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APPLICABILITY OF DISPLACEMENT MEASUREMENTS BY MICROWAVE INTERFEROMETRY IN BRIDGE DYNAMICS

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Abstract: *The terrestrial microwave interferometry is a rather new measuring technique, which allows the measurement of relative displacements of structures with an accuracy of up to 0.01 mm at a sampling rate of up to 4000 Hz, without any kind of instrumentation on the structure. Due to the high sampling frequency, capturing the vibrational behaviour of the measured object is also possible and thus its modal parameters can be directly determined. This paper presents briefly the measuring principle and some preliminary investigations performed to demonstrate the applicability of this measuring technique in structural dynamics of bridges.*

Key words: *Microwave interferometry, dynamic measurements, structural health monitoring.*

1. Introduction

The identification of the dynamic parameters of existing structures is a main issue in structural health monitoring. These parameters are usually determined experimentally by testing the dynamic behaviour of the structure in non-operative situations (e.g. modal testing of concrete floors) or in operational conditions (e.g. dynamic measurements of railway bridges). The first and most important steps in the determination of the modal parameters (natural frequencies, damping ratios, modal shapes) of a structure are the dynamic measurements. They are usually performed by employing conventional sensors such as piezoelectric acceleration sensors, strain gauges or inductive displacement transducers. However, these methods require high labour efforts, as they have to be mostly mounted directly on the object, whereas for several structures with bad accessibility they cannot be implemented at all. Furthermore, it is to be noted that the conventional sensors can be installed only at a limited number of discrete points on the structure.

The microwave interferometry (MI) represents a modern, non-contact measurement technique which allows the dynamic measurement of deformations in real time. The main advantages of this technology are its high accuracy, its high

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sampling rate and its ability to capture the overall motion of the structure that is illuminated by the antenna beam. The non-contact technique is a very important aspect, especially for measurements of railway bridges, as the installation of conventional sensors often requires additional safety measures and sometimes even temporary track closures.

This paper presents briefly the MI measuring principle and some investigations performed for demonstrating its applicability in structural dynamics as well as the validation of the results.

2. Microwave Interferometry

2.1. Measurement Principle

The microwave interferometry principle is based on the measurement of amplitude and phase of the electromagnetic wave transmitted by the radar device (microwave interferometer) and reflected back by the object illuminated by the antenna beam [1]. Since the interferometric phase ϕ lies always between $-\pi$ and $+\pi$, the phase difference between two epochs is expressed as

$$\phi = \phi_{disp} + \phi_{atm} + \phi_{noise} - 2\pi n \, . \qquad (1)$$

ϕ_{disp} represents the phase shift that corresponds to the object movement along the line of sight of the device. This parameter is to be considered in case of displacement monitoring and is related to the line of sight displacement Δr_{disp} as expressed by

$$\phi = -\frac{\lambda}{4\pi} \cdot \Delta r_{disp} \, . \qquad (2)$$

ϕ_{atm} depicts the phase changes caused by atmospheric effects, ϕ_{noise} represents the measurement noise and n is the phase ambiguity, since the integer number of phase cycles cannot be measured, but only the phase difference is measurable. However, in case of short time measurements (typical for investigations in structural dynamics) the atmospheric influences are rather small and can thus be neglected. The phase ambiguity is solved under the assumption that the displacement of the target within one sampling interval does not exceed a quarter of the wavelength of the transmitted wave (i.e. $\pm\lambda/4 = 4.4mm$, $\lambda = 17.4mm.$).

2.2. Microwave Interferometers

The microwave radars IBIS (manufactured by IDS, Italy) and FastGBSAR (manufactured by Metasensing BV, The Netherlands) are two devices that use the MI principle (Fig. 1). Both of them are designed to operate in the Synthetic Aperture Radar (SAR) as well as in the in the Real Aperture Radar mode (RAR). The SAR technique is usually employed when aiming to obtain two dimensional images of the observed area. In case of measurements in structural dynamics only the RAR mode is of interest.

Fig. 1. *MI radars IBIS-S (left) and FastGBSAR (right) Drawin*

The MI radars allow the acquisition of the vibrational behaviour of several points on the structure simultaneously. This is an important advantage in relation to conventional measurement systems.

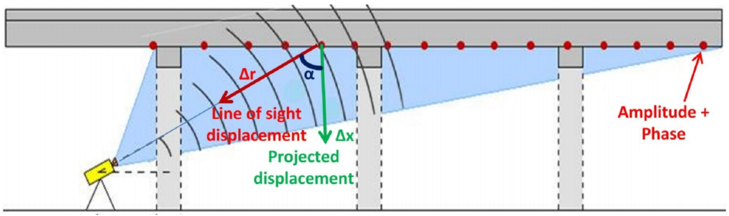


Fig. 2. *Typical measurement situation*

Additionally, since the working principle is based on transmitting microwaves, the MI devices can be operated independently of daylight and weather conditions.

The MI sensor in RAR mode is mounted on a tripod and transmits microwaves with a frequency of 17.2 GHz (Ku-Band). The microwaves are then reflected by discontinuities of the target object (e.g. corners) and received again by the sensor. The amplitude of the received signal depends strongly on the intensity of the reflection. Good reflections are obtained from concrete edges, rocks or any other kind of discontinuities within a structure, whose dimensions exceed the wave length (17.4 mm). A bad reflector is for example the vegetation.

The microwave interferometers can measure only one-dimensional deformations, i.e. in the line of sight of the device. Hence a good understanding of the mechanics of the targeted structure is needed, in order to make realistic assumptions regarding the direction of the movement, which is to be considered when setting up the device. The deformations measured in line of sight the device Δr (see Fig. 2) are then to be projected to the real direction of movement Δx according to equation (3).

$$\Delta x = \frac{\Delta r}{\cos(\alpha)} \tag{3}$$

The MI radars in RAR mode only allow a range resolution, i.e. an averaged displacement value for a number of resolution cells. No azimuthal resolution is provided. This means that the displacement of different moving targets which are situated in the same resolution cell cannot be distinguished (Fig. 3). This effect should be avoided by an appropriate positioning of the device in order that each cell is represented by a dominant reflector [2].

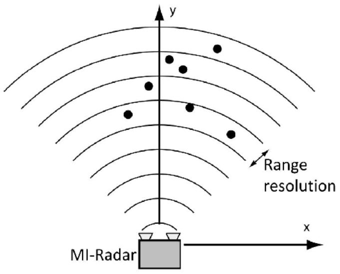


Fig. 3. *Range resolution of a MI radar*

The range resolution in case of MI radars is determined by sampling the frequency using the SFCW principle (Stepped Frequency Continuous Wave) [3]. It can be expressed as function of the bandwidth B of the transmitted wave and the speed of light c as:

$$\delta_r = \frac{c}{2 \cdot B} \tag{4}$$

Assuming a bandwidth of 200 MHz (maximum value allowed by the authorities in Germany), the corresponding range resolution according to eq. 4 is 0.75 m.

Table 1 gives an overview over the main technical specifications of the devices mentioned above.

In general a sampling rate of 200 Hz is considered to be sufficient for measurements in bridge dynamics, as the first natural frequency, which is mostly dominant for the vibrational response, usually lies below 20 Hz.

Specifications of MI radars Table 1

Specification	**IBIS-S**	**FastGBSAR**
Centre Frequency	17.2 GHz	
Wavelength	17.4 mm	
Bandwidth	Up to 200 MHz	
Range resolution	0.75 m	
Accuracy	0.01 mm to 0.1 mm	
Maximum distance	1 km	4 km
Max. sampling rate	200 Hz	4000 Hz

A more detailed overview of the measurement principle is given in [1] and [4]. Further application examples are presented in [5] and [6].

3. Experimental Investigations

The investigations focused on the comparison of the displacement time series measured using conventional displacement sensors and a microwave interferometer, as well as on the comparison of the main modal parameters derived thereof (natural frequencies and modal damping ratios).

For a reliable comparison of the measurement data captured with different systems, it is of great importance that the data are fully synchronised in relation to the corresponding time vectors. A direct synchronisation during the acquisition was not possible in the present case, as the systems are operated using different software, which do not allow the manipulation of the internal clocks. Therefore the synchronisation was done within the subsequent analysis by programming a function which finds the first local maxima of the compared displacement time histories. The time vectors of the data series were then adjusted according to the time points of the local maxima found in the previous step.

3.1. Laboratory Tests

3.1.1. Measurement Object and Set-Up

The structure investigated in the laboratory is a simple supported steel beam (steel type S235JR) with a cross section HEB 100 and a span width of 8 meters (Fig. 4). In order to simulate real measurement situations for the MI devices, the beam was installed 6.8 meters above ground level. Besides the investigations involving the microwave interferometers, the test beam is also used for general investigations in structural dynamics. Therefore it is instrumented with several conventional sensors. At every meter interval, a piezoelectric accelerometer was installed, in order to allow an experimental modal analysis. Additionally, velocity sensors, strain gauges and draw-wire displacement sensors were mounted at the points MP4 and MP8. The complete sketch of the instrumentation is shown in Fig. 5.

Within the frame of this investigation, two measurement set-ups were considered (s. Fig. 5). In the first set-up the MI radar was placed in the vertical plane, directly under the middle point of the beam (MP4). In the second set-up the device was placed

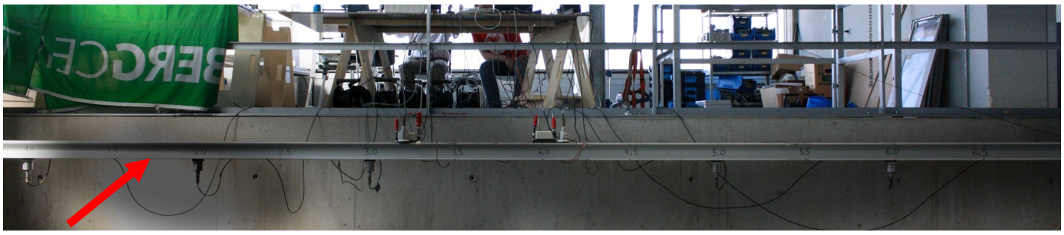


Fig. 4. *Test beam for laboratory investigations in structural dynamics*

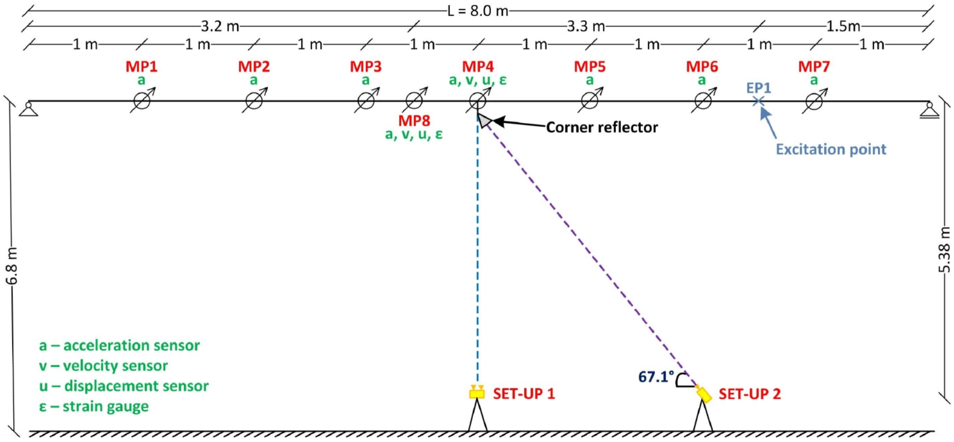


Fig. 5. *Measurement set-up*

in the vertical plane beneath the beam as well, but this time having the same horizontal coordinate as the point MP6.

In both set-ups a corner reflector was mounted at the measuring point MP4, in order to obtain one dominant signal from the resolution cell that includes the point MP4. In this way, a reliable comparison between the measurements performed with the MI sensor and the conventional draw-wire sensor was facilitated.

The excitation of the beam was made at the point EP1, using an impact hammer with a head mass of 5.44 kg (12 lbs).

3.1.2. Results and Comparison with Conventional Sensors

Displacement Measurements

In the first measurement set-up, a direct MI displacement measurement in vertical direction was possible. Assuming that the deformation of the beam occurs only in vertical direction, the displacement measured in line of sight of the MI radar matched in this case the real displacement.

However, in the second set-up, a projection of the measured line of sight displacement according to eq. 3 was necessary.

Fig. 6 shows exemplarily a comparison of two displacement time histories measured in the first set-up using the MI radar and the draw-wire displacement sensor at the point MP4. The two displacement time series match quite well. The maximum difference between them lies below 0.2 mm, which is a satisfactory value, considering that the accuracy specified by the manufacturer is expressed as an absolute value, but not as a percentage. Moreover, the uncertainty of the draw-wire sensor measurement can also account for differences between the two data series.

Natural Frequencies Analysis

The natural frequencies of a structure are usually determined through Fast Fourier Transformation (FFT) of free vibration signals (no-load). These signals can be recorded either during an ambient vibration or during the decay phase generated by an impact loading.

Fig. 7 presents the frequency spectrums obtained through FFT of the decay signals shown in Fig. 6. A very good match between the natural frequencies determined using signals from the two sensors can be seen.

The results were also confirmed by the experimental conventional modal analysis

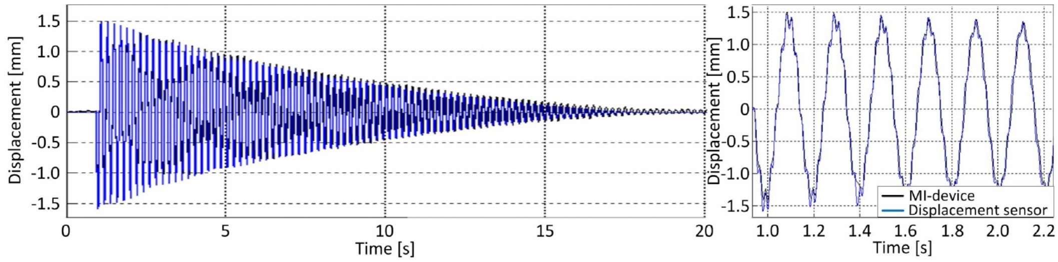


Fig. 6. *Comparison: displacement measured with MI sensor and with a conventional sensor (point MP4). Right: zoom of the measurement data in the interval 0.95-2.2 s.*

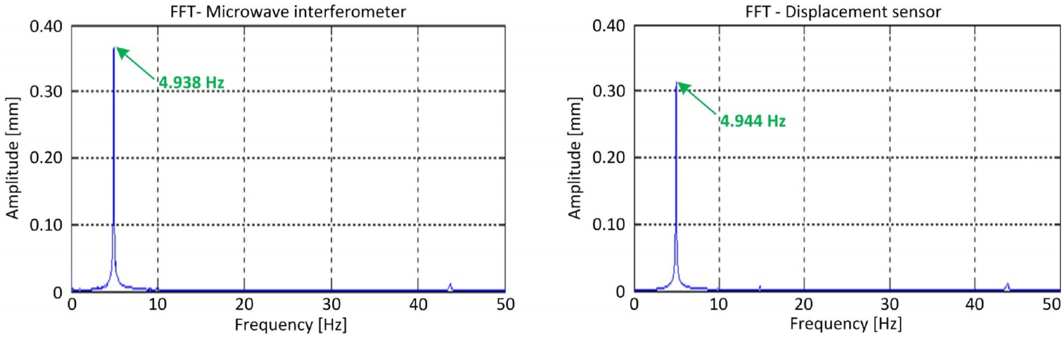


Fig. 7. *Frequency spectrums: MI device and conventional displacement sensor*

performed within the investigation, employing the MISO approach (multiple-input, single-output).

Damping Estimation

In order to compute modal damping ratios of a structure it is necessary to analyse the signal of the decay phase (free vibration) decomposed in individual modes. The decomposition of the displacement time history containing superimposed responses from all excited mode shapes can be done by applying a bandpass filter around each natural frequency. Subsequently, the modal damping ratios ξ can be directly computed using the logarithmic decrement approach (eq. 5). The amplitudes x_n, x_{n+m} and the number of cycles m are to be extracted from the decomposed signals in time domain.

$$\xi = \frac{1}{2 \cdot \pi \cdot m} \cdot \ln\left(\frac{x_n}{x_{n+m}}\right) \tag{5}$$

Fig. 8 shows the estimation of the damping using the displacement time histories from Fig. 6. The results are also in this case in a very good agreement.

The results presented for the laboratory investigations were obtained analysing the data generated by only one impulse excitation in the first set-up. However, during the tests, more excitations were recorded and the corresponding data series were analysed. The results indicate consistently a very good correlation between the two types of sensors used.

Furthermore, the methodology presented above was employed to analyse the measurements in the second set-up as well. The analyses for this scenario also revealed satisfactory results.

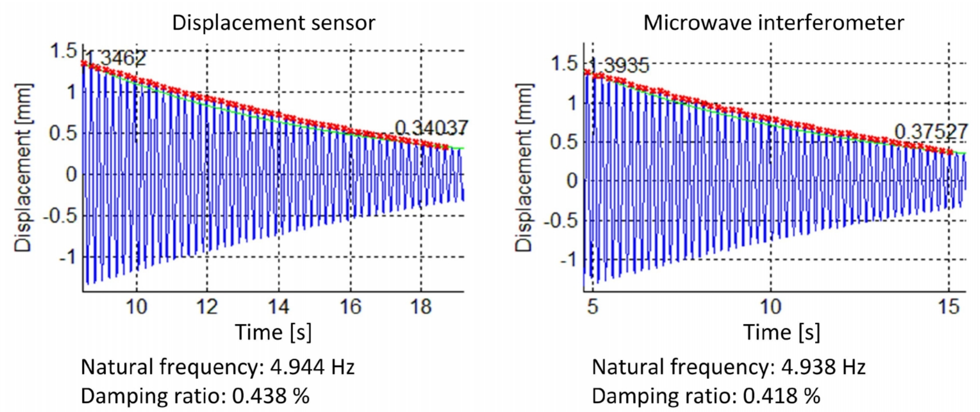


Fig. 8. *Damping estimation for m=50 (time vectors not synchronised)*

3.2. Investigation of a Railway Bridge

After performing the preliminary tests in the laboratory, the authors proceeded to an in situ measurement of a railway bridge, in order to test the applicability of microwave interferometers for dynamic measurements of bridges in operational conditions. For this, displacement measurements, using the MI radar IBIS-S and a conventional inductive displacement sensor, as well as acceleration measurements, using conventional servo accelerometers, were carried out simultaneously. The results were compared afterwards.

3.2.1. Measurement Object and Set-Up

The investigated structure is a plate girder steel bridge with a span width of 16.4 m. The static system of the structure is represented by two parallel, uncoupled, simple supported beams (TBW 1 and TBW 2, see Fig. 9 and Fig. 10). Fig. 10 shows also the complete instrumentation of the structure.

It should be noted, that also in this measurement set-up corner reflectors were placed as close as possible to the other sensors to secure a unique dominant signal from the resolution cells around the measurement points MP 1 and MP 2.

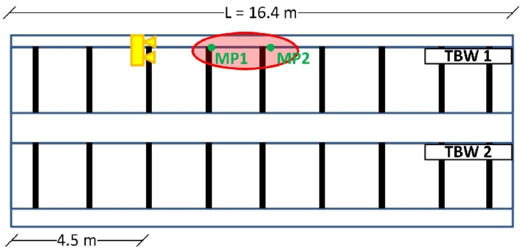


Fig. 9. *Measurement set-up (top view)*

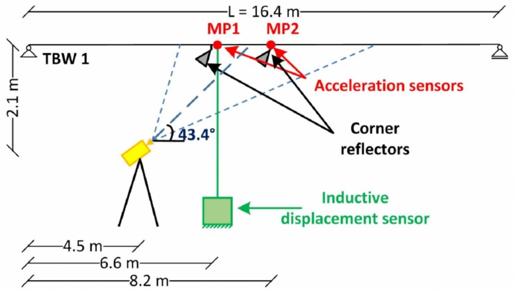


Fig. 10. *Measurement set-up (side view)*

3.2.2. Results and comparison with conventional sensors

Displacement Measurements

Fig. 11 shows exemplarily displacement time series of the points MP1 and MP 2 captured by use of the microwave interferometer IBIS-S. The recorded deformations were caused by the passage of a high-speed train ICE. The signal was sampled at 125.2 Hz.

As shown in Fig. 10, the point MP1 was instrumented also with an inductive displacement sensor (sampling rate 600 Hz). Therefore it was possible to superimpose the deformation from Fig. 11 (at the point MP1) with the deformation measured by the conventional sensor at the same point, for the same train passage (Fig. 12 – with synchronised time vectors). The residuum resulting thereof shows that the differences between the two time series are very small (below 0.4 mm).

Natural Frequencies Analysis

The determination of the natural frequencies using the signal recorded during the train passage is not recommended, as it would be then a problem of forced vibrations with additional mass. The additional mass would result in apparently lower natural frequencies of the structure [7]. Hence the natural frequencies have to be determined through a Fast Fourier Transformation of the signal captured during the decay phase (after the train passage) into the frequency domain. Fig. 13 and Fig. 14 show exemplarily frequency spectrums obtained by analysing signals from all the sensors used, for the same train passage. A very good correlation of the results can be observed.

Damping Estimation

A comparison of the damping, estimated according to eq. 5, using decay signals recorded by all types of sensors used, is shown in Fig. 15. It can be seen that the results of the different sensors are corresponding well.

It should be mentioned that the results presented above refer to only one train passage. However, more train passages were recorded within the investigation. The measurement data from each event were analysed using the methodology presented above. The results are consistent, showing always good agreement between the different sensors used.

Other similar investigations referring to the validation of the MI technology without additional corner reflectors were performed on the same bridge. The results, presented in [8], are as well very satisfactory.

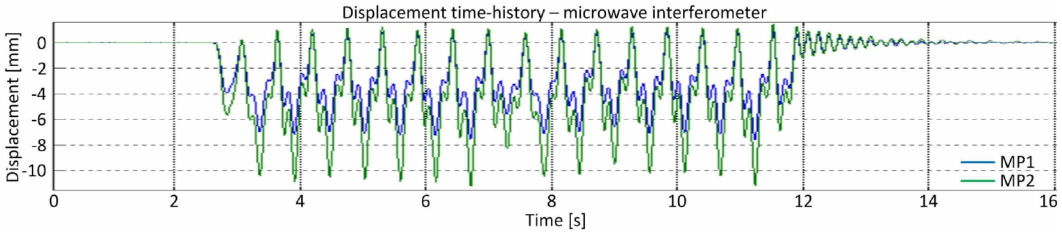


Fig. 11. *Displacement time series measured by the MI radar IBIS-S (passage of ICE)*

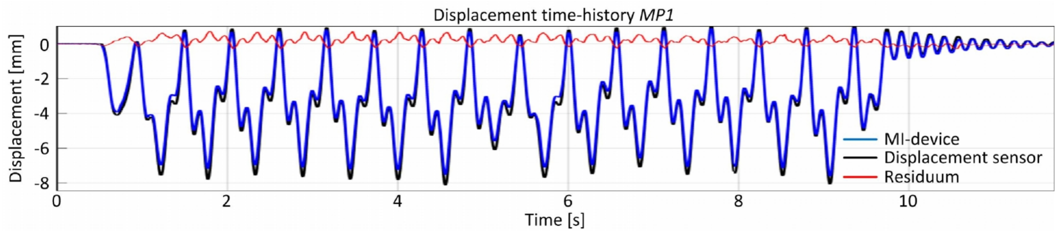


Fig. 12. *Displacement time series measured with an MI radar and a conventional sensor*

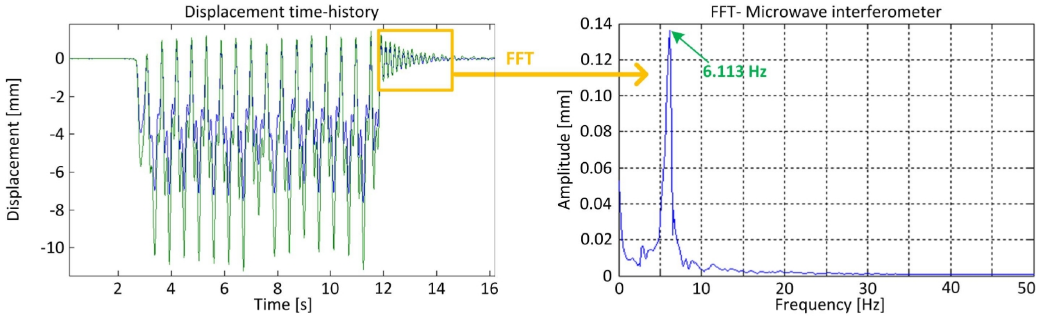


Fig. 13. *Deformation measured with the MI radar (left) and the frequency spectrum resulting thereof (right)*

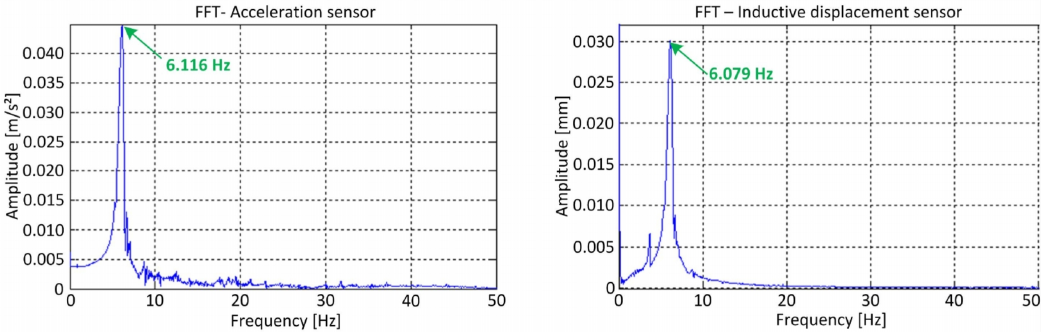
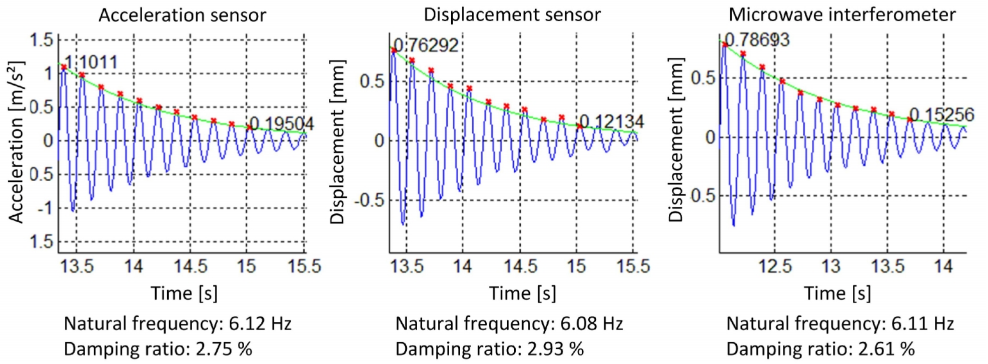


Fig. 14. *Frequency spectrums resulting from the conventional measurements*



Natural frequency: 6.12 Hz
Damping ratio: 2.75 %

Natural frequency: 6.08 Hz
Damping ratio: 2.93 %

Natural frequency: 6.11 Hz
Damping ratio: 2.61 %

Fig. 15. *Damping estimation (m=10), passage of an ICE*

4. Final Remarks

This paper investigates the applicability of the MI technology for dynamic measurements of bridges in operational conditions. For this purpose, experimental investigations were carried out. The first tests were performed in laboratory conditions on a simple supported steel beam. In the next step, an operational railway steel bridge was measured. In both cases, MI radars and conventional sensors were employed and the results were compared. A good quality of the results obtained with the microwave interferometer was confirmed.

Considering the high accuracy of the measurements and the non-contact measurement of multiple points simultaneously, it can be affirmed that the microwave interferometry represents a promising technology for the future of dynamic measurements of bridges.

The non-contact measurements are especially of great importance for railway bridges, as no track closure is required.

However, further investigations have to be carried out. In the presented measurement of the bridge, the MI device was positioned in the vertical plane, directly under the measured object. This scenario is not possible for most bridges. Therefore, other parallel measurements are planned, in order to investigate the effects of an off-centre positioning of the device on the quality of the results.

Another part of the future work will focus on the comparison of the MI devices available in the market – IBIS and FastGBSAR.

References

1. Bernardini, G., De-Pasquale, G., et al.: *Microwave interferometer for ambient vibration measurement on civil engineering structures: 1. Principles of the radar technique and laboratory tests.* In: *Proceedings of EVACES '07 - Experimental Vibration Analysis for Civil Engineering Structures.* Porto, Portugal, 2007.
2. Rödelsperger, S., Läufer, G., et al.: *Monitoring of displacements with ground-based microwave interferometry: IBIS-S and IBIS-L.* In: Journal of Applied Geodesy 4 (2010) No. 1, p. 41–54.
3. Taylor, J.D.: *Ultra-wideband radar technology*. CRC Press, 2001.
4. Rödelsperger, S., Läufer, G., et al.: *Terrestrische Mikrowelleninterferometrie – Prinzip und Anwendungen.* In: Allgemeine Vermessungsnachrichten (AVN) **10** (2010) No. 10, p. 324–333.
5. Schneider, J., Becker, M., et al.: Monitoring of Dynamic Properties of Bridges by Terrestrial Microwave Interferometry. In: *GJBS 2012 - Proceedings of the 9th German-Japanese Bridge Symposium, Volume of Abstracts,* K. Sugiura (ed.), Kyoto, Japan, 10-11 September 2012, p. 59-61.
6. Schneider, J., Becker, M., et al.: *Mikrowellen-Interferometrie zur Strukturanalyse und Bauwerksüberwachung von Tragstrukturen.* In: *1. Brückenkolloquium: Beurteilung, Ertüchtigung und Instandsetzung von Brücken,* Krieger, J.; Isecke, B. (eds.), Ostfildern, 24-26 Juni 2014, p. 201-205.
7. Arsenal Research: *Richtlinie: Dynamische Messungen von Eisenbahnbrücken (Guideline for dynamic measurements of railway bridges),* 2007.
8. Schneider, J., Becker, M., et al.: *Identifikation dynamischer Strukturparameter von Eisenbahnbrücken mittels terrestrischer Mikrowelleninterferometrie.* In: *Schriftenreihe Konstruktiver Ingenieurbau Dresden, Heft 40: 8. Symposium Experimentelle Untersuchungen von Baukonstruktionen,* Curbach, M., Opitz, H., Scheerer, S., Hampel, T. (eds.), Technical University Dresden, Dresden, 2015, p. 47-60.