DOI: 10.61782/fa.2023.1011

THE DESIGN OF AN IMPACT SOUND VIBRATION EXPOSURE DEVICE

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ABSTRACT

Studies on the perception of impact sound in the context of the single-number ratings of floors have exposed the importance of the low-frequency components in perceived annoyance. It is also known that low-frequencies are perceived as auditory stimuli, but also as whole-body vibrations. Nevertheless, the importance of each type of stimulus for impact sounds in the built environment is not known. To better understand this perspective, a vibration exposure device is being developed. The device will be used to accurately reproduce vibrations from field measurements so that subjects can be exposed to vibrations generated by impact sound sources in various building types under laboratory conditions. An overview of the vibration exposure device design is given, including some relevant technical solutions and details. In addition, the calibration principle of the vibration exposure device is presented.

Keywords: *impact sound, vibrations in buildings, vibration perception*

1. INTRODUCTION

Vibrations in the built environment can be caused by a variety of sources, including machinery, human activity, and natural phenomena such as wind, and are an important factor to consider in the structural design of buildings [1]. In fact, vibrations in buildings can be excessive for the use of sensitive equipment and can also have various negative effects on users [2], causing discomfort and even motion sickness. For tall buildings, it can be difficult to mitigate vibrations [3]. Lighter structures such as tall timber buildings present a particular challenge [4], as excessive vibration can cause safety and serviceability issues in the event of wind or earthquake loads.

The focus of our research is on vibrations in buildings generated by impact sound sources, which, although not a safety problem for the building, are known to cause annoyance to its users [5]. It is important to point out that the annoyance caused by impact sound has already been studied through various listening tests [6], but no studies have focused on the perception of impact sound as vibrations. Investigating this aspect is important because it is part of our everyday experience that impact sound can also be perceived in this way.

The current status of the development of the vibration exposure device (VED) is presented. The device will be installed in the anehoic chamber of the InnoRenew CoE Acoustics Laboratory and will allow vibrations from field measurements to be accurately reproduced under laboratory conditions. The vibrations will be reproduced along with the sound field, which will also be captured by field recordings. The VED will allow test subjects to be simultaneously exposed to vibrations and sounds generated by impact sound sources, and thus evaluate their perceptual preferences, psychological responses, and physiological reactions.

2. PERCEPTION OF VIBRATIONS AND LOW-FREQUENCY SOUND

The main mechanism for exposing a person to vibrations is trough physical contact with a vibrating surface [1] .

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[1] In addition, sound at low frequencies can also generate vibrations in the human body [7] However, this mechanism is only relevant for sounds with high intensity, which is not the case for

Therefore, vibrations in the built environment are also assessed by acceleration measurements on different surfaces that characterize the position of the users (sitting, standing, lying down) [8]. In addition, sensitivity to vibrations in different directions is considered in terms of frequency weightings [2]. These are defined in the low frequency range, i.e. below 100 Hz, where human sensitivity to vibrations is highest.

Various studies [6] have shown that sound in frequencies down to 50 Hz is relevant to the subjective response to impact sound. Öqvist et al. [9] has even demonstrated that frequencies down to 20 Hz should be considered when evaluating lightweight structures. In fact, the correlation between the subjective response and the flat frequency-weighted SNQ has improved under such conditions.

An important aspect to consider in this context is the peculiarities of our hearing at low-frequencies and infrasound [10]. Whittle et al. [11] studied the audibility of tones down to 3.15 Hz and found that the hearing threshold increases inversely with frequency, reaching 120 dB at 3.15 Hz. Similarly, for the same frequency range, Møller [12] has shown in the form of equal annoyance curves that our sensitivity to low-frequency sounds decreases substantially at lower frequencies. The review article on low-frequency noise by Leventhall [13] also directly raised the question of whether the ear is the most sensitive receptor for low-frequency sound in the body. It is in this context surprising that none of the previous studies evaluating annoyance from impact sound [6] also included the perception of vibrations.

In the case of the vibration exposure device, test subjects will be exposed to vibrations in combination with the auditory stimuli. The effect of such combined stimulation has already been studied, but to our knowledge not for the case of impact sound. Moreover, the combined effect of the two stimuli is not straight forward to interpret, as the reviews of previous studies targeting this subject point out [14, 15].

3. THE DESIGN OF THE VIBRATION EXPOSURE DEVICE

Devices that expose test subjects to vibrations have already been developed in the form of differently shaped platforms and seats. Such devices were called vibration tables [16], vibration simulators [17], and vibration machines [18]. A recently built and large-scale device is the VSimulators at the University of Exeter [19]. It is capable of reproducing vibrations on a 3.7 m×3.7 m motion platform in six axes in the frequency range of 0.5 - 40 Hz with a maximum displacement of ±21 mm.

Such platforms are an important infrastructure to evaluate the effect of vibrations on humans in different scenarios. However, to accurately reproduce impact sound, which is a relatively weak stimulus, such devices can be noisy due to the hydraulic system that sets them in motion. In addition, the relatively large and rigid floor limits the ability to accurately reproduce the sound field by restricting the positioning of loudspeakers and elements of room acoustic treatment in the room.

Our motivation, then,was to build a device that would allow a single person to place his or her head in the center of the spherically arranged higher-order ambisonics reproduction system, which consists of 64 loudspeakers and a dedicated low frequency driver. The entire system is located in the anechoic chamber of the InnoRenew CoE's

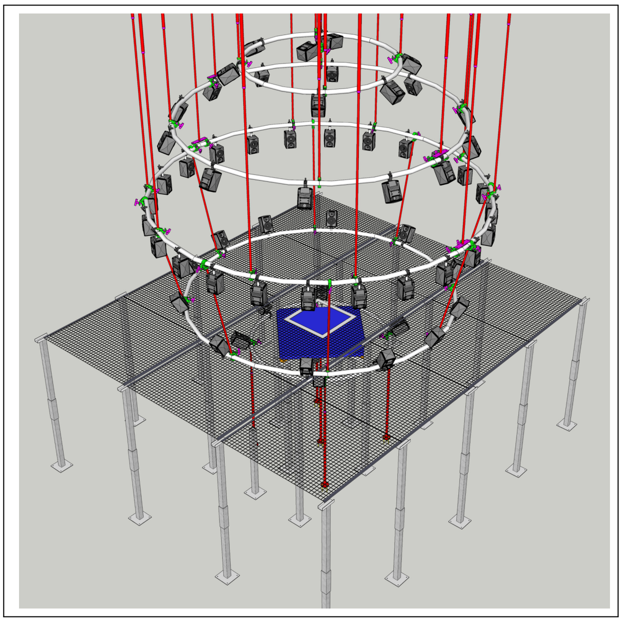

Figure 1. A 3D representation of the positioning of the vibration exposure device (VED) in the central position of the ambisonics reproduction system. The horizontal grid represents the anechoic chamber's sound transparent secondary floor, while the rectangular blue board in the center represents the platform part of the VED.

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impact sound in buildings.

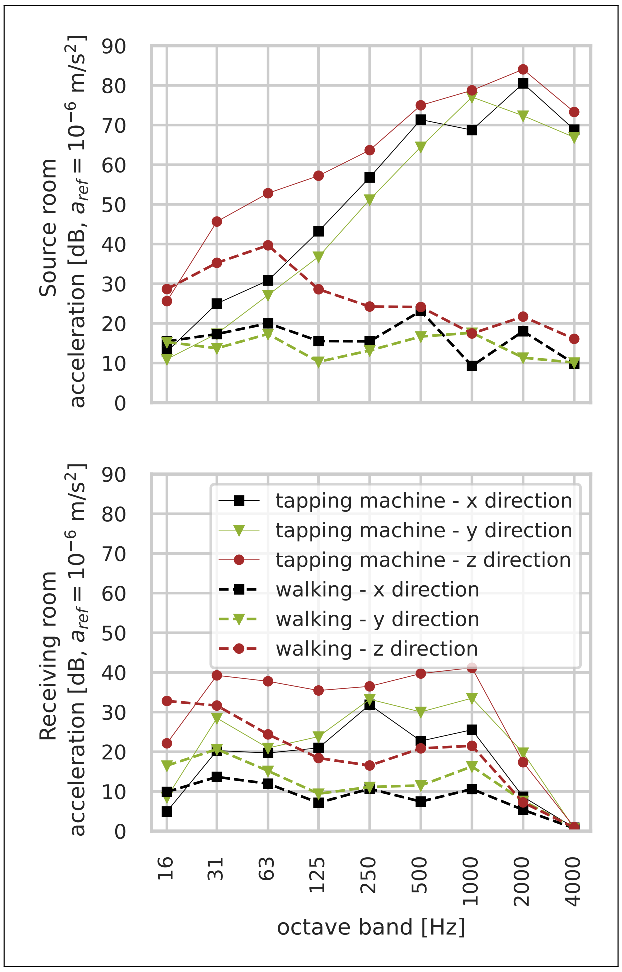

Figure 2. The octave band spectrum of acceleration recorded on the floor of a InnoRenew CoE wooden building as produced by the standardized tapping machine and by walking. The recordings from the source and receiving rooms are shown separately in the top and bottom graphs. For the frequency range below 100 Hz, the vibrations in the vertical (z) direction are at least 10 dB higher than those in the horizontal direction (x and y).

acoustics lab, with an acoustically transparent and flexible secondary floor under which some of the loudspeakers are also installed. In the middle of it is installed a 1 m×1 m rigid platform, as shown in the 3D model in Figure 1.

The VED will only reproduce vibrations in the vertical direction, since these are predominantly generated by impact sources. This conclusion was drawn on the basis of several field measurements in wooden buildings, where the spectrum of acceleration was determined. An example of a particular measuremtn conducted in the InnoRrenew CoE building is shown in Figure 2.

A commercially available linear motion transducer is installed on the underside of the VED platform. Such devices are commonly used in advanced sound reproduction systems for cinemas and computer games to extend the perception of low frequencies by adding vibrations. Thus, these vibration transducers are not intended to reproduce vibrations accurately, but rather to convey an arbitrary intensity of vibrations to the user. For this reason, a calibration procedure is required to use the device in a highly controlled manner (see section 5).

4. TECHNICAL ASPECTS OF THE VED DESIGN

The VED is designed as a rectangular platform (wooden board) supported at its four corners. These rest on highly elastic pads to create a mass-spring system whose resonant frequency is shifted below the frequency range in which the vibrations are to be reproduced. In this context, the frequency range of 10 to 30 Hz is set as the target operating frequency of the VED.

The resonant frequency of such a system varies with its load, which depends mainly on the weight of the test subject. To accommodate a wide range of test subjects, preliminary frequency response measurements were conducted using various loads on the platform, with the accelerator positioned in the center of the platform (see Figure 3).

The acquired frequency responses are shown in Figure 4. From these it can be seen that the addition of weight produces the expected decrease of the resonant frequency and a general reduction in the magnitude of the platform excitation. In general, the resonant frequencies are 8 Hz and below and it appears that a signal correction in the range of +/- 10 dB will be needed to uniformly reproduce vibrations in the frequency range of 10-25 Hz.

As part of the future design, we will stiffen the platform by thickening the wooden board composing it. In this way, we will shift the system resonances associated with the bending modes of the platform to a higher frequency. In fact, the dip in frequency response observed at 30 Hz is most likely due to such an effect. With such an improvement, we expect an increase of the upper operating frequency of the VED to 40 Hz.

Another design decision was to load the board only

Figure 3. Photos of the loading of the platform (not yet installed in the anechoic chamber) during the preliminary frequency response measurements at a load of 45 kg (top) and 90 kg (bottom).

in its central part to avoid excessive loading of individual elastic pads, which could lead to non-elastic responses or damage. This is achieved in practice by restricting user access to the central part of the platform, as can be see in the 3D model in Figure 1.

5. VED CALIBRATION

The vibration excitation signal $x(t)$ is reproduced as an additional audio track to tracks feed to the loudspeaker system. This enables a synchronous reproduction of both stimuli which is an important requirement for the reproduction. The vibration excitation signal output from the audio interface is then fed into the power amplifier that drives the vibration transducer. In parallel, this signal is fed into the B&K LAN-XI acquisition system, which records it together the acceleration $a(t)$ detected by an accelerometer mounted on the underside of the platform. The two signals are recorded via a self-developed Python script that uses Open-API to interface with the LAN-XI acquisition system. By recording the excitation signal and the generated acceleration on the platform, the frequency response of the system can be calculated as follows

$$H(f) = \frac{A(f)}{X(f)}, \tag{1}$$

in which A(f) and X(f) are Fourier transforms of the signals a(t) and x(t), where f stands for the frequency.

Before the start of each listening test, a calibration is performed to measure the frequency response of the VED loaded by each individual test subject. For this purpose, a frequency sweep signal of a few seconds is reproduced by the VED and, based on the acquired frequency response, a correction filter is generated in the form of a FIR filter [20]. The coefficients of the FIR filter are automatically loaded into the convolution plugin, which is applied to the vibration excitation signal track. With the application of this filter, the system is calibrated, i.e. the vibrations are reproduced with the required intensity in the required frequency range for each specific load of the VED.

In addition to calibration, the performance of the VED is continuously monitored during listening tests. In fact, the frequency response of the system can be estimated as long as the excitation signal contains sufficient energy in the frequency range of interest. For this purpose, the reproduced impulse sound stimuli are used.

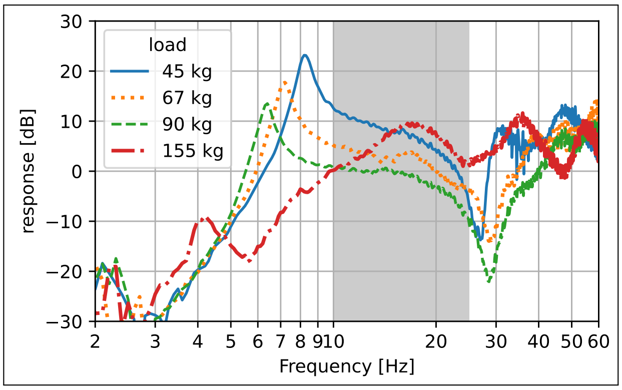

Figure 4. Measured frequency responses of the VED at four different load conditions. The gray area represents the relatively flat frequency range in which the VED will be used.

6. CONCLUSIONS

The importance of vibrations in the built environment have been discussed, along with our current understanding of the perception of low-frequency sounds and infrasound. This explains the motivation to study vibrations in buildings generated by impact sound, which are particularly important in lighter structures such as wooden buildings. In this context, vibrations in the vertical direction are dominant and need to be studied.

For such investigations, the vibration exposure device (VED) will be used as an extension of the higher order ambisionics reproduction system installed in the anechoic chamber of the InnoRenew CoE Acoustics Laboratory. The device consists of a platform on which the standing or seated subject is exposed to the vibrations. The listener's head position is in the center of the spherically arranged loudspeaker array, which allows simultaneous reproduction of sound and vibrations as recorded during field measurements.

Several technical aspects of the design were presented, including the expected operating frequency range of the VED, which is between 10 and 25 Hz. The calibration of the device, which is required to compensate for the different loading of the device by different test subjects, was also explained from a signal processing perspective.

As part of the next steps of the project, the VED will be installed in the anechoic chamber. In addition, some improvements will be made, mainly aimed at extending the operating frequency range of the VED.

7. ACKNOWLEDGMENTS

The authors gratefully acknowledges the European Commission for funding the InnoRenew project (grant agreement #739574) under the Horizon2020 Widespread-Teaming program and the Republic of Slovenia (investment funding from the Republic of Slovenia and the European Union from the European Regional Development Fund). The authors acknowledge the financial support from the Slovenian Research Agency (research core funding No. J4-3087, Engineered wood composites with enhanced impact sound insulation performance to improve human well being (IRIS), and research core funding No. Z1-4388, Toward better understanding the diffuse sound field).

8. REFERENCES

[1] "ISO - ISO 10137:2007 - Bases for design of structures - Serviceability of buildings and walkways against vibrations."

[2] M. J. Griffin, *Chapter 29 Effects of Vibration on People*. 2007.

[3] M. Jafari and A. Alipour, "Methodologies to mitigate wind-induced vibration of tall buildings: A state-of-the-art review," *Journal of Building Engineering*, vol. 33, p. 101582, 1 2021.

[4] S. Chapain and A. M. Aly, "Vibration attenuation in a high-rise hybrid-timber building: A comparative study," *Applied Sciences*, vol. 13, p. 2230, 2 2023.

[5] S. H. Park and P. J. Lee, "Effects of floor impact noise on psychophysiological responses," *Building and Environment*, vol. 116, pp. 173–181, 5 2017.

[6] N. G. Vardaxis and D. Bard, "Review of acoustic comfort evaluation in dwellings: part ii—impact sound data associated with subjective responses in laboratory tests," 2018.

[7] S. D. Smith, "Characterizing the effects of airborne vibration on human body vibration response," *Aviation Space and Environmental Medicine*, vol. 73, 2002.

[8] "ISO - ISO 2631-2:2003 - Mechanical vibration and shock — Evaluation of human exposure to whole-body vibration — Part 2: Vibration in buildings (1 Hz to 80 Hz)."

[9] R. Öqvist, F. Ljunggren, and R. Johnsson, "Walking sound annoyance vs. impact sound insulation from 20hz," *Applied Acoustics*, vol. 135, pp. 1–7, 6 2018.

[10] N. Broner, "Effects of infrasound, low-frequency noise, and ultrasound on people," 2008.

[11] L. S. Whittle, S. J. Collins, and D. W. Robinson, "The audibility of low-frequency sounds," *Journal of Sound and Vibration*, vol. 21, 1972.

[12] H. Møller, "Annoyance of audible infrasound," *Journal of Low Frequency Noise, Vibration and Active Control*, vol. 6, pp. 1–17, 3 1987.

[13] G. Leventhall, "Low frequency noise. what we know, what we do not know, and what we would like to know," 2009.

[14] J. K. Ljungberg, “Combined exposures of noise and whole-body vibration and the effects on psychological responses, a review,” 2008.

[15] J. K. Ljungberg and F. B. Parmentier, “Psychological effects of combined noise and whole-body vibration: A review and avenues for future research,” *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 224, 2010.

[16] T. Miwa, “Evaluation methods for vibration effect,” *Industrial Health*, vol. 5, 1967.

[17] A. G. Woods, “Human response to low frequency sinusoidal and random vibration: A description of a series of tests made with a vibration simulator to evaluate the effect of vibration on task performance,” 1967.

[18] A. Meisthr, D. B. Uer, N. N. Kurerov, A. M. Metz, R. Mucke, R. Rothe, H. Seidel, I. A. Starozuki, and G. A. Uvorov, “Evaluation of responses to broad-band whole-body vibration,” *Ergonomics*, vol. 27, 1984.

[19] “University of Exeter - VSimulator - https://vsimulators.co.uk (visited 12.5.2023).”

[20] J. G. Proakis and D. G. Manolakis, *Digital Signal Processing*. Pearson Prentice Hall, 2007.