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# Application of wavelet transform to defect detection of building's structure

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## 1. Introduction

In recent years, in Lithuania the collapses of roofs and columns in accidents have occurred frequently. Various methods are being developed to examine the damage to the buildings. Many of them use various transformations of the measured signal such as Fourier transformation [1]. It allows on the base of modal analysis to analyse the structure's diagnostic signals, which changes due to construction defects. The problem is that Fourier transformation is based on one basic functions group – *sin*() and *cos*() and thus limits the analysis of non-stationary diagnostic signals. Therefore relevant methods for diagnostics purposes are those which allow analysing non-stationary signals, and also to associate them with the possibilities to determine the moment when the process becomes non-stationary. In our opinion, one of the possible methods is wavelet analysis. Wavelet transform has been increasingly applied to different engineering problems in recent years. One field of engineering which can apply the wavelet transform is damage detection [2-4] in the context of structural health monitoring. Damage detection is based on the assumptions that dynamic properties of the mechanical system change [5, 6]. There are a lot of studies for the identification of modifications in a system's dynamic response that is caused by structural damage were developed on the base of energy components of signals' wavelet decompositions [7-10]. Damage of the building is generally defined as the change in the structure characteristic which will affect the structure behaviour now and in the future.

Detecting means that the characteristic quantity before and after some moment should be compared to determine the damage occurring process [11, 12]. Therefore, it is important to detect damage using signal processing methods. Fourier transform method or Wavelet signal processing methods make it very suitable for signal processing and analysis. For structural determination of damages the wavelet method was used previously [13]. The wavelet method is new enough and effective for the diagnostics of structural damage. There is a close relationship between the wavelet method and frequency and time issues. The ability of this method is suitable for recognition of damage location [14].

Within the building engineering profession and its related researchers, wavelet-based techniques and applications continue to be developed. Examining the various subdiscipline areas, such as earthquakes, structures and materials results have indicated that wavelet based techniques can often provide a unique insight into the analysis and characterization of time series data, versus classical methods [15-22].

In this study, damage to structures, an analysis has been made in order to be detected by continuous wavelet transform (CWT).

## 2. Structure model and experiment system

In order to make experimental measurements the flooring structure system was designed. The structure of the floor is based on flat triangular bending elements model, whereas pillars were modelled from dimensional framework elements that could be stretched/compressed, bent and twisted. The pillars are set perpendicularly to the base and the floors. The load is evenly distributed for both floors. The model of the structure's model and experimental setup is shown in Fig. 1.

Fig. 1 Laboratory model of flooring building and experimental setup

The measurement points of the laboratory model of the flooring building as mechanical structure is shown in Fig. 2. The sensors, attached to the system at specific nine points are measuring dynamical processes at the structure.

Table 1 provides natural vibration frequencies of the floor structure model. This model can be used to simulate roof overload phenomenon. In case of the pressures or excessive loads on the roof the dynamic processes at the indicated measurement points should change. Using this assumption we also will try to analyse the influence of defects to the change of the measured dynamical process.

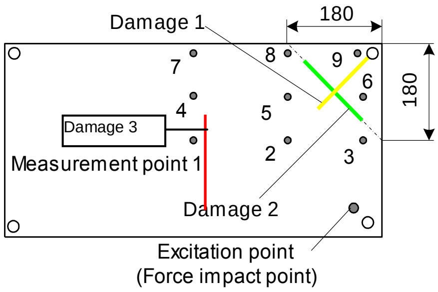


Fig. 2 Measurement points of the flooring structure model

Table 1

Natural vibration frequencies of the flooring model

| Model No | Frequency, rad/sec. | Frequency, Hz | Period, sec. |
|---|---|---|---|
| 1 | 144.03 | 22.922 | 0.043625 |
| 2 | 151.19 | 24.062 | 0.041559 |
| 3 | 252.48 | 40.184 | 0.024886 |
| 4 | 277.3 | 44.133 | 0.022659 |
| 5 | 288 | 45.836 | 0.021817 |
| 6 | 624.93 | 99.46 | 0.010054 |

In this experiment, the sampling frequency is 4098 Hz. The analysis of the data from measurement system was made using the MATLAB. For this purpose, considered measurement and data collection system was consisting of modal hammer for structure excitation, some transducers, and response analyzer Pulse 3560 of Brüel&Kjer.

### 2.1. System response

The Fig. 3 depicts acceleration response of the system as triggered at the second 1.

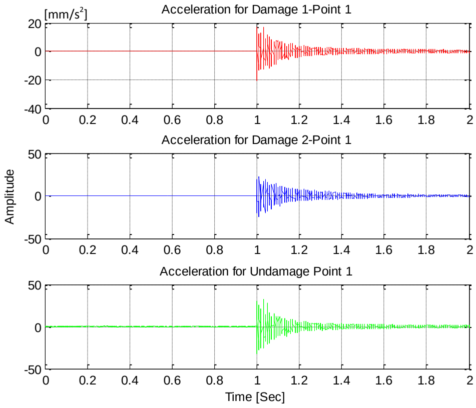


Fig. 3 System response of acceleration

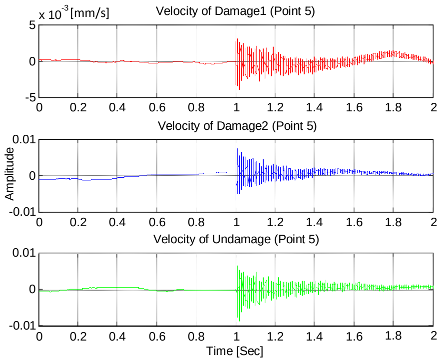


Fig. 4 System response of velocity

Similarly, the chart of vibrational velocity range is given in Fig. 4. To wavelet analysis of velocity of the damaged structure are important to analyse the system response. The system can be made for comparing the response of both damaged and undamaged structures and their data points.

## 3. Mathematical background

Although a lot of time-frequency transformations are available, only the Wavelet Transform (WT) is uniquely capable of adaptively adjusting to the Heisenberg uncertainty principle. The wavelet transform concedes that arbitrarily good resolution in both time and frequency is not possible [21].

Most of the signals in practice are time domain signals in their raw format. Plot time-domain signals obtain a time-amplitude representation of the signal. This representation is not always the best representation of the signal for most signal processing related applications. In many cases, the most distinguished information is hidden in the frequency content of the signal. The frequency spectrum of a signal is basically the frequency components of that signal. The frequency spectrum of a signal determines what frequencies exist in the signal. Frequency content of a signal can be found using Fourier Transform (FT). Besides the widely used Fourier transform scientists also apply Hilbert transformation, Short-Time Fourier transformation, wavelet analysis and Wigner Distribution. The Wavelet Transform provides the time-frequency representation and it is basically required to analyse non-stationary signals. WT solves the dilemma of resolution to a certain extent. WT is capable of providing the time and frequency information simultaneously, hence giving a time-frequency representation of the signal [22].

### 3.1. Continuous wavelet transform

The use of wavelet transform is particularly appropriate since it gives information about the signal both in frequency and time domains. Let $f(x)$ be the signal, the continuous wavelet transform of $f(x)$ is then defined as

$$Wf(a,b)=\int_{-\infty}^{+\infty} f(x)\psi_{a,b}^{*}(x)\,dx \qquad (1)$$

where (*) indicates the complex conjugate, and

$$\psi_{a,b}(x)=\frac{1}{\sqrt{|a|}}\psi\left(\frac{x-b}{a}\right);\ a,b\in R,\ a\neq 0 \qquad (2)$$

Here, $\psi$ is called as a wave or the mother wavelet and it have two characteristic parameters, namely, dilation (a) and translation (b), which vary continuously. The translation parameter, "b", controls the position of the wavelet in time. A "narrow" wavelet can access high-frequency information, while a more dilated wavelet can access low-frequency information. This means that the parameter "a" varies with different frequency.

$$\int_{-\infty}^{+\infty}\psi(x)\,dx=0 \qquad (3)$$

And it provides the admissibility condition as below

$$C_{\psi} = \int_0^{+\infty} \frac{\left|\psi(\omega)\right|^2}{\omega} d\omega \tag{4}$$

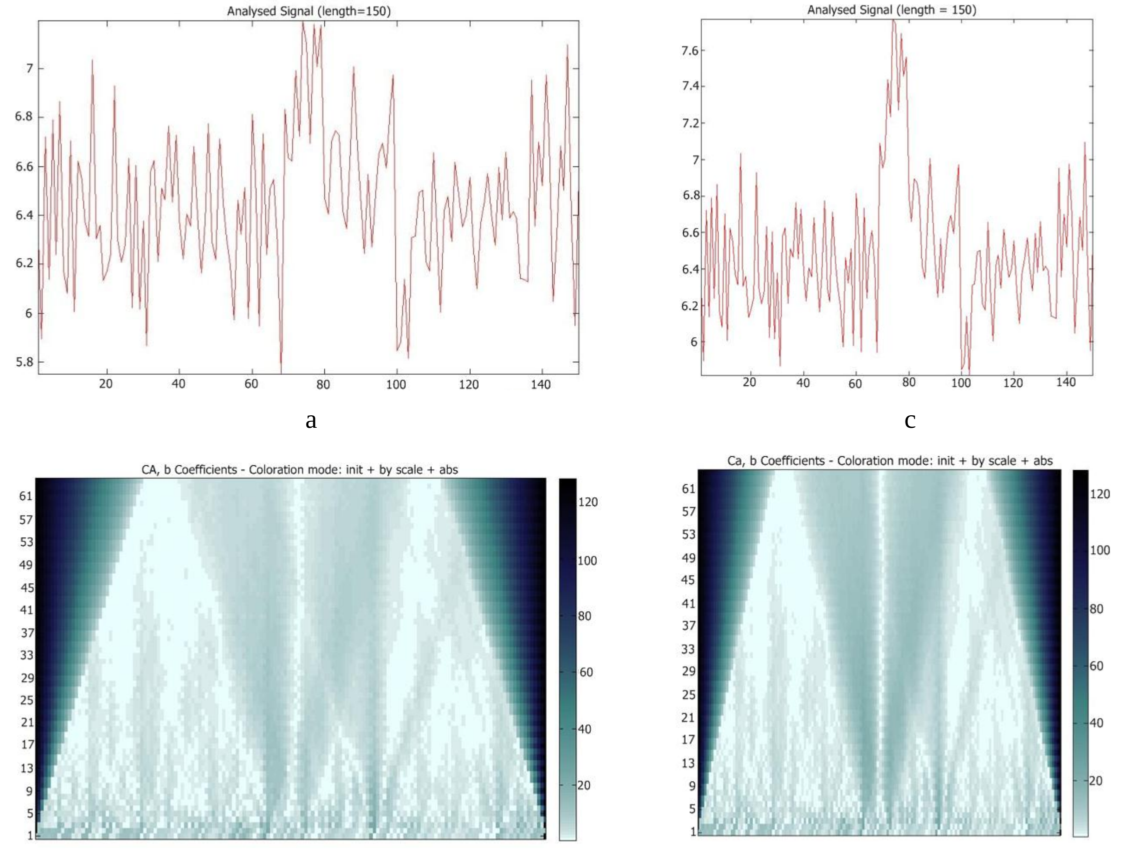
Here, $\psi(\omega)$ stands for the Fourier transform of $\psi(x)$. The admissibility condition implies that the Fourier transform of $\psi(x)$ vanishes at the zero frequency [23-25].

### 3.2. Feature extraction and analysis via continuous wavelet transform

This paper analyses the application of the continuous wavelet analysis method.

The principal aim is to extract features from potential building's monitoring system data using wavelet transform. The non-stationarity of the signal is revealed due to the changing building's behaviour.

The possibilities of feature extraction using wavelet method was analysed using generated signals. Firstly one or more harmonic signals were generated. Then non-stationarity of the signal is modelled by adding generated burst signal to the generated normal distribution signal. The amplitude of the burst signal corresponds to particular portion of the mean of the generated "normal" signal. This compound signal with the help of Matlab package was analysed using wavelet transformation (Fig. 5).



a c

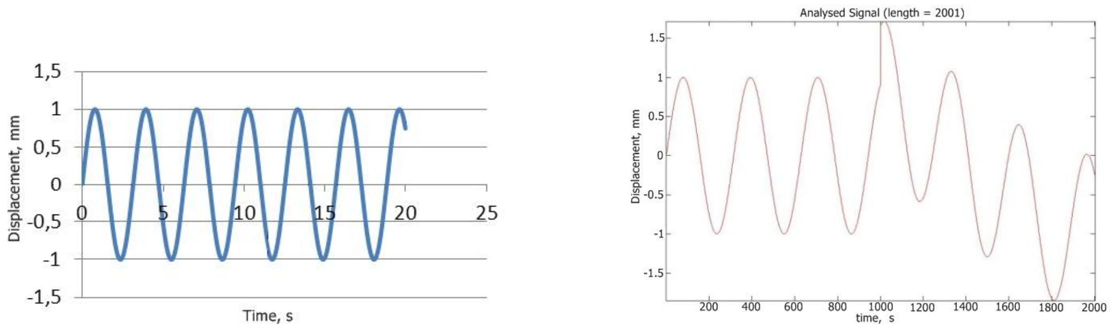
b d

Fig. 5 Wavelet transformation of the stationary noise, distributed according normal distribution including burst signal (burst amplitude is 10% of the mean of the noise signal: a – raw signal, b  continuous wavelet transformation of the signal (a) and burst amplitude of 20% : c – raw signal, d  continuous wavelet transformation of the signal (c))

The results show that wavelet method displays non-stationarity of the signal (darker areas in the middle of the image). Also the harmonic process was modelled using the assumption that building monitoring is performed at specific time intervals and the change in the data can be noticed during monitoring interval, and between monitoring intervals. Two harmonic signals were generated: $y_1 = sin(2t)$ and $y_2 = sin(0.23t)$ and wavelet transformation was applied. The results are provided in Fig. 6 and Fig. 7.

The situation when the object's condition changes at the time moment between the monitoring intervals was analyzed. That is we assume that at first monitoring interval we observe stationary harmonic signal and at the second – non-stationary signal. Fig. 8 depicts signal before the change and after it (at the 1000th moment signal changes)). For separated signal (Fig. 8, a) wavelet image is created. In case of stationary signal (Fig. 8, b) the result is an image where darker ellipses are neatly arranged and in case of non-stationary signal (Fig. 8, c) – the image is disordered.

Haar wavelet transform was also used to analyse signal spectrum (to analyse the signal change). Vibrations of the excited floor with several defects of the building's laboratory model were analysed. The spectrum at the first measurement point was analysed. In case of the defect additional spectral components appear, Haar wavelet transformation also shows them in Fig. 9. We can confirm that the 3rd defect can be detected best when measuring at the 1st point (see Fig. 2).

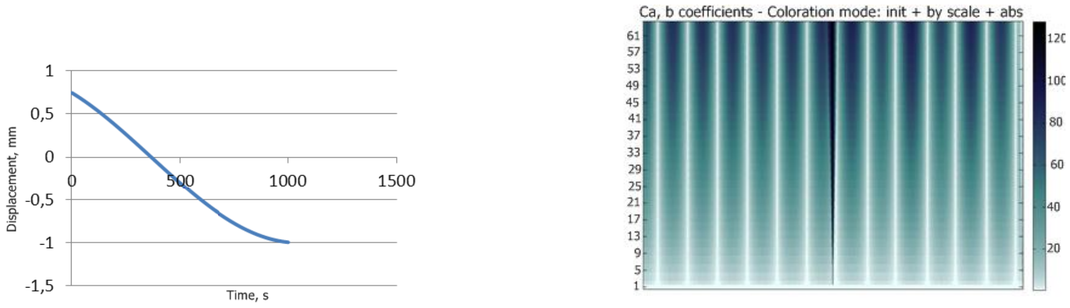


$y_1 = sin(2t)$

a

$y = y_1 + y_2 = sin(2t) + sin(0.23t)$

c



$y_2 = sin(0.23t)$

b

d

Fig. 6 Transformation of two harmonic signals using Haar wavelet: a) first harmonic signal; b) second harmonic signal; c) the sum of the two harmonic signals; d) Haar wavelet transform of the sum of two harmonic signals

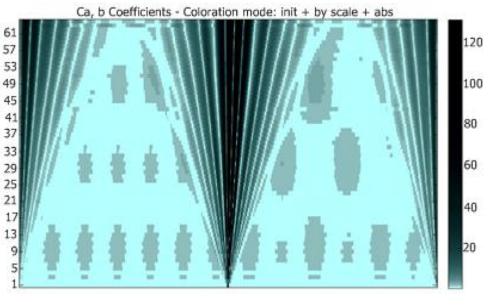
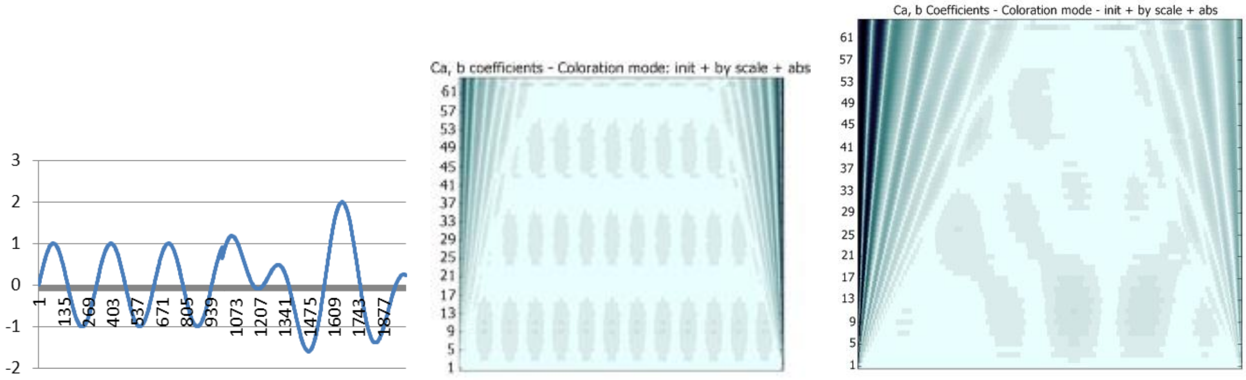


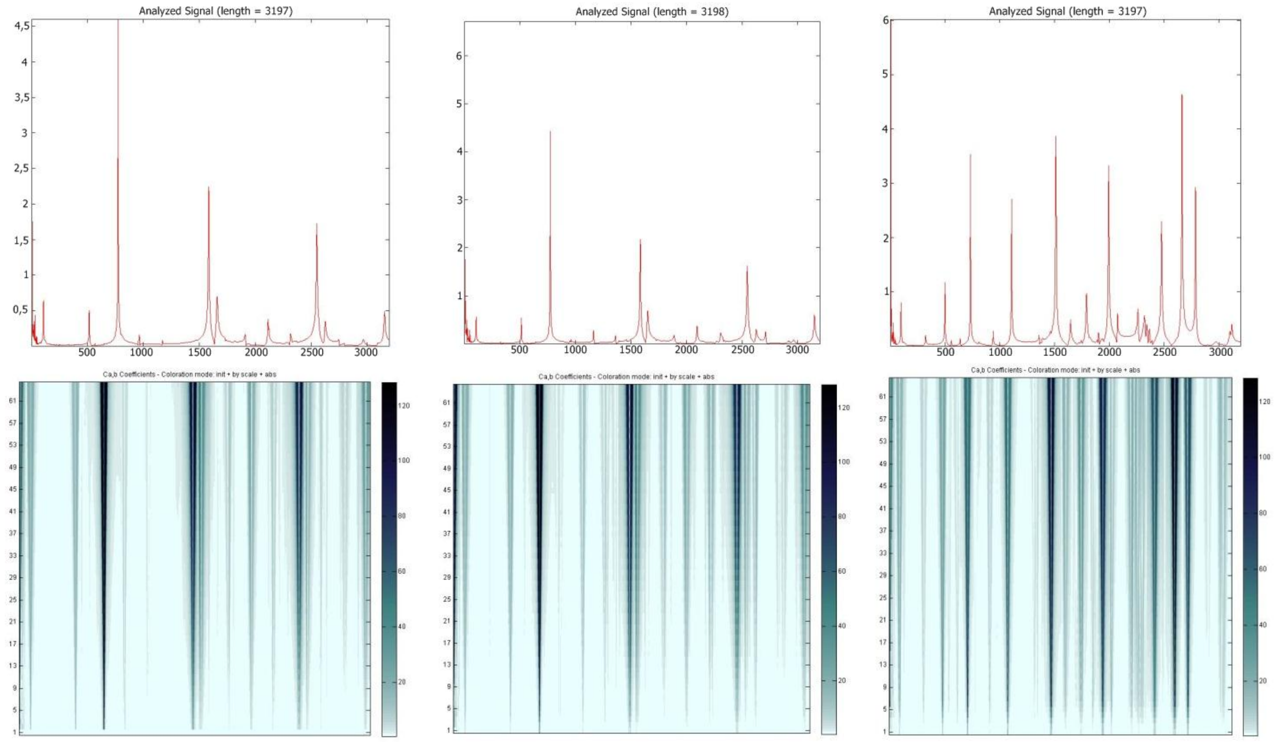
Fig. 7 Transformation of two harmonic signals using Meyer wavelet

The application of wavelet method allows distinguishing the results between spectres which were obtained for different conditions of the measured objects. Therefore it must be noted that the informativeness of the result of the wavelet transformation depends on the place of measurement point on the monitored object and the nature of the defect. For example, the transformation of the results obtained from the first measurement point is more informative for the floor with the defect 3 than for the floor with the defect 1. Thus numerical results are important for practical application of the wavelet.



a b c

Fig. 8 Identification of the change of the structure of the monitoring data using wavelet transform: Modelled data of stationary monitoring: observation before signal change and after it (at the 1000th discrete moment the signal changes); b) The result of Meyer wavelet of stationary signal before the change of the signal structure; c) Meyer wavelet transform after the change of the generated monitored signal structure

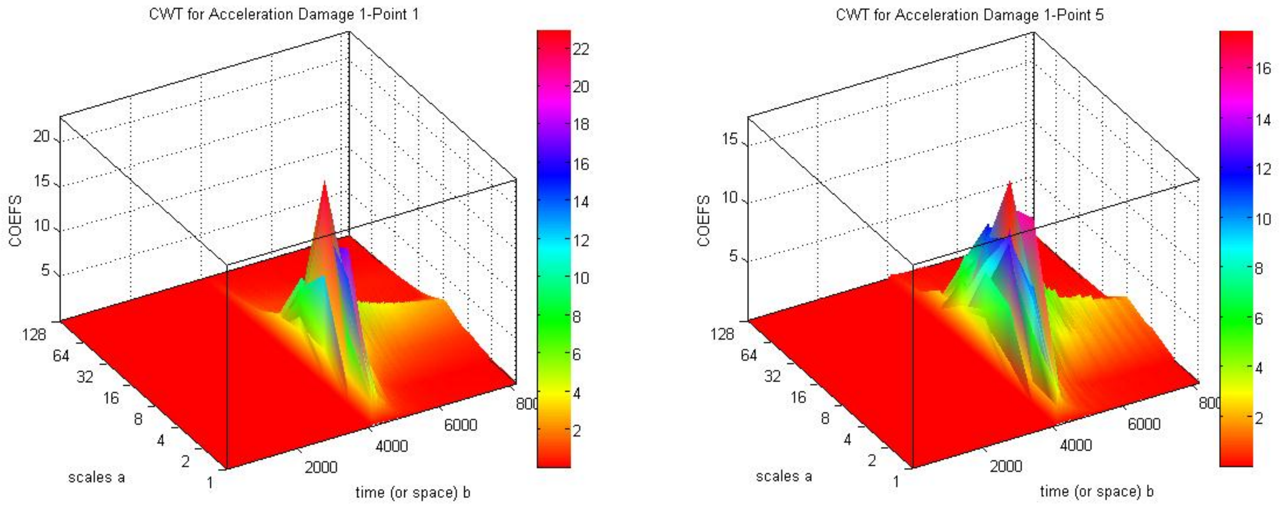


a b c

Fig. 9 The results of using Haar wavelet for defect detection with experimental data: a) floor without defect; b) floor with defect 1; c) floor with defect 3

The signal wavelet transformation results for experimental modal analysis data (Figs. 3 and 4) are provided in Figs. 10-13.

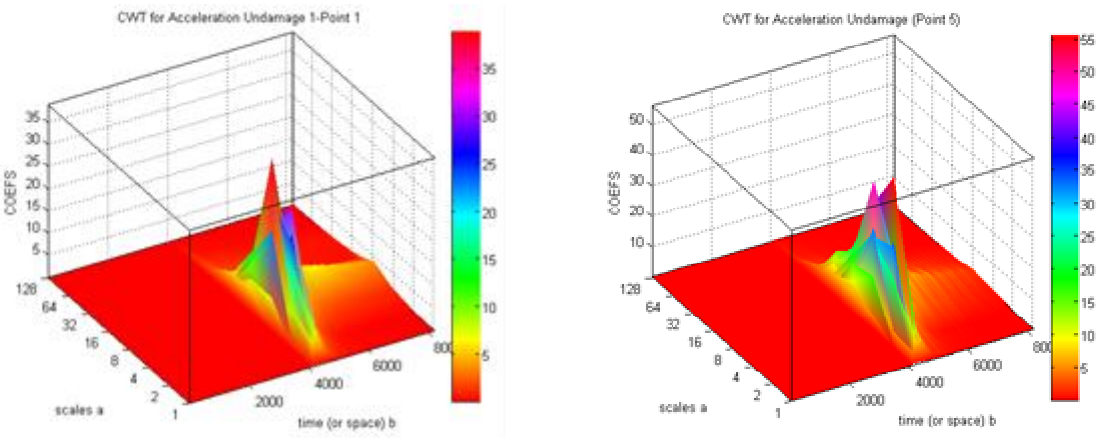
This method is quite successful in making the diagnosis the top floor of building's laboratory model. CWT analysis was performed for the1 stand 5th point in Fig. 10. Here, the point 1 and point 5 is owned by a different frequency components, can be clearly seen. This change in the colour scale can be realized. Colour scale is an inverse relationship between scale and frequency. This inverse relationship represents an increase scale decreased frequency. Here, the time axis is the same for both graphics. However, the two graph axis scale is different. Point 5, both high and low frequency content spread over a wider area. Fig. 10, a is different from to as the coefficient in Fig. 10, b.



a b

Fig. 10 Analysis of the CWT for damaged top floor acceleration in points 1 and 5

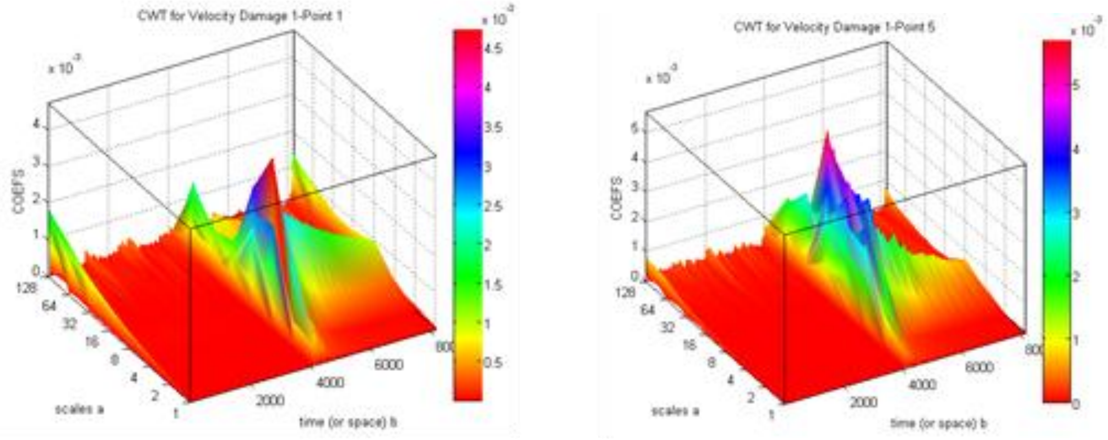
Significant differences between 8 and 16 scales can be seen in Fig. 11. This situation explains the differences in this frequency band also. In this section, comparisons between Figs. 10 and 11, and Figs. 10, a and 10, b can be done.



a

b

Fig. 11 Analysis of the CWT for undamaged top floor acceleration in points 1 and 5



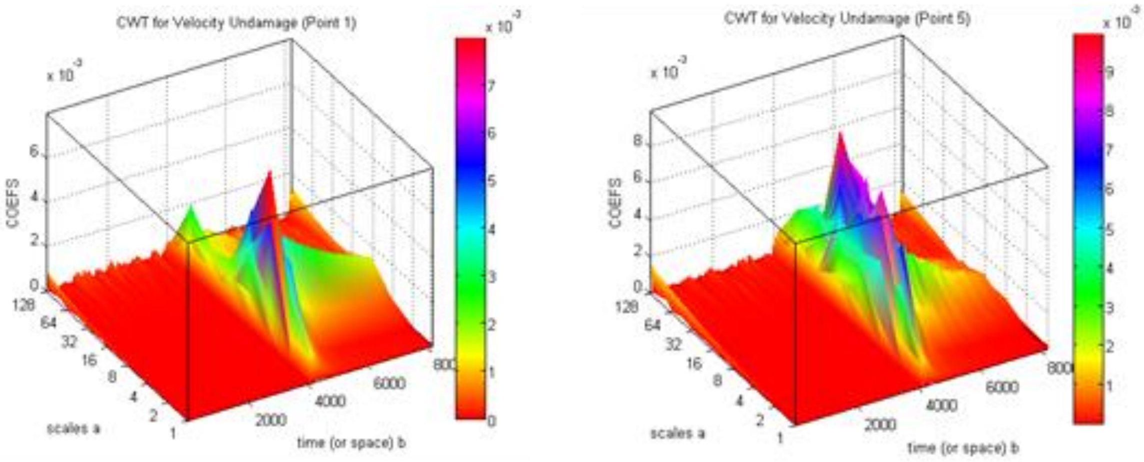
a

b

Fig. 12 Analysis of the CWT for velocity data of the damaged top floor

Similarly, Figs. 12, a and 12, b The CWT method can easily be identified with the frequency bands. If examined, the Displacement points for point 1 and point 5 are seen to be quite different. In fact, the frequency content of the starting and ending periods of each other's opposite. Point 1 has high-frequency components which is available in first seconds. However, points 5 with higher coefficients are low-frequency components.

Comparison can be made between point 1 and point 5 in Fig. 13. In this study, the key to the analysis, feature extraction is one of the velocity of vibration changes according to the state of monitoring object. As a result of starting with pulse effect 1 second, high amplitude and low frequency features are composed in point 5. The coefficient of the amplitude has been reached level 3 in the firth second from point 5, amplitude level of the point 1 is remains at 1.5.



a

b

Fig. 13 Analysis of the CWT for velocity data of undamaged top floor

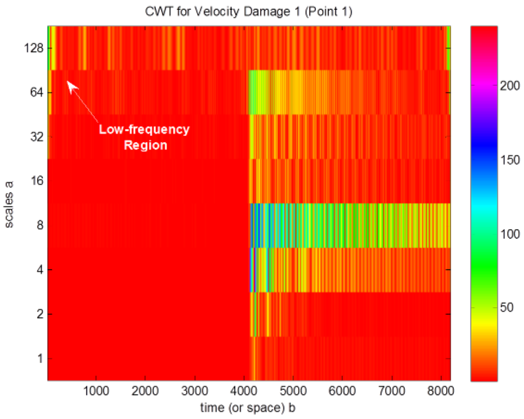


Fig. 14 CWT of the velocity measured in damaged structure

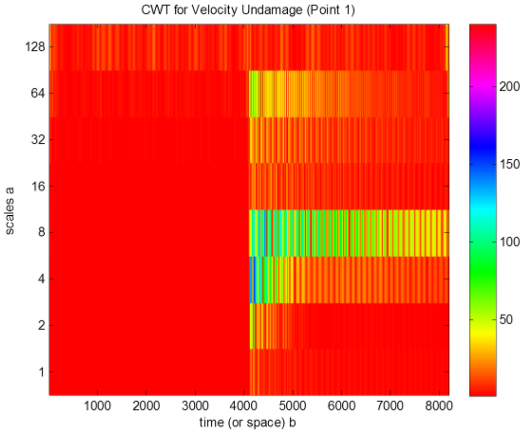


Fig. 15 CWT of the velocity measured in undamaged structure

Analyses of the CWT for the velocity structures are shown in Figs. 13 and 14. Analysis in Fig. 13, according to point 1 to point 5 is seen to have higher coefficients.

## 4. Results and discussion

The analyses of damages in the style structure, different methods are used and CWT method as new application include on this issue. In this study, experimental data collection was analysed by CWT in the structures. The results are quite satisfactory. The displacement data, the results of the analysis for the low-frequency and high amplitude were found to contain features.

Figs. 14 and 15 show the results of CWT analysis of velocity of the structures. The situation has been analysed to the same point. One of the important findings of the study, low-frequency components of the velocity found to points, for undamaged structure the 128-band frequencies, these components do not scale. Because of this feature, undamaged points and damage point determined characteristic features of low-frequency feature which the scale is the level of 128. In this study, we can distinguish undamaged and damaged areas with the frequency regions.

In the conducted study, experiments were made on point more than the number of those being used in the study. Wavelet analysis method for determination of the state changing in construction of the building has very successful results.

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## BANGELIŲ TRANSFORMACIJOS TAIKYMAS STATINIŲ KONSTRUKCIJOS DEFEKTAMS APTIKTI

Reziumė

Dėl atšiaurių žiemų ir konstrukcijų deformacijų veikiant sniego apkrovoms Lietuvoje ir kitose šalyse dažnai įgriūva stogai. Todėl svarbu stiprinti statinių stabilumo kontrolę. Konstrukcijų defektai gali būti aptinkami įvairiais metodais. Šiame straipsnyje aprašomas bangelių transformacijos metodas.

Tolydi bangelių transformacija taikoma defektuotos statinio konstrukcijos vibracijų analizei. Remiantis rezultatais, gautais modeliuojant duomenų struktūros pokyčius, atsiradus defektams, t. y. statinio konstrukciniams elementams praradus stabilumą, bei taikant įvairias bangelių funkcijas, parodyta, kad šis metodas tinka konstrukcijų defektų diagnostikai. Atliekant tolydžiąją bangelių transformacijos analizę, konstrukcijų defektai aptinkami pagal dažnines charakteristikas, fiksuojant defekto atsiradimo momentą.

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## APPLICATION OF WAVELET TRANSFORM TO DEFECT DETECTION OF BUILDING’S STRUCTURE

Summary

Various methods can be used to detect the defects of structures. In this paper wavelet transform method is used.

Continuous wavelet transform (CWT) is applied to vibration signal analysis of building’s construction with defect. The results, which were obtained by modelling the changes in data pattern assuming that the building's construction element lost its stability, i.e. defect emerged, and by applying different wavelets, showed that this method is suitable for diagnostics of defects in the construction. With the CWT analysis, buildings construction’s defects were detected according the frequency characteristics, also determining time moment of defect appearance.

**Keywords:** Wavelet transformation, Fault detection, building’s construction.

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