration values, if the tripod is placed on a vibrating surface and in a vertical position (laser spot directed up or down). Comparative measurements with the use of a calibrator excluded the possibility of faulty operation of the laser heads used. Compensation of the laser heads vibrations by placing acceleration sensors on them did not bring expected results. However, the recommended intermediate weight was not used in this experiment, which may affect the final results achieved.

REFERENCES

[1] PN-B-02171:2017: *Evaluation of the vibrations impact on people in buildings* (in Polish)

[2] J. Kawecki, A. Kowalska, *Analysis of Influence of Vibrations on Humans in Buildings in Standards Approach*. Archives of Civil Engineering, 58 (2), 223–239, 2012.

[3] J. Kawecki, K. Stypula, *Methods of Assessment for Vibration Impact on People in Buildings*. Proceedings of the Eleventh International Conference on Computational Structures Technology, Civil-Comp Press, Stirlingshire, Scotland, 177, 1–9, 2012.

[4] A. Kowalska–Koczwara, K. Stypula, *Assessment of the Vibration Influence on Humans in Buildings in the Standards of Different Countries*. Procedia Engineering, 161, 970–974, 2016.

[5] A. Ebrahimpour, R.L. Sack, *A rewiew of vibration serviceability criteria for floor structures*. Computers and Structures, 83, 2488–2494, 2005.

[6] BS 6472-1:2008: *Guide to evaluation of human exposure to vibration in buildings. Part 1: Vibration sources other than blasting*

[7] MathWorks®, *Audio Toolbox™ Documentation*. https://www.mathworks.com/help/audio/, (Access: 19.05.2023).

[8] J. Kawecki, K. Stypula, *Providing vibration comfort to people in buildings exposed to traffic impacts*. (in Polish) Publishing house of the Krakow University of Technology, Krakow 2013.

[9] Matlab® DSP System Toolbox https://www.mathworks.com/products/dsp-system.html, (Access: 19.05.2023).

[10] P. Nazarko, R. Wdowik, J. Porzycki, Methodology of measuring ultrasonic oscillations of tools using LDV (in Polish), Pomiary Automatyka Robotyka, 7 (10), 2013, 160–165, DOI: 10.14313/PAR_200/160.

[11] K. Nering, A. Kowalska–Koczwara and K. Stypula, *Annoyance Based Vibro–Acoustic Comfort Evaluation of as Summation of Stimuli Annoyance in the Context of Human Exposure to Noise and Vibration in Buildings*. Sustainability, 12, 9876, 2020; doi:10.3390/su12239876

[12] MathWorks®, *Matlab Help Center*. https://www.mathworks.com/help/matlab/ref/cumtrapz.html, (Access: 4.09.2023).

Sent to the editorial office: 29.09.2023
Published: 18.10.2023