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Izvorni znanstveni članak

Dynamic Deformation Monitoring of a Technological Structure

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ABSTRACT. Building structures are extremely sensitive to the influence of outdoor conditions, especially the influence of wind, temperature changes in the surroundings caused by sunshine, and the effect of the building's own or operating load. According to the resonance of the structure with the surroundings, vibrations and oscillations in relatively high frequency intervals (1–100.0 Hz) occur. These phenomena significantly affect the static and dynamic characteristics of structures as well as their safety and functionality. The paper provides an example of monitoring these phenomena using surveying methods and instrumentation. The monitored structure (a desorbing tower) has a cylindrical shape. The measurements were made by a total station with a measurement frequency ca 2 Hz. The main point of the paper is an analysis of the dynamic behaviour of the structure using different methods for the spectral analysis of a time series. The use of a fast Fourier Transform and a Lomb-Scargle periodogram is described, and the frequencies of the structure's oscillation are calculated.

Keywords: total station, dynamic deformation, frequency analysis, Fast Fourier Transformation, Lomb-Scargle periodogram.

1. Introduction

At the present time it is increasingly necessary to monitor the dynamic deformation of civil engineering structures, as it affects the stability and safety of those structures. Dynamic deformation is generally described as vibrations, inclinations and other changes in a relatively short period, which are represented in a frequency range by values from 0.1 Hz and higher. In these cases it is important to know not only the trajectory and amplitudes of the structure's movement but also the frequency of these movements.

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The Department of Surveying at STU in Bratislava (Slovakia) has been performing monitoring of dynamic effects on civil engineering structures of different types and dimensions. The presented paper provides an example of a desorbing tower, which is a part of an ammonia production line at a chemical company, Duslo Ltd. Šal'a (Slovakia). The aim of these measurements was a determination of the size and frequency of the tower's inclination and the contribution of the operating load and weather conditions on these movements. Due to many limitations the measurements were performed by a total station in a fully automated (robotic) mode with a data registration frequency of about 2 Hz.

2. The desorbing tower

The cylindrically shaped desorbing tower consists of two parts – the bottom part with a height of 27.4 m and a diameter of 4300 mm and the top with a height of 34.4 m and a diameter of 4964 mm (Fig. 1). These two parts are joined by a conically shaped ring, with height of 1.8 m. The whole tower's height is 63.6 m, and its inside is divided into 5 blocks by filter gratings. The tower is based on a reinforced concrete block and is fixed to this block by 20 M80 type screws (Friedrich Uhde 1970).

Fig. 1. *The desorbing tower (left) and the anchorage of the tower on the foundation (right).*

The dynamic load caused by the production line and the weather conditions (the effects of wind) affect the tower's base and its anchorage. The structure is permanently moving, and the top of the tower moves along an elliptical trajectory. Due to this continuous movement, the connecting screws are exposed to very high mechanical loading, and the welding of more production lines that are connected on the top of the tower has been damaged. The aim of the measurement was to determine the trajectory of the tower's top and the frequency of this movement.

3. Measurement method and the configuration of the control points

Due to the large amplitude and inclination values for determining the trajectory of the tower's top, the polar method was chosen. The measurement was performed by the Leica TCRA1101 robot station, which is equipped with an ATR function (Fig. 2). The accuracy of the robot station is given as a 0.3 mgon for angle measurement and 1.0 mm + 1 ppm for distance measurement (Leica Geosystems 1998). The prism was positioned at the top of the tower at a height of 63.0 m (Fig. 3 and 5). According to the different times needed for the distance measurement, the data acquisition's frequency varies from 1.66 Hz to 2.50 Hz.

Fig. 2. *The Leica TCRA1101 robotic station.*

The configuration of the check points (reference frame) and the control point is illustrated in Fig. 3. The stability of the total station during the measurement was checked by observations to 3 points (VB1, VB2 and VB3), which were signalized by Leica GPR1 prisms fixed on the surrounding buildings (Fig. 4). North arrow (Fig. 4) defines zero azimuth of wind direction.

Next to the control point a Nexus meteorological station at the tower's top was positioned (Fig. 5). The meteorological station measured the weather conditions: air temperature, wind speed and wind direction. All the measured data were registered on a computer by registration period of 30 sec. Time stamp and synchronization of the data was realized by computer system time.

The measurements of the tower's movements were performed in three sets, which correspond to three different conditions (Table 1). The first measurement set was performed during full production before the tower's planned reconstruction. The second measurement was performed during the tower's reconstruction without any operational loading, and the last one was performed after the tower's reconstruction to verify the correctness of the reconstruction work. During the reconstruction the damping plate between the steel structure and the concrete block was changed and fixed by screws (Kopáčik and Lipták 2011).

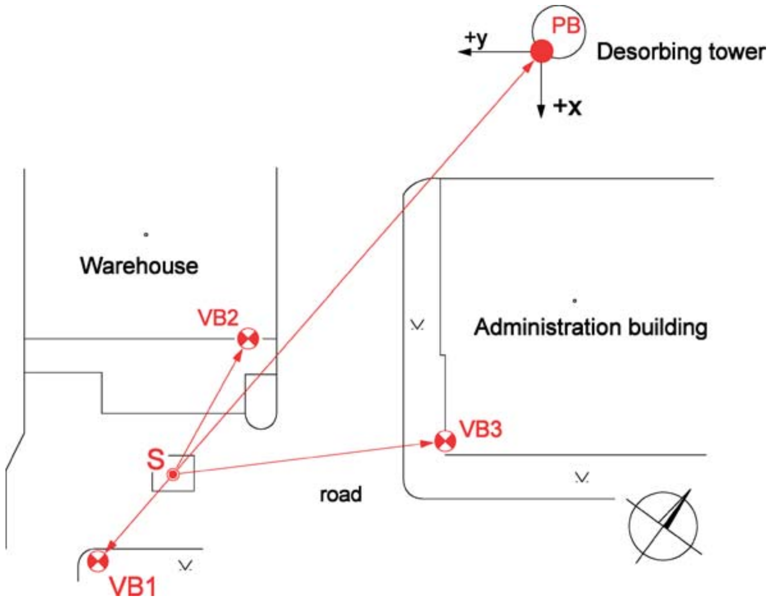

Fig. 3. *Check points (VB) and the control point (PB).*

Fig. 4. *Check points.*

Table 1. *Characteristics of the measurement sets.*

Epoch	1st	2nd	3rd
Date	12.04.2011	03.08.2011	18.08.2011
Time	9:35 – 10:35	9:15 – 10:15	8:45 – 9:45
No. of registered points	5560	5712	5529
Weather	+14 °C to +24 °C, sunshine, wind	+19 °C to +28 °C, sunshine, wind	+23 °C to +27 °C sunshine, wind

Fig. 5. *The prism and Nexus meteorological station on the top of the tower.*

In the case of dynamic loaded structures, it is also desirable to describe their movement (deformation) both by the trajectory (3D position) and the frequency spectrum. Generally, the structure's natural frequency or the frequency of the forced vibration of the structure can be described using different methods of spectral analysis. From these the fast Fourier Transformation and the Lomb-Scargle periodogram at high-pass filtered data are applied.

4. Tower movement

The position of the control points was obtained by a 2D local coordinate system (Fig. 3). The orientation of the coordinate system axes was the same as the orientation of the buildings and the main technological equipment in the factory. The reduction to the 2D system was possible as a result of the very small changes (up to 0.5 mm) in the vertical direction, which is limited by the tower's maximum inclination. Table 2 contains the range of the tower's movement determined in each epoch of the monitoring.

Table 2. *Measured displacements in each axis.*

Epoch	Time [hour]	Axis	Minimal value [mm]	Maximal value [mm]	Range [mm]
1st 12.04.2011	9:35 – 10:35	X	–53.2	27.3	80.5
		Y	–71.1	35.0	106.1
2nd 03.08.2011	9:15 – 10:15	X	–6.5	6.3	12.8
		Y	–6.4	6.3	12.7
3rd 18.08.2011	8:45 – 9:45	X	–42.2	44.3	86.5
		Y	–57.8	49.2	107.0

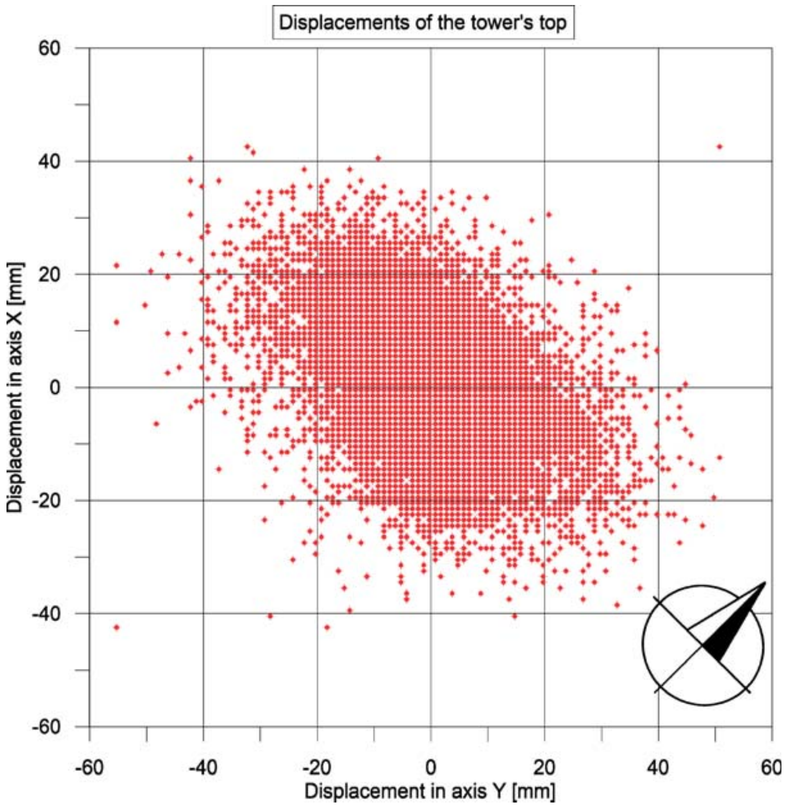

Fig. 6. *Displacements at the top of the desorbing tower (12.04.2011).*

The encasement of the tower's movements has an elliptical shape (Fig. 6). The displacement ranges up to 100 mm in both axes, indicating the significant effect of the production loading.

5. Frequency analysis of the tower's deformation

The frequency spectrum and vibration frequency were estimated for each epoch and coordinate axis separately. The data processing consisted of several steps, including data filtering, determination of the frequency spectrum, and identification of the significant frequencies in the spectrum (Fig. 7).

The first step in the processing of the data was the elimination of the long-term components from the data sets. For the spectral analysis the residuals were used after the application of a moving average filter using five samples. Spectral density estimation methods for a time series generally assume that the data sets in time series are evenly registered and that the fast Fourier Transformation (FFT) can generally be used for estimating the oscillation frequencies. This requirement is not always performed and may be the result of missing data or unstable regis-

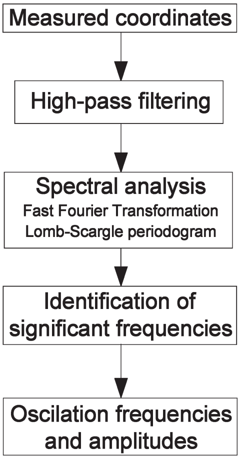

Fig. 7. *Data processing steps.*

tration frequencies. This problem occurs when the measurement by the total station is made in a kinematic mode. These measurements are also influenced by a jitter effect due to the variable periods of the data registration. Fig. 8 shows time differences between the measurement periods that occur in measurements by a total station.

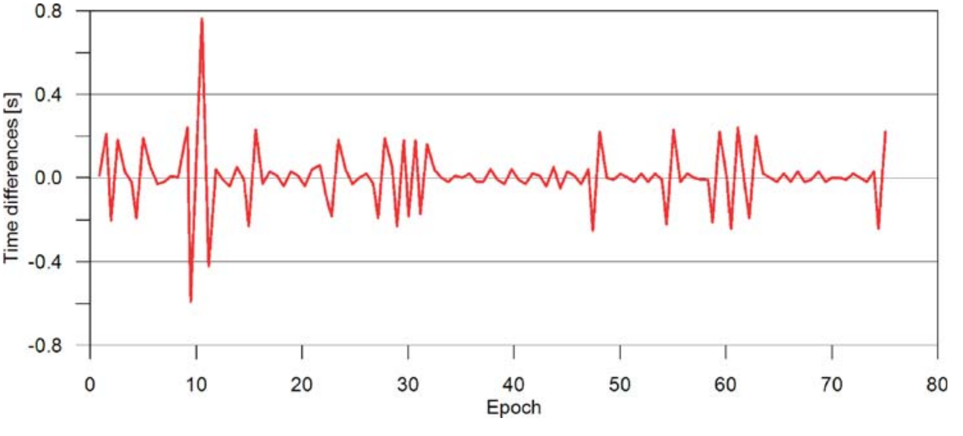

Fig. 8. *Different frequencies (periods) of the data registration.*

To estimate the spectral density of a time series with a variable frequency of data registration, there are two possibilities – using the Lomb-Scargle methodology or by the application of the discrete Fourier Transformation with an average registration frequency. The application of the second methodology generates distortion in the estimated values. In both cases the significant frequencies are identified by statistical tests.

5.1. Lomb-Scargle methodology

The Lomb-Scargle methodology published by Lomb (Lomb 1976) is used very often in the earth sciences for a spectral analysis of unevenly distributed data (Pytharoulis and Stathis 2008). The Lomb-Scargle periodogram is defined as

$$P(T) = \frac{1}{2\sigma^2}\left\{\frac{\left[\sum_{i=1}^{N}(x_j - \bar{x})\cos\left(\frac{2\pi(t_i-\tau)}{T}\right)\right]^2}{\sum_{i=1}^{N}\cos^2\left(\frac{2\pi(t_i-\tau)}{T}\right)} + \frac{\left[\sum_{i=1}^{N}(x_j - \bar{x})\sin\left(\frac{2\pi(t_i-\tau)}{T}\right)\right]^2}{\sum_{i=1}^{N}\sin^2\left(\frac{2\pi(t_i-\tau)}{T}\right)}\right\}, \quad (1)$$

where the parameter τ is defined as

$$\tan\left(\frac{4\pi\tau}{T}\right) = \frac{\sum_{i=1}^{N}\sin\left(\frac{4\pi t_i}{T}\right)}{\sum_{i=1}^{N}\cos\left(\frac{4\pi t_i}{T}\right)}, \quad (2)$$

where N is the number of measurements in the data set, t_i the time of registration, $\bar{x}$ the mean value calculated for the data set, and σ^2 the variance of the data set (Lomb 1976). The significance level of each peak in the time series is defined by

$$p = [1 - (1 - e^{P(T)})]^N. \quad (3)$$

The significance level p is used to determine the power level z_0. This is the level above which the detected signal (peak) is statistically significant. The power level z_0 is defined as

$$z_0 = -\ln[1 - (1 - p)^{1/N}]. \quad (4)$$

5.2. Fast Fourier Transformation

The Fourier transformation describes a signal using harmonic functions and can also be used for transforming a signal from a time domain to a frequency domain. The Fourier transformation is generally defined as

$$F(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} f(t)e^{-i\omega t}\mathrm{d}t. \quad (5)$$

The practical application of the Fourier transformation procedure requires that the analysed data sets have a finite amount of data. The spectral density of a time series can be determined using the fast Fourier Transformation (FFT) by

$$D_k = \sum_{j=0}^{N-1} y_j w(j) e^{\frac{2\pi ijk}{N}}, \quad (6)$$

where $k = 0, 1, ..., N–1$, and w is the spectral window function (Cooley and Tukey 1965). In our case the Hamming spectral window was used. For determining the significant frequencies from the discrete frequency spectrum, Fisher's asymmetric statistical test of periodicity was applied (Cipra 1986). The statistics of Fisher's periodicity test are based on the standardized spectrum of the time series X_t and is given by

$$W = \max_{j=1\ldots m} Y_j, \tag{7}$$

Y_j are the standardized spectrum values. The statistical test is based on a comparison of the test statistic W with the critical value of Fisher's test at the significance level $\alpha = 0.05$. The critical value of the test is given as

$$g_F(\alpha) = 1 - \left(\frac{\alpha}{m}\right)^{1/(m-1)}. \tag{8}$$

The null hypothesis H_0 at the level $\alpha = 0.05$ can be rejected if W is greater than the critical value $g_F(\alpha)$, which means that the tested frequency is statistically significant (Siegel 1980).

5.3. Frequency estimation in data sets

For the frequency analysis various sets of measurements of a 60 minute duration were prepared (Table 2). According to the different (non-stable) registration frequencies, the number of the measured data in each set varied from 5319 to 5530. The movement of the tower's top was described by the trajectory projected to the horizontal plane (their amplitudes and frequencies) in the X and Y directions. The measurement was made under all three different conditions described in Tab. 2. The analysis was made separate for the X and Y directions in all the data sets. Figs. 9, 10 and 11 represent the measured and filtered values for the X direction (left) and the wind direction and speed (right). Relation to wind direction and local coordinate system is described by Fig. 6. The periodograms estimated by the Lomb-Scargle methodology (left) and by FFT (right) are shown in Figs. 12, 13 and 14. The dominant frequencies in the analysed time series are shown in Tables 3, 4 and 5.

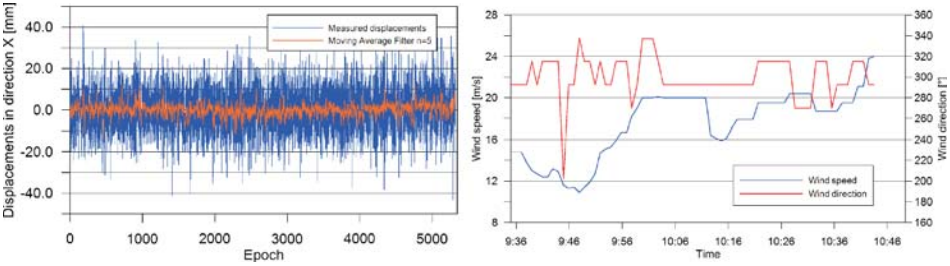

Fig. 9. *Measured and filtered data (left) and the weather conditions (right) – first measurement.*

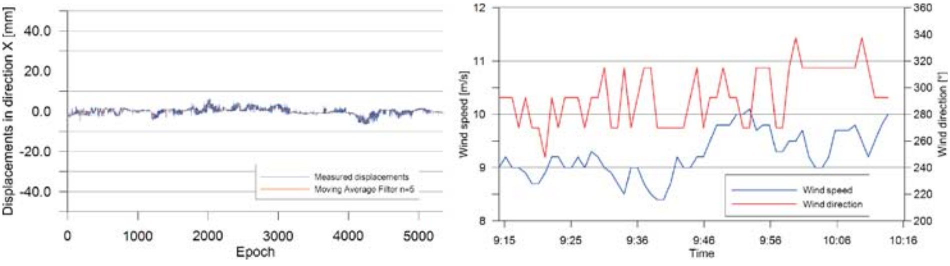

Fig. 10. *Measured and filtered data (left) and the weather conditions (right) – second measurement.*

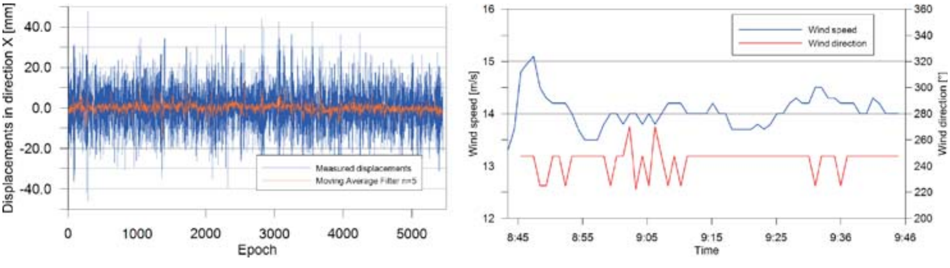

Fig. 11. *Measured and filtered data (left) and the weather conditions (right) – third measurement.*

According to the results, it could be concluded that the production has a crucial influence on the dynamic loading and deformation of the tower, which is underlined by the oscillations (elliptical trajectory) of the tower's top with amplitudes up to 90 mm in the *X* and 110 mm in the *Y* directions. The first and third measurements were performed during the full operational loads. The weather conditions were very similar, whereas the wind speed varied during each measurement from 10 m · s^{-1} to 20 m · s^{-1}.

Table 3. *Significant frequencies – first data set.*

1st epoch 12.04.2011 09:35 – 10:35	Axis	Lomb-Scargle methodology	Fast Fourier Transformation
Number of measurements		5319	
Number of significant frequencies	*X*	96	1
	Y	112	2
Dominant frequencies f [Hz]	*X*	0.65	0.67
	Y	0.60 0.64	0.64
Dominant periods T [sec]	*X*	1.54	1.49
	Y	1.67 1.56	1.56

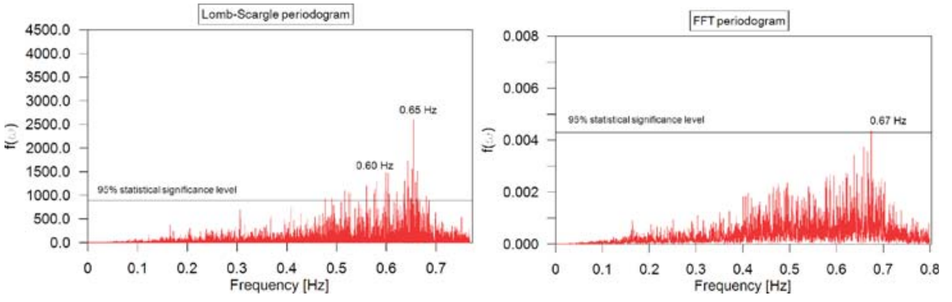

Fig. 12. *Periodogram for the X direction – first measurement.*

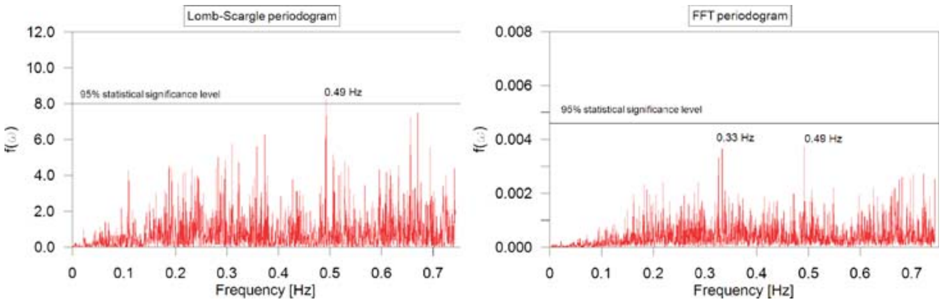

Fig. 13. *Periodogram for the X direction – second measurement.*

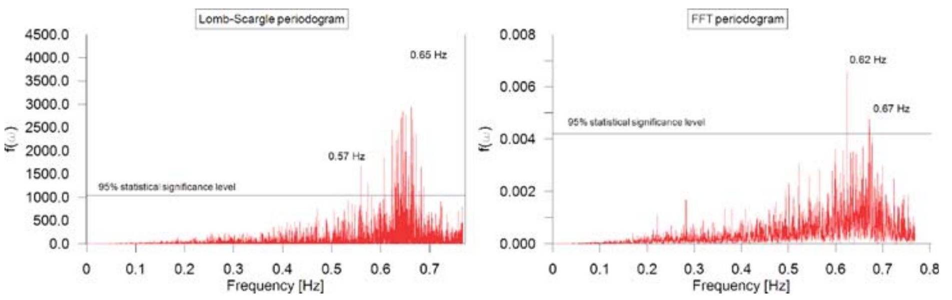

Fig. 14. *Periodogram for the X direction – third measurement.*

Table 4. *Significant frequencies – second data set.*

2nd epoch **03.08.2011 09:15 – 10:15**	**Axis**	**Lomb-Scargle methodology**	**Fast Fourier Transformation**
Number of measurements		5361	
Number of significant frequencies	*X*	1	0
	Y	0	0
Dominant frequencies f [Hz]	*X*	0.49	0.49
	Y	0.63	0.52
Dominant periods T [sec]	*X*	2.05	2.05
	Y	1.59	1.92

Table 5. *Significant frequencies – third data set.*

3rd epoch 18.08.2011 08:45 – 09:45	Axis	Lomb-Scargle methodology	Fast Fourier Transformation
Number of measurements		5530	
Number of significant frequencies	X	183	3
	Y	91	1
Dominant frequencies f [Hz]	X	0.65	0.62 0.67
	Y	0.65	0.65
Dominant periods T [sec]	X	1.54	1.61 1.49
	Y	1.54	1.54

Based on the estimation of the spectral density, the frequency range of the tower's movement was determined to be in a range of 0.5 Hz to 0.7 Hz, which represents time periods from 1.4 sec to 2.0 sec. The small variation in the calculated significant frequencies around the dominant frequency at the range of ± 0.1 Hz in the data sets of the first and third control measurements is probably caused by the unstable frequency of the tower's movement or by measurement noise. The relative accuracy of the estimated spectral density is up to 0.5%.

The significance test of the estimated frequency values showed that frequencies estimated by the Lomb-Scargle methodology are more significant than frequencies estimated by the FFT methodology. This is caused by the different algorithms used for estimating the spectral density estimation and the different significance levels of the algorithms used.

According to the results of the second measurement (during the reconstruction without an operating load), it could be concluded that the weather conditions (wind loading, etc.) have a minimum influence on the tower's movement or on its deformation – the amplitudes are smaller than 10 mm. Only one significant frequency of 0.49 Hz was identified by the Lomb-Scargle methodology for the direction X, but it was at the threshold of significance. The displacements describe the slow random movements of the tower's top in a horizontal plane, which could be caused by the small speed of any wind, sunshine or other loading of the structure without any significant periodic components and cannot be detected by the used interval of measurements.

6. Conclusions

The paper presents the results of the monitoring of the dynamic deformations of a desorbing tower at the chemical factory of Duslo, Ltd., in Šaľa (Slovakia). The geometry of the measured structure and the various operating restrictions affect the realization of the geodetic monitoring. The movement of the tower's top was determined by a polar method using a Leica TCRA1101 robotic station. The oscillation frequency of the structure's movement was determined by two different algorithms: the Lomb-Scargle and the Fast Fourier Transformation.

The major reason for using the Lomb-Scargle approach for the spectral analysis of the desorbing tower's movement was the fact that the algorithm is appropriate for estimating unevenly registered data in a time series. This problem generally occurs in cases when measurements are performed by total stations. The FFT algorithm is applicable in this case, when the average time of the data registration is calculated. This may cause a distortion of the calculated values, a lower degree of accuracy of the estimated characteristics (power spectrum, etc.), and finally lead to estimating false frequency values. In this case the Lomb-Scargle methodology gives a more reliable result; however, it is much slower than the FFT algorithm.

It can be concluded that the dynamic deformation of the structure presented by the horizontal movement of the tower's top with frequencies from 0.5 Hz to 0.7 Hz is mainly caused by the operational load. This conclusion is confirmed according to the control measurements made before, during and after the reconstruction work. Changes in the wind speed and direction only cause random non-periodic movements of the tower. The deformations measured during the second and third control measurements show that the reconstruction work only had a weak influence on the structure's deformations. These results present important information about the behaviour of the monitored structure caused by the operating load and atmospheric conditions.

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Praćenje dinamičkih deformacija tehnoloških struktura

SAŽETAK. Strukture zgrada iznimno su osjetljive na utjecaj vanjskih uvjeta, posebno na utjecaje vjetra, temperaturne promjene u okolini uzrokovane sunčevim zračenjem, a također i na utjecaj vlastitog ili operativnog opterećenja. Prema rezonanciji strukture s okolinom, javljaju se vibracije i oscilacije u relativno visokim frekvencijskim intervalima (1–100,0 Hz). Ta pojava znatno utječe na statičke i dinamičke karakteristike struktura, kao i na njihovu sigurnost i funkcionalnost. U radu se daje primjer praćenja tih pojava geodetskim metodama i instrumentima. Struktura koja se prati (desorpcijski toranj) ima cilindrični oblik. Mjerenja su provedena pomoću totalne stanice mjernom frekvencijom oko 2 Hz. Doprinos u radu je analiza dinamičkog ponašanja strukture upotrebom različitih metoda i spektralnih analiza vremenskog niza podataka. Opisana je upotreba brze Fourierove transformacije i Lomb-Scarglovog periodograma i izračunate frekvencije strukturnih oscilacija.

Ključne riječi: *totalna stanica, dinamička deformacija, analiza frekvencija, brza Fourierova transformacija, Lomb-Scarglov periodogram.*

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