Selected Issues of Measurement Methodology in the Context of Assessing the Impact of Vibrations on People in Buildings

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Abstract

Vibrations transmitted through soil into buildings have the potential to inflict structural damage or accelerate the building's degradation, while also exerting an influence on the occupants' comfort. These oscillations can elicit annoyance among building inhabitants, and in extreme cases, manifest as disturbances in sleep patterns, headaches, and even neuropsychiatric disorders. Particularly concerning are vibrations within the low-frequency spectrum, ranging from 5 to 25 Hz, as this encompasses resonant frequencies of human internal organs. Despite extensive prior research efforts and the stipulations delineated in regulatory standards, the comprehensive understanding of vibrations' impact on individuals within buildings remains elusive, primarily due to the inherently subjective nature of vibrational perception among diverse individuals. Evidenced by recent amendments in national standards and international ISO norms, ongoing adjustments underscore the evolving comprehension of this phenomenon. The article comprehensively elucidates guidelines essential for the precise execution and thorough analysis of measurements about the impact of vibrations on individuals situated within buildings that passively receive such vibrations. These recommendations encapsulate a multifaceted approach, encompassing both the requisite specifications for equipment and instrumentation as well as the judicious selection of measurement locations and the meticulous scrutiny of recorded data. A pivotal facet in the measurement methodology of vibrations' impact on individuals within buildings lies in the discerning selection of measurement point locales. Diverse standards proffer disparate directives in this regard, thereby necessitating a comparative analysis elucidated within the article. Moreover, the article delves into the intricacies of choosing the measurement range and applying corrective filters during analysis, underscoring their significance in ensuring accuracy and reliability. Nonetheless, at the core of the methodology lies the critical determination of vibration duration, an indispensable consideration for comprehensive analysis. Finally, the article addresses a crucial aspect concerning data analysis: the frequency of sampling the recorded signal, which holds profound implications for the fidelity and efficacy of subsequent analyses and interpretations. Through an exhaustive exploration of these facets, the article furnishes invaluable insights into optimizing the methodology for evaluating the impact of vibrations on individuals within built environments.

Keywords: *vibration, human perception, in-situ measurements, vibration impact on people*

1. Introduction

The propagation of ground-borne vibrations into buildings is a multi-faceted process with ramifications that extend far beyond surface-level structural concerns. While the immediate worry often revolves around the risk of physical harm and accelerated deterioration of buildings, the impact of these vibrations is profound and wide-reaching. They not only pose a threat to the structural integrity of the built environment but also significantly influence the overall habitability of these structures. This influence transcends the realm of physical repercussions, delving into the psychological and physiological well-being of the individuals who occupy these spaces. From inducing feelings of discomfort and unease to potentially affecting sleep quality and overall health, the effects of ground-borne vibrations on building occupants are diverse and profound, warranting careful attention and consideration in architectural and urban planning endeavours.

Indeed, the repercussions of such vibrations are often tangible, manifesting as heightened levels of annoyance among building occupants. In more severe cases, these vibrations can lead to a spectrum of adverse health outcomes, ranging from disruptions in sleep patterns to the onset of headaches, and in extreme cases, the manifestation of neuropsychiatric disorders [1-3]. This highlights the substantial impact of vibrations on human comfort and welfare within built environments, emphasizing the critical importance of addressing and mitigating their effects in architectural and urban design practices.

Of particular concern are vibrations within the low-frequency spectrum, typically ranging from 5 to 25 Hz. Within this frequency band, lie resonant frequencies of various human internal organs, including the heart, lungs, and brain, rendering them particularly susceptible to adverse effects [4,5]. These vibrations can penetrate deep into the body, potentially causing physiological disturbances and discomfort. The potential harm posed by these vibrations underscores the imperative of comprehensive assessment and mitigation strategies to safeguard occupants' health and well-being. Given the intricate interplay between these low-frequency vibrations and the human body's internal organs, there's a pressing need for thorough evaluation and proactive measures to minimize their impact. This involves not only identifying potential sources of vibration but also implementing effective engineering solutions and design interventions to mitigate their transmission into built environments. Additionally, raising awareness among building occupants about the potential health risks associated with low-frequency vibrations is essential, enabling them to recognize symptoms and take appropriate actions to minimize exposure. By addressing these concerns through a holistic approach that considers both structural and human factors, we can create safer and more comfortable environments for everyone.

Despite extensive historical research efforts and the establishment of regulatory standards, achieving a comprehensive understanding of vibrations' impact on building occupants has proven elusive. One of the primary challenges stems from the inherent subjectivity in the perception of vibrations among individuals. What may be tolerable to one person could be highly discomforting to another, making it challenging to establish universally applicable thresholds for acceptable vibration levels.

Furthermore, the effects of vibrations on human physiology are multifaceted and can vary depending on factors such as frequency, amplitude, duration of exposure, and individual susceptibility. While certain adverse health effects, such as headaches or sleep disturbances, may be more readily observable, the long-term consequences of chronic exposure to vibrations remain a subject of ongoing investigation.

As such, ongoing research endeavours are vital in refining our comprehension of this complex interplay between vibrations and human physiology. These efforts involve interdisciplinary collaboration between engineers, architects, psychologists, and medical professionals to elucidate the underlying mechanisms driving the physiological response to vibrations and develop more accurate predictive models.

Evidencing this ongoing refinement are the recent revisions observed in standards across various nations and within international ISO norms [6, 7]. These revisions signify a proactive approach to addressing the complexities inherent in assessing vibrations' effects on building occupants. They reflect a concerted effort among regulatory bodies, researchers, and industry professionals to adapt methodologies and guidelines in response to evolving scientific insights and empirical observations. These revisions not only aim to update existing standards but also strive to incorporate emerging research findings and technological advancements. For instance, advancements in sensor technology and computational modelling have enabled more accurate and detailed measurements of vibrations, allowing for a more nuanced understanding of their effects on human physiology. Similarly, interdisciplinary collaborations have facilitated the integration of insights from fields such as psychology and epidemiology, providing a more holistic perspective on the impact of vibrations on human health and well-being. Thus, the quest for a more nuanced understanding of vibrations' effects on building occupants remains an ongoing endeavour, guided by the imperative of ensuring the health, comfort, and safety of individuals within built environments. By continuously refining standards and methodologies, as well as fostering interdisciplinary collaboration and knowledge exchange, we can strive towards creating environments that promote optimal living conditions and enhance the quality of life for all.

2. Selection of Buildings and Measurement Point Locations

Buildings situated within zones susceptible to ground-borne vibrations, where such vibrations may adversely affect individuals, often find themselves within designated dynamic influence areas (cf. Table 1). These areas delineate regions where the interaction between ground-borne vibrations and structures is of particular concern, necessitating careful assessment and mitigation measures. However, it's crucial to recognize that the extent of dynamic influences can vary significantly due to a multitude of factors, each contributing to the complex vibrational landscape experienced by buildings. Soil conditions stand out as one of the primary factors influencing the propagation of ground-borne vibrations. Variations in soil composition, density, and geological formations can dramatically alter how vibrations travel through the ground. Loose or unconsolidated soils, for example, tend to transmit vibrations more readily than dense or compacted soils. Similarly, the presence of geological features such as rock outcrops or underground cavities can introduce additional complexities, affecting the transmission and attenuation of vibrations in unpredictable ways. Moreover, the types of passing vehicles and their characteristics play a significant role in shaping the vibrational environment. Heavy vehicles, such as trucks or buses, generate more substantial vibrations compared to lighter vehicles like cars or bicycles. The intensity of these vibrations can further vary depending on factors such as vehicle speed, road surface conditions, and traffic volume, all of which contribute to the dynamic loading experienced by nearby structures. In essence, the susceptibility of buildings to ground-borne vibrations is not solely determined by their proximity to potential sources but also by the intricate interplay of soil dynamics and vehicular activity. Understanding these multifaceted influences is essential for accurately assessing the risks posed by vibrations and implementing effective mitigation strategies to safeguard the well-being of building occupants.

In light of these considerations, the selection of appropriate buildings for vibration measurements requires a holistic approach that takes into account various factors, including local geological conditions and traffic patterns. A comprehensive understanding of these factors is crucial for accurately assessing the potential impact of ground-borne vibrations on building occupants. Firstly, a thorough geological survey of the area is essential to identify soil characteristics, geological formations, and any potential geological hazards that may influence the transmission of vibrations. This information helps in predicting how vibrations propagate through the ground and interact with structures. Similarly, an analysis of traffic conditions is indispensable for evaluating the magnitude and frequency of vibrations generated by passing vehicles. Factors such as the volume of traffic, vehicle types, road surface conditions, and speed profiles can all influence the vibrational environment experienced by nearby buildings. This data aids in identifying areas where vibrations are likely to be most significant and where measurement efforts should be prioritized. Furthermore, when conducting vibration measurements, careful consideration must be given to the placement of measurement points within selected buildings. Ideally, measurement points should be strategically positioned to capture representative data that accurately reflects the prevailing vibrational environment. This may involve placing sensors at different heights and locations within the building to account for variations in vibration intensity and distribution. Additionally, the duration of measurements is important to capture variations in vibration levels over time, including fluctuations due to changes in traffic patterns or other external factors. Long-term monitoring can provide valuable insights into seasonal or temporal trends in vibration exposure, helping to refine risk assessments and mitigation strategies. By integrating information on local geological and traffic conditions and employing appropriate measurement techniques, researchers and engineers can enhance the accuracy of vibration assessments and better protect building occupants from potential health risks associated with ground-borne vibrations.

Tab. 1. The scope of dynamic influence zones.

Source of vibration	Range [m]	Source of vibration
Railway	25-50	Railway
Road, tramway	15-25	Road, tramway
Shallow underground	40	Shallow underground

The selection of measurement point locations represents a pivotal consideration in the comprehensive assessment of vibrations' impact on individuals within buildings. This aspect is underscored by the nuanced variations in regulatory provisions across different jurisdictions, necessitating a meticulous examination of pertinent standards. Within the framework of ISO standards, for instance, delineations regarding the measurement of vibrations transmitted to the human body exhibit a degree of ambiguity. ISO standard [6] stipulates measurements should be taken at the surface interface between the body and the adjacent surface. However, such a directive lacks precision in its definition, prompting the need for further elucidation. In contrast, ISO standard [8] provides a more refined specification, advocating for measurements to be conducted at the centre of rigid surfaces, typically within a proximity not exceeding 10 cm from the centroid. This delineation emanates from the broader scope of ISO standard [9], which predominantly addresses vibrations of a generalized nature. Despite serving as a foundational reference, the prescriptive clarity of ISO standards is subject to interpretation, necessitating scrutiny. Conversely, the British standard [10] adopts a somewhat divergent approach, advocating for measurement points to be positioned at the centre of a room. However, the extent of the zone where vibration impact measurements can be conducted is delineated, spanning from 1/3 to 2/3 of the length or width of the ceiling. Such provisions reflect a nuanced perspective that accounts for spatial considerations within the built environment. The Polish standard [11], on the other hand, advocates for measurement points to be located within at least one room on the highest floor, in proximity to the source of excitation. The stipulation regarding the placement of the measurement point at the centre of the room is contingent upon the absence of compelling reasons for an alternative location, such as unconventional structural configurations of the ceiling. Upon closer examination, the provisions outlined in the Polish standard exhibit a conservative inclination, prioritizing precautionary measures. Conversely, the requirements articulated in the British standard warrant further scrutiny to ascertain their efficacy and applicability within diverse environmental contexts. Thus, a nuanced understanding of these regulatory nuances is imperative to ensure the robustness and reliability of vibration impact assessments within built environments.

3. Selection of Appropriate Measurement Equipment

During measurements, displacements, velocities, and accelerations of vibrations can be recorded. Accelerations of vibrations are most commonly recorded nowadays, as this parameter allows for an easy assessment of the impact of vibrations on people. During measurements, it is also important to use devices that enable accurate signal recording from as low as 1 Hz, or even below this value. Although in most cases, the vertical direction plays a decisive role, measurements should be conducted simultaneously in three orthogonal directions: the "x" direction is assumed in all measurements to be perpendicular to the excitation, the "y" direction is parallel, and the "z" direction is vertical. According to standard [11], the use of a measurement disc is recommended, which should have a mass of at least 30 kg and a diameter of 30 cm (Fig. 1).

Fig. 1. Measurement disc.

4. Signal Recording and Analysis

The signal recording should cover frequencies ranging from 1 to 120 Hz so that after applying a low-pass filter, frequencies up to 80 Hz can be included in the assessment. Another aspect is the duration of vibrations, which, according to [11], falls within the range where the amplitude value of vibration acceleration does not drop below 0.2 times the maximum amplitude value in the recorded waveform (Fig. 2).

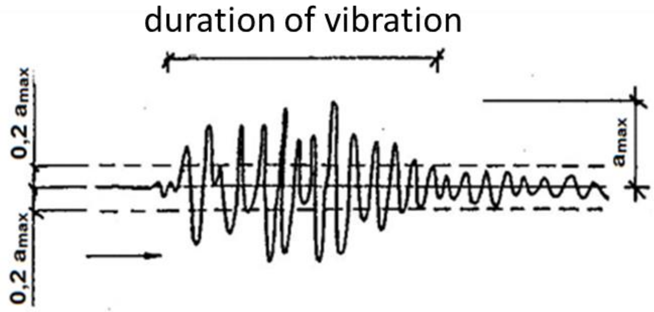

Fig. 2. Illustration of vibration duration

The ISO standard [9], primarily used for general vibration measurements, requires the signal recording time to be at least 30 minutes. The standard [7] refers to the duration of vibrations, stating that the recorded signal should be sufficient to ensure reasonable statistical accuracy. This definition is broad and imprecise, and the duration of vibrations significantly influences the results of signal analysis, especially concerning the widely used and recommended RMS method [7]. In the German standard [12], analysis is conducted in cycles lasting 30 seconds, after which data from the cycles are averaged.

$$f_N = \frac{f_S}{2} \tag{1}$$

This means that with a cutoff frequency fN equal to 120 Hz, the sampling frequency fS should be at least 240 Hz. In practice, the minimum value is set at 2.5 times the highest recorded frequency, i.e., in the case of human vibrations, the sampling frequency should be at least 300 Hz. The higher the value of fS, the better the quality of the results, but at the same time, the analysis time is longer and there are greater hardware requirements.

5. Methods of Assessment

There are three most popular methods for assessing the impact of vibrations on people in buildings: the root mean square method (RMS), the vibration dose value method (VDV), and the maximum transient vibration value method (MTVV). The RMS method is referred to as the "basic method" in standard [9], while the VDV and MTVV methods are referred to as additional methods. These two methods, especially VDV, are recommended as supplementary methods in situations with high peak factor values.

The RMS method averages the acceleration values throughout the vibrations:

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

In this equation:
aw(t)- represents the weighted value of vibration acceleration as a function of time [m/s²],
T - denotes the measurement time [s].

The MTVV method also averages the acceleration values but is more sensitive to occasional shocks and transient vibrations due to the use of a short integration time constant.

$$a_w(t_0) = \left[\frac{1}{\tau} \int_{t_0-\tau}^{t_0} a_w^2(t)dt \right]^{\frac{1}{2}} \tag{3a}$$

$$MTVV = \max[a_w(t_0)] \tag{3b}$$

In this equation:
τ - represents the integration time constant, where using = 1
τ=1 s is recommended,
t0 - denotes the observation time (instantaneous time).

The VDV method is best suited for situations where peaks occur in the recorded signal, as it utilizes the fourth power instead of averaging, as used in RMS and MTVV.

$$VDV = \left[\int_0^T a_w^4(t)dt \right]^{\frac{1}{4}} \tag{4}$$

In practical vibration impact measurements on people, the average vibration accelerations are presented in 1/3-octave bands. As a result, information is obtained not only about threshold exceedances but also about the frequency band in which the exceedance occurred. This is particularly useful during the building design phase, as it allows for fine-tuning the floor or even the entire building structure to prevent exceedances in specific frequency bands. The RMS method appears to be the most useful. The best additional method for assessing the impact of vibrations on people in buildings, especially when peaks are present in the recorded signal, is the VDV method. Its sensitivity to peak values in the recorded signal arises from equation (4), which determines it, and in which vibration acceleration appears to the fourth power. The procedure for determining VDV values seems fundamentally similar to the procedure used in the RMS method. However, the problem arises at the very beginning when, after applying the appropriate correction filter, the values of weighting functions corresponding to the individual vibration directions must be applied. Additionally, there are differences in the weighting function values for the same directions in different standards. A prime example is the comparison of two standards that first introduced the VDV method, namely the British standard [10] and ISO [9]. In both standards, differences in weighting function values are observed in the vertical direction, while these differences are insignificant in the horizontal direction.

6. Conclusion

From the article, the following conclusions can be drawn:

- The measurement-interpretation methodology is a key aspect of the article in assessing the impact of vibrations on people in buildings. This methodology outlines the procedures and approaches necessary for accurately evaluating the effects of vibrations on building occupants.
- Locating the measurement point on the ceiling of the room at its center is a practical guideline to ensure reliable results in assessing the impact of vibrations on people. Placing the sensor in this position helps capture a representative measure of the vibrations experienced throughout the room, leading to more accurate assessments.
- The duration of vibrations significantly influences the assessment results, especially concerning two different assessment methods. Understanding how the duration of vibrations affects the outcomes of vibration assessment is crucial for interpreting the results accurately and implementing appropriate mitigation measures.
- The VDV method incorporates vibration intensity directly by using the fourth power in its formula, while the RMS method accounts for vibration intensity through the correction factor n. Therefore, the length of the analyzed signal has a substantial impact on the assessment results obtained using both methods.
- The range where acceleration amplitudes exceed 0.2 times the maximum amplitude may serve as a suitable measure of vibration duration, although this approach is stringent. Understanding the significance of this threshold aids in selecting an appropriate duration for vibration assessment and ensuring the accuracy of the evaluation process.

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