Influence of Type of Frequency Weighting Function on VDV Analysis

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Abstract. Transport vibrations are the subject of many research, mostly their influence on structural elements of the building is investigated. However, nowadays, especially in the centres of large cities were apartments, residential buildings are closer to the transport vibration sources, an increasing attention is given to providing vibrational comfort to humans in buildings. Currently, in most countries, two main methods of evaluation are used: root mean squared method (RMS) and vibration dose value (VDV). In this article, VDV method is presented and the analysis of the weighting functions selection on value of VDV is made. Measurements required for the analysis were made in Krakow, on masonry, residential, two storey building located in the city centre. The building is subjected into two transport vibration sources: tram passages and vehicle passages on very close located road. Measurement points were located on the basement wall at ground level to control the excitation and in the middle of the floor on the highest storey (in the place where people percept vibration). The room chosen for measurements is located closest to the transport excitation sources. During the measurements, 25 vibration events were recorded and analysed. VDV values were calculated for three different weighting functions according to standard: ISO 2631-1, ISO 2631-2 and BS-6841. Differences in VDV values are shown, but also influence of the weighting function selection on result of evaluation is also presented. VDV analysis was performed not only for the individual vibration event but also all day and night vibration exposure were calculated using formulas contained in the annex to the standard BS-6841. It is demonstrated that, although there are differences in the values of VDV, an influence on all day and night exposure is no longer so significant.

1. Introduction

Vibration excitation in buildings comes mainly from external sources such as: industrial machinery (building machines during building process) such as vibration road rollers [1], pile driving [2] etc. or transport excitation from roads [3], railway [4], subway [5] or trams [6]. However, internal sources can also produce vibrations in building (ex. air conditioners, domestic equipment, door banging and footfalls). Human walking is the most common excitation in buildings especially when light-weight floors are present in the building [7, 8].

Vibrations that are transmitted through the ground to building may influence on the building structure but more often, it can result in discomfort of the occupants. Humans are more sensitive to unexpected low-frequency vibrations and to provide vibrational comfort in buildings could be the basic element for buildings design criteria [9]. That is why human exposure to vibrations in buildings is the subject of many studies.
There are some methods of evaluation of human exposure to vibrations in buildings. The basic method acc. ISO standard [10] is RMS method. For vibration with high value of so-called crest factor CF, additional method of evaluation should be considered together with the basic one. There are two additional methods of evaluation: VDV and MTVV method, but the VDV is more popular. In British standard [11], VDV method is even the only method of evaluation. British standard was published in 2008 and VDV method is clearly explained in that edition. But ISO standard [10] (general requirements) which requires using additional method of evaluation for crest factor greater than 9, do not explain this method of evaluation and do not gave reference levels. Additionally, ISO standard [12] which is especially dedicated for human exposure to vibrations in buildings, introduces weighting functions which are different from those included in [10] and there are still no reference levels of evaluation in it. This lack of reference thresholds can lead to incorrect results in evaluation of human perception of vibration. In this paper influence of weighting function selection on results of evaluation method based on VDV analysis is investigated.

The VDV is not a mean value like RMS but rather determines the value of exposure to vibration and is more similar to the level of exposure to sound or sound energy. In the provisions of ISO [10] and British [11] standards, there are small differences in weighting functions for vertical direction (z). They differ in frequency below 5 Hz and for frequency higher than 25 Hz. So, for the most unpleasant frequencies for the human body (5-25Hz), the weightings are the same in both standards. The most problematic is ISO standard [12] in which it is allowed to use the so-called combined weighting function Wm, when the position of the human body during the measurement is unknown. The differences between three weighting functions present in ISO [10, 12] and British [11] standards are shown in Figure1.

As could be seen from above figure, Wb function (acc. [11]) and Wk function (acc. [10]) do not differ so much from each other. The combined weighting function Wm (acc. [12]) could be the problem especially without reference thresholds given for this function.

2. Methodology
VDV value is given by the formula acc. to ISO standard [10]:

\[
VDV = \sqrt{\frac{1}{T} \int_{0}^{T} v(t)^2 \, dt}
\]
where: \( a_w(t) \) – is weighted acceleration as a function of time \([\text{m/s}^2]\);
\( T \) – is the duration of measurement \([\text{s}]\).

According to formula (1) in VDV analysis, some main steps should be made:
- recorded acceleration should be filtered by Butterworth’s filters in one third octave bands,
- values obtained in one third octave bands should be multiplied by the weighting functions according to the chosen standard regulations,
- weighted values raise to 4 power,
- area under the obtained graph is calculated (integration),
- thus, obtained integrals are raising to the \( \frac{1}{4} \) power,
- sum of the values in different octave bands and get one VDV values – through the calculation from \( \text{m/s}^2 \) we obtained \( \text{m/s}^{1.75} \).

As a result of the above procedure, a vibration dose value for a single vibration episode is obtained. This value should not be a basis for assessing the influence of vibration on humans. Only 16-hour daily exposure and an 8-hour night exposure is the basis for evaluation of vibration comfort. Only reference thresholds of daily and night exposure to vibration are given in [11] and are listed in Table 1.

| Room destination                | Low probability of adverse comments | Adverse comments possible | Adverse comments probable |
|---------------------------------|------------------------------------|---------------------------|---------------------------|
| Residential buildings – 16h day | 0.2 – 0.4                          | 0.4 – 0.8                 | 0.8 -1.6                  |
| Residential buildings – 8h night| 0.1 – 0.2                          | 0.2 – 0.4                 | 0.4 – 0.8                 |
| Office buildings – 16h day      | 0.4 – 0.8                          | 0.8 – 1.6                 | 1.6 – 3.2                 |
| Workshops – 16h day             | 0.8 – 1.6                          | 1.6 – 3.2                 | 3.2 – 6.4                 |

The ISO standard does not provide similar ranges, even in [12], which is dedicated to the passive perception of vibrations. There is only the laconic comment in [12] that there is too much of the variables, such as temperature or noise, to be able to provide evaluation criteria.

To use an evaluation from Table 1, calculation of daily or night exposure should be made. Once again, British standard [11] is very helpful and gives following formula:

\[
VDV_{b/d,day/night} = \left( \sum_{n=1}^{N} VDV_{b/d,tn}^4 \right)^{0.25}
\]

, where: \( VDV_{b/d,ln} \) – VDV value for single vibration episode,
\( N \) – number of episodes per day/night.

It’s worth noting that VDV value for one vibration episode should be representative for that kind of excitation. Above formula could be used for \( N \) different VDV values, but then it should be well-estimated (ex. from train timetable) how many events of similar nature occur per day or night.
Sometimes recorded signal lasts longer than one event, because acc. [10] in some countries measurement duration should last at least 30 minutes. So, recorded signal, especially in city centres, may include more than one vibration episode. Then formula (3) should be used:

\[
VDV_{b/d,day} = \left( \frac{t_{\text{day}}}{t_{\tau}} \right)^{0.25} \cdot VDV_{b/d,\tau}
\] (3)

Where:
- \( t_{\text{day}} \) – time of exposure from individual source of vibration,
- \( t_{\tau} \) – the duration of vibrations for a representative sample

3. Analysed building
The building chosen for analysis is located in Krakow at Mogilska St. It is a two-storey residential building of traditional, masonry construction. This building is exposed to vibration from two sources of excitation:
- car and heavy truck passages on the road located 1 m from the building,
- tram passages on the track located 10 m from the building.

Both excitation sources are located in the zones of dynamic influences. The view of eastern elevation is given in Figure 2.

![Figure 2. View of the building.](image)

Measurement points for human exposure to vibration were located in the middle of the floor, closest to the excitation and in the residential room. Example of measurement point is shown in Figure 3.
Figure 3. Second floor plan with localization of measurement point

4. Measurement results
Measurements which were held on 06.23.2013 in the building at Mogilska St. in Krakow last approx. 40 minutes. During that time, 25 vibration episodes were recorded. For every episode VDV value was
calculated using three different weighting functions (acc. [10, 11 and 12]). Results of these calculations are listed in Table 2.

Table 2. VDV values for vibration episodes using three different weighting functions.

| No. | Excitation source | VDV<sub>in</sub> (Wb acc. BS [11]) | VDV<sub>in</sub> (Wk acc. ISO [10]) | VDV<sub>in</sub> (Wm acc. ISO [12]) |
|-----|------------------|----------------------------------|----------------------------------|----------------------------------|
| 1   | Tram 105 N (2 wag.) | 0.0788                           | 0.0707                           | 0.0346                           |
| 2   | Tram 105 N (2 wag.) | 0.1143                           | 0.1083                           | 0.0584                           |
| 3   | Tourist bus       | 0.2172                           | 0.2705                           | 0.1567                           |
| 4   | Tram EU8N (further track) | 0.0454                          | 0.0427                           | 0.0217                           |
| 5   | Tram 105 N (3 wag.) | 0.0697                           | 0.0644                           | 0.0321                           |
| 6   | Tram 105 N (2 wag.) | 0.0747                           | 0.0684                           | 0.0375                           |
| 7   | Tram EU8N (further track) | 0.0416                          | 0.0382                           | 0.0202                           |
| 8   | Tram GT8S         | 0.0458                           | 0.0425                           | 0.0219                           |
| 9   | Tram EU8N (further track) | 0.3187                          | 0.3183                           | 0.1726                           |
| 10  | Heavy truck       | 0.0756                           | 0.0731                           | 0.0392                           |
| 11  | Tram 105 N (3 wag.) | 0.1227                           | 0.1186                           | 0.0609                           |
| 12  | Heavy truck       | 0.1015                           | 0.1008                           | 0.0574                           |
| 13  | Tram E1-C3        | 0.0581                           | 0.0541                           | 0.0276                           |
| 14  | Tram 105 N (3 wag.) | 0.0886                           | 0.0804                           | 0.0404                           |
| 15  | Tram 105 N (3 wag.) | 0.0735                           | 0.0682                           | 0.0390                           |
| 16  | Tram GT6          | 0.0588                           | 0.0551                           | 0.0299                           |
| 17  | Tram 105 N (3 wag.) | 0.0768                           | 0.0708                           | 0.0348                           |
| 18  | Heavy truck       | 0.2049                           | 0.2017                           | 0.1050                           |
| 19  | Heavy truck       | 0.3375                           | 0.3446                           | 0.1745                           |
| 20  | Tram 105 N (3 wag.) | 0.0638                           | 0.0599                           | 0.0316                           |
| 21  | Heavy truck       | 0.2349                           | 0.2327                           | 0.1251                           |
| 22  | Heavy truck       | 0.2966                           | 0.2955                           | 0.1575                           |
| 23  | Heavy truck       | 0.0867                           | 0.0857                           | 0.0469                           |
| 24  | Tram EU8N (further track) | 0.0392                          | 0.0370                           | 0.0199                           |
| 25  | Tram GT8S (closer track) and Tram 105 N 3 wag. (further track) | 0.0914                           | 0.0867                           | 0.0474                           |

As could be seen from above, VDV values obtained using Wb and Wk are close to each other, which should be expected because these two weighting functions are very similar and they are even the same in the frequency range between 5 and 25 Hz. VDV values obtained using combined weighting function Wm are smaller than these obtained using both weighting functions on “z” direction.

VDV values listed in Table 2 are values calculated for single vibration episodes. To make an assessment according Table 1, VDV for daily or night exposure should be made. First 40 minutes’ exposure should be calculated using formula (2). After that day and/or night exposure should be calculated according to formula (3).

- **Using Wb acc. [11]:**
  \[
  VDV_{b, 40'} = 0.444 \\
  VDV_{b, day} = 0.983 \text{ - adverse comments probable} \\
  VDV_{b, night} = 0.695 \text{ (half intensity of tram and cars passages) - adverse comments probable}
  \]

- **Using Wk acc. [10]:**
  \[
  VDV_{k, 40'} = 0.454 \\
  VDV_{k, day} = 1.005 \text{ - adverse comments probable} \\
  VDV_{k, night} = 0.711 \text{ (half intensity of tram and cars passages) - adverse comments probable}
  \]

- **Using combined Wm [12]:**
  \[
  VDV_{m, 40'} = 0.243
  \]
VDV_m, day = 0.538 - adverse comments possible
VDV_m, night = 0.381 (half intensity of tram and cars passages) - adverse comments possible

There are no differences in assessment of influence of vibration on humans in building when Wb and Wk are used. Result of evaluation is the same using both these weighting functions: adverse comments are probable which means that complaints from building occupants should be expected and that vibration are too annoying for vibrational comfort in this building. When Wm weighting function is used result of evaluation is different. Adverse comments are possible which means about 0.5 probability of complaints. It is worth remembering that Table 1, according to which this assessment is made, is enclosure in British standard [11]. That is why Wb and Wk frequency weightings are much better that Wm.

5. Discussions and conclusions
Vibration dose value VDV is included, first of all, in ISO standard [10] which is dedicated to whole body vibrations and hand-arm vibrations too. That is why it is often used when vibrational comfort in vehicles is analysed (ex. [13]). But VDV analysis is also considered for vibrational comfort in buildings because in some countries this method of assessment is treated as basic method [11], in others as additional method [10, 14]. VDV analysis is then used for assessment of vibrational comfort in buildings for such sources of excitation like: railways [15], roads, trams and other transport vibrations, but it is mostly used for the so called human induced vibrations [16-19]. In all publications from [15] till [19], VDV value is calculated acc. British standard [11] and Wb is taken into account. Methodology in these papers is the same as explained in chapter 2. Authors of these articles do not analyse an influence of weighting functions selection on the result of VDV analysis. From analysis made in this paper, some conclusions can be drawn:
- Assessment of human exposure to vibrations in buildings made using VDV analysis should take into signal analysis weighting function Wb, because reference thresholds listed in Table 1 are dedicated to this function,
- It is possible to take weighting function Wk into consideration because the differences between Wb and Wk are small and in the range of 5 and 25 Hz values of both of these functions are the same,
- Using frequency weightings Wb or Wk in evaluation of human perception to vibration, according to Table 1, is slightly better than using Wm,
- Heavy trucks and buses gives higher values of VDV than tram passages. In this case, it could be of course caused by the differences in distances: tram to building (10 m) and road to building (1 m).

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