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ASSESSMENT OF THE IMPACT OF BLASTING WORKS ON BUILDINGS LOCATED IN THE VICINITY OF OPEN-PIT MINES USING MATCHING PURSUIT ALGORITHM

Detonation of explosives creates strong para-seismic vibrations. Such vibrations can damage buildings or other infrastructure located in the vicinity of such detonations, and can be burdensome to people living in such areas. This paper describes the usefulness of Matching Pursuit (MP) algorithm in assessing the impact of blasting on the surrounding areas, and proves that by taking into account frequency changes over time, vibration analysis can help make much more profound and reliable predictions in this field.

Keywords: Matching Pursuit algorithm, blasting technique, signal analysis, vibration structure, impact of vibrations on buildings

1. Introduction

For many years, studies have sought to create a scientific database and procedures to safely complete jobs involving the use of explosives in order to ensure the safety of structures affected by para-seismic vibrations travelling across the ground and to buildings, and to make such vibrations less burdensome for people (so as not to cause discomfort). Such research has covered the geological structure of blasting sites and the ground which propagates vibrations, blasting techniques, estimated and actual vibration levels, interactions between buildings and the ground, and monitoring and recording of the impact on civil structures. The above-mentioned issues need to be explored to protect the environment against excessive vibrations (Pyra et al., 2015).

A crucial element of such research is to assess how vibrations affect civil structures. Legal regulations make entities that work with explosives responsible for protecting the environment

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against the consequences of such works. This also includes the negative impact of vibrations created by blasting on civil structures. Any successful use of explosives will always produce vibrations propagated away from the blasting site. There is no doubt about this; however, not all vibrations that propagate through the environment and reach civil structures are harmful and burdensome to people who live there.

Vibrations caused by explosives are pulsed and short-lasting, and, as a result, less harmful than those generated as a result of vehicle traffic, which last longer and may cause major damage to civil structures.

To protect buildings against the harmful effects of para-seismic exposure, it is crucial to identify the parameters that are closely linked to building damage (Kuzu & Hüdaverdi, 2005; Olofsson, 1990).

Many authors (Kuzu & Hüdaverdi, 2005; Dowding, 1985) consider Peak Particle Velocity (PPV) to be this parameter. This is also the case in nearly all standards related to the effects of vibrations on civil structures. However, PPV does not reflect either the complexity or duration of such interaction, or the complex nature of vibrations, and these parameters significantly influence the assessment of such effects.

It seems that for the analysis of the levels of vibrations created by explosives it is a gross simplification to use such an inaccurate parameter as PPV.

Given the above, it may be worthwhile to consider in greater detail another vibration feature, namely frequency. Many standards used to assess the impact of vibrations produced by blasting works recognise the significant impact of this parameter on damage suffered by civil structures.

2. Materials and methods

2.1. Using Matching Pursuit to examine vibration structure

The most relevant and reliable data on the structure of recorded vibrations can now be captured using Matching Pursuit (MP) (Durka, 2004; Mallat & Zhang, 1993; Pyra & Sołtys, 2016; Sołtys et al., 2017), the latest algorithm for analysing frequency changes over time, based on an iterative matching of signal to a set of functions, where at each stage of the approximation, part of the signal to which a function has been matched, is removed and other functions are compared to the rest of the signal. This makes it possible to avoid unnecessary repeated processing of the same parts of the signal. Functions that are matched to the signal are referred to as time-frequency atoms, and are included in an extensive set known as a dictionary. In practice, this algorithm relies on Gabor dictionaries with Gabor atoms, i.e., sine-modulated Gaussian envelopes. The greater the percentage of signal energy accounted for by the atoms in the dictionary, the better the approximation. As the signal is processed, the number of matching atoms is exhausted, and the rest has less and less energy. The process of approximating atoms to the signal is a finite one. The algorithm stops when about 95% of the signal's energy has been accounted for (or after a specific number of iterations), while the rest is regarded as the approximation error (e.g. signal noise).

MP results are presented as energy density distribution based on Wigner distribution, also known as the Wigner map (Fig. 1).

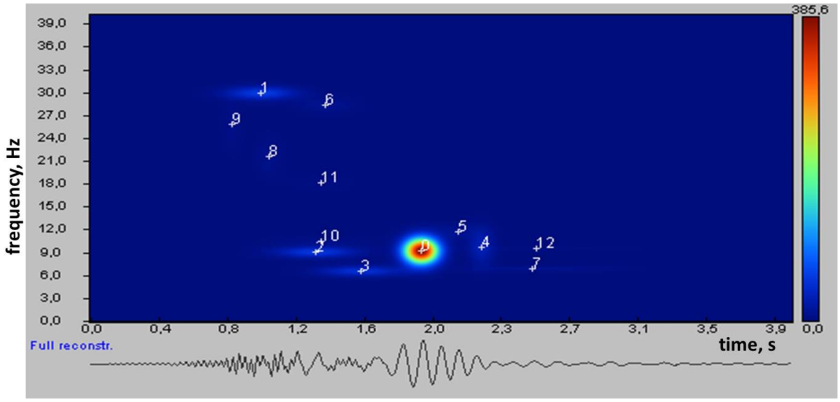


Fig. 1. Sample Wigner map for the signal in the time domain

Wigner map presents Gabor atoms (in the form of blobs) matched to the actual signal to reconstruct it and accounted for 95% of its energy. As shown in Figure 1, Gabor atoms make it possible to place in time the characteristic frequencies that are relevant for the signal structure. The intensity of each atom's colour corresponds to the energy density represented across different frequencies. In line with the law of conservation of energy, the total energy of all matched time-frequency atoms corresponds to the signal energy.

For instance, Figure 2 shows five Gabor atoms matched to specific parts of the recorded signal. Atoms 0, 1, 2, 3, and 4 account for 58.4%, 8.7%, 8.1%, 7.1%, and 4.6% of the signal energy, respectively.

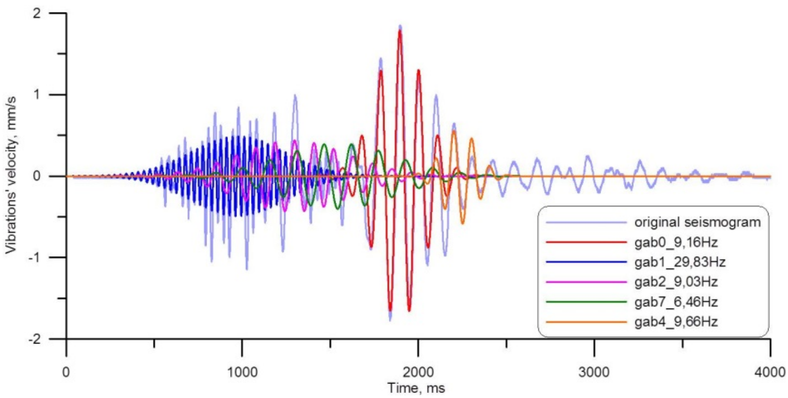


Fig. 2. Gabor atoms matched to recorded vibrations

In order to demonstrate the accuracy of reconstructing the actual signal using Gabor atoms, Fig. 3 shows the actual vibrations (blue) with the reconstructed signal drawn over it (red).

The vibration analysis examples discussed below show how useful MP algorithm is in assessing the impact of blasting works on the environment.

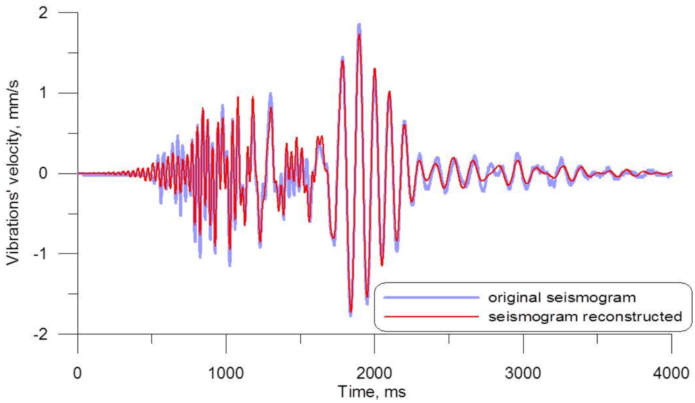


Fig. 3. A comparison of the actual time function and its reconstruction using Gabor atoms

3. Results

3.1. Comparing analysis results for vibrations generated by the detonation of explosives in open-pit mines

The first to be analysed were results for two blasting rounds, with 2 explosives detonated in the first, and 42 in the second. Both rounds were detonated on the same operating bench. Given the impact of the explosive weight, there is a general trend in the global literature to analyse such impact in relation to a delay in milliseconds (Siskind et al., 1980). The minimum delay that allows the impact of the explosive charge in a round to be disregarded is 9 ms. In the described example, the maximum charge weight per millisecond delay, in both the first and the second rounds, was about 33 kg.

For sample seismograms for vibrations recorded at each station (2 and 3'), see Figures 4 and 5. The analysis assumed component horizontal vibration velocities, x and y, since under standard *PN-B-02170:2016-12* (Polish Committee for Standardization, 2016), which applies in Poland, these parameters are taken into consideration when assessing the impact of vibrations on protected civil structures.

The recorded vibrations were examined using time-frequency analysis on the basis of the MP algorithm. Analysis results are show in Figures 6 through 11, as visualisations on Wigner-Ville maps and spatial (3D) representations, as well as histograms, with the most relevant Gabor atoms identified to explain the percentages of signal energy transmitted by individual component frequencies of the recorded vibrations.

Based on the figures above, and given that 2 explosive charges were detonated in Round I and 42 in Round II, with the same charge weights per millisecond delay, the following conclusions can be drawn:

- Gabor atoms 0, which account for the largest proportion of signal energy, are characterised by maximum vibration velocity, which are comparable for both rounds; in the ground, these values are respectively 0.49 mm/s (Round I) and 0.52 mm/s (Round II). And for the building foundation these are actually identical, at 0.085 mm/s,

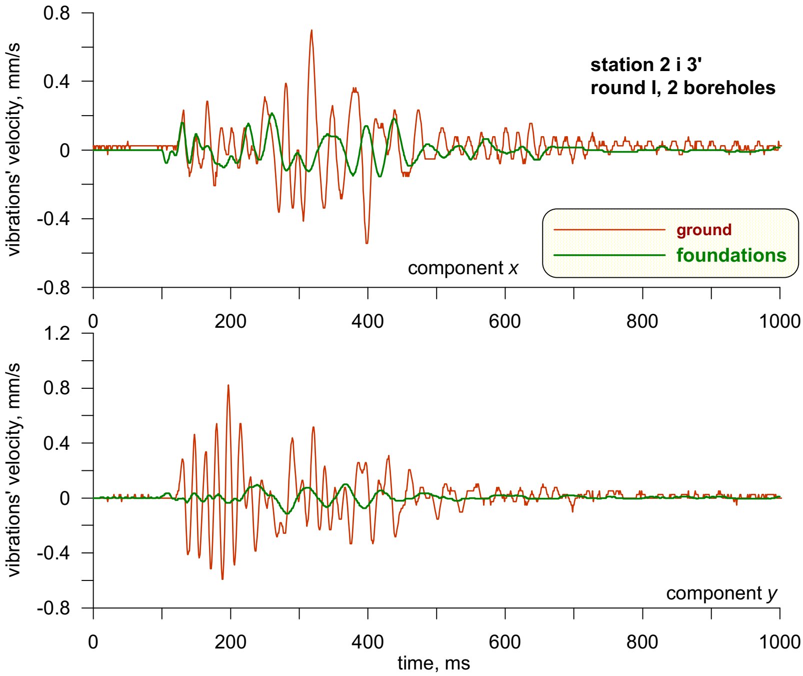


Fig. 4. Seismograms for vibrations recorded at stations 2 and 3’ – Round I

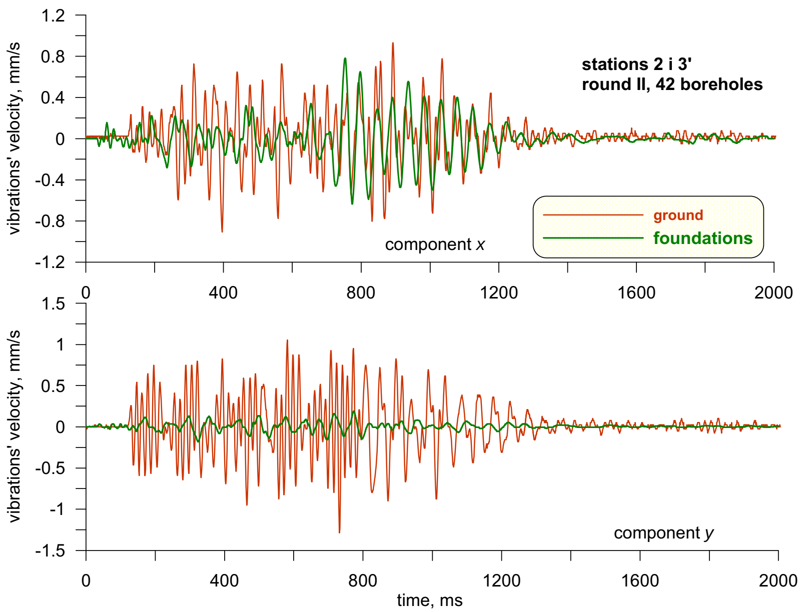
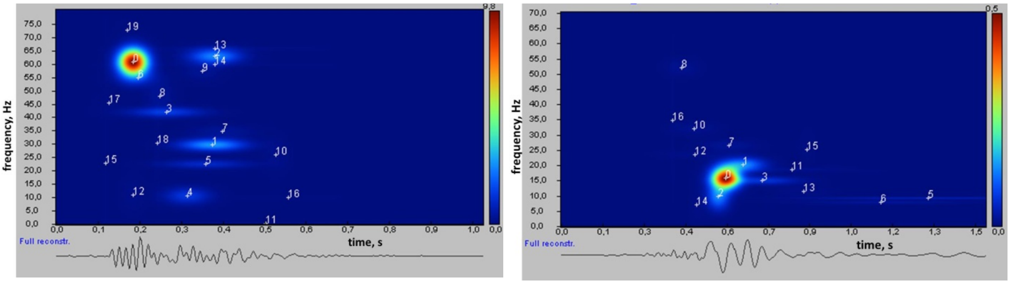
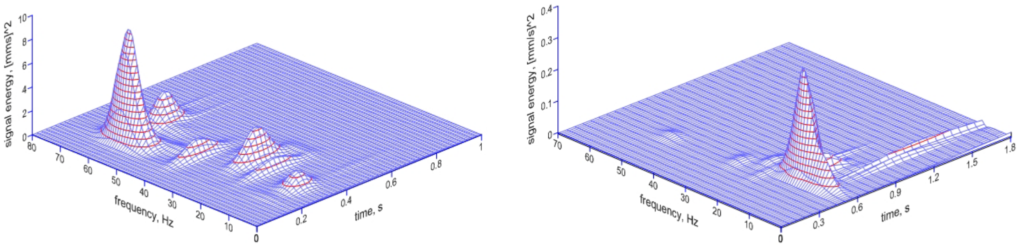


Fig. 5. Seismograms for vibrations recorded at stations 2 and 3’ – Round II



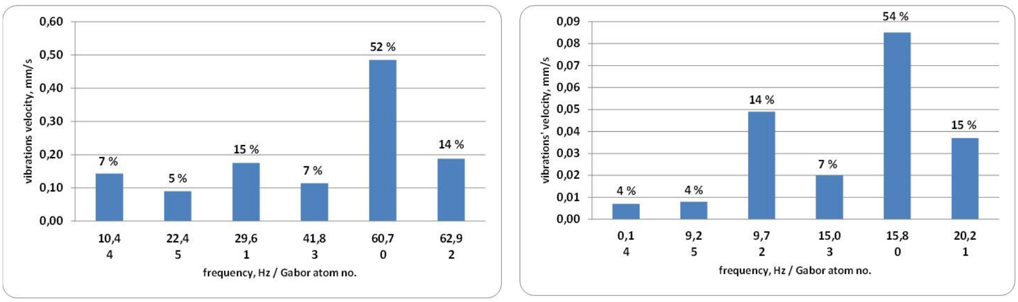
a) ground b) foundation

Fig. 6. MP analysis – Wigner-Ville map of ground and building foundation vibrations – (Round I) – component *y*



a) ground b) building foundation

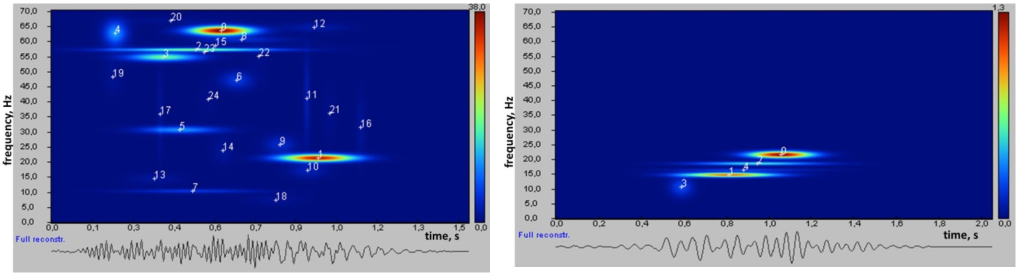
Fig. 7. MP analysis of ground and building foundation vibrations – spatial representation (Round I) – component *y*



a) ground b) building foundation

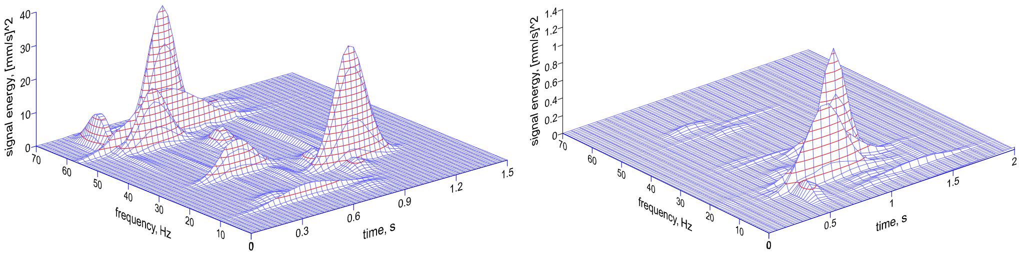
Fig. 8. Gabor atom histogram – MP analysis of ground and building foundation vibrations (Round I) – component *y*

– for ground vibrations, the dominant frequencies for each round were comparable at 60.7 Hz (Round I) and 63.7 Hz (Round II),
– energy representations of vibration structures for both rounds (Figures 7 and 10) are visibly different, which is evident from the markedly different number of charges fired



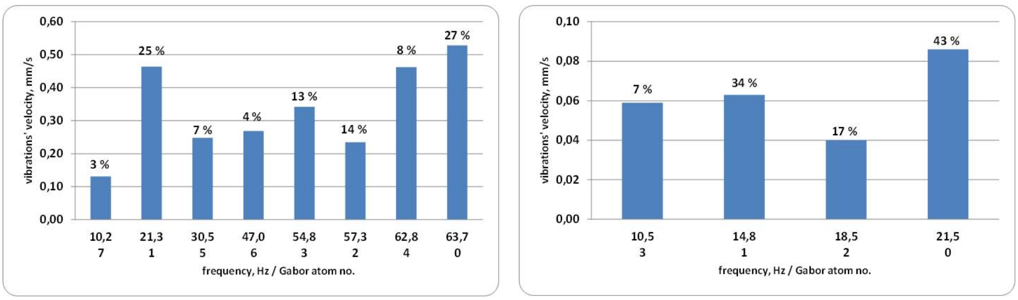
a) ground b) foundation

Fig. 9. MP analysis – Wigner-Ville map of ground and building foundation vibrations – (Round II) – component y



a) ground b) building foundation

Fig. 10. MP analysis of ground and building foundation vibrations – spatial representation (Round II) – component y



a) ground b) building foundation

Fig. 11. Gabor atom histogram – MP analysis of ground and building foundation vibrations (Round II) – component y

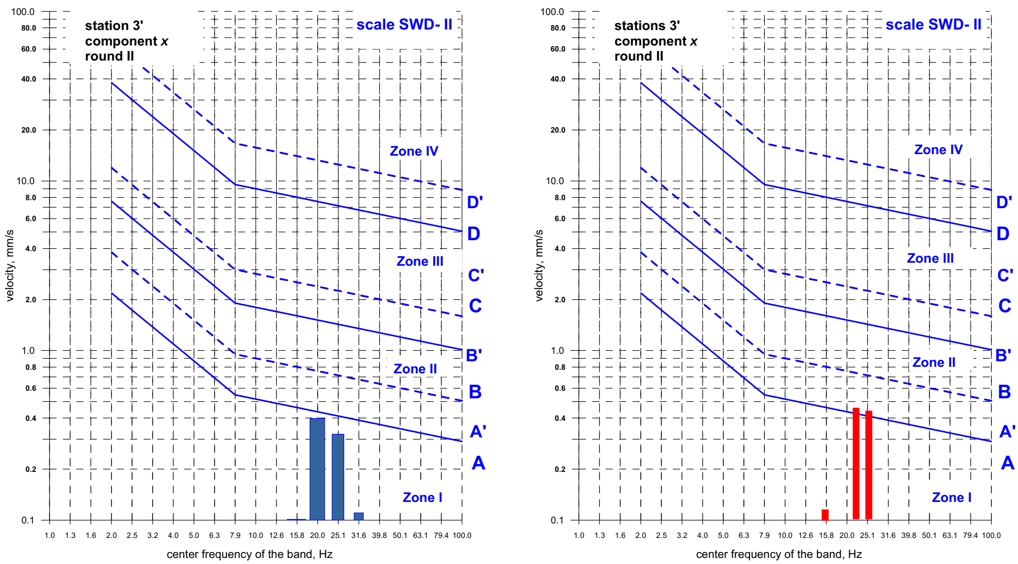
in each round (different total charge per round). This means that any impact assessment should also take into consideration vibration energy, rather than only maximum velocity. This piece of knowledge was offered by MP analysis.

– In Round II Gabor atom 0 with dominant ground vibration frequency 63.7 Hz accounts for only 27% of the energy (in Round I, for 52%), and Gabor atom 1 with 21.3 Hz at a velocity of 0.46 mm/s accounts for 25% of the signal energy, which is only slightly less than atom 0 at 63.7 Hz. This can be due to the millisecond delay used in a greater number of charges,

– there is a visible and clear variation in vibration frequency at the interface between the ground and building foundation (higher frequencies are attenuated). In Round I, the dominant frequency was 15.8 Hz, and in Round II 21.5 Hz.
– the frequency characteristic of the ground in Round II, i.e. 21.3 Hz, is almost identical to the dominant frequency of the foundation, 21.5 Hz, which accounts for 43% of signal energy. This frequency is also recorded in seismogram phase II (Fig. 5),
– finally, it is important to note the duration of Gabor atom signals, as evident in spatial representations (Figures 8 and 11). In Round I, the duration of Gabor atom 0 signal, both for the ground and building foundation, is very short (about 0.16 s), while in Round II it is longer (0.4 ÷ 0.5 s), which results in a longer exposure of the civil structure to the vibrations (longer exposure = greater impact energy).

In addition, using scale SWD-II, the study assessed how vibrations recorded in Rounds I and II affected a protected building (Fig. 12). The figure shows impact assessment using indirect method (1/3 octave filtering) based on MP algorithm, for horizontal component *x*, as amplitude values for horizontal component *y* were below 0.1 mm/s.

Figure 12 shows that the level of vibrations, whether subjected to 1/3 octave band filtering or analysed using MP algorithm, is similar. Due to the pulsed nature of such vibrations, these can be categorised as Zone I under SWD-II and considered to have a negligible effect on buildings.



a) 1/3 octave analysis b) MP algorithm

Fig. 12. Assessing vibration impact on the basis of 1/3 octave analysis and MP algorithm (Round II) – component *x*

Analyses of seismic effects generated by millisecond blasting have shown that time delays between the detonation of consecutive explosive charges affects vibrational frequency characteristics (Pyra & Sołtys, 2016; Polish Committee for Standardization, 2016). The frequency related to millisecond firing is very frequently dominating in the structure of the created vibrations. This observation is supported by the structure of vibrations produced during the detonation of a series of 35 charges, 65 kg each, in a limestone mine. The detonation used i-kon electronic blasting system, and the delay was 60 ms. For the seismogram of the recorded vibrations, see Figure 13, and for the analysis of the vibrations for each component using MP algorithm, Figures 14 through 16.

The results of this analysis show that it is difficult to separate Gabor atoms for each of the 35 explosive charges fired one after another. The high precision provided by the electronic blasting system (accuracy up to 1 ms) caused the detonation of individual charges to generate vibrations with virtually uniform dominant frequency, 16.7 Hz, as represented by the most significant Gabor atoms 0, which account for the largest proportion of signal energy (Fig. 16). For horizontal components *x* and *y,* these account for nearly 80% of signal energy, which means that

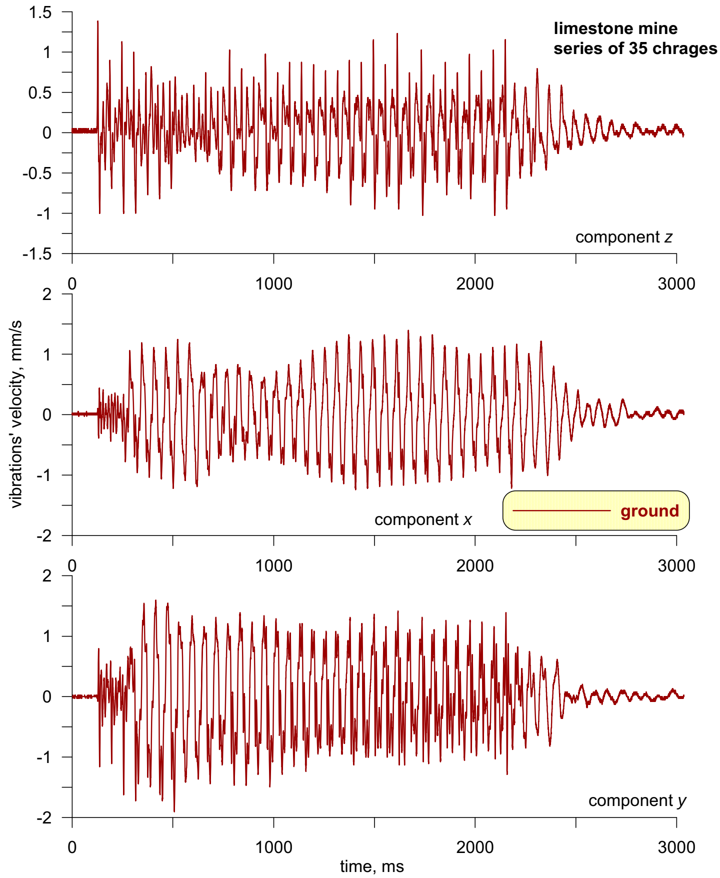
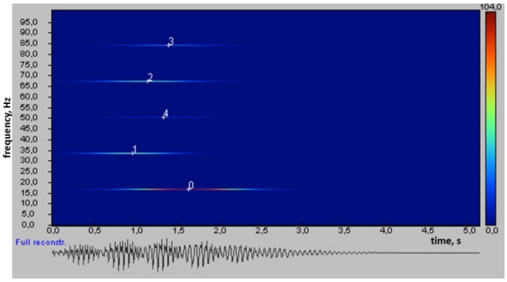
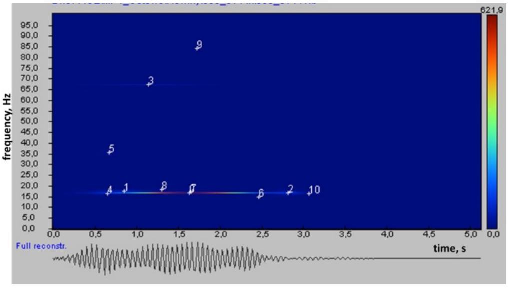


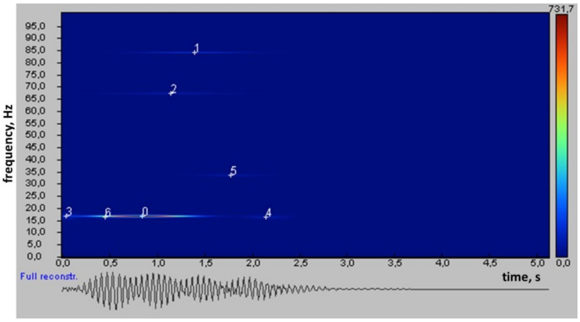
Fig. 13. Seismogram of vibrations recorded for explosive charges detonated in a limestone mine using an electronic blasting system (60 ms delay)



a) component z

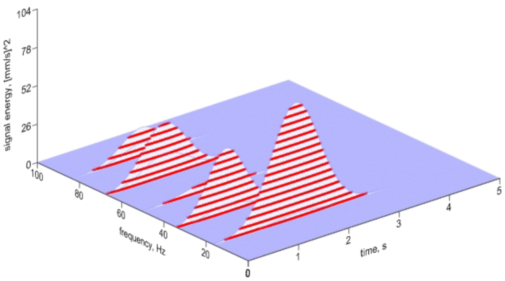


b) component *x*

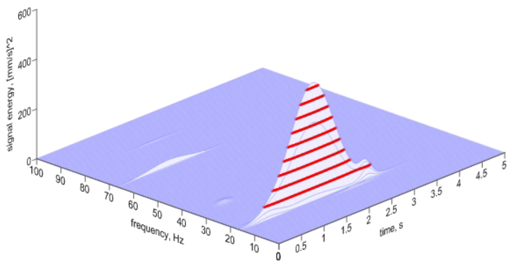


c) component *y*

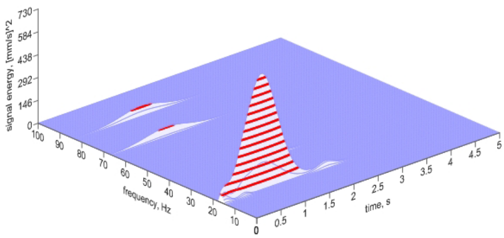
Fig. 14. MP analysis – Wigner-Ville map of ground vibrations



a) component *z*



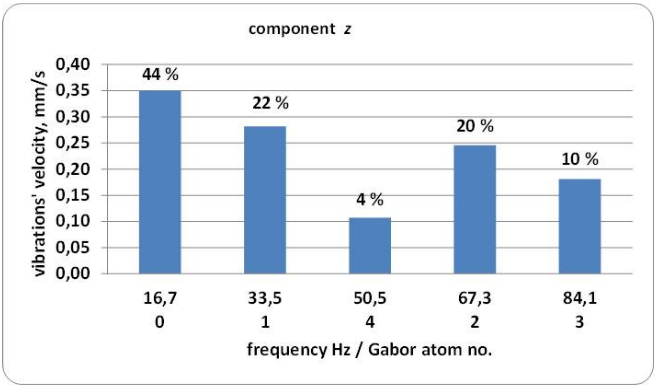
b) component *x*



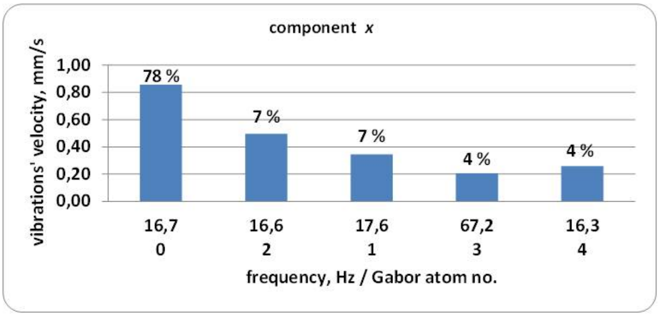
c) component *y*

Fig. 15. MP analysis of ground vibrations – spatial representation

a)



b)



c)

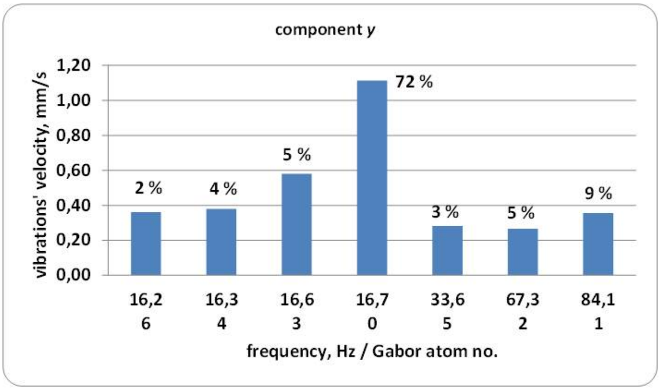


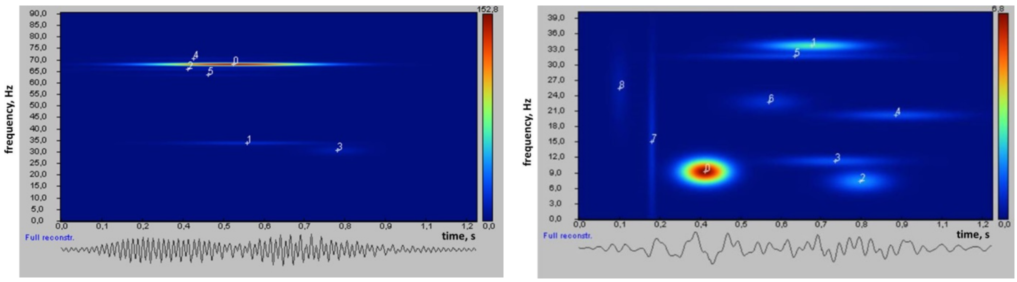
Fig. 16. Gabor atom histograms – MP analysis of ground vibrations

the impact of other frequencies can be disregarded, as they play a minor role in reconstructing the original process.

Blasting works with ever more advanced and accurate blasting systems makes it necessary to analyse the impact of millisecond delays on the frequency levels and characteristics of the produced vibrations. My research on the choice of delay appropriate for specific blasting conditions has shown that such vibrations tend to have frequencies corresponding to the delay used. This is true for vibrations propagating both through the ground and when they reach the foundation.

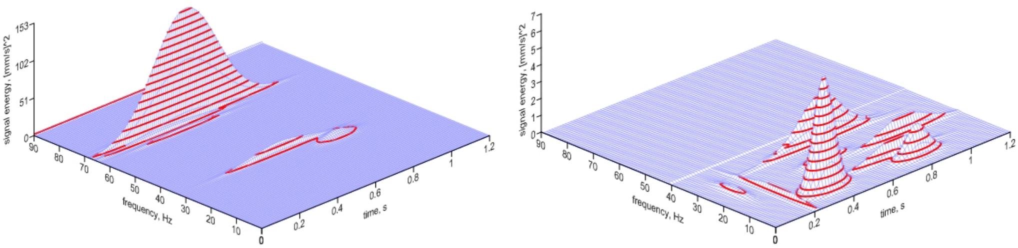
In the discussed example, a 60 ms delay was used, and the produced characteristic frequency was 16.7 Hz.

In addition, to further emphasise the importance of the above-mentioned conclusions, Figures 17 through 19 show analysis results for vibration levels for horizontal component *x* using MP algorithm, for electronic blasting with a delay of 30 ms, also in a limestone mine.



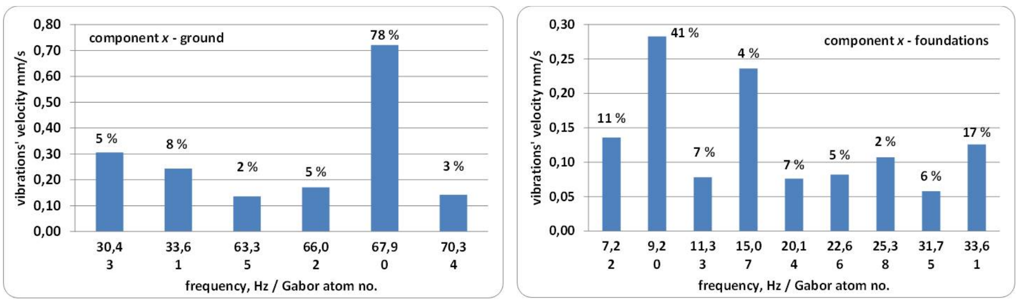
a) ground b) foundation

Fig. 17. MP analysis – Wigner-Ville map of ground and building foundation vibrations – 30 ms delay – component *x*



a) ground b) foundation

Fig. 18. MP analysis of ground and building foundation vibrations created by millisecond-delay (electronic) firing of explosive charges – 30 ms delay – spatial representation



a) ground b) building foundation

Fig. 19. Gabor atom histogram – MP analysis of ground and building foundation vibrations – 30 ms delay

The spatial representation and histograms depicting analysis results for ground and building foundation vibrations clearly show the impact of highly accurate millisecond delays. For a 30 ms delay, the dominating frequency is 67.92 Hz (78% of signal energy) and a (dominating) natural frequency of delay is 33.61 Hz (8%); at a point when vibrations reach the foundation, vibrations are considerably attenuated, and their structure changes to low band – 9.17 Hz (41% of signal energy) and 33.61 Hz (17%).

These examples of findings from the analysis of vibration levels based on MP algorithm show how significant millisecond delays might be for the structure of vibrations generated by the detonation of explosive charges, and this, in turn, might impact on the interactions between buildings and ground, which is very important for making the choice of millisecond delay best matching local conditions.

4. Discussion and conclusion

The assessment of vibrations generated during explosive blasting is difficult and raises many concerns. One of the reasons for this is that such vibrations have different characteristics than those that are continuous and harmonic, and are the subject of standard *PN-B-02170:2016-12* and its SWD scales.

MP algorithm opens up new opportunities for exploring correlations between:

- source characteristics and the level and characteristics of propagated vibrations in local geological/mining conditions,
- characteristics of ground vibrations and the degree to which these are attenuated when reaching the foundations of protected buildings.

It also offers detailed information to confirm that

- the proportions of individual frequencies in signal energy are crucial,
- the duration of individual Gabor atom signals significantly affects vibration levels, with short durations possibly representing high velocity amplitudes but small percentages of signal energy, while long atom signals can show low velocity amplitudes but large percentages of signal energy, which could suggest that these be taken into consideration when assessing vibration impacts,
- for explosive charges fired with a delay, natural frequencies characteristic of that delay may appear, and this information could be valuable for selecting the appropriate delay for explosive charge detonation.
- MP algorithm accurately identifies Gabor atoms and, consequently, frequencies that make up the vibration signal,

All these are of crucial importance for research on vibration propagation near blasting sites and its impact on buildings.

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