Perception of Structure-Borne Sound in Buildings in Context of Vibration Comfort of Human in the Buildings

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Abstract. Structure-borne noise is an extremely complex issue considering comfort of room users. The purpose of this work is to focus on the impact of vibration on humans in building together with the structure-borne noise generated by vibrating partitions of the room. Radiation of noise from vibrating partitions creates structure-borne noise, which is an additional stimulus, in addition to mechanical vibration of the floor. This means it may result in reduced comfort. Based on the review of current knowledge, it can be concluded that the perception of two simultaneous stimuli causes more annoyance than considering stimuli separately. Considering the fact that vibrations and structure-borne noise, due to the mechanics of the phenomenon, usually occur together, it is necessary to analyse the existing comfort assessment criteria. In addition, validity of given existing criteria has to be verified in the light of the phenomenon of structure-borne noise. This task was carried out using models with different approaches to the phenomenon. Basing on the given values of accelerations or velocities of floor two models were created. First model consists of single vibrating plate, with known vibration velocity. Vibrating plate radiates sound inside the modelled room. Sound pressure level was estimated using simple theoretical formulas present in literature. Second model is prepared as 3D FEM model with shell elements surrounding the room. Air was modelled inside room with 3D elements. Sound pressure level was calculated from simulations. The work aimed at determining the legitimacy of the assumption in the Polish standard PN-B-02171:2017 of mechanical vibration perception threshold and the admissible values determining mechanical vibrations.

1. Introduction
Structure-borne noise in buildings is important aspect for building residents. Importance of this phenomenon stems from its mechanics. Vibrating surfaces of given room – walls, floors, façade – radiate sound into considered room [1]. Vibrating floor has to be considered in terms of vibration comfort using vibration dose value (VDV), weighted RMS acceleration or maximum transient vibration value (MTVV) [2] [3] [4]. Space inside the room also has to be evaluated using acoustical criterion of sound level with various time steps or evaluation periods [5] [6] [7].

In work [8] considering two stimuli exposure consisting of noise and vibration subsequent tests considering this problem were summarized [9], [10], [11], [12], [13]. The work [8] presents the study carried out to determine the method of predicting a subjective response to simultaneously occurring noise and vibrations in buildings near the railway. For purpose of this article, effects of laboratory tests and its conclusions were applied to performed analysis in this article.

The analyzed room is the room with floor dimensions of 4 x 3m with the room height of 2.7m. The reverberation time of the room was assumed to be 0.6s for each of the analyzed 1/3rd octave bands performed in simplified method of sound radiation coefficient. The walls of the room are made of gypsum-plasterboard walls made of double board 2 x 12.5mm, and the floors are made of reinforced
concrete 250mm thick. One of the vertical partitions of the room is the glazing of the facade along the shorter side of the room made of 4mm thick glass.

Criteria of mechanical vibration and noise level used in this article to perform analysis are listed in Table 1.

| Centre frequency of the band $f$, Hz | Root mean square (RMS) value of vibration velocity $v_z$, ms$^{-1}$, perception threshold in direction $x \times y$ | Sound pressure level of hearing threshold based on A-weighting $[14]$ |
|-------------------------------------|-------------------------------------------------|--------------------------------------------------|
| 1.0                                 | 0.00159                                          | 0.00057                                          | 148.6                                           |
| 1.25                                | 0.00113                                          | 0.00045                                          | 140.8                                           |
| 1.6                                 | 0.00079                                          | 0.00036                                          | 132.3                                           |
| 2.0                                 | 0.00056                                          | 0.00028                                          | 124.6                                           |
| 2.5                                 | 0.0004                                          | 0.00028                                          | 116.9                                           |
| 3.16                                | 0.00029                                          | 0.00028                                          | 108.9                                           |
| 4.0                                 | 0.0002                                           | 0.00028                                          | 100.7                                           |
| 5.0                                 | 0.00016                                          | 0.00028                                          | 93.1                                            |
| 6.3                                 | 0.00013                                          | 0.00028                                          | 85.4                                            |
| 8.0                                 | 0.0001                                           | 0.00028                                          | 77.8                                            |
| 10.0                                | 0.0001                                           | 0.00028                                          | 70.4                                            |
| 12.5                                | 0.0001                                           | 0.00028                                          | 63.4                                            |
| 16.0                                | 0.0001                                           | 0.00028                                          | 56.7                                            |
| 20.0                                | 0.0001                                           | 0.00028                                          | 50.5                                            |
| 25.0                                | 0.0001                                           | 0.00028                                          | 44.7                                            |
| 31.6                                | 0.0001                                           | 0.00028                                          | 39.4                                            |
| 40.0                                | 0.0001                                           | 0.00028                                          | 34.6                                            |
| 50.0                                | 0.0001                                           | 0.00028                                          | 30.2                                            |
| 63.0                                | 0.0001                                           | 0.00028                                          | 26.2                                            |
| 80.0                                | 0.0001                                           | 0.00028                                          | 22.5                                            |
| Corrected RMS value of vibration velocity $v_z$, ms$^{-1}$ | 0.0001                                           | 0.0029                                          | Sound level of single band equal to 0dBA        |

Detailed criteria for chosen types of rooms used in further analysis are listed in Table 2.

In general, both stimuli – mechanical vibration of floors and noise level in room – are evaluated separately. The same case is when mechanical vibrations exceed permissible values. Polish standard [4] British standard [15] and international standard [2] in common use consider vibrational comfort only. Similar case is when evaluating acoustical comfort with sound level [7]. Of course if sound (even structure-borne) exceeds acceptable values it means that exists relatively high probability of adverse effects on health of residents. Good example is Norwegian standard [6], where there is a method of evaluation low frequency structure-borne noise. Still this standard emphasize noise as the harmful one stimulus. There is a problem of simultaneous perception of stimuli which is not considered in building design and in standards. It is worth mentioning that in scientific literature this problem exist and was analyzed only in some aspects [16], [17].
Table 2. Mechanical vibration multipliers [4] and sound level curve shift [7] in relation to the room function.

| Room function                        | Vibration velocity multiplier for vibration perception threshold, to create criterion for different room functions, [-] | Curve shift of sound level perception threshold to create criterion for different room functions, [db] |
|--------------------------------------|---------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------|
| Living room daytime                  | 4                                                                                                             | 20                                                                                                       |
| Living room nighttime                | 1.4                                                               | 15                                                                                                       |
| Office                               | 4                                                                                                             | 20                                                                                                       |
| Operating theatre in hospital        | 1                                                                                                             | 20                                                                                                       |

In further analysis living room in daytime will be omitted due to fact that it equals to office room.

2. Methodology of calculations

In order to perform noise/vibration criteria analysis, following assumptions were made:

- Basing on vibration perception threshold given in [4], ratio between vibration acceleration and velocity was determined as shown in Figure 1. This ratio is assumed to enable recalculation of vibration velocities to accelerations.

![Figure 1. Ratio between vibration acceleration and velocity (based on [4]).](image)

- In order to recalculate weighted vibration accelerations RMS to VDV values following scenario was assumed: the crest factor of excitation is below 6.0, signal is harmonic with given frequency, excitation lasts 10[s]. Values of frequency weighting are taken from [15]. Vibration acceleration signal is represented by pure sine wave with center frequency of analyzed 1/3rd octave band to give acceleration RMS value equal to those listed in Table 1.
- Vibration velocity can be recalculated to sound level in room using formulas (1) and (2).
- Sound power is reduced by factor 4 due to non-uniform radiating surface velocities
- The only surface vibration in room is the floor with dimensions of 4 x 3m.
- Frequency of analysis is limited to 16Hz (hearing threshold frequency) to 80Hz of octave bands (maximal frequency band to analyze vibrational comfort).
\[ W = \rho_0 c_0 S \langle \tilde{v}^2 \rangle \sigma \]  

(1)

Where \( W \) – sound power \([W]\), \( \rho_0 \) – air density \([kg/m^3]\), \( c_0 \) – longitudinal wave propagation velocity in air \([m/s]\), \( S \) – surface area of vibrating plate, \([m^2]\), \( \langle \tilde{v}^2 \rangle \) – time- and space-averaged square of velocity of vibrations of the partition \((m/s)^2\), \( \sigma \) – radiation efficiency factor [-], calculated using exact method ([18], [19] and [20]).

\[ L_p = 10 \log_{10} \frac{W}{W_0} - 10 \log \frac{A}{4}, \ W_0 = 10^{-12}[W], \ A = 1.161 \frac{V}{RT} \]  

(2)

Where \( A \) – of the acoustic absorption of the room \([m^2]\), \( V \) – room volume \([m^3]\), RT – room reverberation time \([s]\).

For 3D MES model, all above assumptions, with exclusion of assumptions connected with formulas (1) and (2) and reverberation time, are applied.

Mesh size limit was set to 32cm to provide at least quarter of wavelength of bending wave in room partition in analyzed frequency range – from 16Hz to 80Hz 1/3rd octave frequency bands. Quadrilateral mesh elements were used for proper convergence and stable results. Application of acceleration perception threshold (see Table 1) was made at the center of floor at the area of 5x5cm rectangle. Application of predefined acceleration spectrum as a point boundary condition was not able due to high risk of singularity occurrence nearby point with this boundary condition. Room was supported with pin supports at each edge of upper and lower floor. To simplify only isotropic structural loss factor was considered as damping. In Figure 2 axonometric view of FE model was presented.

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**Figure 2.** Axonometric view 3D FEM model of analyzed room with quadrilateral mesh elements

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3. **Comparison between two methods of sound level calculation**

Below in Figure 3 are presented results of sound level originating from vibrating floor. Example of results consist of sound level envelope discussed in this article obtained from two methods of
calculation. As an example results with vibration multiplier equal 1 (room function – operating theatre, see Table 2). Comparison between two methods of calculation were done.

![Figure 3](image3.png)

**Figure 3.** Sound pressure level resulting from vibrating floor using two different methods.

Method which use simple formulas (1) and (2) to estimate sound pressure level in room gives higher values in general. Only 63Hz frequency band with 4.9dB difference and slightly 80Hz with 1.2dB difference show opposite behavior. In further analysis envelope of obtained results (see Figure 3) from methods using formulas (1) and (2) and FEM are taken into account.

4. **Proposed two-stimuli evaluation method**

To provide answers about two-stimuli exposure and response in context of comfort of human individual, based on work of [8]. Authors used $\psi$ as notation for overall annoyance. Limits of analyzed values in [8] were for SEL 50dBA to 75dBA and for VDV 0.06ms$^{-1.75}$ to 0.50ms$^{-1.75}$. For this article it was decided to extend given limits. Following interpretation of this work [8] was presented in Figure 4 and Figure 5.

![Figure 4](image4.png)

**Figure 4.** Magnitude estimates of relative annoyance of SEL (pure noise) given with formula (3) and VDV (pure vibration) given with formula (4). [8]
Formulas (3) and (4) were obtained basing on laboratory test performed on ten men and ten women between 21 and 61 years of age. Both formulas (3) and (4) were estimated using linear regression. The correlation coefficient for formula (3) was very high (r=0.917) and result were highly significant (p<0.005). For formula (4) similar correlation coefficient with laboratory test results was calculated (r=0.973) with high significant results (p<0.005).

\[
\psi = 10^{0.036 \cdot SEL - 0.512}
\]  
(3)

\[
\psi = 10^{1.18 \log_{10} VDV + 2.57}
\]  
(4)

The summation of noise and vibration annoyance based on laboratory test results [8] was presented in Figure 5.

![Figure 5. Magnitude estimates of total annoyance by exposure to sound (SEL) and vibration (VDV) described by formula (5). [8]](image)

Formula (5) was evaluated by multiple regression analysis of magnitude estimates on two variables representing noise and vibration. The correlation coefficient was high (r=0.958) and results were highly significant (p<0.005).

\[
\psi = 22.7 + 243 \cdot VDV^{1.18} + 0.256 \cdot 10^{0.036 \cdot SEL}
\]  
(5)

As it was shown in this chapter, formulas (3), (4) and (5), give good estimation of median magnitude of human annoyance. Thus these formulas will be used for further analysis in this article.

5. Theoretical verification of existing criteria

In order to check if proposed criterion may be useful in comfort evaluation, the method of estimation sound level in room from vibrating plate will be used with correction of sound level in 63Hz and 80Hz 1/3rd octave band. This correction is applied from the envelope obtained from comparison between vibrating plate method with 3D FEM model.
It was decided to check the existing criteria for chosen room types, taken into consideration in this article, using earlier assumptions and the following method:

- Assume proper vibration velocity (for vibrating plate model) or acceleration (for 3D FEM model) RMS value for single 1/3rd octave band.
- Calculate radiated sound level in considered room and sound exposure level.
- Calculate vibration dose value basing on vibration acceleration with proper weightings [3].
- Evaluate annoyance for noise and vibration separately and in total.

Results of such calculations are listed in Table 3.

**Table 3.** Estimated annoyance [8] of single stimuli and stimuli combined based on maximal vibration velocity in center frequency in center frequency of 1/3rd octave band.

| Type of the room | Center frequency of 1/3rd octave band | LA[dB] | SEL (10s) [dBA] | VDV (10s) [ms] | Pure noise annoyance [-] | Pure vibration annoyance [-] | Combined annoyance [-] |
|------------------|--------------------------------------|--------|-----------------|----------------|--------------------------|---------------------------|------------------------|
| Office room      | 16Hz                                 | 22,5   | 32,5            | 0,0638         | 4,55                     | 14,44                     | 36,06                  |
|                  | 20Hz                                 | 28,5   | 38,5            | 0,0969         | 7,50                     | 16,01                     | 39,63                  |
|                  | **25Hz**                             | **34,3**| **44,3**       | **0,0736**     | **12,08**               | **17,09**               | **44,28**             |
|                  | **31,5Hz**                           | **39,7**| **49,7**       | **0,0763**     | **18,96**               | **17,85**               | **50,71**             |
|                  | 40Hz                                 | 45,3   | 55,3            | 0,0771         | 30,15                    | 18,07                    | 60,49                  |
|                  | 50Hz                                 | 51,4   | 61,4            | 0,0766         | 49,95                    | 17,91                    | 77,45                  |
|                  | 63Hz                                 | 63,8   | 73,8            | 0,0733         | 140,10                   | 17,03                    | 154,53                 |
|                  | 80Hz                                 | 61,0   | 71,0            | 0,0657         | 110,33                   | 14,95                    | 127,53                 |
| Living room in nighttime | 16Hz | 13,4   | 23,4            | 0,0223         | 2,14                     | 4,18                     | 27,28                  |
|                  | **20Hz**                             | **19,4**| **29,4**       | **0,0244**     | **3,52**                 | **4,64**                 | **28,77**             |
|                  | **25Hz**                             | **25,2**| **35,2**       | **0,0258**     | **5,67**                 | **4,95**                 | **30,82**             |
|                  | 31,5Hz                               | 30,6   | 40,6            | 0,0267         | 8,90                     | 5,17                     | 33,75                  |
|                  | 40Hz                                 | 36,2   | 46,2            | 0,0270         | 14,16                    | 5,24                     | 38,32                  |
|                  | 50Hz                                 | 42,3   | 52,3            | 0,0268         | 23,46                    | 5,19                     | 46,30                  |
|                  | 63Hz                                 | 54,7   | 64,7            | 0,0257         | 65,79                    | 4,93                     | 82,60                  |
|                  | 80Hz                                 | 51,8   | 61,8            | 0,0230         | 51,81                    | 4,33                     | 70,17                  |
| Operating theatre | 16Hz | 10,5   | 20,5            | 0,0159         | 1,68                     | 2,81                     | 25,98                  |
|                  | **20Hz**                             | **16,5**| **26,5**       | **0,0174**     | **2,76**                 | **3,12**                 | **27,12**             |
|                  | **25Hz**                             | **22,2**| **32,2**       | **0,0184**     | **4,45**                 | **3,33**                 | **28,71**             |
|                  | 31,5Hz                               | 27,7   | 37,7            | 0,0191         | 6,99                     | 3,48                     | 31,00                  |
|                  | 40Hz                                 | 33,3   | 43,3            | 0,0193         | 11,11                    | 3,52                     | 34,57                  |
|                  | 50Hz                                 | 39,4   | 49,4            | 0,0191         | 18,41                    | 3,49                     | 40,84                  |
|                  | 63Hz                                 | 51,8   | 61,8            | 0,0183         | 51,64                    | 3,32                     | 69,35                  |
|                  | 80Hz                                 | 48,9   | 58,9            | 0,0164         | 40,67                    | 2,91                     | 59,64                  |

It can be seen from Table 3 that combined annoyance gives higher values than single stimulus annoyance summed in total. Deviation varies and tend to decrease with power of stimuli. It may results from fact, that the lower stimulus power is, the larger extrapolation of the method [8] has to be done.
The analysis of existing criteria is given Table 4. It is worth to underline, that the analysis is done for external source of noise and vibrations excitation. Thus considering the sound level may periodically exceed limit value but in the relation to analyzed period it has to stay below limit value. This opens way to calculate how much incidents may happen in given period.

Following algorithm of analysis was used:

- Recalculation of the incident intensity based on single incident level and maximal sound level in given period (day or night)
- Estimation of VDV value based on calculated intensity in given period.
- Comparison of obtained VDV value with limit value of VDV corresponding to low probability of room residents’ complaints.

Table 4. Estimated incident intensity (number of incidents) with resultant VDV with given criterion for low probability of room user complaints based on maximal vibration velocity in center frequency in center frequency of 1/3rd octave band.

| Type of the room | Center frequency of 1/3rd octave band | Single incident level [dBA] | Maximum LAeq,16h (daytime) | Maximum LAeq,8h (nighttime) | Calculated number of incidents based on noise level (daytime) | Calculated number of incidents based on noise level (nighttime) | Value of VDV [ms\(^{1.75}\)] estimation (daytime or nighttime) | Value of VDV [ms\(^{1.75}\)] corresponding low probability of room user complaints |
|-----------------|---------------------------------|---------------------|-----------------|-----------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------------|
| Office room     | 16Hz                            | 22,5                | 35 -            | 101536 -        | 1,14                        |                             |                             | 0.4                               |
|                 | 20Hz                            | 28,5                | 35 -            | 25318 -         | 0,88                        |                             |                             | 0.37                              |
|                 | 25Hz                            | 34,3                | 35 -            | 6737 -          | 0,67                        |                             |                             | 0.26                              |
|                 | 31.5Hz                          | 39,7                | 35 -            | 1924 -          | 0,51                        |                             |                             | 0.12                              |
|                 | 40Hz                            | 45,3                | 35 -            | 531 -           | 0,37                        |                             |                             | 0.13                              |
|                 | 50Hz                            | 51,4                | 35 -            | 131 -           | 0,26                        |                             |                             |                                   |
|                 | 63Hz                            | 63,8                | 35 -            | 7 -             | 0,12                        |                             |                             |                                   |
|                 | 80Hz                            | 61,0                | 35 -            | 14 -            | 0,13                        |                             |                             |                                   |
| Living room in nighttime | 16Hz                            | 13,4                | -               | 25 -            | 75351 -                     | 0,37                        |                             |                                   |
|                 | 20Hz                            | 19,4                | -               | 25 -            | 18789 -                     | 0,29                        |                             |                                   |
|                 | 25Hz                            | 25,2                | -               | 25 -            | 4999 -                      | 0,22                        |                             |                                   |
|                 | 31,5Hz                          | 30,6                | -               | 25 -            | 1428 -                      | 0,16                        |                             | 0.13                              |
|                 | 40Hz                            | 36,2                | -               | 25 -            | 394 -                       | 0,12                        |                             |                                   |
|                 | 50Hz                            | 42,3                | -               | 25 -            | 97 -                        | 0,08                        |                             |                                   |
|                 | 63Hz                            | 54,7                | -               | 25 -            | 6 -                         | 0,04                        |                             |                                   |
|                 | 80Hz                            | 51,8                | -               | 25 -            | 11 -                        | 0,04                        |                             |                                   |
| Operating theatre | 16Hz                            | 10,5                | 35 -            | 1624577 -       | 0,57                        |                             |                             |                                   |
|                 | 20Hz                            | 16,5                | 35 -            | 405095 -        | 0,44                        |                             |                             |                                   |
|                 | 25Hz                            | 22,2                | 35 -            | 107786 -        | 0,33                        |                             |                             |                                   |
|                 | 31.5Hz                          | 27,7                | 35 -            | 30782 -         | 0,25                        |                             |                             |                                   |
|                 | 40Hz                            | 33,3                | 35 -            | 8491 -          | 0,19                        |                             |                             |                                   |
|                 | 50Hz                            | 39,4                | 35 -            | 2088 -          | 0,13                        |                             |                             |                                   |
|                 | 63Hz                            | 51,8                | 35 -            | 119 -           | 0,06                        |                             |                             |                                   |
|                 | 80Hz                            | 48,9                | 35 -            | 231 -           | 0,06                        |                             |                             |                                   |

As it can be seen in Table 4, the 1/3rd octave frequency band can be divided into two groups. First group is where to exceed sound level in given period, the VDV has to exceed given limit. This can be
interpreted as frequency band range where vibrations are more annoying than noise and it tends to move limit frequency band higher in relation to results in Table 3. It might arise from fact that in [8] signal was taken from real incidents of train pass-by yet in this article signal is purely synthetic.

6. Conclusions
Based on the results of analysis in presented article following conclusions can be made:

- Two-stimuli exposure of human in evaluated room can be performed using proposed two-stimuli evaluation method or similar.
- Evaluation of one stimulus, may provide incomplete information of comfort due to fact that mechanical vibrations are the source of structure born sound, which adds to mechanical vibration stimulus.
- In low frequencies ranges, vibrations tend to be source of annoyance in higher manner than noise. It stems from two reasons. The first is fact that human ear tends to hear less with lowering the sound frequency. Second is fact that there is a sound radiation insulation in frequencies below coincidence frequency of vibrating plate [21]. In this article coincidence frequency is equal to 73Hz.
- There is balance frequency of noise and vibration annoyance. Depending on method of analysis it may vary. Synthetic test performed in this article tends to increase this frequency in regard to method [8]. Also this frequency depends on room type as non-balanced, in terms of structure-borne sound, criteria are in common use.
- Above balance frequency noise tend to be more annoying than vibrations. In terms of structure-borne noise it may be important to consider criteria not only regarding mechanical vibration but also noise generated by vibrating partition.
- As it was shown in Figure 3 used method for estimation of sound level is very important analysis presented in this article. Envelope was decided to be used as more conservative approach. Even if envelope of minimal values from both simulations were to be used, still the structure-borne noise in 63Hz and 80Hz is a real issue.

In further studies in-situ measurements will be performed. Such measurements will test the hypothesis of structure-borne noise importance in evaluation of existing mechanical vibration criterion. This article shows that if low coincidence frequency of partitions is present in a room it might be important to consider the exposure to simultaneous exposure to both stimuli. For now, only simulations shows that this problem may exist. Relative importance of noise and vibration still depends on partition material.

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