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Wavelet descriptors of paraseismic vibrations in building protection

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Abstract. In quarries, blasting works usually result in creation of serious danger for the surrounding buildings and constructions. Most methods used currently for low-frequency vibration hazards estimation are usually based on simple spectral analysis. Such an analysis is not really adequate to the nature of such a signal consisting of non-stationary series of impulses.

The authors of the paper suggest usage of wavelet analysis for paraseismic signal description. With the proper choice of wavelet function, scanning of the scalogram allows: good localization in time and good localization in frequency of events critical for sake of the signal maximum power and energy; it also allows for testing events relation depending on series of explosions and the millisecond delays in between fired explosives.

Having accessed a vast experimental results from blasting works, the authors elaborated signal descriptors in a form of vector of hazards, which is simpler than a 1/3 octave spectrum and more sensitive to the blasting conditions and parameters and wave propagation in the ground. The results of the research are potentially a base for standards and safety-related guidelines development. Also suggestions for quantitative comparison factors are presented for the eventual reference scale.

Keywords: wavelet transform, paraseismic vibration, signal processing, building protection

1. Introduction

With currently observed tendencies of increasing the number of road and building investments, one should expect increase in mineral resources exploitation used in building, mainly breakstone and limestone. That shall effect in quarries development, which expanding will take more and more space moving their boundaries closer to the inhabited areas. Until now, mostly classical methods of paraseismic vibrations analysis are used [7]. New methods based on 1/3 octave filtering and Fourier transform are introduced but their character is often inadequate to the paraseismic signals. Still, a description method of paraseismic vibrations is searched that would clearly expose those features of vibration signals that are critical from the point of view of vibration hazards elimination in proximity of quarries, with special consideration to the phenomena of vibration transfer from the ground to the building foundations.

Wavelet analysis [8] is already well known tool, but because of its high demands towards computing machines only in last years it is becoming more and more popular. Continuous Wavelet Transform (CWT) is one of many time-frequency analysis tools, allowing time variance tracing of particular frequency components of the analysed signal. As opposed to Short Time Fourier Transform (STFT), WT is good enough in exposing local features in both domains — time and frequency — which is very important in non-stationarity of considered type of signals [1, 2].

2. Signal preparation

Figure 1 shows signal preparation stages for the analysis.

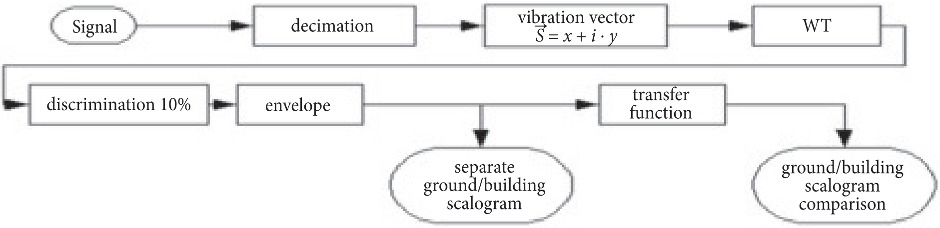

Fig. 1. Signal preparation stages

The vibration signal is measured on the building foundation and on the ground in the building neighborhood. The recorded signal is first decimated to limit the size of data. Sampling frequency of 500 Hz is just enough in this application. Then, out of horizontal components x, y of signal, the vibration vector $\vec{s}$ is created. For this example's simplicity, the vertical component z is not taken into account. The wavelet coefficients are calculated. Since that generates huge amount of data, they are reduced with 10% discrimination and envelope calculation. The transfer function of the vibrations might be calculated by dividing wavelet coefficients of the signal recorded on the buildings foundation by coefficients of the signal recorded on the ground. Figure 2 shows an example of both results of separate signals' coefficients and transfer function.

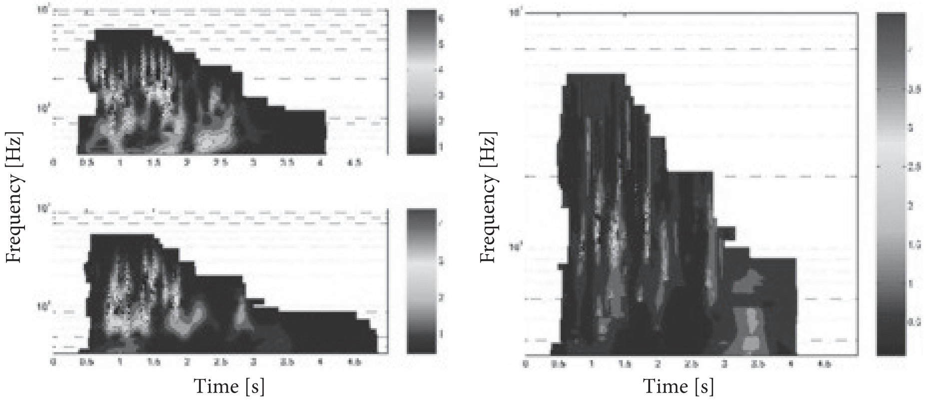

Fig. 2. Sample scalograms of vibration signals

In all figures, frequency is used instead of scale. Frequency is calculated based on scale and wavelet type as follows:

$$F_a = \frac{\Delta t \cdot F_c}{a}, \tag{1}$$

where: a — scale;
F_a — frequency associated with given wavelet at given scale;
F_c — center frequency of the given wavelet (here biorthogonal 2.8, $F_c = 0.883$ Hz);
Δt — sampling period.

3. Energetic reprezentation of CWT

CWT preserves the energy of signal, described with Eq. (2):

$$E_S = \frac{1}{\eta}\iint\limits_S cwt^2(a,b)\frac{dadb}{a^2}, \tag{2}$$

$$S = A \times B,$$

where: $\eta := \int\limits_{-\infty}^{\infty} \frac{\left|\hat{\psi}(\omega)\right|^2}{|\omega|} d\omega < +\infty$ — normalization coefficient of chosen form of wavelet function [4] hence, local value of energy related to the area $[a, a + \Delta a] \times [b, b + \Delta b]$ of the form:

$$E_\Delta(a,b) \approx \frac{1}{\eta} cwt^2(a,b)\frac{\Delta a \Delta b}{a^2} \tag{3}$$

emerges from Eq. (2) with the condition $S \to \Delta a \Delta b$, As a result, a power distribution of the signal in the area $A \times B$ is a square function of CWT, Eq. (4):

$$I_c(a,b) = \frac{1}{a^2} cwt^2(a,b) = \left[C(a,b)\right]^2 \tag{4}$$

and its linear representation has a form of Eq. (5):

$$C(a,b) = \frac{1}{a} cwt(a,b) \tag{5}$$

and is CWT modification related to the scale unit (constant bandwidth spectrum analogy) [1, 2].

3. Seismic event

So, we have a spectrogram of a ground vibration. As one can notice, there are several phenomena which could be described as a „seismic event". Such an event is a significant „hill" in the spectrogram, which could be seen in a figure below [3].

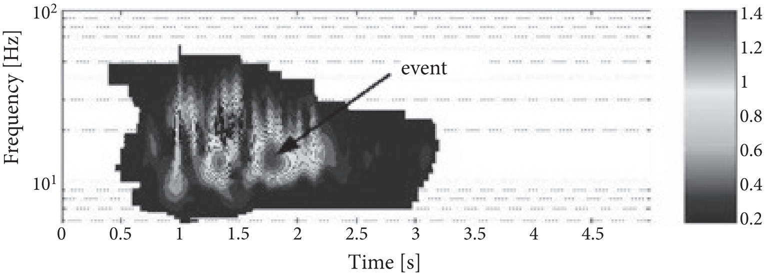

Fig. 3. An example of seismic event (scale converted to frequency)

Let us have a closer look at the event. A seismic event could be viewed as general area in time-frequency space. It might be described with several parameters like the time expansion ΔT, the time localization t, the frequency extrusion ΔF, and frequency localization. The event has one more parameter assigned which might be understood as its „elevation" — that is energy of the event defined with Eq. (6):

$$E_w = \int_{\Delta T} \int_{\Delta F} C_{xx}(f,t)\,df\,dt, \tag{6}$$

where: E_w — event energy;

t, ΔT — time, time range;

f, ΔF — frequency, frequency range;

C_{xx} — wavelet coefficients of observed paraseismic signal.

So, we get a feature vector of an event containing its critical parameters (Fig. 4):

$$\vec{q} = [\Delta T, f, E] \tag{7}$$

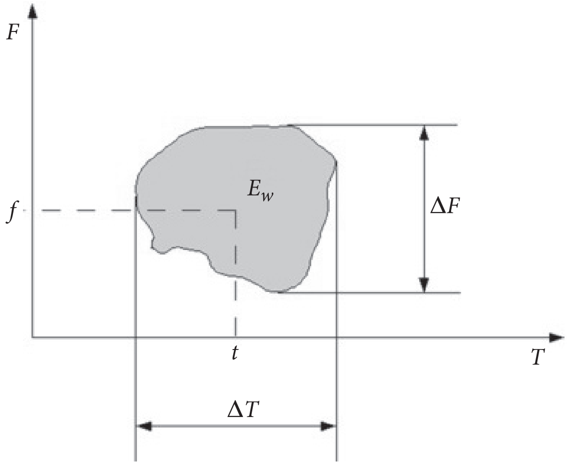

Fig. 4. *Seismic event* parameters definition

Since ΔT, f, and E are variables of different measures, units and values, we shall introduce scaling factors a_t, a_f, and a_E of such units and values so that the vector $\vec{p}$ is normalized vector $\vec{g}$ and its components are of no measure or unit:

$$\vec{p} = \left[\frac{\Delta T}{a_t}, \frac{f}{a_f}, \frac{E}{a_E} \right]. \tag{8}$$

4. Vector of hazards

A vector, which coordinates allow assessment of momentary power maximum for 3D vibrations, its localization — (Δa, Δb) area and space direction allows *in situ* better estimation of hazards than currently used methods.

Let us rewrite above statement for simplicity:

$$\vec{g} = [\alpha, \beta, \gamma], \tag{9}$$

where: α, β, γ — normalized components derived from the vector $\vec{p}$, Eq. (8).

For more observations of the phenomena feature, a matrix can be built which describes all significant events appearing in the signal:

$$G = \begin{bmatrix} \alpha_1 & \beta_1 & \gamma_1 \\ \alpha_2 & \beta_2 & \gamma_2 \\ \vdots & \vdots & \vdots \\ \alpha_n & \beta_n & \gamma_n \end{bmatrix}, \tag{10}$$

where n is the number of events in a single signal.

Such a matrix might be plotted in 3D chart, one vector per row. Now, the question of assessment criteria arises. With the vector $\vec{v}$, normalized with the carefully chosen a_t, a_f, and a_E factors it is very easy to set safety limits for the vibration observation. All events' vectors should contain themselves totally in unity sphere in the co-ordinate system. Such situation is shown in Fig. 5. In this case, all the vector coefficients are positive so, it is enough to present only one eighth of the 3D space.

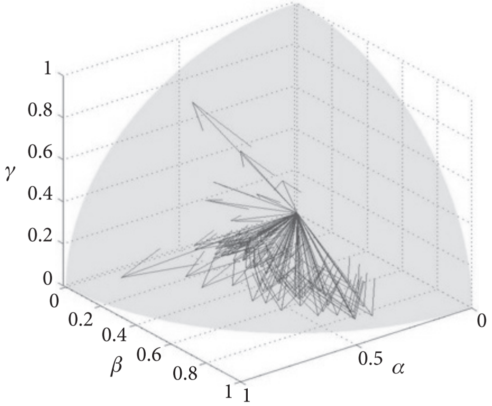

Fig. 5. Feature vector visualization, vector limit surface, only positive halves of axes shown as relevant. α, β, γ are the components of the vector $\vec{h}$ (see Eq. 12)

5. 3D trajectories

There are more components that add to the hazard vector. Let us consider the vibration signal of three components: x, y, z. Its plot in 3D space produces a movement trajectory. Wavelet transform is used in this case to find critical trajectories defining limits of safe vibration parameters, see Fig. 6. Figure 7 shows the transformation stages for the trajectories.

Reconstruction is conducted after preliminary scalogram testing for seismic events. Then, the signal fragments are selected to reflect the area of seismic event existence. After reconstruction u, v, w components are calculated and appended with proper scaling coefficients to the vector $\vec{p}$:

$$\vec{p} = \left[\frac{\Delta T}{a_t}, \frac{f}{a_f}, \frac{E}{a_E}, \frac{u}{a_u}, \frac{v}{a_v}, \frac{w}{a_w} \right], \tag{11}$$

which results in the extended vector $\vec{g}$ and the matrix **G**:

$$\vec{g} = [\alpha, \beta, \gamma, \delta, \varepsilon, \zeta], \quad \mathbf{G} = \begin{bmatrix} \alpha_1 & \beta_1 & \gamma_1 & \delta_1 & \varepsilon_1 & \zeta_1 \\ \alpha_2 & \beta_2 & \gamma_2 & \delta_2 & \varepsilon_2 & \zeta_2 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \alpha_n & \beta_n & \gamma_n & \delta_n & \varepsilon_n & \zeta_n \end{bmatrix}, \tag{12}$$

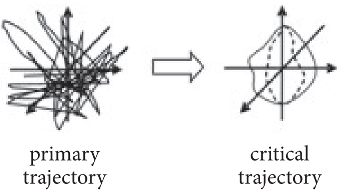

Fig. 6. Primary to critical trajectory transformation

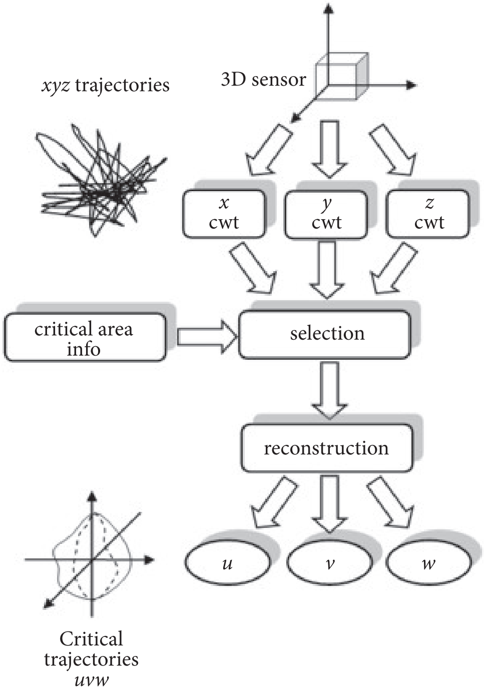

Fig. 7. Transformation diagram for trajectories

The scaling coefficients a_y, a_f, a_E, a_u, a_v, a_w are the factors of different units. After normalization, the vector of hazards has no units and no direct relevance to its physical aspect. Instead it constitutes a mathematical measure for assessment of hazards caused by vibration. This allows the comparison between different occurrences of the vibration independently of the place and type of ground they were recorded on. The authors do not suggest the method for choice of the scaling coefficients at the moment as it requires further research.

6. Example

The example shows hazard vectors and primary trajectory for one sample vibration signal recorded on the foundation of the building. The scalogram contained three seismic events. The respective hazard vectors are presented in Fig. 8(a). Also, the sample primary trajectory for the x-channel (longitudinal vibration signal) is presented in Fig. 8(b).

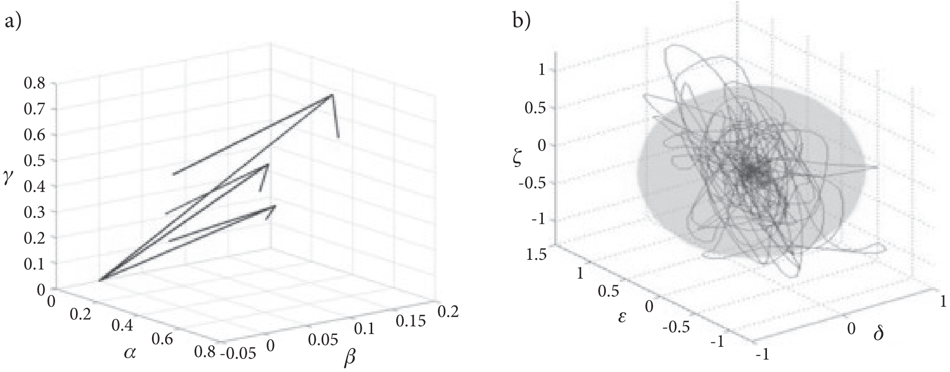

Fig. 8. a) Sample hazard vectors, g — three events of the largest energy chosen, the events differ in time and frequency range; b) sample primary trajectory plot together with critical trajectory (green)

7. Summary

The paper presents construction of a hazard vector and hazard matrix for paraseismic vibrations using digitally recorded vibration signal and wavelet transform as a method of analysis. Process of observation approach frees oneself form necessity of having detailed knowledge on the object of the measurement, which is often very hard if not impossible to acquire. The presented solution utilizes well known mathematical tools for the area where there is a lack of modern approach and modern tools of analysis and it is the first simple proposal. Further extension to the theory is still elaborated since there is a large number of measurement data. The results will be published in future.

After several years of measurement material collection and research, the authors have proposed a solution for description of paraseismic vibration with the use of wavelet transform. The question of proper wavelet function choice for paraseismic vibration was discussed in Ref. 3.

Further research involves assessment of critical parameters variation range in acquired research material and application of factor analysis for estimation of main synthetic factors differentiating 3D vibration signals.

Symbols & abbreviations

CWT — Continuous Wavelet Transform,
C_{xx} — CWT coefficients,
WT — Wavelet Transform,
STFT — Short Time Fourier Transform,
ΔT — time range,
ΔF — frequency range,
$\boldsymbol{g}$ — vector of hazards,
$\boldsymbol{G}$ — feature matrix.

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Deskryptory falkowe drgań parasejsmicznych w ochronie budynków

Streszczenie. Drgania gruntu związane z pracami strzałowymi w kopalniach odkrywkowych mogą stwarzać zagrożenie dla pobliskich budynków. Jego ocena dokonywana jest zazwyczaj w oparciu o prostą analizę spektralną mało adekwatną impulsowej i niestacjonarnej naturze drgań w miejscu posadowienia budynku. Autorzy proponują wykorzystanie analizy Falkowej. Właściwy wybór falki pozwolił na dobrą lokalizację czasowo-częstotliwościową lokalnych maksimów mocy i w konsekwencji selekcję i opis ilościowy cech sygnału krytycznych z punktu widzenia potencjalnych zagrożeń. Ich zbiór uzyskany w oparciu o bogaty materiał eksperymentalny *in situ* uzasadnia zdaniem autorów wprowadzenie charakterystyki wektora zagrożeń jako syntetycznej charakterystyki docelowej stwarzającej potencjalną podstawę bardziej precyzyjnej organizacji robót strzałowych, zwłaszcza odstępów czasowych i kolejności wybuchów. Przedstawiono przykłady analizy realnych sygnałów.

Słowa kluczowe: analiza falkowa, drgania parasejsmiczne, przetwarzanie sygnałów, ochrona budynków