Bridge Monitoring Using TLS, Accelerometersand Ground Based-Radar Interferometry

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Key words: accelerometer, fast fourier transformation, ground-based radar, singular value decomposition, terrestrial laser scanning

SUMMARY

The paper deals with long-term and dynamic geodetic monitoring of a steel bridge construction - the Liberty Bridge. The bridge allows join for pedestrians and cyclists between Bratislava city district Devínska Nová Ves (Slovak republic) and Schlosshof (Austria). For the dynamic monitoring of the construction was used the technology of ground-based radar interferometry and accelerometers, for the long-term monitoring the technology of terrestrial laser scanning. The monitoring, the Singular Value Decomposition data processing using Fast Fourier transformation (ground-based radar) and of matrixes (for TLS) and the results are described. Results are compared with model frequencies calculated for the bridge by FEM.

SUMMARY

DerArtikelwidmetmitlangfristigen und dynamischen geodätischen Messungen der Eisenkonstruktion der Brücke der Freiheit in Bratislava, die bildet die neue Verknüpfung zwischen der Stadtviertel Devínska Nová Ves (in Slowakei) und Schlosshof (in Austria). Die dynamischen Messungen wurden mit terrestrischem Radarinterferometer und Beschleunigungssensoren durchgeführt, für die langfristigen Messungen wurde die Methode der TLS verwendet. In der Artikel sind die Messungen, die Datenverarbeitung mit FFT (für Radarmessung) und Singular Value Decomposition (TLS) beschreiben. Die Ergebnisse sind mit Modelwerten der Frequenzen, die von FEM wurden gerechnet, vergleichen.

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1. INTRODUCTION

Bridge structures are usually exposed to the greatest extent by external influences such as weather conditions, loading by some objects and long-term influences such as instability of subsoil of foundations and seasonal temperature averages. These factors have a significant influence on the behaviour of the structure, which results in deformation of the whole structure or its parts. Changes in a structure's deformations typically have a cyclical behaviour. Therefore, the rate of the structure's stress and the magnitude of the impact of individual factors on the structurecan be determined.
The paper presents the possibility of the long-term deformation monitoring of bridge structures using the technology of terrestrial laser scanning (TLS) and dynamic deformation monitoring by accelerometers and ground-based radar (GB radar).

2. INOVATIVE TECHNOLOGIES FOR LONG-TERM AND DYNAMIC BRIDGE MONITORING

2.1 The Technology of the Terrestrial Laser Scanning

The advantage of TLS over conventional surveying methods is the efficiency of the spatial data acquisition. TLS allows for a contactless determination of the spatial coordinates of points lying on the surface of the measured object. The scan rate of current scanners (up to 1 million points per second) allows for a significant reduction in the time necessary for the measurements; they respectively increase the quantity of the information obtained about the object measured. To increase the accuracy of the results, selected parts of the monitored construction can be approximated by single geometric entities sing regression. In this case the position of the measured point is calculated from tens or hundreds of scanned points (Vosselman, 2010).

2.2 The Technology of the Acceleration Measurements

Accelerometers are sensors for measurements non-gravitational accelerations of the objects. For the bridge monitoring are applicable sensors with small nominal range of measurements. Principle of the measurements can be based on the inductive, piezoelectric or capacitive sensors. Accelerometers realize measurements with relative high frequency up to 5000 Hz (Wenzel, 2009). These frequency range is sufficient for bridge vibration measurements. Measured signal after drift and noise filtering can be integrated into displacements. These technology is good applicable for the bridge monitoring in combination with other technologies.

2.3 The Technology of the Ground-Based Radar Interferometry

Ground-based radar (GB radar) is an innovative measurement approach for the dynamic deformation monitoring of large structures such as bridges (Wenzel, 2009), (Bernardini, 2007) and (Pieraccini, 2007). GB radar measurements use the Stepped Frequency Continuous Wave (SF-CW) technique. This approach enables the detection of target displacements in a radar's line of sight. The basic principle of the technique is the transmission of a set of sweeps, which consist of a number of electromagnetic waves at different frequencies. A pulse radar generates short-term duration pulses to obtain a range resolution, which is related to the pulse durations according to

$$\Delta r = \frac{c\tau}{2}, \tag{1}$$

where c is the speed of light in a free space, and τ is the time of the pulse's flight. At each time interval of the measurements, the components of the received signals represent a frequency response measured at the number of discrete frequencies. The application of an Inverse Fourier Transformation frequency response is transformed to a time domain. The system then builds a one-dimensional image - a range profile, where the reflectors are resolved with a range resolution according to their distance from the GB radar(Fig. 1).

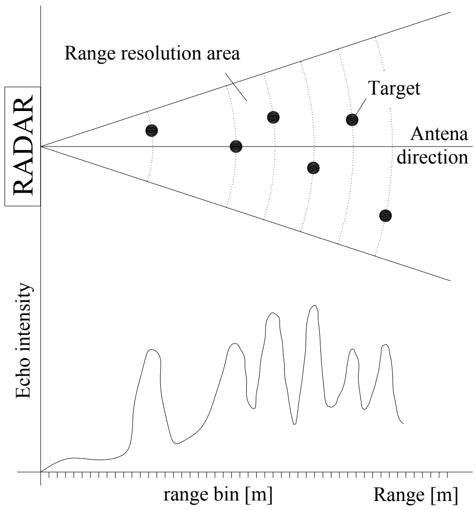

Fig. 1 Radar range bin resolution

When the range profile is generated, the displacements of the targets are detected by the Differential Interferometry technique. This approach compares the phase delay of the emitted and reflected microwaves. Radial displacement is therefore linked with the phase delay $\Delta\varphi$by the following

$$d_p = \frac{\lambda}{4\pi}\Delta\varphi, \tag{2}$$

where λ is the wavelength of the signal.

3. MATHEMATICAL MODELS FOR DATA PROCESSING IN THE DEFORMATION MONITORING BY TLS, ACELEROMETER AND GROUND-BASED RADAR

Mathematical models in data processing of the TLS measurements are based on the orthogonal regression analysis for modelling of the approximated geometric shapes. The data processing of the dynamic deformation is based on spectral analysis of the time series measured by high frequency. In this chapter there are described both approaches in the analysis of the measurements.

3.1 Processing and Analyzing the TLS Measurements

The vertical displacements of measured points are determined as the difference between heights of these points in each epoch. The height of points is calculated using orthogonal regression. During data processing of the initial measurement the observed points are defined by square fences. These fences define approximately the same set of points in each epoch. The coordinates of points, lying in the fences, are exported to single text files and are used for calculating regression planes. The position of the observed points in xy plane is defined by coordinates of the intersections of diagonals of fences. The advantage of this procedure is that the position of observed points does not change, with the thermal expansion of the construction. Heights of observed points are calculated by projecting the points into regression planes. Their mean errors were obtained using law of propagation of uncertainty, from the mean error of transformation and the mean error of regression planes, calculated from the orthogonal distance of points from these planes. Orthogonal regression is calculated from the general equation of a plane by applying of Singular Value Decomposition:

$$\mathbf{A} = \mathbf{U}\Sigma\mathbf{V}^{T} \tag{3}$$

where the$\mathbf{A}$ is the design matrix, with dimensions $nx3$, and n is the number of points used for the calculation. The column vectors of $\mathbf{U}^{nxn}$ are normalized eigenvectors of matrix $\mathbf{AA}^{T}$. The column vectors of $\mathbf{V}^{3x3}$ are normalized eigenvectors of $\mathbf{A}^{T}\mathbf{A}$. The matrix $\mathbf{\Sigma}^{nx3}$ contains eigenvalues on the diagonals. Then the normal vector of regression plane is the column vector of $\mathbf{V}$ corresponding to the smallest eigenvalue from $\mathbf{\Sigma}$(Lacko, 2008).

The tilt of pylons is determined by modelling of the sethorizontal sections in the local coordinate system of the bridge, because the way of anchorage of pylons did not allow the determination of tilt on the base and on the top of the pylons. In each height level are modelled coordinates of the intersection of the axis of pylons with horizontal plane. The intersections are obtained as the centres of horizontal regression ellipses. Points of cloud from common thick slice around the defined height level are projected into regression horizontal plane, and then from these points are modelled regression ellipses using Fitzgibbon's algorithm.

An ellipse is a special case of a general conic which can be described by an implicit second order polynomial (Fitzgibbon et al., 1999) and (Halíř et al., 1998)

$$aX^{2} + bXY + cY^{2} + dX + eY + f = 0 \tag{4}$$

where X, Y are the coordinates of points, a, b, c, d, e and f are the coefficients of general equation of conic. Equation (4) defines the algebraic distance of point from the conic, so the calculation minimizes the sum of squares of algebraic distances of points from the ellipse. For each point of cloud can be formulated the equation (4).The equation can be solved directly by the standard least squares approach, but the result of such fitting is a general conic and it needs not to be an ellipse. To ensure an ellipse-specificity of the solution, a constraint for the parameters has to be formulated in form (Fitzgibbon et al., 1999):

$$4ac + b^2 = 1 \tag{5}$$

The minimization of the sum of squares of algebraic distances after consideration of (5) and introducing the Lagrange multipliers can be solved by equations:

$$\begin{aligned} \mathbf{A}^T\mathbf{A}a &= \lambda\mathbf{C}a \\ a^T C a &= 1 \end{aligned} \tag{6}$$

where: $\mathbf{a} = (a \quad b \quad c \quad d \quad e \quad f)^T$ is the vector coefficients of equation (3). The matrix **C** defines the constraint (5). Regression ellipse is calculated by Fitzgibbon's algorithm finding the eigenvector corresponding to the smallest eigenvalue of matrix $\mathbf{A}^T\mathbf{A}$.

3.2 Determination of Displacements from the Accelerometer Measurements

Accelerometers generate an output signal in the form of a time series of the accelerations. Determining relative displacements can be accomplished by several methodologies. The most common method is the double integration of the acceleration by a rectangular or trapezoidal rule. Generally, this problem can be described by the formula

$$s(t) = s_0 + v_0 \times t + \int_0^t \left(\int_0^t a(t)dt \right) dt \tag{7}$$

The selection of the appropriate sample rate has a significant effect on the accuracy of the calculations. In this case it is recommended to provide the measurement with a sample rate at least twice that of the highest significant frequency of the vibration of the structure. Another important factor influencing the accuracy of the integration of the measurements is the implementation of a high-pass filter. By using a suitable filter, the long-term components of the measured signal (e.g., drift) can be eliminated. It is necessary to design such a filter with a minimum frequency and magnitude response. This effect of the filter on the raw measurements can be analysed by a transfer function.

3.3 Processing and Analysis the Ground-Based Radar Measurements

Radar measures displacements in radial direction. In the case of dynamic deformation is important to transform these deformations into vertical direction. Radial displacements of the targets can be transformed into vertical displacements according to Fig. 2.

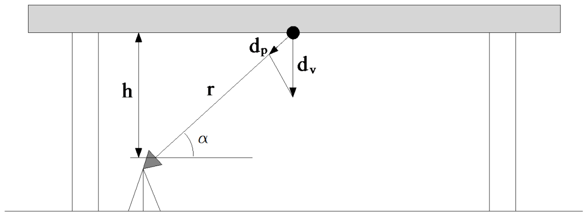

Fig. 2 Transformation radial displacements into vertical direction

3.4 Spectral Analysis of the Dynamic Measurements

Spectral analysis approach is the same for analysing the accelerometer and GB radar measurements. In the case of determining bridge vibration modes, spectral analysis methods are used. The most often used is the Fourier transformation. This approach describes a time-dependent signal by harmonic functions, which can be used to transition the signal from the time to the frequency domain. The signal can be expressed continuously or in a discrete form. In practical applications, a finite number of the data is analysed by the numerical method of the Fourier transformation, known as the discrete Fourier transformation (DFT). Calculation of the DFT can be realized by several algorithms. In the case of the dynamic deformation of bridges, the fast Fourier transformation (FFT) is most often used. The FFT is defined as

$$X_x(f) = \sum_{k=0}^{M} \gamma_x(k) w(k) e^{i 2\pi f k / f_s}, \tag{7}$$

where $\gamma_x(k)$ is the autocorrelation function, and $w(k)$ is the spectral window function (Cooley and Tukey, 1965). The significant frequencies of the signals are determined by Fisher's periodicity test. The amplitudes and phase shifts of the signals can be estimated by the least squares method.

4. A CASE STUDY

The application of the long-term and dynamic deformation monitoring terrestrial laser scanning and ground-based radar is verifying on the steel bridge structure for pedestrians and cyclists in Bratislava.

4.1 Liberty Bridge

The Liberty Bridge is part of cycling route between Bratislava city district Devínska Nová Ves (Slovak Republic) and Schlosshof (Austria). It crosses the river Morava at the river kilometer 4.31, a transverse cycling route, billabong of the river Stará mláka, ruins of the old bridge and a bunker of border fortification. The bridge is built on quaternary fluvial and anthropogenic sediments, the thickness of which is from 5 m to 8m. The total length of the bridge structure is 525.0 m (Agócs and Vanko, 2011) and (Kopáčik and Lipták, 2012).

Fig. 3 Liberty cycling bridge

The substructure consists of reinforce-concrete pillars, in which are anchored the supports of main structure. Measurement is focused on the determination of displacements of suspended bridge consists of 3 sections withspans 30.0 m + 120.0 m +30.0 m = 180.0 m over the river. The reinforcing girder is tubular, triangle shaped with orthotropic deck. The middle section has a shape of circular arc with radius of 376.35 m. The deck is composed of metal plate, of steel girders positioned in trnasverse direction and of longitudinal reinforcements. The cross slope of the deck is 2% from the longitudinal axis of the bridge to edges, the clearance width equal to the width of the traffic lane 4.0 m. Structure of the main construction is suspended on four pylons, which are designed as dual hinged rectangular frames. Diameter of pylons is 0.914 m, their height is 17.7 m.

4.2 Long-term Monitoring by TLS

The monitoring is performed by half-year measurement epochs TLS Leica ScanStation2. Scanned is the bottom side of the middle section of suspended structure and the pylons from one position of the scanner. The scanner is positioned on the Slovak side of the river approximately in longitudinal axis of the bridge so that can scan the whole bottom side of the structure (Fig. 4).

The reference network consists of four control points. Because of the fact that the bridge is built in a natural reservation, there are no possibilities to make observation sites. Due to this restriction two of control points are stabilized on the base of the pillars on the Slovak side by metallic fasteners and two of them are the points of original setting out network of the bridge, stabilized by observational pillars. All of the control points are signalized by Leica HDS targets.

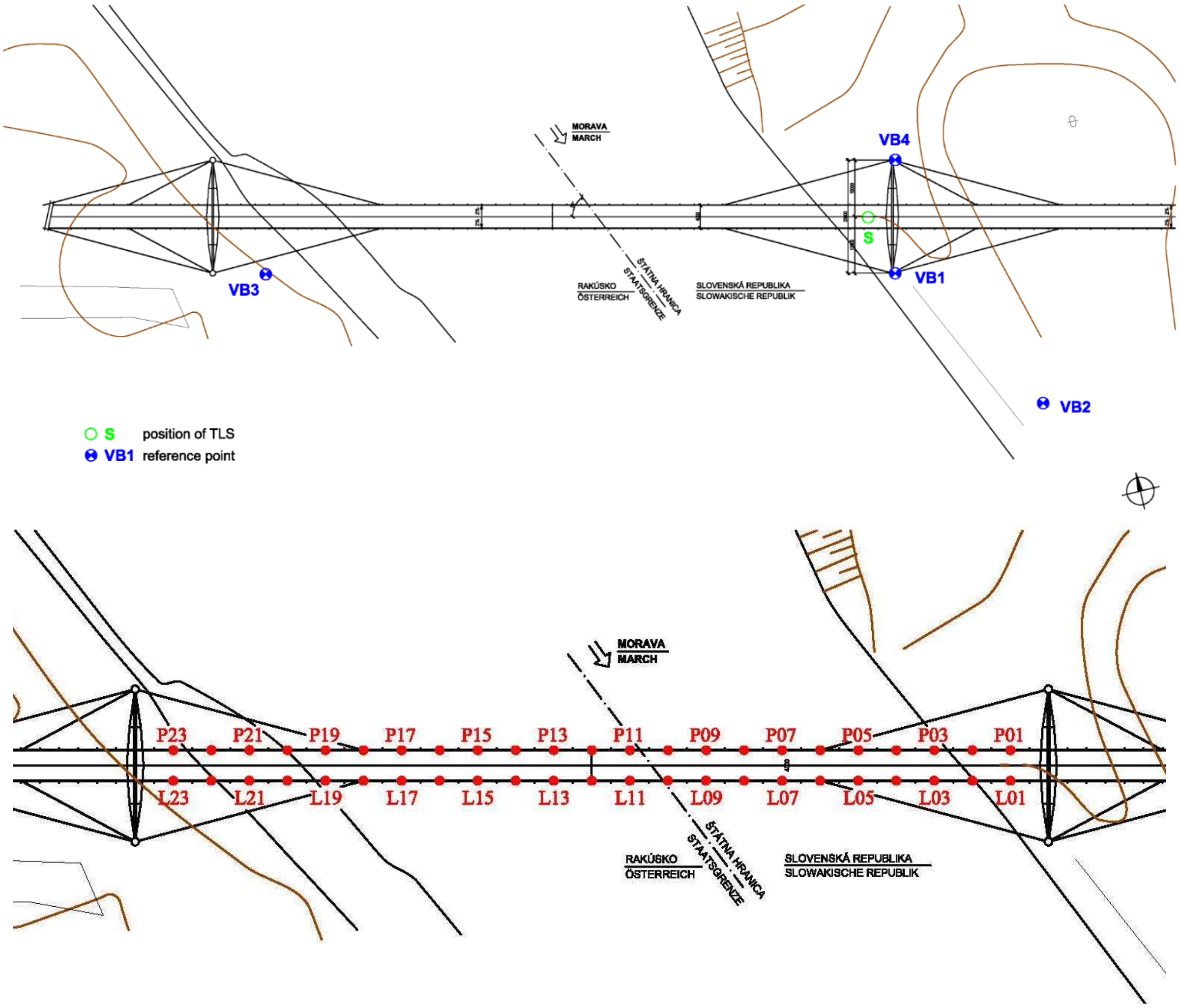

Fig.4Reference (up)and observed (bottom) points configuration

Before the each measurement epoch the construction is divided into 9 sections, in each section is defined the resolution of the scanning in a short script, what enables to short the time of scanning. The minimal point density on the bottom side of the deck was 3 mm x 3mm on the surface of the scanned part of the construction and 20 mm x 20mm on the surface of the pylons. During the scanning are measured the weather conditions and the temperature of the construction also.

The data obtained by TLS are transformed to the local coordinate system of the bridge, defined by the control points. The data processing is focused on the determination of vertical displacements of observed points positioned on the bottom side of the bridge deck and on the determination of the tilt of the pylons.

The tilt of the pylons is determined at five height levels of 102.00 m (approximately 1 m above the anchor of the pylons to the fundamentals), 105.85 m, 109.70 m, 113.55 m and 117.40 m (approximately under the top of the pylons) in the local coordinate system of the bridge, because the method of the anchorage of the pylons did not allow for the determination of a tilt on the base and top of the pylons. At each height level the coordinates of the intersection of the axis of the pylons with the horizontal plane are modeled. The intersections are obtained as the centers of the horizontal regression ellipses. The points of the cloud from a 0.2 m thick slice around the defined height level are projected into the regression horizontal plane; then, from these points regression ellipses using Fitzgibbon's procedure in Matlab are modeled.

4.3 Dynamic Deformation Monitoring by Ground Based Radar and Accelerometers

Dynamic deformation monitoring is realized by a ground-based radar IDS IBIS-S which measures dynamic displacements by comparing the phase shifts of reflected radar waves collected at the same time intervals. Displacement is measured in a radial direction (line of sight). The minimal radial range resolution of the radar is 0.5 m. The accuracy of the measured displacements is at a level of 0.01 mm, but it depends on the range and quality of the reflected signal (Bernardini, et. al., 2007) and (Gentile, 2009). The measurements and data registration are managed by the IBIS-S operational software installed in a notebook.

Verification of the radar measurements is provided by HBM B12/200 one-axial accelerometers, which are supported by an HBM Spider 8 A/D transducer. The sensors measure acceleration in a vertical direction. These inductive sensors have an operatingfrequency of up to 200 Hz and a measuring range of up to200m.s^{-2}. The accuracy of the sensors is defined by a relativeerror of up to ±2% (HBM, 2000). The measured signal is digitizedby a HBM Spider 8 A/D transducer and saved to the computer by Catman Easy software. The sensors are positioned at the centre of the structure and are fixed on the deck by loading rods (Fig. 6).

The repeated dynamic measurements are realized during different types of loading of the structure - walking, running and jumping of one person (80 kg weight) at the structure. The types of loading used are designed based on the FEM (Finite Element Method) model of the structure (Excon, 2010). The frequency of the data registration by the GB radar and accelerometersis realized at the level of 100 Hz due to the requirements to achieve a higher accuracy of the relative displacements and the occurrence of significant frequencies of structural deformations, which were higher than 10 Hz. The advantage of the GB radar is the synchronized scanning of the entire structure (Fig. 5).

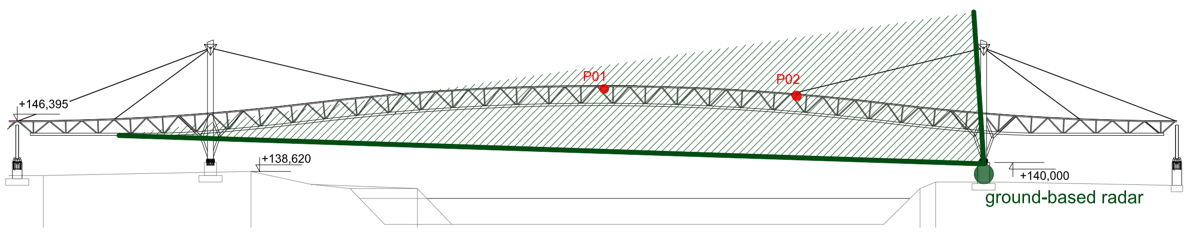

Fig. 5Measured area by ground-based radar and accelerometers (red points)

Raw displacement data by ground-based radar are measured in a radial direction (direction in the line of sight). For our purposes we needed to obtain vertical deformations. The first step in the data processing of the radar measurements is therefore setting the geometry of the structure and defining the position of the radar and observed points. We can define observed points manually using corner reflectors or by finding good parts on the structure which have acceptable reflection parameters. In our case the second option was chosen. A good reflection of the signal from the structure defines the range bin profile by SNR ratio.

Determining the relative displacements by the accelerometers is realized by the double integration of the accelerations measured. The accelerometer drift and integration errors are eliminated by a Butterworth high-pass filter with a cut-off frequency at the level of 0.5 Hz. This filter attenuates the magnitude of the spectrum at the frequency of 1 Hz by 0.7 %, which has no significant influence on the displacements determined. The filter is applied before and after the first integration of the velocities.

Before the spectral analysis of the vertical displacements obtained by GB radar and accelerations measured by accelerometers, each measured time seriesare filtered by the Butterworth high-pass filter with a cut-off frequency of0.1 Hz. This filter attenuates the signal amplitudes with a 1 Hz frequency on the level of 0.2 %. This has a minimum influence on the estimation of the expected dominant frequencies of the structural deformations. In this case, it is important to remark that the high-pass filter used does not affect the phase shifts of the signals because it is a zero-phase (symmetrical) filter. Determining the natural frequencies of the structural deformations at each measured point is realized by an auto-spectral analysis using the FFT method.

4.4 Discussion of the Results

Table 1 lists the displacements of the selected observed points. The measurements show the displacement of all of the observed points except for the points on the ends of the suspended structure.

Tab. 1 Vertical displacements of the observed points

Point No.	March 2013			Point No.	March 2013		
	Δz [mm]	$\sigma_{\Delta z}$ [mm]	Decision		Δz [mm]	$\sigma_{\Delta z}$ [mm]	Decision
L01	1	1.7	no shift	P01	1	1.8	no shift
L02	-1	1.6	no shift	P02	-1	1.6	no shift
L03	-2	1.4	5 % - 30 %	P03	-1	1.4	no shift
L04	-3	1.4	5 %	P04	-3	1.3	5 %
L05	-5	1.4	5 %	P05	-4	1.3	5 %
L06	-6	1.3	5 %	P06	-5	1.4	5 %
L07	-9	1.3	5 %	P07	-7	1.3	5 %
L08	-10	1.3	5 %	P08	-8	1.3	5 %
L09	-11	1.3	5 %	P09	-9	1.3	5 %
L10	-12	1.3	5 %	P10	-9	1.3	5 %

Observed points have not changed their position, because the structure is anchored to the supporting structure at these parts.The displacements towards the centre of the bridge are increasing and have negative values. In the middle of the bridge they reach values of -13 mm respectively, -10 mm. This is partly caused by the lower temperature of the structure in the control epoch of the measurement and partly by the load of a 10 cm layer of fallen snow.The Figure 6 shows the inclinations of the pylons at the Slovak side of the river Morava. Maximum inclinations achieved are at the level of 20 mm.

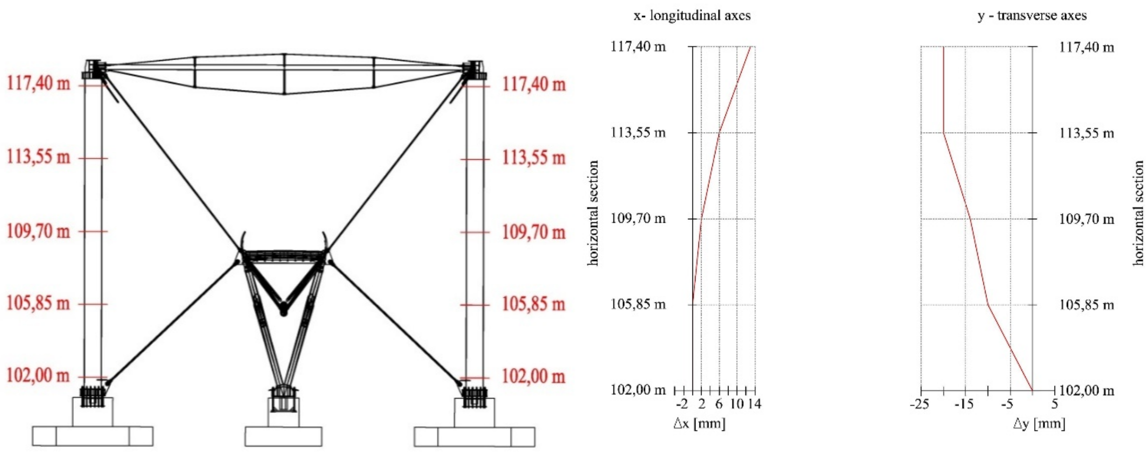

Fig. 6 Inclination of the pylons

For verification of the results of TLS was not used any traditional surveying method, because during the construction of the bridge were not stabilized any targets or equipment and facilities enabling the geodetic monitoring of the structure.

In the case of the dynamic monitoring, the effect of pedestrians walking has a minimum influence on the vertical displacements. The rapid movement of pedestrians affects the maximum vertical displacements two times more than during the loading by a pedestrian's walking. The jumping of pedestrian affects the maximum displacements at a level of around 4.85 mm at the centre of the structure (Fig. 7 left). The results from accelerometer and ground-based radar have good compliance with maximum differences in local deformations at the level lower than 1 mm.

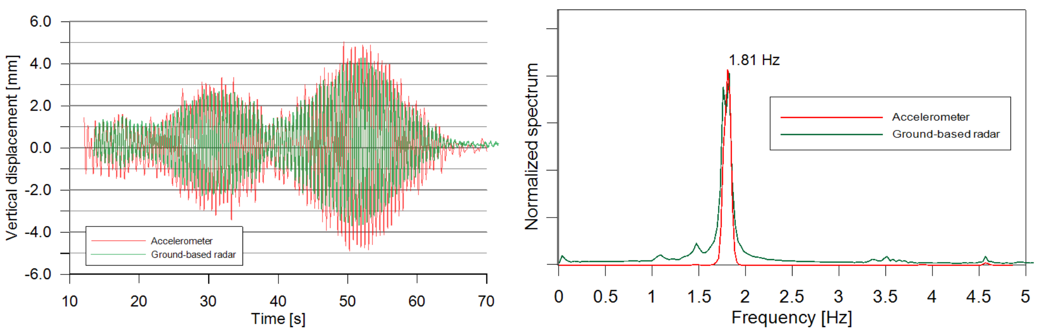

Fig. 7Vertical displacements at the center of the structure (left) and auto-spectral analysis (right) during the jumping

Tab. 2 Dominant frequencies of the deformation at the center of the structure

Vibration mode	Natural frequency [Hz]	Measurement epoch			
		1	2	3	4
2	1.63	1.53$^{(2)}$	-	1.53$^{(2)}$	-
22	2.15	-	2.05$^{(1)}$ 2.01$^{(2)}$	-	1.80$^{(1)}$ 1.82$^{(2)}$
23	2.49	-	-	2.90$^{(1)}$ 2.97$^{(2)}$	-
44	3.76	-	3.99$^{(1)}$ 3.71$^{(2)}$	-	3.51$^{(2)}$
59	4.69	-	-	4.59$^{(1)}$ 4.56$^{(2)}$	-
	>5.00	-	-	9.10$^{(1)}$ 9.11$^{(2)}$	9.07$^{(2)}$

$^{(1)}$ Accelerometer, $^{(2)}$ Ground-based radar

Table 2 contains the natural frequencies of the structural deformations obtained by the FEM model and the corresponding frequencies determined by the spectral analysis at the center of the structure. The FEM model contains 5 vibration modes of deformation, which has a significant influence on the structure's dynamic deformation. Table 2 shows the significant influence of pedestrians on the dynamic response of the monitored structure. The dominant frequencies of the deformations estimated during the loading by walking and running have a good rate of compliance with the 22nd vibration mode of the structure. The estimated frequencies approximately at the 2.00 Hz level are probably affected by the walking of pedestrians because the frequency of a pedestrian's steps during standard walking has similar values.The structural oscillation at the frequency level of 1.81 Hz is affected by the jumping at the structure (Fig. 7 right). The estimated frequency is similar to the 2nd natural frequency. According to the results of the FEM model, this natural frequency has a dominant influence on the structure's stability. This assumption was confirmed during the experiment by the low stability of the pedestrian moving on the structure. The average amplitudes of the estimated dominant frequencies are at the levels from 1.0×10^{-3} m.s^{-2} to 3.0×10^{-3} m.s^{-2}. The spectral analysis provide an estimate of the significant frequencies of the structure's deformation at the levels higher than 5 Hz, too. These frequencies have only a minimum influence on the stability and dynamic response of the monitored structure.

5. CONCLUSIONS

The paper presents possibilities in combination of the long-term and dynamic deformationmonitoring of the bridge structure by TLS, accelerometers and ground-based radar. It describes the methodology of the measurements realisation and processing and analysis of obtained data.A practical application of the deformation monitoringis realized at the cycling Liberty Bridge at Devínska Nová Ves near to the Bratislava. TLS is good applicable for long-term monitoring if the other technologies are not possible to use. Ground-based radar and accelerometers are applicable for dynamic measurements for completion of the long-term monitoring.

The results can significantly contribute to the prediction of possible failures of the structure. Failures can be reflected by anticipated temporal changes in the modal frequencies at the measured points of the structure and can be investigated by terrestrial laser scanning.

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