Vibration analysis of bridges using fiber optic sensors

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Abstract. Analysis of the dynamic behavior of bridge structures became the high impact last years. Differences between the calculated and measured vibration modes of the structure measured in regular (constant) intervals enable the determination of possible non-perfection of the structure. This could be followed more in detail using another methods general used for bridge behavior diagnostic.

The paper brings the methodology for identification and analysis of chosen dynamic characteristics of the bridge structure deformation using fiber optic acceleration sensors. Describes the basic principle of sensors based on fiber Bragg grating and the theoretical and practical aspects of the vibration modes determination using time series analysis with high sample rate. Using appropriate mathematical models (filters) and spectral analysis could be identified and described significant frequencies of the structure vibration. These are compared with the theoretical model which describes the dynamic behavior of the bridge and frequencies calculated by FEM.

The mathematical model of the data processing was verified at the small pedestrian and cycling bridge. The bridge structure was loaded by controlled (regulated) pedestrian traffic during the measurement. Using designed mathematical model was the data processed and determined the significant vibration modes in the structures vibration. Comparison of results with FEM characteristics could be used for the model calibration and increase their quality, also.

Keywords. Fiber optic sensors, deformation, deformation, frequency analysis.

1 Introduction

Bridge structures are usually exposed to the greatest extent by external influences such as weather conditions and loading by some objects. 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, which reflect the influences of the surroundings. Therefore, the rate of the structure‘s stress and the magnitude of the impact of individual factors on the structure can be determined.

Nowadays, knowledge of the dynamic characteristics of a bridge structure's behaviour is increasingly important. They are mainly caused by wind and the moving of objects on the structure (pedestrians, cyclists, vehicles). These affect the resonant behaviour of the structure, which result in the dynamic deformation of the structure. These are usually described by the modal characteristics of the structure's deformation (vibration modes). For the safe operation of the structure it is necessary to modelling these deformations and monitor them during loading tests. Also long-term monitoring of the structure using suitable methodologies is essential. These data significantly contribute to the stable and safe operation of the bridge and can be used for the calibration of a structural numerical model (Kohut et al., 2012), (Braun et al., 2014) and (Wenzel, 2009).

For these can be used different technologies. One of them are fiber optic sensors. Fiber optic sensors work on the principle of changes of physical properties of the light transition in glass fibers. Mechanical deformation of the fiber glass causes changes in the light refraction index. This can be used for measurement structural deformations.

Nowadays, there are several kind of technologies based on fiber optic sensors, such as interferometric sensors, distributed sensors and sensors with a fiber Bragg grating. For dynamic deformation monitoring of bridge structures, the fiber Bragg grating technology is the most used. Fiber Bragg grating sensors have a similar mechanical structure as the most of electronic sensors. In the case of FBG sensors the Bragg grating is used for quantification of measured signal. In difference to electric sensors, where the deformation cause changes in output electricity, the fiber Bragg grating affect the change in refraction signal. High stability of the signal transfer to long distances, multiplexing and comparable precision to electric sensors, able the more often usage of these sensors for structural deformation monitoring (Glisic & Inaudi, 2007), (Guan et al., 2004), (Honglei et al., 2011), (Min et al., 2014) and (Zhang, 2006).

Paper is focused to vibration analysis using fiber optic accelerometers, describes the principle of the fiber optic technology, especially the fiber Bragg grating (FBG) sensors. The vibration analysis of the bridge deformation is generally based on the methodology of the spectral analysis of time series. Practical application of the FBG accelerometers and used methodology of data processing is described on the case study realized at the small bridge structure for pedestrians.

2 Fiber optic sensors

Optical fiber are used mainly in telecommunication, medicine, biological applications and structural monitoring. The optical fiber is the most used technology for data transfer, today. During last several decades, the development in fiber optic technology have been strongly increasing. First applications were realized in medicine for light and image transfer. The first optical fibers had the attenuation at the level up to 100 dB/km. It was caused by contamination of used fiber glass, what was non-acceptable for long distance signal transfer. Recent optical fibers have high purity of glass material and their attenuation is very low at the level under 0.2 dB/km (Thyagarajan & Ghatak, 2007) and (Cusano et al., 2011)

Great approach has been achieved in 1978, when Ken O. Hill discovered photosensitive effect in Germanium fibers. Flaring by ultra violet UV light causes permanent change in refraction index of a fiber. This effect was exploited for the development of regular grating in optical fiber, which can reflect the selected spectrum of the transferred signal in optical fiber. The spectral shape of the reflected signal is changed by temporal changes and by the grating deformation. These properties build the base for development of the first FBG, which was later integrated into many types of sensors for custom purposes. For commercial purposes was the technology available in 1995 (Mitsche, 2005).

2.1 Fiber Bragg Grating sensors

FBG is very simple device. FBG is a grating, which is manufactured in the core of optical fiber. This grating reflects only a part of the transmitted signal band at specific wavelength (from 380 nm to 780 nm). The reflected signal band is depended on the grating spacing, which is depended on the temporal and pressure changes or other mechanical strain and it causes shifting of the reflected signal band wavelength. Based on these properties of the FBG were developed different types of sensors.

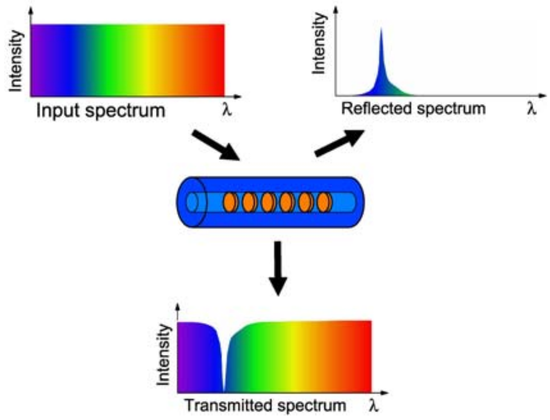

Fig. 1 Principle of FBG sensors

FBG is a component with periodic changes of the refraction index in each spacing of the fiber core. These changes are manufactured by flaring of the UV light with periodical pattern of defined energy level. After this, a grating works as mirror, which reflects selected wavelengths of the transmitted signal.

霧科OE仫isible spectrum of the transmitted signal is passing through the grating and part of the signal is reflected and the other part is passing onwards. Reflected wavelength band is passing Bragg condition:

$$\lambda_B = 2.n_{eff}.\Lambda, \tag{1}$$

where Λ is reflected wavelength (Bragg wavelength), n_{eff} is effective refraction index which is in linear relation with the grating spacing (Sylex, 2014).

2.2 Principle of deformation measurement

In equation (1) the reflected wavelength is passing the Bragg condition. Temperature changes or mechanical strain of fiber cause grating deformation and change of effective refraction index and grating spacing. This affects shift of the reflected signal wavelength. Changes in wavelength are in relationship with changes in temperature and strain, what is used for quantification of grating deformation (Antunes et al., 2012).

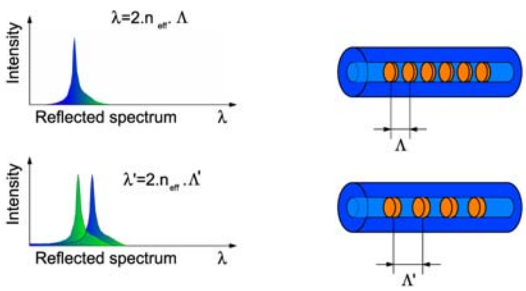

Fig. 2 Grating deformation

2.3 Signal generation and processing

The device for signal generation and signal processing is known as interrogator. The recent FBG are able to measure several physical quantities. Advantage of the FBG usage is the possibility of serial connection of different types of sensors, which is known as multiplexing. Interrogator is able to identify every sensor connected to the common canal using different modes. Most often used modes are Time Division Multiplexing (TDM) and Wavelength Division Multiplexing – WDM) (Zhang, 2006).

TDM is based on known speed of the light transferred in optical fiber, where each sensor is identified by different time stamp. Using WDM, interrogator can identify each sensor by specific wavelength of the FBG. The possible number of sensors at same canal is depended on the spacing range of the FBG and the spectral range of the signal which is generated by the interrogator (Sylex, 2014).

3 Vibration analysis of bridge structures

The main purpose of vibration analysis of the bridge dynamic deformation is the determination of vibration modes and frequencies. Each vibration mode is described by shape of structural deformation at typical frequency of its repetition.

Vibration analysis is primarily based on spectral analysis and signal processing. Identification and analysis of vibration modes can be divided into several steps which are fluently followed-up on previous steps:

- preliminary determination of vibration frequencies at each measuring point,
- calculation of averaged normalized power spectral density (ANPSD) of vibration of whole structure,
- filtration of dominant ANPSD of the structure,
- calculation of common frequencies of structural vibration using cross-spectral analysis,
- calculation of phase shifts of measured signal between measuring points at common vibration frequencies which are corresponding to ANPSD frequencies,
- identification of vibration modes.

In the first step the preliminary frequency analysis of structural deformation is realized. The reason is verification and filtering measured time series for drift or other low frequency elimination. This step is realized using numerical methods 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

$$X_x(f) = \sum_{k=0}^{M} \gamma_x(k) w(k) e^{i2\pi fk/f_s}, \tag{2}$$

where $\gamma_x(k)$ is the autocorrelation function, and $w(k)$ is the spectral window function (Cooley & Tukey, 1965).

An alternative is the application of the Welch method, which uses the FFT algorithm. In this case, the spectral density of the time series is computed from overlapped segments. These segments are analysed by the FFT method. The results give a smooth periodogram and greater accuracy of the frequencies determined. However, the resolution of the magnitude spectrum is unfortunately lower (Welch, 1967).

Next step of analysis is focused on calculation of common vibration frequencies of whole structure of several time series. Spectral analysis of several time series is based on determination of common vibration frequencies of the time synchronized measurements. Distribution of spectral density in synchronized time series is very often extremely differentiated. For calculation of common spectral density, normalized values of spectra are used:

$$X_i^{norm}(k) = \frac{X_i(k)}{\sum_{k=0}^{k-n} X_i(k)}, \qquad (3)$$

Normalized periodograms have the same weight. Final ANPSD is calculated as arithmetic average of all normalized periodograms:

$$X_{priem}(k) = \frac{1}{p}\sum_{i=1}^{p} X_i^{norm}(k), \qquad (4)$$

ANPSD describes the spectral density distribution of every time series, which can provide the global view on dynamic properties of a monitored structure. Identification of significant frequencies is realized using Fisher statistical test of periodicity (Wenzel, 2009).

Next step is focused on filtering of the time series in frequency domain using band-pass filtering. This step is realized for selection of frequency bands at significant frequencies of vibration. In this case is critical to use an algorithm which does not generate phase delaying of the signal. This factor can cause incorrect determining of the phase delays of analysed signal. Good applicable algorithm is Butterworth filter, which is the filter with irregular impulse response. This filter has longer frequency response but on the other side the filter has minimum attenuation in pass band and ripple in filtered band (Trauth, 2010).

A cross-spectral analysis of two time series (signals) is used for the cross-correlation and the time delay between them. It can be described as a different dynamic response to external effects (wind, pedestrians, cyclists, etc.). The cross-spectral density of the two time series can be estimated by the FFT of the cross-correlation function as

$$X_{xy}(f) = \sum_{k=0}^{M} \gamma_{xy}(k) w(k) e^{i2\pi fk/f_s}, \qquad (5)$$

where $\gamma_{xy}(k)$ is the cross-correlation function, and *w(k)* is the spectral window function (Bracewell, 1965).

The signals at a specific period can be defined by correlation of two time-synchronized their coherence. Cross-spectral analysis able to calculate phase delay between two signals what has critical significance in determining the vibration mode at common vibration frequencies.

Based on the analysis of amplitudes of frequencies and phase delays between measured signals at each measuring point can be identified the vibration mode of the structure. Accuracy of vibration mode identification is arising with a number of used sensors. Higher number of sensors can ensure more reliable determination of vibration mode.

4 A case study

The practical use of the fiber optic accelerometers and spectral methods of data processing described in the previous chapter were realized on an actual bridge structure. Bridge structures for pedestrians are usually designed as flexible structures with higher values of deformation amplitudes than road and railway bridges. Experimental measurements were realized on a pedestrian bridge over the river Malý Dunaj in Bratislava (Slovakia). The known modal characteristics of the structure's dynamic deformations are useful for verification of the measured deformations.

4.1 Pedestrian bridge over the Malý Dunaj

Pedestrian bridge over the river Malý Dunaj is situated in Vrakuňa, which is city district of Bratislava (Slovak republic). Bridge is relative flexible suspended steel structure. The bridge deck is built by steel girder of length 54.00 m and width of 2.70 m. The girder consist from 4 beams in the main direction and 26 crossbeams in 2.00 m spacing. The connection of the bridge deck and the pillar is solved using two roller-bearings. The deck hanging consist from two steel cable, left and right side the deck, and 9 vertical hanging of diameter of 30 mm in distance of 5.40 m, fixed on the crossbeams. According this is the deck divided into 10 bridge field. The deck is covered by steel plates of 10 mm thickness. Both side of the bridge is railing of 1.14 m height (Dopravoprojekt, 1991).

Fig. 3 Pedestrian Bridge over the river Malý Dunaj

4.2 Measurement system

Bridge structure as typical suspension bridge has relatively high range of vertical bending and torsional oscillation. For verifying the stability of the bridge structure, was designed the measurement system based on FBG accelerometers.

For measuring of vibration were used accelerometers Fibersensing FS6500 (Fig. 4). These sensors has acceptable parameters for dynamic monitoring of bridges. Declared sensitivity of sensors is at the level of 75 pm/g with measurement range 10 g. Central measurement wavelength varies between 1510 to 1590 nm (Fibersensing, 2015).

Fig. 4 Accelerometer Fibersensing FS6500

Signal interrogation for accelerometers Fibersensing FS6500 is realized by interrogator Sylex FBG Scan S-line 800D. This interrogator works on principle of spectrometer with CCD member. Interrogator is able to read a signal from up to 75 sensors at one canal. Frequency range of measurements is up to 2 kHz and spectral range of measurable wavelength is from 1515 to 1590 nm.

For experimental measurements were used 6 sensors situated in three cross sections, where the structural deformations are typical for the monitored structure. Distribution of accelerometers at the structure illustrates Fig. 5

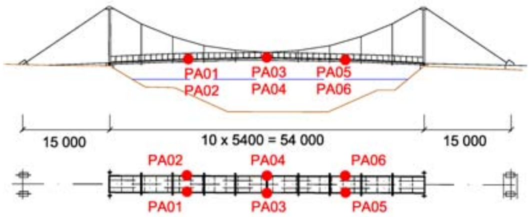

Fig. 5 Configuration of measuring points

The FBG sensors are relatively high temperature sensitive, which causes temperature drift of the measurement signal. Temperature data are applied for temperature compensation of the measured acceleration and for additional interpretation of temperature changes in the structure, also. For registration of temperature changes were used contact temperature sensors Pt1000/TG7 (Cometsystem, 2015). These sensors were located at the same places like the accelerometers.

4.3 Experimental measurements

Experimental testing of FBG sensors Fibersensing FS6500 and the developed mathematical model of vibration analysis was realized 22nd April 2015. Measurements were realised during the several types of typical loading of the structure, such moving of pedestrians or cyclists at the bridge. These types of loading affect ambient vibration of the bridge. Another types of structure loading were realized by organized jumping in specified position on the structures – specific dynamic loading.

Each epoch has a duration of approx. 2 minutes. The frequency of the data registration by the accelerometers were set to 200 Hz, due to the requirements to achieve a higher degree of accuracy of the relative displacements and the occurrence of significant frequencies of structural deformations, higher than 10 Hz.

5 Data processing and analysis

The data processing is based on application of mathematical model described in chapter 2. Results were verified by numerical model of the bridge structure developed by Finite Element Method (FEM). FEM describes several significant vibration modes, which have crucial influence on the bridge stability and dynamics. Next will be discussed results of the frequency analysis of the 1st vibration mode, with the most significant frequency 1.42 Hz (Fig. 6).

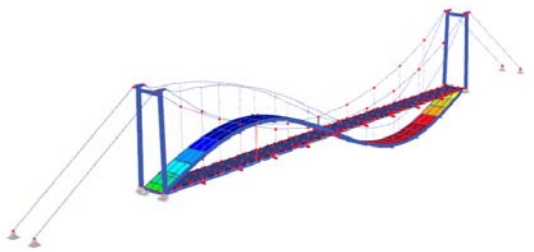

Fig. 6 1st vibration mode of the structure determined by FEM with significant frequency 1.42 Hz

Measurements were realized during the specific dynamic loading - jumping of one person in the surrounding of measuring points PA01 and PA02 (Fig. 5). Measured accelerations illustrates Fig. 7. It can be seen significantly higher maximum values of accelerations at the points PA01 and PA02, comparing to other measurement points. The minimum level of the maximum acceleration was registered at points PA03 and PA04. Points PA05 and PA06 exhibit slightly lower values of maximum accelerations and time delay at level of half of period of oscillation towards the points PA01 and PA02, which corresponds with the 1st vibration mode determined by FEM (Fig. 6).

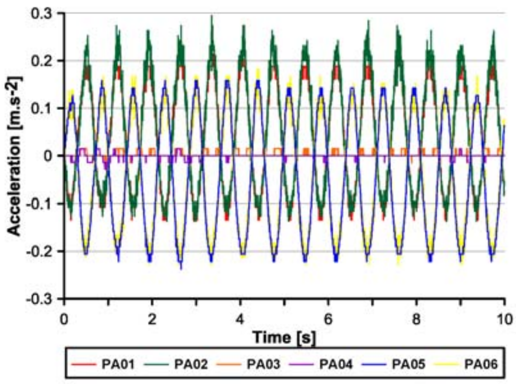

Fig. 7 Measured accelerations at measuring points

The first step of data processing is generally the determination of significant frequencies of the structure's vibration at each measuring point. Table 1 presents significant frequencies and normalized amplitudes of each point. Fig. 8 illustrates ANPSD of the whole bridge structure.

Table 1. Measured frequencies of the structure's 1st vibration mode (1.42 Hz)

Measuring point	Frequency [Hz]	Normalized amplitude	Difference * [%]
PA01	1.415	0.2945	0.35
PA02	1.416	0.2773	0.28
PA03	1.416	0.0299	0.28
PA04	1.415	0.0092	0.35
PA05	1.416	0.1711	0.28
PA06	1.416	0.2122	0.28
ANPSD	1.416	0.2014	0.28

* Difference between model and measured frequency

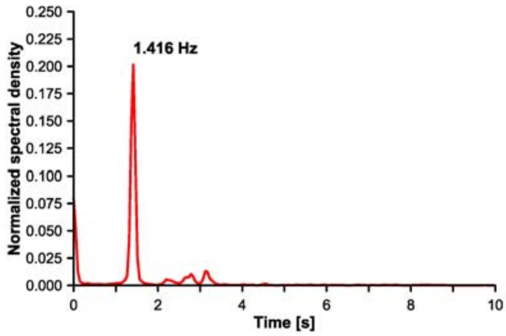

Fig. 8 ANPSD of the structure's vibration

The measured frequencies are relatively in high compliance with model frequencies. Differences between the measured frequencies and FEM are up to 0.35 %, which could be valuated as very good compliance. Difference can be caused by the nonsufficient accuracy (density) of the FEM – pure information about the steel quality, types (class) of welding and screw joints.

In next step could be identified common characteristics of the vibration modes at different points of the structure using cross-spectral analysis. Table 2 and Table 3 describe normalized amplitudes and phase delays between signals measured at different points at the frequency of the 1st vibration mode.

Table 2. Common normalized amplitudes and phase delays at measuring points PA01, PA03 and PA05

1st measuring point	2nd measuring point	Normalized amplitude	Phase delay [°]
PA01	PA03	0.2344	5.7721
PA01	PA05	0.3948	179.3334
PA03	PA05	0.2426	173.5612

Table 3. Common normalized amplitudes and phase delays at measuring points PA02, PA04 and PA06

1st measuring point	2nd measuring point	Normalized amplitude	Phase delay [°]
PA02	PA04	0.1747	4.2910
PA02	PA06	0.3833	179.6874
PA04	PA06	0.1973	175.3964

Phase delay between measuring points positioned at the same bridge hanging reach minimum values, (up to 2°), which represent time delay of signals at the level of 0.01 s. These values are in good compliance with FEM, calculated for vertical bending vibration mode without torsional oscillation.

Table 4 describes normalized values of the structural deformation at each point. Figure 9 illustrates the normalised structure deformation at the measuring points and the FEM for the 1st vibration mode.

Table 4. Normalised structure deformation for the 1st vibration mode

Measuring point	Normalized deformation
PA01	0.2344
PA02	0.1747
PA03	-0.0068
PA04	-0.0416
PA05	-0.1968
PA06	-0.1468

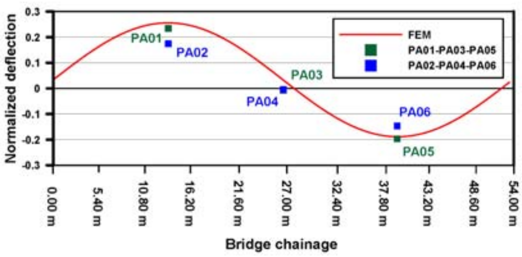

Fig. 9 Normalised structure deformation determined by experimental measurements and FEM

The structure deformation at both, the left and right side of the bridge is in correspondence with the FEM (Fig. 9). It is not possible to make the comparison of the measured and the model structure deformation using absolute values of deformation, because the FEM generates normalised values of structure deformation, only. These express the deformation between structure points each other, we are able to compare the changes in the shape (form) of the structure, only. Even though the shape of the structure is generated by small number of sensors (points) is in good compliance with the FEM (Fig.9). To increase the accuracy of the structure vibration mode determination by acceleration measurement it's needed the completion of the measurement system by higher number of sensors. Resulting this could be the structure deformation determined with higher resolution and reliability.

Conclusion

The paper presents the possibility of determination of structural deformations using FBG accelerometers during the dynamic loading of the structure. For determination the oscillation frequencies and analysis of vibration modes was developed methodology and mathematical model, based on spectral analysis and signal processing. Practical usage of FBG accelerometers and the application of the developed methodology of data processing was realized at the pedestrian bridge in Vrakuňa (city district of Bratislava). Results of experimental measurements correspond with the developed FEM of the structure and can be used for their calibration. Determination of vibration modes and changes of modal frequencies will significantly contribute to prediction of the possible failures of the structure, also. Temporally changes in the modal frequencies reflect the actually condition of the structure and their eventually changes. Following, these could be investigated, more detailed by another surveying methods, such as terrestrial laser scanning.

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