Measurement-Interpretation Methodology for the Evaluation of Human Perception of the Vibration in Buildings

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Abstract. The article contains guidelines related to the proper performance and analysis of the measurements of human perception of the vibration in buildings. The recommendations apply to both hardware requirements and the selection of measurement points as well as the analysis of the recorded signal. The buildings located in the so-called dynamic impact zone are the subjects of the analysis of the influence of vibrations on people in the buildings. In this article, the range of dynamic impact zones from different dynamic excitation is listed. An extremely important aspect of the measurements of the human perception of the vibrations in buildings is the selection of the location of measurement points. In different national standards, there are different guidelines which are compared in the article. The most proper locations are investigated. A separate issue is the selection of the measuring range and the selection of corrective filters for the analysis. New trends in this matter are shown and requirements according to the different standards are compared. A separate problem is determining the duration time of vibrations, which should be taken into analysis. It is worth noticing that the choice of duration can have a significant influence on all the results of the analysis of human perception of the vibration in buildings and many standards do not give any recommendations in this subject. The last problem of the methodology of measurements of human perception of the vibrations associated with the analysis of the measurement data is the sampling frequency of the recorded signal. The so-called N-qyst frequency has been shown in the paper and explained in a specific example...

1. Introduction

Vibrations propagating through the ground to the building may not only be damaging to the building structure, or can cause its accelerated consumption, but also may influence on the comfort in the rooms. These vibrations may be annoying for residents of buildings, and in the extreme cases may lead to sleep disorders, headaches and neurotic conditions [1-3]. Especially vibrations from the low frequency range from 5 to 25 Hz could be harmful, because in this range resonant frequencies of human internal organs are located [4, 5]. The influence of vibrations on people residing in buildings, despite many researches carried out in the past, despite the requirements in the standards, is still not fully recognized because of the subjective nature of vibration perception by different people. This is evidenced by changes that have been introduced over the last years in the standards of individual countries and in the international standards ISO [6, 7]. One of the aspects of the evaluation of the influence of vibrations on people in buildings is the connection of analysis results with the position of the human body in a chosen room. Three human body positions are considered. In the sitting and standing position, the person percept vibrations through the feet or the seat surface in such a way that...
the "z" axis that runs along the spine is the vertical axis, while the "x" (back - front) and "y" axes (side to side) are horizontal axes. In the recumbent position, the whole body surface precepts’ vibrations in such a way that the "z" axis becomes horizontal and the "x" axis is vertical (Figure 1).

![Figure 1. Basic axes of the human body][1]

The vibration sensitivity differs from the direction of their operation in such a way that for frequencies below 4 Hz horizontal vibrations are more perceptible than vertical ones, while above this frequency, the situation is opposite and these vertical vibrations are more noticeable.

This work describes a set of good practices that should be followed during measurements of human perception of vibrations transmitted to the building through the ground. This set consists of: the selection of locations for measuring points in the building, the use of appropriate measuring equipment, the duration of registration time, adequate signal analysis, which will allow reliable evaluation, the choice of evaluation method depending on the objective to be achieved, clear and unambiguous summary of the results of the evaluation.

2. **Selection of the buildings and locations of measurement points**
Buildings selected for analysis should be within the range of the so-called zones of dynamic influences (Table 1).

| Vibration source       | Range of zone [m] |
|------------------------|-------------------|
| Railway                | 25-50             |
| Tram, road             | 15-25             |
| Shallow underground    | 40                |

Referring to the range of the railway, in recent years an interesting study has been created based on experimental research, which postulates extending the range of this zone due to the perception of vibrations by people up to 60 m for passenger trains [9], and in the case of cargo trains up to 100 m [10].

An extremely important aspect, of the measurements of the influence of vibrations on people in buildings, is the selection of the location of measurement points. In this respect, there are some differences in the standard provisions of different countries. According to the ISO standard [6], vibration measurements transmitted to the human body should be measured on the surface between the body and this surface. This is a very imprecise definition. On the other hand, in the ISO standard [8], the reference to the measuring point says that vibrations transmitted to the human body should be measured in the middle of rigid surfaces (usually at a distance of 10 cm from this area). This more precise definition is due to the scope of the ISO standard [8], which contains requirements mainly relating to the whole body vibrations. The British norm [11] in this area is not as restrictive as in ISO [8]. It indicates the center of the room, but the range of the zone, in which the measurements of the influence of vibrations on people could be made, is from 1/3 to 2/3 length / width of the floor. According to the Polish standard [12], measuring points should be located in at least one room on the top floor, as close as possible to the excitation source. The measuring point should be located in the geometric center of the room, provided that there were no premises for its other location (eg. with an unusual structural layout of the floor). It seems that requirements written in the Polish standard are on the safe side, while British standard requirements should be investigated.

3. Appropriate measurement equipment
During the measurements, you can record the accelerations and velocity vibrations which is related to the easy assessment of the impact of vibrations on people using this parameter. During the measurements, devices are also important, which should enable correct signal recording from as little as 1 Hz and even below this value. The measurement, although in most cases the vertical direction has a decisive role, should take place simultaneously in three orthogonal directions: the "x" direction is assumed in all measurements perpendicular to extortion, the "y" direction is parallel, and the "z" direction is the vertical direction.

According to the standard [12], it is recommended to use a measuring disk, which should have a mass of at least 30 kg and a diameter of 30 cm (Figure 2). This is related to human weight simulation.
4. Signal registration and analysis

Signal recording should contain frequencies in the range from 1 to 120 Hz, so that after applying a low-pass filter the frequencies up to 80 Hz can be included in the evaluation.

A separate aspect is the duration of vibrations, which according to [12] is in the range in which the value of vibration acceleration amplitudes does not fall below 0.2 of the maximum amplitude value in the recorded waveform (Figure 3).

![Figure 2. Measurement discs](image)

![Figure 3. Method of determining the duration of vibrations [13]](image)
The ISO standard [8], used mainly for the whole body vibration measurements, requires that the signal recording time should be at least 30 minutes. Standard [7] includes a reference to the duration of vibration, which states that the recorded signal should be sufficient to ensure rational statistical accuracy. This definition is very wide and imprecise, while the duration of vibration has a significant impact on the results of the signal analysis, especially referring to the RMS method widely used and recommended in [7]. In the German standard [14] the analysis takes place in cycles lasting 30 seconds, and then the data from the cycles are averaged.

The last aspect related to the analysis of measurement data is the sampling frequency of the recorded signal, which according to the Nyquist [15] criterion should correspond to the principle that the highest frequency recorded in the signal \( f_N \) is half of the sampling frequency \( f_S \) (formula 1).

\[
f_N = \frac{f_S}{2}
\]  

This means that at the cut-off frequency \( f_S \) equal 120 Hz, the sampling frequency \( f_S \) should be equal 240 Hz at least. In practice, the minimum is set at 2.5 times the highest registered frequency, i.e. in the case of vibration on humans, the sampling frequency should be at least 300 Hz. The higher the \( f_S \) value is, the better is the quality of the results, but the longer the analysis time is, the greater are the hardware requirements.

5. Evaluation methods

There are three most popular evaluation methods: root-mean-squared method (RMS), vibration dose value method (VDV) and maximum transient vibration value method (MTVV). The RMS method is called “basic method” in the [8] standard, while VDV and MTVV methods are called additional methods. These two methods, especially VDV is recommended as additional methods in high crest factor value situations.

RMS method averages acceleration values in duration time:

\[
a_w = \left[ \frac{1}{T} \int_0^T a_w(t)^2 dt \right]^{\frac{1}{2}}
\]

where: \( a_w(t) \) – is weighted acceleration as a function of time [m/s\(^2\)], \( T \) – is the duration of measurement [8].

MTVV method also averages acceleration values but is more sensitive for occasional shocks and transient vibration by using a short integration time constant:

\[
a_w(t_0) = \left[ \frac{1}{\tau} \int_{t_0-\tau}^{t_0} a_w(t)^2 dt \right]^{\frac{1}{2}}
\]

\[
MTVV = \max[a_w(t_0)]
\]

where: \( \tau \) – is the integration time for running averaging, is recommended to use \( \tau = 1 \) s, \( t_0 \) – is the time of observation (instantaneous time).

VDV method is the best for peaks because it uses fourth power instead of the second power as is used in RMS and MTVV:
\[
VDV = \left[ \int_0^T a_v^4(t) dt \right]^{1/4}
\] (4)

In the measurement practice of the influence of vibrations on people, the root mean square values of the accelerations are presented in the 1/3 octave bands. As a result, information is obtained not only about exceeding the threshold values, but also about the frequency band in which this exceeded occurred. This is particularly useful at the building design stage, because you can then "tune in" the structure of the ceiling or even the building in such a way that exceedances in individual bands do not occur. RMS method seems to be the most useful method. The best additional method to assess the influence of vibrations on people in buildings, when there is a peak in the recorded signal, is the VDV method. Its sensitivity to peak values in a registered signal is due to the formula (4) from which it is determined, and in which vibration acceleration occurs in the fourth power. It seems that the procedure for determining the VDV value is similar, in essence, to the procedure used in the RMS method. The problem, however, appears at the very beginning, where after applying the appropriate correction filter; the weight functions values corresponding to the individual vibration directions should be used. In addition, there are differences in weight functions values in the same directions used in different standards. The best example is the comparison of two standards that were the first to introduce the VDV method, i.e. British standards [11] and ISO [8]. In both standards, there are differences in weight functions values in the vertical direction, while in the horizontal directions these differences are negligible.

6. Conclusions

The practical aspect of the article is the measurement and interpretation methodology which should be used in the evaluation of the influence of vibration on the people. Additional practical guidance for the vibration measurements, so that the results of the evaluation of the impact of vibrations on people are reliable, is the location of the measuring point on the floor of the room in its geometric center. The second important aspect raised in the article, especially in the context of two different evaluation methods, is the influence of the vibration duration on the evaluation results. It should be remembered that the VDV defined as a vibration exposure influences the vibration perceptibility and comfort. However, the RMS method influences the human vibration exposure only to a small extent (through the correction factor n). Hence, the influence of the length of the analyzed signal on the evaluation result carried out by both methods is significant. It seems that the range in which the acceleration amplitudes are higher than 0.2 of maximum amplitude is proper to use as the duration of vibration, although it is very restrictive.

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