Investigation of the Degree of Vibrations’ Transmission Transferred Through the Subsoil to the Structure

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Abstract. The work presents the course and results of tests to determine the coefficient of transmission of vibrations from a building sub-base to a building structure. Vibration of structure is caused by quasi-seismic excitation; in presented example it is vibrations caused by tram passage. The factor of transmission is relationship between vibrations recorded on the object and the level of vibrations on the ground without an existing object. The value of the transmission degree will enable better design of the building.

1. Introduction

Vibration measurement is used mainly for monitoring safety of existing structures in civil engineering practice [1]. However it is a very common situation in which an object should be designed, and the object will be influenced by vibrations coming from an existing source of vibrations. This situation is the diagnostic situation "C" according to [2]. The procedure involves performing measurements at the place where the designed building is to be constructed and taking into account the reduction factor of vibration transferred from the ground to the foundation of the building. Similarly, the Polish Standard [3] recommends that in such a situation (an existing source of vibrations and non-existent, planned vibration receiver - a designed building), vibration measurements should be made at the place of the designed building and the "changes of vibration parameters at the ground-foundation interface" should be taken into account. In both items [2 and 3], it was not specified how to estimate the reduction factor.

It seems probable that the vibrations measured on an existing object will be different - with the same source of vibrations - from vibrations recorded on the ground without the object. In this article, the degree of transmission reduction combine parameters of vibrations measured on the object and parameters of the vibrations measured on the ground substrate at the place where the building is located in a situation when there is no building. In any real situation, the value of the transmission coefficient can be determined after the construction of the object, and thus after the completion of the design process. At this time, its value is no longer relevant from the design point of view. Unfortunately, you cannot use theoretical solutions. Due to the complexity of the problem (layered substrate, variable location of non-harmonic excitation, complexity of the building object and the vibration transmission not fully understood), existing theoretical models are inappropriate. The aim of this work is to attempt to estimate the level of transmission based on the study of one object. The work is preliminary, the conclusions from the conducted research and analyses will enable further clarification of further research.
2. Vibration measurement
Dynamic measurements were performed with the use of a Brüel & Kjær PULSE™ system [4]. The 3560-C PULSE chassis were used for measurement, it allows to connect up to 17 transducers, all with the frequency range from DC to 25.6 kHz. Because the 3560 PULSE measurement system contains Dyn-X acquisition modules, all inputs reach the dynamic range of 160 dB with ideal linearity and phase matching – mean noise level is no bigger than 4 μV. During measurements nine seismic, high sensitivity accelerometers DeltaTron 8340 were used as well as modal hammer type 8210. The seismic accelerometers 8340 have sensitivity 10000 mV/g, noise level ±0.025mg and measurement range 0.5 g. The parameters of modal hammer are as follow: sensitivity 0.225 mV/N, maximum force 22.1 kN, frequency range 500 Hz, modal mass 5.44 kg. Four different tips were used during measurements.

![Figure 1. Sketch of measurement place](source: www.geoportal.wroclaw.pl)

As a measurement object, a residential house located near the tram line was selected. The minimum distance from the building to the nearest tramway rail is only 2.75 m. Measurements were made at three points P1, P2, P3 (figure 1). Measurement point P1 was located on the ground in front of the building, P2 1 m above the ground, on the corner of the building and P3 on the ground. Point P3 was located 12 m away from the building but distance from P3 to the tramway rail was the same as for the point P2. With such a localization points, one can treat measurements made at point P3 as measurements made in a situation where there is no building (designing stage), and measurements made at point P2, as measurements made in a situation where the building already exists. At each measurement point, measurements were made in three mutually perpendicular directions. Direction x - horizontal axis parallel to the track, y direction - horizontal axis, perpendicular to the track and z - vertical axis direction.
A total of 46 passing trams were measured: 24 rides on track No. 1 (track closer to the building and measuring points) and 22 rides on track No. 2 - track located further from the measurement points. In addition, vibrations at the measuring points were measured due to impacts of the modal hammer: 30 impacts on the rail and 30 impacts on the sleeper near P1 and P2; and 30 impacts on the rail and 30 impacts on the sleeper in the vicinity of P3. The recorded waveforms were analysed both in time and frequency domain.

3. Results and discussions

In monograph [5], the vibration reduction coefficient, in the context of vibrations transmission from the ground, was defined as

$$W = \frac{Y_s \text{max} - Y_c \text{max}}{Y_s \text{max}}$$  \hspace{1cm} (1)

where: $Y_s \text{max}, Y_c \text{max}$ = maximum displacement (velocity, acceleration) of vibrations, respectively, on the ground and foundation of the structure, the authors stated that this coefficient value ranges from 30-80%. Such a level can significantly influence on the forecast of dynamic action on an object.
Figure 4 shows the time history of vibrations caused by passing tram measured in three directions x, y, z at the measurement point P1 and P3. The upper row corresponds to the vibration recorded at the measuring point P1 and the lower one at point P3. The left column corresponds to the x direction, the middle to y direction and the right to z direction.

![Vibration waveforms](image)

**Figure 4.** Vibration waveforms containing P-2 and P-3 measurements for 3 components (x, y, z), (track 1, tram ride No.: 1, type of tram: Konstal)

It is evident that extreme values (marked with red points) occur at various measuring points in different parts of the time history. For this reason, it was decided to modify the formula (1). First, one should consider not the amplitude in the entire time course but the individual harmonic components; second, measurements in P2 and P3 should be compared. Measurements made on the building (P2) and on the ground (P3) - what can be treated as measurements on building and measurements on the ground before construction of the object.

\[ nT(f_i) = \frac{a_{P2}(f_i) - a_{P3}(f_i)}{a_{P3}(f_i)} \]  

(2)

where: \( a_{P2}(f_i) \), \( a_{P3}(f_i) \) - acceleration of vibrations of the structure foundation and of the ground in the \( f_i \) band, respectively. The band can be understood as the centre frequency of the band in the Fourier’s analysis, or the middle frequency of the \( 1/n \) octave band [6], in this paper the Fourier transform approach is used. A graphic representation of the reduction coefficient defined in this way is shown in the figure 5.
Figure 5. Vibration reduction coefficient, direction x and y

In the figures, the horizontal axis is the frequency axis, the coloured lines show the variation of the transfer coefficient depending on the frequency. All lines refer to one type of tram. The blue and red lines respectively show the smallest and largest value of the coefficient and the thick black line the proposed envelope of the coefficient. It is evident that the nature of the coefficient for the x and y directions is similar. The coefficient has positive values (i.e. there is a reduced vibration on the building compared to ground vibrations) in the range of 20-80 Hz. In the range of 0-20 Hz, the values of the coefficient are negative, i.e. there is a vibration gain. The explanation for this fact is the low excitation levels in the considered frequency band, with low vibration levels, the relative measurement error increases and distorts the final result.

The character of the coefficient in the vertical direction (z direction) is completely different.

Figure 6. Vibration reduction coefficient, direction z

As can be seen only in a narrow band of 45-60 Hz, the resultant coefficient is positive (black line). Individual tram travels give positive coefficients, however, with values lower than those on horizontal
directions (x and y). By analysing the Fourier spectra of individual passes, showed on the figure 7, it can be seen that the maximum spectrum for tram going on track 2 in P3 occurs at 44 Hz and at P2 at 41 Hz. Recorded vibration were caused by the passage on track 2. There is a tram stop in vicinity of the building, so increasing the maximum frequency can be related to the acceleration of the vehicle.

![Figure 7. Fourier spectrum measured in P2(left) and P3 (right), direction z](image)

The differences in the amplitudes of vibrations recorded at points P2 and P3 may result from the different technical condition of the track, tram rolling stock or different speed of travel, so from different levels and character of excitation. In order to eliminate possible differences, excitation was applied by hitting a rail or a sleeper with a modal hammer. Due to the force transducer mounted in the hammer head, it is possible measure force and to normalize the measured vibrations to the same level of excitation force. The following figures show an example of the spectral analysis of vibration excited by the hammer hit on the rail near point P3 and near point P2. On the right side of the figure one can see the spectrum of the impact force and on the left side one can see the spectrum of acceleration in the x direction.

![Figure 8. Fourier spectra measured in P3, force (right) and response (left), direction x](image)

All spectra were normalized, i.e. the response was reduced to the same level of excitation force (unit force). The impact was carried out by hitting with the modal hammer with different tips. In this analysis, due to the low frequencies occurring, better results give a softer tip. The soft tip makes the pulse duration...
longer and thus the narrower frequency bandwidth. In each case, the shock spectrum is relatively flat from which it can be claimed that all frequencies in the structure receiving the vibrations are equally stimulated. After normalizing the spectra and applying the formula (2), the coefficient was obtained. The following figures show the coefficient obtained for a single series of strokes (left side) and the coefficient for all series and its envelope (thick, black line - the right side of the drawing), successively for x, y and z direction.

Figure 10. Vibration reduction coefficient, direction x.
Single realization (left), all realizations and envelope (right).

Figure 11. Vibration reduction coefficient, direction y.
Single realization (left), all realizations and envelope (right).

The nature of the vibration reduction coefficients for horizontal directions (x and y) are similar - in the range of 40-90 Hz the coefficients have high values of 0.8-0.9. However, around 20 Hz there is a clear decrease in the value of the coefficient. This is due to the fact that the accelerations measured on the ground have a spectral maximum around 20 Hz. In subsequent tests, the system of attaching accelerometers to the ground should be checked in order to confirm or exclude its effect on the results.
Figure 12. Vibration reduction coefficient, direction z. Single realization (left), all realizations and envelope (right)

The coefficient in z direction has two minima, one around 20 Hz and the other around 70 Hz. The first may be cause by the system for mounting accelerometers to the ground, perhaps the eigenfrequencies of the fixing system is just around 20 Hz. On the other hand, around 70 Hz, the building’s response has very low level (quasi-anti-resonance), this together with the increased response in the ground (P3), gives the local minimum of the vibration reduction coefficient.

4. Conclusions
The paper presents the method of measuring the vibration reduction factor. Since only one object has been tested, one must be aware that conclusions cannot be generalized. For vertical direction (z) the character of coefficient is slightly different than for the horizontal directions (x and y). Undoubtedly, an impact on the results is generated by the characteristic frequencies i.e. the object's eigenfrequencies, frequencies associated with excitation, and frequencies associated with the measurement chain. In the frequency range generated by tramway passage, i.e. 40-60 Hz, the values of the coefficient are high 80-90% for horizontal directions and around 80% for vertical direction. Such high values of the vibration reduction factor should be taken into account in the design process. At the same time, one should consider the ranges of natural frequencies of the designed object, because in these bands the values of the coefficient are low and could be even negative.

References
[1] Wyjadłowski M. Methodology of dynamic monitoring of structures in the vicinity of hydrotechnical works – selected case studies. Studia Geotechnica et Mechanica. 2017, vol. 39, nr 4, pp. 121-129.
[2] Kawecki J., Stypuła K., Zapewnienie komfortu wibracyjnego ludziom w budynkach narażonych na oddziaływania komunikacyjne, Cracow, 2013, (in Polish)
[3] Polish Standard PN-B-02170:2016, Evaluation of the harmfulness of buildings vibrations due to ground motion (in Polish)
[4] Wójcicki Z., Grosel J., Sawicki W. Eksperymentalne badania dynamiczne budowli, Wroclaw 2014, (in Polish)
[5] Kawecki J., Dulińska J., Kozioł K., Stypuła K., Tatara T., Oddziaływania parasejsmiczne przekazywane na obiekty budowlane, Cracow 2014, (in Polish)
[6] Brandt A., Noise and Vibration analysis, Wiley 2012