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IMPROVED BLAST VIBRATION ANALYSIS USING THE WAVELET TRANSFORM

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Explosive blasting is commonly used for the retrieval of usable materials or to excavate underground spaces. One of the most significant side effects produced by the explosive blasting process is the generation of vibrations which propagate through the ground and can travel great distances. Since it is becoming increasingly common for mining sites to be located near urban areas, the generated ground vibrations can induce not only cosmetic and structural damage, but also discomfort or injury to residents. Blasting engineers are constantly faced with an unavoidable compromise; while the purpose of a blast is to fragment as much rock as possible, any increase in the size and energy of the blast can generate larger ground vibrations near the surrounding urban areas. The current monitoring and analysis of ground vibrations due to blasting are simplistic approaches which monitor only the dominant frequency and peak particle velocity of the measured ground vibrations. This paper presents initial research into the use of the wavelet transform to provide an improved approach for investigating and analysing blast-induced ground vibrations. An overview of the two time-frequency methods; the short time Fourier transform, and wavelet transform, is included, along with an outline of the process for selecting a suitable wavelet for blast-induced vibrations. A series of blast-induced vibration records were obtained from a quarry in Wallonia, Belgium, and analysed using the two time-frequency methods for comparison.

Keywords: blast vibration, blasting, ground vibrations, vibration analysis, wavelet analysis

1. Introduction

Urban areas are constantly subjected to ground vibrations from various man-made sources. The ground vibrations must be carefully controlled and monitored in order to ensure that they do not induce damage to structures and discomfort to occupants in these urban areas. The most common man-made sources of ground vibration in urban areas are road and rail traffic, construction machinery, pile driving, and explosive blasting. Table 1 presents the typical frequency and particle motion ranges for these man-made sources of excitation. From the table, it is evident that explosive blasting produces very high level and broad frequency ground vibrations in comparison to the other sources.

Table 1: Typical ranges of the frequency, and particle motions by man-made sources, from ISO 4866 **[1]**.

Source of Excitation	**Frequency Range [Hz]**	**Particle Velocity Range [mm/s]**	**Particle Acceleration Range [m/s^2]**
Road and rail traffic	1 – 100	0.2 – 50	0.02 – 1
Blasting	1 – 300	0.2 – 100	0.02 – 50
Pile Driving	1 – 100	0.2 – 100	0.02 – 2
Outside Machinery	1 – 100	0.2 – 100	0.02 – 1

Some potential mechanisms of structural damage due to ground vibrations generated by an explosive blast can range from superficial (e.g. crack formation and extension, loosening of plaster, etc.) to severe (e.g. large crack formation and extension, foundation shift, etc.) [2]. As it is becoming increasingly common to find mining sites located close to urban areas, careful blast planning and monitoring procedures must be followed. In some cases, preliminary testing may also be required, and the site engineer is responsible for ascertaining as much information about the blast as possible in order to make informed decisions [3].

The current analysis approach for blast-induced vibrations, discussed in Section 2, are aimed at providing an overview of the measured blast-induced ground vibrations and rely on the use of simplistic single-number indicators. Furthermore, since blast-induced ground vibrations measured in the far-field are highly nonstationary, improved understanding and analysis can be achieved using more advanced approaches. The research presented in this paper is focused on demonstrating the effectiveness of the Wavelet Transform (WT) to analyse the highly nonstationary blast-induced ground vibrations in comparison with standard analysis approaches.

2. Blast-Induced Vibrations

Explosive blasting is generally used to break a rock mass into sufficiently small fragments, which can then be transported and processed for use in various applications, or to excavate underground spaces such as tunnels. To achieve this, boreholes are drilled into a section of the rock mass and explosives are placed inside. The explosives are then detonated in a predetermined sequence to fragment the rock mass, exerting high pressures on the borehole walls [4]. One main side effect of explosive blasting is the generation of ground vibrations, which can propagate in numerous directions and can reflect / refract between the layers of the soil, as demonstrated in Fig. 1. Due to the nature of blasting, the generated ground vibrations are highly nonstationary and have a very short duration. This section discusses the various approaches for analysing blast-induced ground vibrations.

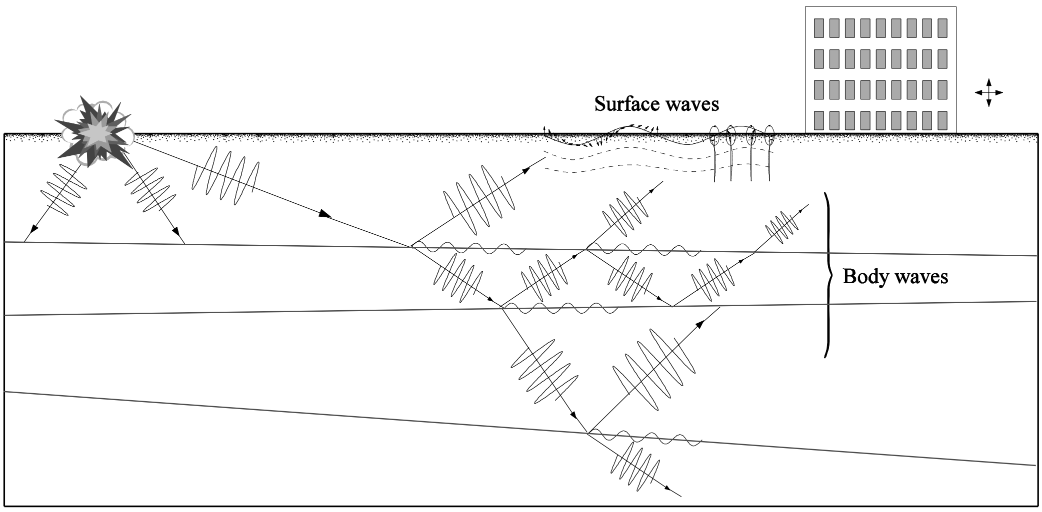

Figure 1: An illustration of the propagation of body and surface waves generated by an explosive blast.

2.1 Current Analysis Approach

The current standard analysis technique for blast-induced ground vibrations near structures is outlined in DIN 4150-3 [5]. It is the principal guide for monitoring ground vibrations, based on studies which linked threshold values to structural damage. The standard stipulates that the three-axes of the ground vibrations are analysed to determine the Peak Particle Velocity (PPV) and the dominant frequency. Initially, the PPV was solely used to predict structural damage, however empirical evidence led to the introduction of a Z-Curve to link the dominant frequency, computed using the Fourier Transform (FT), to the PPV to predict damage for three general types of structures. An example analysis using the Z-Curve with blast vibration data is presented in Fig. 2. The main drawback of the standard analysis approach is that it only provides a simplistic overview of the entire vibration waveform. The user is unable to obtain any localised information on the signal's energy content.

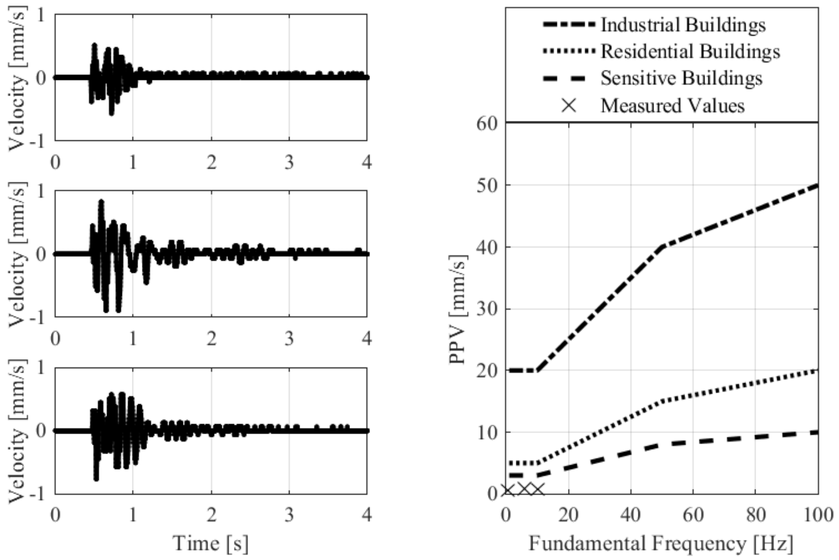

Figure 2: Typical example of blast-induced ground vibration analysis, with the measured vertical, radial, and transverse time histories, and the results presented on the DIN 4150-3 Z-Curve (right).

2.2 Time-Frequency Analysis Methods

This section discusses two time-frequency analysis methods to improve the analysis of blast-induced ground vibrations.

2.2.1 Short Time Fourier Transform

The Short Time Fourier Transform (STFT) is one of the most widely used methods to analyse nonstationary vibration records. Due to the technique's widespread use, no detailed discussion on its implementation is presented (see [6] for further details). The STFT decomposes a signal into equal sections, and computes the time-frequency distribution for each section. However, the STFT is subject to Heisenberg's uncertainty principle, limiting the time and frequency resolutions as per Eq. (1).

$$\delta t = \frac{1}{\Delta f} \tag{1}$$

where δt is the sub-record length (time between estimates), and Δf is the frequency resolution.

From Eq. (1), it is evident that a finer frequency resolution requires a longer time window, and vice-versa. Depending on the lowest frequency required, the user's ability to obtain accurate estimates that are well localised in time is often limited.

2.2.2 The Wavelet Transform

The WT has been the subject of research for numerous decades, and has a proven mathematical framework. The WT has two distinct implementations; the Discrete Wavelet Transform (DWT), and the Continuous Wavelet Transform (CWT). The DWT is best used for de-noising and compression of signals and images, since it can represent a signal with fewer coefficients in comparison to the CWT. However, the CWT allows for fine scale analysis and is used in this research to analyse the blast-induced vibrations. The CWT is continuous for two reasons: 1) the CWT is performed at every scale up to the maximum scale that is determined by the user, and 2) the wavelet is smoothly shifted across the entire domain of the signal. The CWT provides the scale-dependent structure of a signal as it varies with time, and since the scale-dependent structure is essentially the instantaneous frequency, the CWT is able to compute the time-frequency distribution of a signal [7]. The WT of a signal $x(t)$ is defined in Eq. (2).

$$W(a,b)=\frac{1}{\sqrt{a}}\int_{-\infty}^{\infty}x(t)\psi^{*}\left(\frac{t-b}{a}\right)dt \tag{2}$$

where $\psi(t)$ is the mother wavelet translated by b and dilated by a, $*$ denotes conjugation, and t is time.

The translation parameter b is used to move the wavelet along the length of the signal to find changes at each location in time where the wavelet is centred. The dilation factor a acts as a scaling parameter for the mother wavelet and stretches or shrinks the wavelet in time. A larger scaling factor stretches the mother wavelet and corresponds to low frequencies (i.e. slowly varying changes in the signal), while a smaller scaling factor shrinks the mother wavelet and corresponds to high frequencies (i.e. abruptly varying changes in the signal). This ability to shift and scale the mother wavelet is one of the principal advantages of using the CWT, enabling the transform overcome the aforementioned temporal-frequency limitation of the STFT.

It is important to correctly set the scales when using the CWT to obtain relevant time-frequency resolutions. The scales are defined in terms of octaves and voices, where the number of octaves N_{oct} determines the frequency range, and the voices per octave N_{voi} determines the number of samples, or scales, across each octave. While there is no exact relationship to convert scales to frequency, a close approximation to determine the pseudo-frequency F_a can be used, given in Eq. (3).

$$F_a=\frac{F_c}{a\cdot dt} \tag{3}$$

where F_c is the wavelet's centre frequency, a is the dilation factor, and dt is the sampling period.

Another principal advantage of the WT over the STFT is the large selection of wavelets available. Various mother wavelets have been developed and used for numerous applications, and the choice of mother wavelet depends on a number of factors. The general rule for wavelet selection is to choose a wavelet which has the greatest similarity to the features the user desires to extract [8]. Analytical wavelets are well-suited for time-frequency analysis as they do not have negative frequency components. Of the numerous wavelets available, the Morlet wavelet is very useful for time-frequency distributions. The Morlet wavelet is a complex exponential function multiplied by a Gaussian window, and its scale can be more easily expressed in the frequency domain [9]. The selected mother wavelet to analyse the ground vibrations is the analytic Morlet wavelet, shown in Fig. 3.

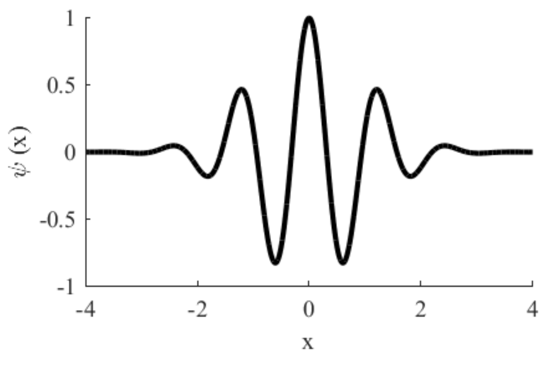

Figure 3: The Morlet mother wavelet used with the Continuous Wavelet Transform in this study.

Finally, a conceptual illustration is presented in Fig. 4 to demonstrate the time-frequency (time-scale in the case of the CWT) relationships of the FT, the STFT, and the WT. Note how the WT overcomes the traditional time-frequency relationship by using translation and dilation factors to modify the mother wavelet and provide an improved representation.

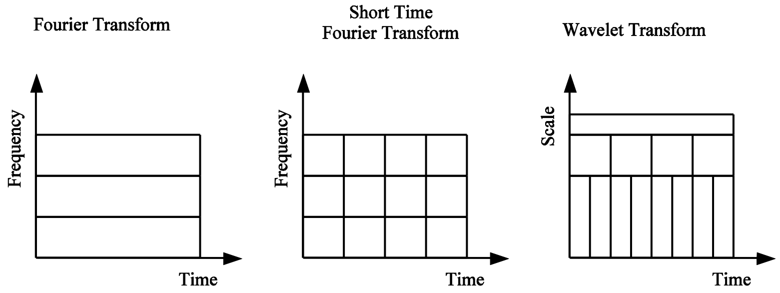

Figure 4: Conceptual comparison of the time-frequency relationship using the Fourier Transform, the Short Time Fourier Transform, and the Wavelet Transform.

3. Experimental Analysis

A series of blast vibration measurements were obtained for a variety of different blast designs and locations surrounding a quarry near Tubize, Belgium. Seismometers were used to measure the tri-axial velocity of the ground (vertical, radial, and transverse) at various locations around the site. The measurements were recorded as part of required monitoring procedures during the period of January 2015 to January 2016. Despite the large number of records, only two blast-induced ground vibration records (tri-axial records sampled at 1024 Hz for a duration of 4.5 s) are presented in this paper. The time histories of the vertical ground vibration measurements analysed in this study, labelled BL_01, and BL_02, are presented in Fig. 5. It should also be noted that preliminary inspection of the data revealed no significant energy content above 100 Hz, and so the analysis shown in this paper is presented from 0 – 100 Hz.

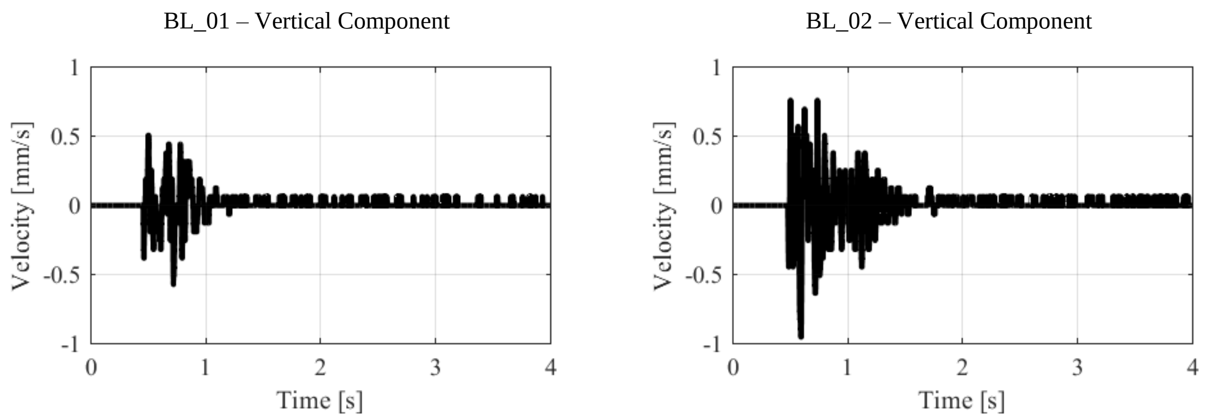

Figure 5: Sample time histories of the blast-induced ground vibrations analysed in this paper.

Prior to providing a comparison between the CWT and the STFT to analyse the blast-induced ground vibrations, it is important to demonstrate the effect of varying the sub-record length of the STFT. As shown in Eq. (1), increasing the sub-record length results in a finer frequency resolution, and Fig. 6 presents the time-frequency analysis of the vertical vibration component of record BL_01 using different sub-record lengths (δt) of 0.25, 0.50, 1.00, and 2.00 s. Due to the short duration of the record and low frequency range of interest, it is difficult to clearly identify the distribution of the energy content using the STFT for any of the sub-record lengths set. Furthermore, rapid changes in the frequency content of the vibration records are unable to be clearly identified without a significant loss in frequency resolution.

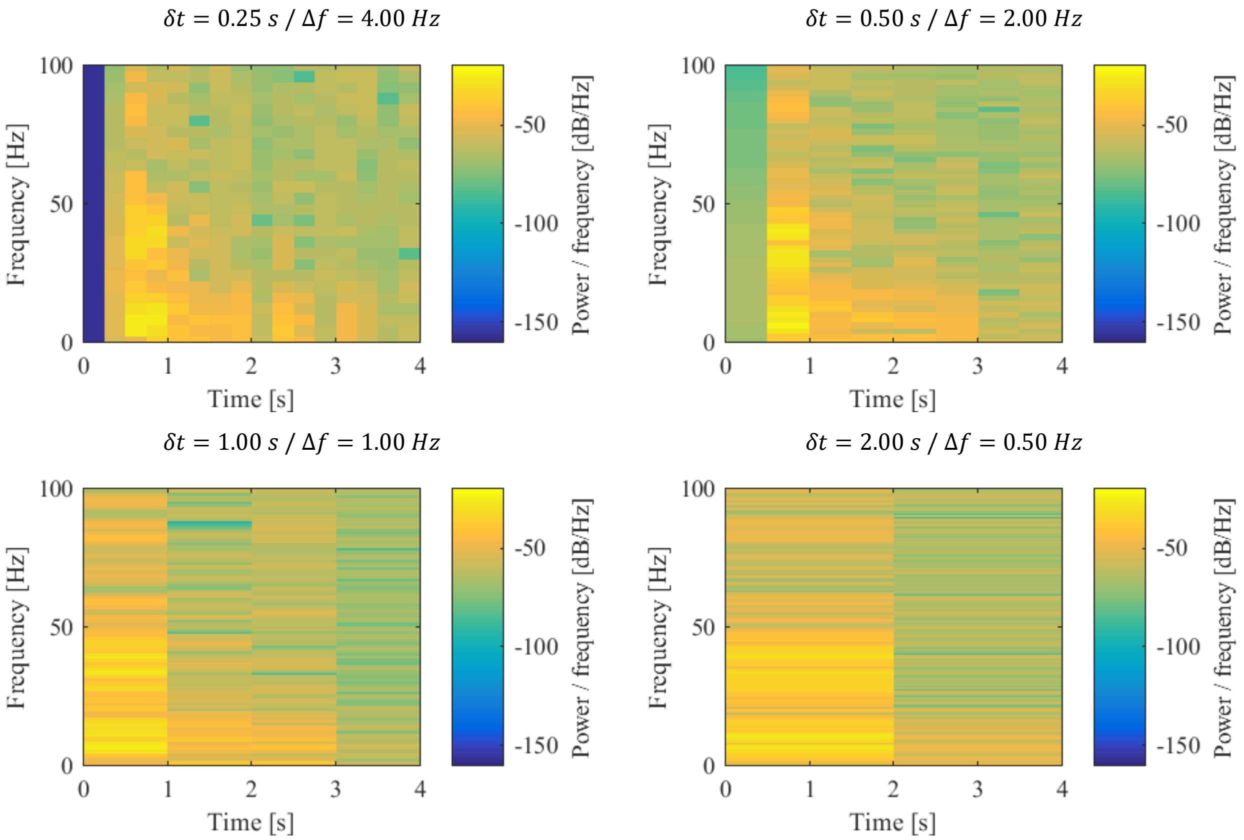

Figure 6: Comparison of the influence of varying the sub-record length (δt) of the Short Time Fourier Transform on the time-frequency analysis of the vertical vibration component from record BL_01.

Next, the time-frequency distribution of the blast-induced vibration records using the STFT with a sub-record length of 0.25 s, and the CWT are compared. The CWT was used with the analytical Morlet wavelet, and set to have 10 octaves, each with 10 voices per octave. The vertical vibration of record BL_01 is analysed using both the STFT and the CWT, shown in Fig. 7. From the figure, it can be seen that the CWT provides a far superior time-frequency distribution of the blast-induced ground vibrations. The changes in the frequency content of the record can be easily identified using the CWT, while the STFT is unable to clearly detect these abrupt changes.

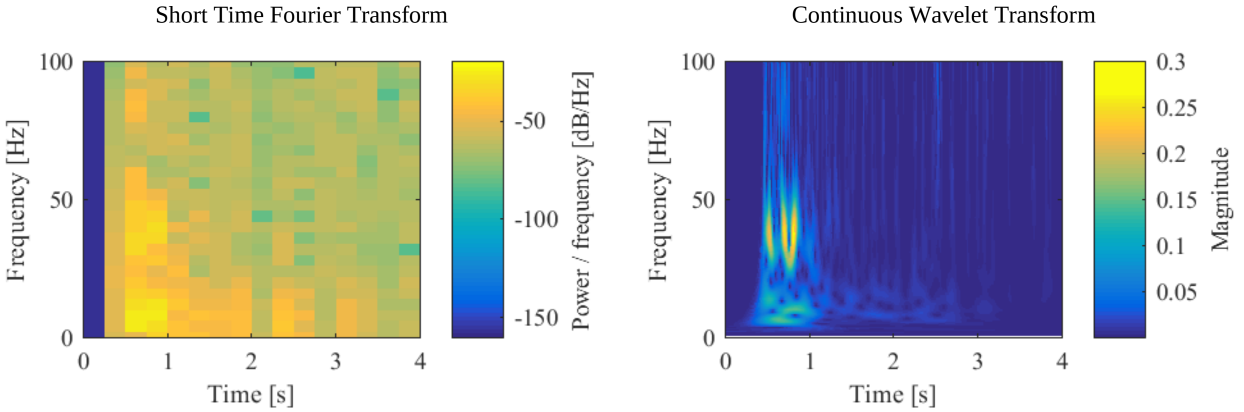

Figure 7: Comparison of the time-frequency analysis of the vertical component of the ground vibration record BL_01 using (a) the Short Time Fourier Transform ($\delta t = 0.25\ s$ / Δf = 4.00 Hz), and (b) the Continuous Wavelet Transform (N_{oct} = 10, N_{voi} = 10).

Having demonstrated the advantage of using the CWT over the STFT, the CWT was used to analyse the vertical, radial, and transverse components of the two vibration records. The time-frequency analysis of the ground vibration records are presented in Fig. 8, display only the first 2 s of the data. Despite the short duration, and rapidly changing content of the tri-axial ground vibration records, the CWT's time-frequency analysis is able to provide localised information and the scale is fine enough to identify multiple dominant frequencies.

For example, the evolution of the frequency content of the vertical component of record BL_01 shows three significant peaks in the range of 30 – 45 Hz, with smaller peaks at approximately 7, 10, and 15 Hz. The information is well localised and each dominant frequency can be easily identified. The other records each have a similarly complex time-frequency distribution, and the clear identification of localised dominant frequencies from such a short record is something that the STFT is unable to achieve without a significant loss in the frequency resolution.

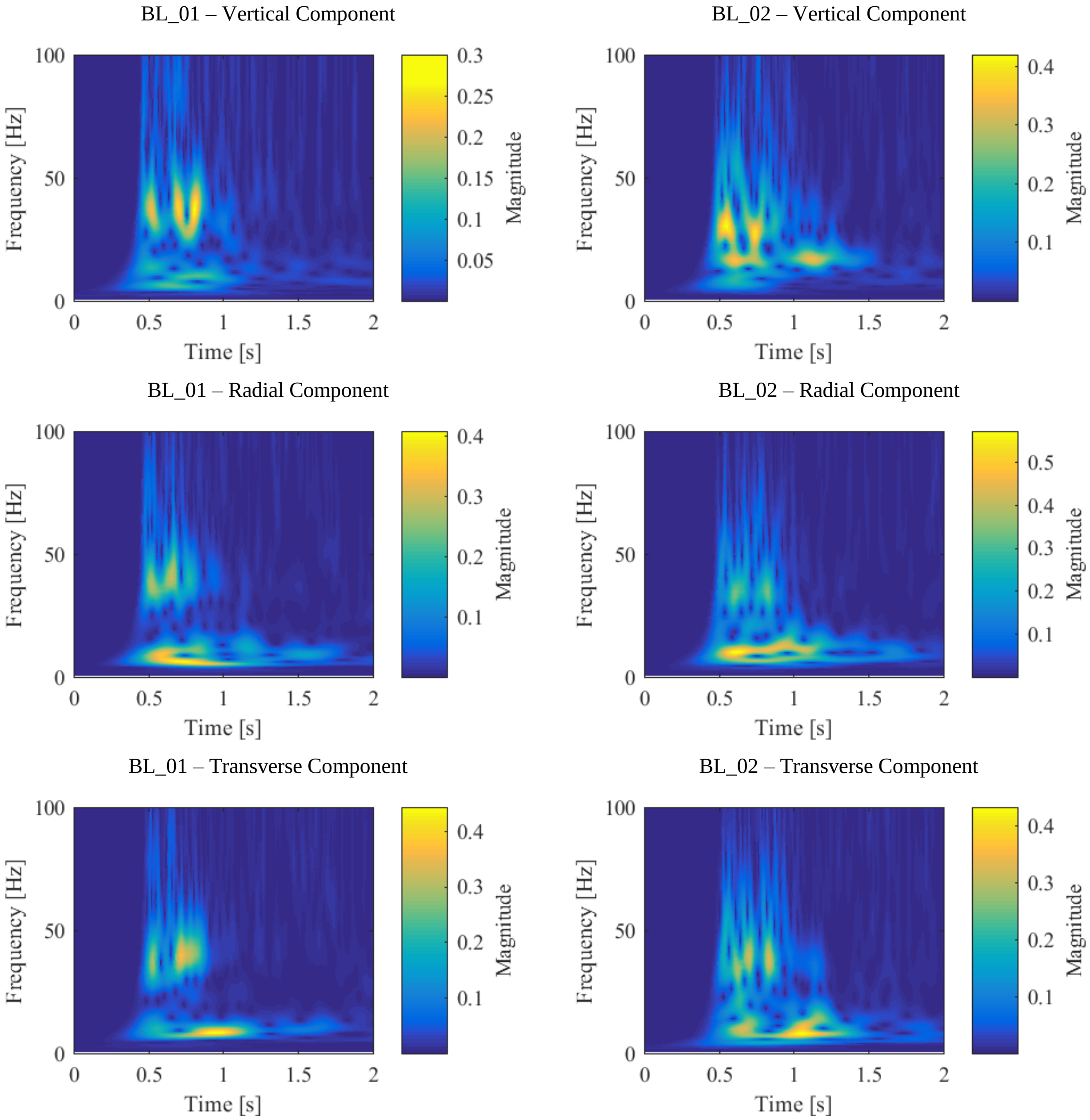

Figure 8: Time-frequency analysis using the Continuous Wavelet Transform (N_{oct} = 10, N_{voi} = 10) of the vertical, radial, and transverse components of the two blast-induced ground vibration records.

4. Discussion and Conclusions

Blast-induced ground vibrations pose a significant issue to structures and inhabitants in surrounding urban areas. The monitoring and analysis of blast-induced vibrations ensures that the ground vibrations generated are within the acceptable limits (often set out by various standards organisations). However, the main limitation of these standard methods for blast vibration monitoring and analysis is the lack of localised information provided. Furthermore, the short duration and highly nonstationary nature of the ground vibrations generated by an explosive blast pose additional challenge in their analysis. This paper presented an initial investigation into the use of the CWT (with the Morlet mother wavelet) to provide an improved analysis and representation of the measured blast-induced vibrations generated. Conventional analysis techniques were also discussed, including the FT, and the STFT. Blast-induced ground vibration measurements from a quarry in Belgium were analysed using the STFT, and CWT to establish the time-frequency distribution. The initial results showed that the CWT provides a superior time-frequency analysis of blast-induced vibration records compared to using the STFT. The CWT can be used to provide detailed, localised information on the frequency content of the blast-induced ground vibrations without the trade-off in temporal and frequency resolutions inherent in the STFT.

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