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THE FOOTBRIDGE JESÍPEK – APPLICATION OF RADAR INTERFEROMETRY FOR DYNAMIC RESPONSE EVALUATION

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Abstract. Recent advances in radar systems have led to the development of radar interferometry (RI) methods for contactless vibration monitoring of large-scale structures, i.e. bridges, water tower reservoirs, and factory chimneys. Interferometric radars are devices capable to measure with 200 Hz sampling frequency and relative movement precision of 0.1 mm up to 0.01 mm. The major part of this paper describes an in-situ footbridge experiment near Hradec Králové. Radar interferometry devices were deployed along with ordinary techniques compounded by accelerometers, wiring, and acquisition station. Experiment was focused on the evaluation of basic dynamic structural properties such as natural frequencies and mode shapes. A lot of attention was also given to the result comparison of these measurement methods. Test results have confirmed the applicability of RI for bridge vibration monitoring.

Keywords: Bridge dynamics, radar, radar interferometry, accelerometers.

1. Introduction

Radar interferometry is a contactless geodetical measurement method operating with electromagnetic microwaves. The technique is based on a well-known conventional RADAR principle, i.e. Radio Detection And Ranging. The fundamental characteristic of commonly used radar is its ability to determine the range of the target (i.e. distance) by measuring the time of transmitted and back-reflected echoes. The interferometric radar device enables to characterize slow static displacement and fast variable movement as well. The capability of radar is substantially bigger than the name of this technique implies. Typical characteristics such as the velocity, acceleration, displacement, size and shape of the target can be evaluated [1, 2].

The goal of this measurement was to test the radar technique in-situ in real field conditions and to find the capabilities of this method in practice for bridge engineering purposes. The main objective of this project was to find out the advantages and disadvantages of the RI method compared to the common measurement technique using accelerometers.

2. Radar interferometry principle

The RI method operates with the microwave interferometer device called IBIS (Image By Interferometric Survey) developed by the Italian company IDS (Ingegneria dei Sistemi). The main characteristic of this radar system is the ability of real-time simultaneous deflection measurement of several points (targets) at the same time. The IBIS radar is capable of working in static as well as dynamic modes. The device operates with the following principles:

- Stepped Frequency Continuous Wave (SF-CW),
- differential interferometry.

Differential interferometry provides target displacement data simply computed from phase shift. The radar emits sinusoidal waves in the direction of the target. The waves are reflected from the target. Received echoes carry information about the time and the phase angle. For non-moving mass, there is no phase shift at any time difference. In addition to the echo of moving one, the phase differences are proportional to displacement exhibited in time [1, 3–5].

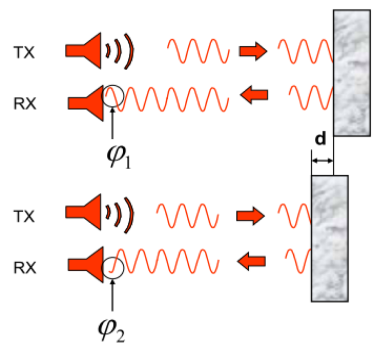

Figure 1. Schematic representation of radar interferometry [3].

The principle of differential interferometry is illustrated in Figure 1. Look at phase angle φ_1, φ_2 and

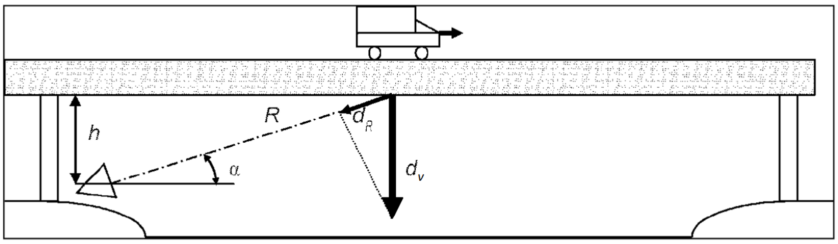

Figure 2. Projection of measured deflection to vertical movement [3, 6].

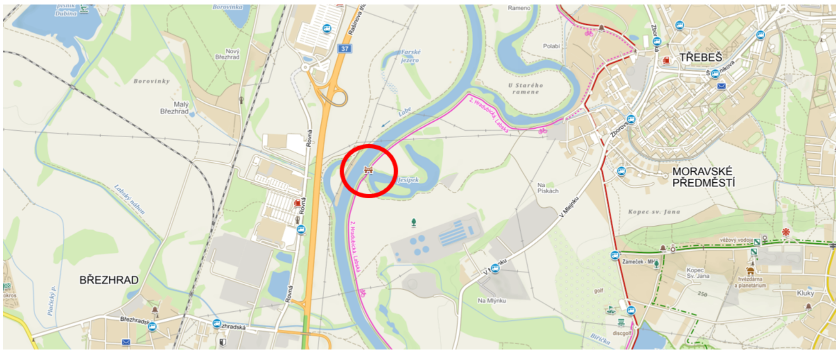

Figure 3. Position of the Jesípek footbridge nearby Hradec Králové city.

distance d. Distance d is described by the following formula:

$$d = -\frac{\lambda}{4\pi}(\varphi_2 - \varphi_1), \tag{1}$$

where

λ is wavelength,

φ_1 is phase angle in time t_1,

φ_2 is phase angle in time t_2.

All characteristics measured by interferometric radar are determined in the direction of the target, which is not identical to the desired direction. Configuration of the radar and object is presented in Figure 2.

Hence, it is necessary to evaluate appropriate displacement by the following formula:

$$d_v = \frac{d_r \cdot R}{h}, \tag{2}$$

where R/h is the projection factor [3, 6].

3. Jesípek footbridge experiment

3.1. Structure description

This part of the paper describes undertaken experiment near the city of Hradec Králové. The footbridge for pedestrians and cyclists was observed. The structure links the cycling roadway from Hradec Králové to Vysoká nad Labem. The object is situated on the Labe river channel called Jesípek in the periphery of HK city. See Figure 3.

The footbridge is designed as the Langer beam structure also known as the Nielsen-Lohse system bridge. The girder with the bridge deck is supported by an arch via connected hangers. The bridge deck is composite and compounds of a reinforced concrete slab fixed to the main girder and steel crossbeams through steel joints. The span of the footbridge is 52.4 m. The arch is cambered 11 m [8].

Figure 4. Jesípek footbridge.

All steel components except slab joints and hangers are made from the steel S355 according to European steel standard grades. For the other parts following materials were used:

- Slab joints: S235 steel grade.
- Slab: C30/37-XF3 concrete class.
- Reinforcement bars: B500B steel grade.
- Hangers: DIN EN 12385 stainless steel grade.

The supporting structure has the following dimensions. The main girder is a welded box shape of 400 × 400 mm, the arc is also a welded profile of 412 × 420 mm. The cross-section of hangers is a circle of 10 mm diameter made of Pfeifer PE7. The deck is compounded of I-shape crossbeams with a variable height from 400 mm to 140 mm and a concrete layer 120 mm thick. Structure is shown in Figure 4 [8].

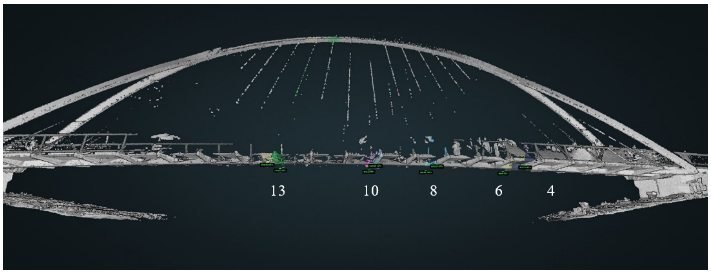

Figure 5. Geometric 3D model, crossbeam section numbering [7].

Figure 6. Measurement devices prepared in position. A detailed view of the accelerometers.

3.2. Traffic and weather conditions

The examined structure was full-time observed within an ordinary pedestrian and cycling service. Traffic on the footbridge was not excluded during the experiment. The measurements were focused to determine the natural frequencies and mode shapes of the structure. An object oscillation was observed. The total length of the continuous measurement was 50 minutes.

The experiment was undertaken during the summer season. Climatic conditions:

- Clear and sunny weather,
- air temperature between 29.3–30.1 °C,
- humidity range was 42–47 % [7].

A pedestrian group with synchronized walking frequency was assembled. A human-induced excitation was used within the experiment as well.

3.3. Measurement method

The dynamic response was concurrently examined by two techniques: namely, the radar interferometry method and the ordinary method compounded of accelerometers, wiring and acquisition station as well.

Interferometric radars R1 and R2 Two radars IBIS made by Italian manufacturer IDS were used. The properties of utilized interferometric devices are as follows:

- Radar R1:
  - ▷ IDS Radar IBIS – FS Plus.
  - ▷ SN 010-19-000314.
  - ▷ Antenna: IBIS-ANT3-H17V15.
  - ▷ Accelerometer (radar vibration only).
- Radar R2:
  - ▷ IDS Radar IBIS – RU 172.
  - ▷ SN 053.
  - ▷ Antenna: IBIS-ANT3-H17V15.
  - ▷ Accelerometer (radar vibration only) [7].

Acceleration transducers During the experiment a data acquisition station SIRIUS Type 6ACC-2ACC+, and 8 piezoelectric acceleration sensors Brüel&Kjaer type 8344 with the following characteristics were used:

- Natural frequency higher than 10 kHz,
- sensor sensitivity is approximately 2500 mV/g,
- transverse sensor sensitivity is less than 5 %,
- working frequency range is from 0.2 Hz to 3 kHz,
- operating temperature range is from −50 °C to +100 °C.

The lower working frequency range limit of these sensors is low enough to be convenient to use for dynamic experiments realized on bridges [9, 10].

Accelerometers were linked via cables to the eight-channel data acquisition station SIRIUS made by the DEWESoft company. Sensors were attached to steel weights with neodymium magnets. There were four weights, three of which were situated on the right edge of the deck in a position of the crossbeams number 4, 6 and 10. The last weight was situated on the left edge of the deck in the position of crossbeam number 10. See Figure 5.

Sensors were oriented in 3 directions (x, y, z) according to the Cartesian coordinate system. The horizontal axis x was aligned with the longitudinal footbridge axis, and the horizontal axis y was perpendicular to the longitudinal axis. The axis z was aligned with the vertical direction. See Figure 6.

FIGURE 7. Radars are based on position. A detailed look at radar R1.

Both radars R1 and R2 were utilized during the experiment. Due to a lack of accessibility on the south bank both radars were placed on the north bank. Interferometers were situated beneath the footbridge deck. Measured characteristics were evaluated at the bottom of the deck. The acceleration sensors were situated on the top of a concrete slab. Measured characteristics were evaluated on the top of the deck. A detailed look at IBIS with the direction of aim is illustrated in Figure 7.

The bottom of the deck has a very diverse surface with a periodic pattern. The entire relevant structure area was fully observed. Each crossbeam was incorporated into a different range area (Rbin). The resolution was high and the reflection conditions were very good. Supporting devices such as reflectors were not necessary to be installed. The radar parameters and settings for this experiment were the following:

- IDS Radar R1:
  - ▹ Sampling frequency: 200 Hz.
  - ▹ Signal reach: 35 m.
  - ▹ Radial resolution: 0.75 m.
  - ▹ Vertical radar inclination: 13.9 °.
- IDS Radar R2:
  - ▹ Sampling frequency: 199.6 Hz.
  - ▹ Signal reach: 40 m.
  - ▹ Radial resolution: 0.75 m.
  - ▹ Vertical radar inclination: 7.4 ° [7].

4. Results

This section describes the results of performed modal analysis and human-induced vibration response analysis. Natural frequencies and mode shapes were evaluated. Peak values of displacements and accelerations were determined.

Dynamic data were converted from the time domain into the frequency domain by using Fast Fourier Transform (FFT) analysis. Significant frequencies can be seen from the following figures Figure 8 and Figure 9.

The first five natural frequencies determined by the accelerometers and four natural frequencies determined by the radars with related mode shapes are written out in the following table. See Table 1.

As we can see, radars were able to record the vertical vibration only. The 3rd natural frequency bounded to a lateral oscillation was not determined by the radar interferometers. The direction of aim measurement limitation took effect. Therefore, additional radar devices should be used for the lateral vibration response evaluation.

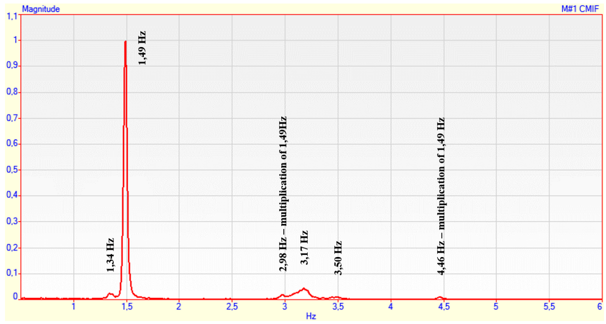

FIGURE 8. The frequency spectrum of radar data.

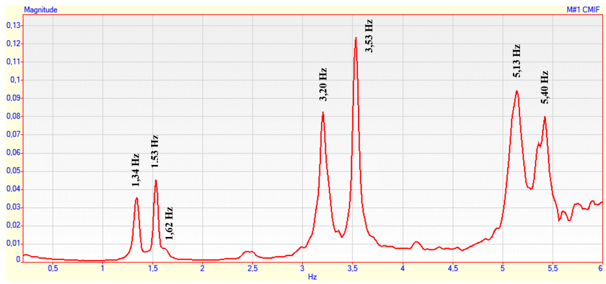

FIGURE 9. The frequency spectrum of acceleration transducer data.

However, the most interesting part of the experiment was the time interval from 426 s to 516 s in the position of crossbeam number 10 (R1 Rbin 22 and R2 Rbin 29). This time range represents human-induced vibration by a group of people with a synchronized walking frequency identical to the natural frequency of the structure. Excited frequency was bounded to the 2nd vertical bending mode shape.

The interferometric radars recorded movement in the direction of the aim. Vertical displacement components were computed using Equation (2). The acceleration transducer's time domain data were converted to displacement data by the double numerical integration performance. Simpson's rule formula was used. Compared displacement results are shown in Figure 10.

In the previous chart in Figure 10, there can be seen, that positive peak values of displacement determined by interferometric radars are almost identical to the double integration values of the ordinary accelerometer technique. This does not apply to negative peak values

Radar interferometry f [Hz]	Accelerometers f [Hz]	Mode shape Type
1.34	1.34	1st vertical bending mode
1.49	1.53	2nd vertical bending mode
-	1.62	1st horizontal lateral bending mode
3.18	3.20	3rd vertical bending mode
3.50	3.53	4th vertical bending mode

TABLE 1. Natural frequencies.

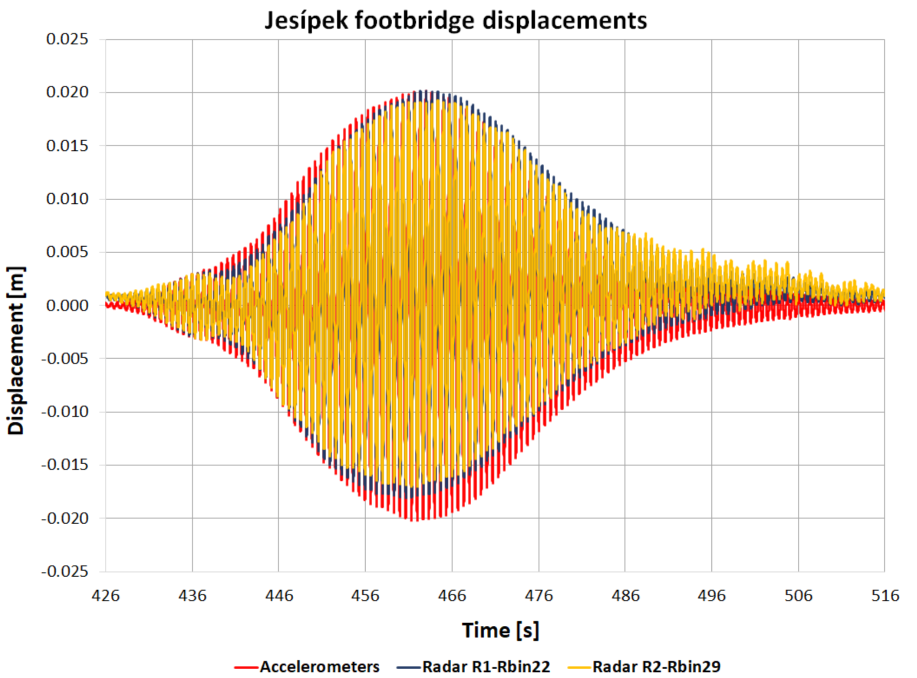

FIGURE 10. Determined displacements in the crossbeam No. 10 position.

where the difference is 2 mm up 3 mm. The maximum amplitude of the oscillation is ±20 mm.

Acceleration values measured by sensors and values evaluated from radars are shown in Figure 11.

A double numerical derivation was performed for the radar displacement data evaluation. A strong frequency noise in the radar signal data was observed in the previous chart (Figure 11). Determined values provided by radar interferometers are abnormally high. The measurement line with transducers Brüel&Kjaer type 8344 was set up to be able to record accelerations up to a frequency of 120 Hz. By further research, other frequencies were detected in the radar data, but the acceleration transducers were unlikely to have not recorded any of them.

From the time 2485 s only one radar was working. There was significantly less frequency noise in radar signal data. It was discovered that frequency noise was caused by parallel radar placing. Reflected radar R1 and R2 waves apparently have influenced each other.

The inconvenient frequency components in higher-range areas were filtered out. A low-pass filter with a cut-off frequency of 35 Hz was used. After that, we can see a very good match between the commonly used technique and the RI method. The response evaluated by radar interferometry devices in the time domain 426 s to 485 s reflects very well response determined by accelerometers. Peak values of acceleration amplitudes evaluated by both methods are almost identical. Amplitude of acceleration was ±2 m×s^{-2}. See Figure 12.

Unlike that, there are still noise frequencies in the time domain from 486 s to 516 s. This part could not be filtered out without any influence on other frequency components occurring in the observed structure.

5. CONCLUSION

In this paper, the evaluation of the footbridge experiment realized in the field conditions was shown. The radar interferometry method was tested in practice along with commonly used techniques. After basic data operations and data filtering, there can be stated in this particular test that the radar interferometry (RI) method has reflected a dynamic response with

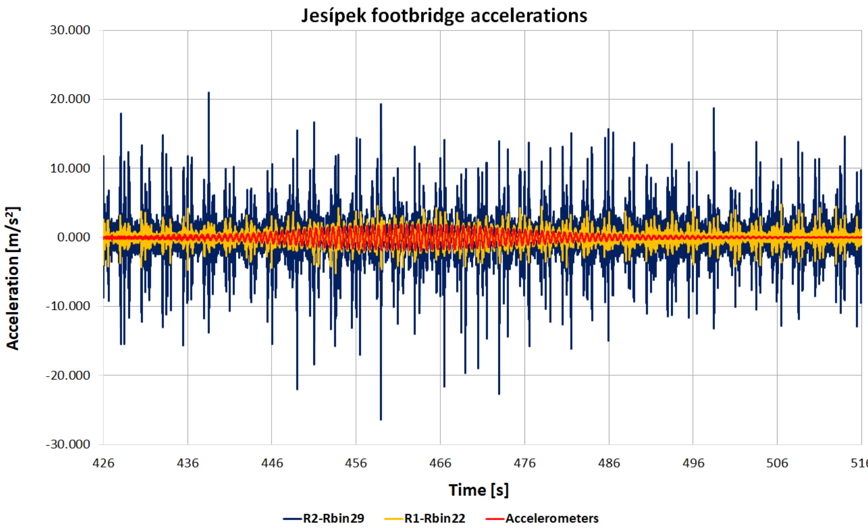

FIGURE 11. Comparison of raw data from radars and sensors.

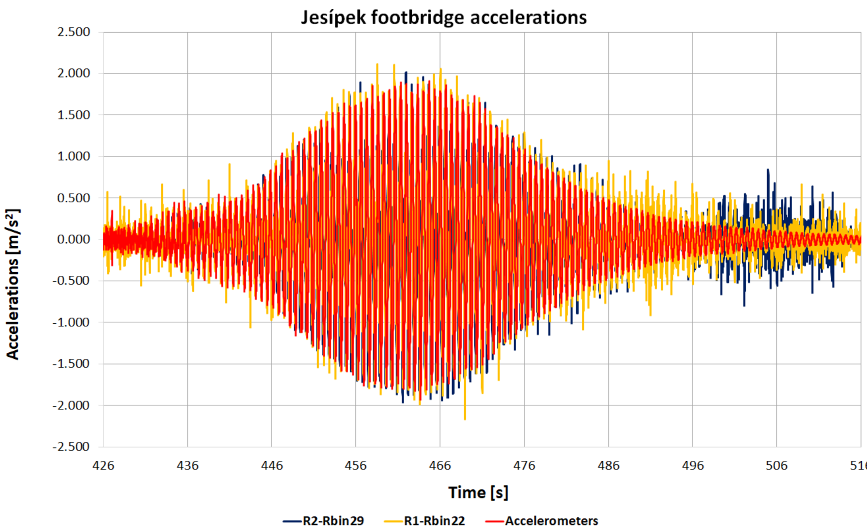

FIGURE 12. Acceleration values in the crossbeam No. 10 position.

a very good match. Test results confirmed the applicability of the IBIS radar for vibration monitoring in the bridge engineering practice.

On the other hand, we should note that inconvenient frequency components contained in the signal can devalue the entire experiment. Not all of them can be easily separated and filtered out. Also, we should mention that suitable conditions in this particular experiment for the RI method were ensured. Interferometric devices had a clear line of view and no additional supporting equipment as reflectors were necessary to be installed. The pattern of the deck bottom surface was convenient as well.

All factors should be considered in the planning of further experiments. Especially placing and mutual interaction of the interferometric radars should be genuinely considered.

Acknowledgements

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