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The Effect of Temperature Changes on Vertical Deflections of Metal Rail Bridge Constructions Determined by the Ground Based Radar Interferometry Method

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Abstract. The paper describes possibilities of the relative new technique – ground based radar interferometry for precise determining of the effect of temperature changes on vertical deflections of metal bridge structures.

The ground based radar interferometry method is used in practice, among other things, for the quick contactless determination of vertical deflections of metallic railway bridge structures. The precision in deflection determination is up to 0.01 mm in real time. At the same time, it is also possible to capture and analyze the oscillation frequencies of the monitored object with a maximum frequency of up to 50 Hz. Deflections are determined at multiple points of the object at the same time, for example on individual cross beams. This allows to obtain both general and detailed information about the behaviour of the structure under its dynamic load and to monitor the impact of vehicle passages or their groups.

Moreover, the ground based radar interferometry method is not sensitive to temperature changes. It can therefore to be used successfully to determine the effect of temperature changes on deflections and deformations of metallic objects, such as bridge structures. The influence of temperature changes is of two kinds. First, a direct effect on the very structure causes deformations due to thermal expansion of the metallic material. Furthermore, it is the effect on the character of the dynamic deformations caused by load changes - the transit of vehicles. This character varies with temperature, as demonstrated by experimental measurement in practice.

Practical examples from practice documented by experimental measurements are given in the article. For example, at a 75m long metal bridge over a six-hour period with a temperature change of 25°C, a vertical deflection - lifting the bridge deck was about 9.5mm due to the thermal expansion of the material. There has been also a change in the nature of the dynamic deflections caused by train passes. At low night temperatures (about 14°C), deflections were much smoother than at high afternoon temperatures (about 39°C).

1. Introduction

Precise determination of the effect of temperature changes on vertical deflections of bridge structures is important for controlling and monitoring their technical state. The temperature variations mainly affect the modal characteristics of bridges. A description of how these effects can be investigated can be found in more publications, e.g. in [1], [2], [3] and [4]. Several measuring techniques are currently used to determine the effect of temperature changes on deflections and deformations of bridge constructions. An accelerometers are usually used [5]. The accelerometers are also used in combination with GPS technology [6]. Very often only GNSS technology is used [7], [8], [9] and [10]. In some cases, the absolute hydrostatic levelling system or optical deformation sensors and electric inclinometers are also used [11].

If we look for other methods of contactless measuring the deflection of bridges (bridge deck), then it is necessary to define the requirements that these methods should meet. Such requirements may include, for example, the ability to measure real-time deflections for short- and long-term loads in normal traffic (e.g. the transit of vehicles or vice versa standing columns of vehicles or stress tests). Further dynamically capture and detect frequency and amplitude of vibration of the monitored object in the frequency range e.g. from 0.05 to 50 Hz. Ability to determine the deflection size with an precision better than 0.1mm, because the deflection size typically ranges from a few tenths of a millimetre to a few millimetres. Possibility to determine deflections at multiple locations simultaneously (in parallel) so it is possible to obtain both general and detailed information on the behaviour of the structure under its dynamic load.

The measurement method based on ground radar interferometry principles complies with all of these requirements. Its great strength lies in the fact that it is possible to simultaneously determine different deflections in many places on the same bridge. For example, on the bridge of a length of 100m is possible to simultaneously monitor up to about 100 points. Examples of the use of ground radar interferometry technology for determining deflection of bridges are given, for example, in [12], [13], [14] and [15]. This contribution is focused on the measurement of vertical deflections of railway bridges by IBIS-S interferometric radar (IBIS-FS) of the Italian manufacturer IDS - Ingegneria Dei Sistemi. The deflections caused by both temperature changes and vehicle passages (dynamic loads) were determined (measured) and discussed.

2. Basic principles of radar interferometry with IBIS-S

Basic principles of radar interferometry with IBIS-S are described e.g. in [15]. IBIS-S is a terrestrial coherent radar interferometer, for detail information see e.g. [16]. It works in microwave spectrum with frequency of 17.1 – 17.3 GHz (Ku). The reflected radiation is recorded with sampling frequency from 10 to 200 Hz. Maximum effective range is 1 km. The standard deviation according to manufacturer is 0.01 mm under ideal conditions. The resolution in range direction is 0.75 m.

All movements are measured in line of sight (LOS). If the radar's line of sight is not parallel with expected direction of the movement then the real movement have to be computed from LOS movement by using the following formula $d=dR/\sin(\alpha)$, where $\sin(\alpha)=h/R$ and so $d=dR \cdot R/h$, see figure 1. The situation of measurement is usually as in the figure 1. The distance R is measured by the radar, the height difference h is necessary to determine with additional geodetic measurement.

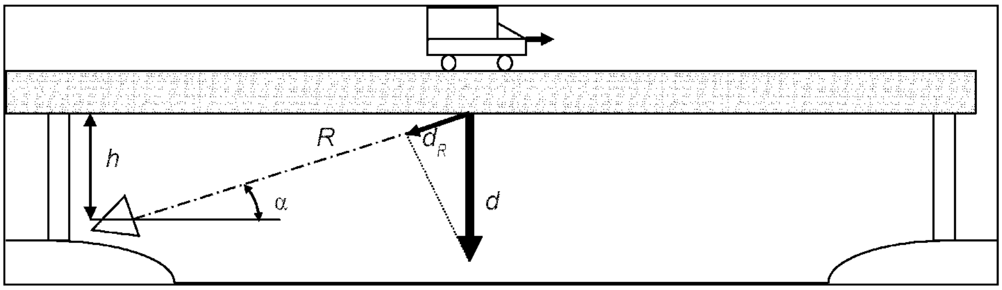

Figure 1 - Line of sight movement (*dR*) and real movement (*d*) (source: [17])

Certain usage policies must be followed to successfully deploy this technique in practice [15]. These policies are:

- Ground interferometry radar is sensor measuring only relative movements in its line of sight (LOS).
- Radar is not able to discern movement perpendicular to its line of sight.
- There is a maximum movement between two subsequent acquisitions that is possible to correctly determine. This value corresponds to phase difference $\Delta\varphi = 2\pi$. For example for IBIS-S this maximum movement is ±4.38 mm (for $\Delta R = 0.75$ m). If this value is exceeded the resulting movement is incorrect. This error cannot be detected. The frequency of acquisition can be up to 200 Hz, so it is possible to observe movements with speed up to 0.876 ms^{-1}.
- It allows monitoring area of interest from distance up to 1km without the need to install additional sensors or optical targets in case of good reflection. In the other case is necessary to install additional corner reflectors.
- It is possible to simultaneously observe multiple points on the object. So it is possible to get both, detail and whole information about behaviour of the object.
- The movements are measured directly and in real time.
- Observations are possible during both day and night and almost regardless of climatic conditions.
- The standard deviation of the movements determining is about 0.01 mm and mostly depends on the quality of reflected signal, i.e. size of the corner reflectors and the distance from radar. The basic verification of precision was done through comparison of two independent methods (IBIS-S and total station SOKKIA NET1AX). The results are in [18]. It was recognized that this technology could be used to determining of movements with precision in the range from 0.01 mm to 0.1 mm.

3. An example of measuring vertical deflections of a metal railway bridge

As part of the verification of the possibilities of using the terrestrial interferometric radar technology, the deflections of the steel rail bridge near town Rataje nad Sázavou, Czech Republic (Figure 2) were determined.

Figure 2 - Rataje nad Sázavou railway bridge

The radar position was located on a grassy bank below the southern end of the bridge (the opposite bank from the entrance to the tunnel). The radar was built on a heavy wooden tripod below a bridge axis approximately 10 meters from its start, with a good view of the steel crossbeams, which provide a good reflection of the radar signal (Figure 3). The measuring parameters were set as follows: sampling frequency (frequency of acquisition) 100 Hz, maximum range 70 m and radial resolution (resolution in range direction) 0.75 m. The schematic of the radar placement and the part of the bridge being measured is in figure 4. The temperature was measured on both sides of the bridge. The measurement was carried out on 19 July 2014 period from 4:42am for about 19 hour.

Figure 3 - View of bridge steel crossbeams from the standpoint of the radar.

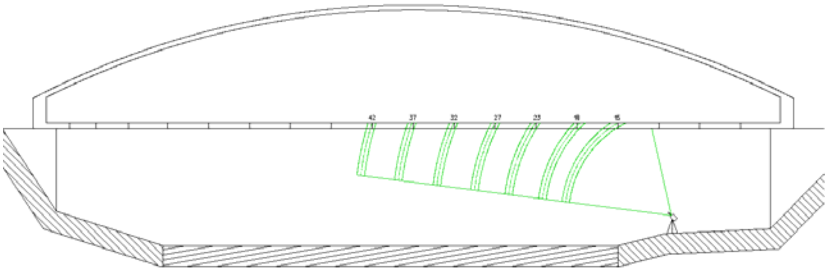

Figure 4 - Side view of the radar location and the measured part of the bridge.

4. Results and discussions

The first measurement results are the **vertical deflections** of the bridge at the locations of the individual transverse beams (crossbeams) **due to the train load**. The total number of train passes was 27. The following figures show the deflections of the selected crossbeams over time in 12 selected train passes. Crossbeams are marked in the figures as Rbin 18, Rbin 25, Rbin 30, Rbin 35, Rbin 39 and Rbin 45, as indicated by the radial area in which the beam is located. E.g. Rbin 18 denotes an area at 18 x 0.75 = 13.5 m from the radar, and so on. Approximately in the middle of the bridge structure is Rbin 39, while Rbin 18 is closest to the radar and is the first crossbeam in terms of measurement. In the pictures the direction of the train passage is always given (in the direction of the radar view is the direction Rataje - Ledečko). The actual transit time, the temperature on the east side of the bridge construction and the temperature on the western side of the bridge construction are also given.

In figure 5, a typical bridge deflection can be observed when the train passes in the radar direction. The nearest crossbeam labelled Rbin 18 (blue) decreases as the first. Deflection reaches over 2 mm on this beam, and there are two peaks. It can therefore be assumed that the passing train had two axles (only a motor wagon). A similar two maxima have also deflections of other crossbeams. With increasing distance of the crossbeams from the radar their deflections increase. The largest deflection of approximately 3.7 mm reaches the Rbin 39, which is approximately at the centre of the bridge structure. Passage occurred at 5:37am in the morning when the construction temperature was relatively low, only 14.1 °C on the east side and 14.2 °C on the west side.

Figure 6 again shows a typical bridge deflection this time when passing the train in the anti-radar direction. The two outermost crossbeams labelled Rbin 45 and 39 decreases as the first. A maximum deflection of about 6.3 mm is on the Rbin 39 beam, and four maximum dips indicate a train with three cars. Passage occurred at 6:17am, and the temperature was relatively low, only 14.5 °C to the east and 14.5 °C to the west side of the bridge structure.

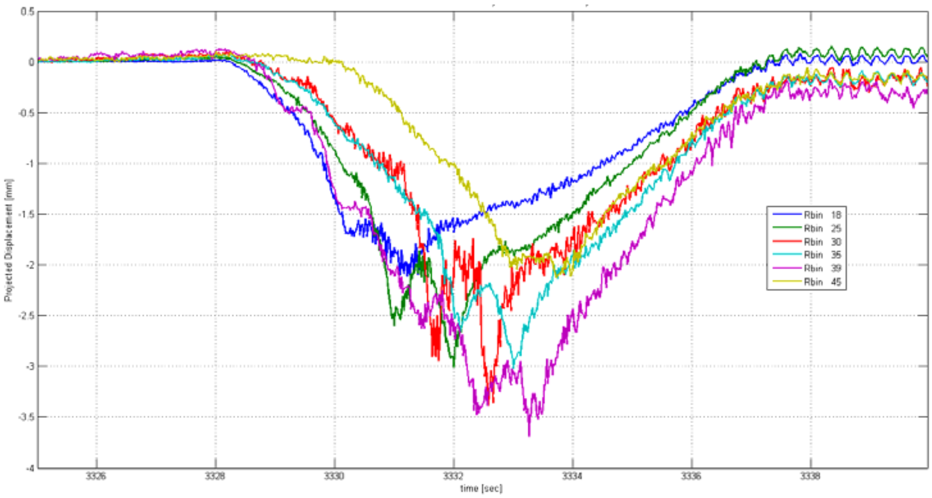

Figure 5 - Deflections caused by train passage in radar view, 5:37am, 14.1 and 14.2 °C

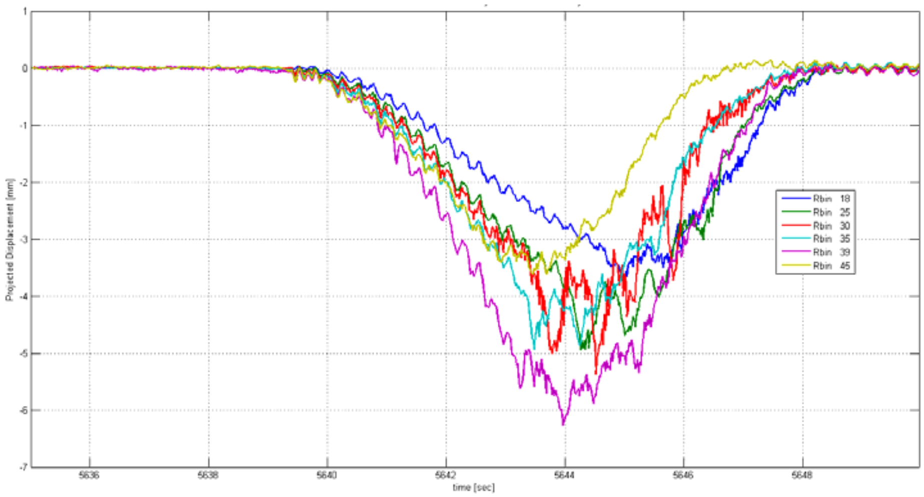

Figure 6 – Deflections caused by train passage in anti-radar direction, 6:17am, 14.5 and 14.5 °C

Figures 7 to 10 show the deflections in the passage of different types of trains. Maximum deflection reaches the level of about from 3.3 mm through 5.2 mm, 8.2 mm to 14.8 mm depending on the number of wagon of the train, thus the load.

Figures 11 to 14 document transit trains in the afternoon. Significant changes in the behaviour of the structure due to its warming are evident. In particular, the crossbeams labelled Rbin 39 and 45 at the centre of the bridge show an increased rate of their movements. Besides the actual deflection also occurs to the rapid vibration of an amplitude of 1-2 mm.

This increased rate of oscillation persists in the middle crossbeams in some cases up to the evening hours. This can be seen in figure 15, which documents the passage of the train at 8:12 pm when the temperature of the structure was still 27.2 °C. In contrast, figure 16 shows the return behaviour of the structure to the original characteristics when it cooled to 18.1 and 18.3 °C at 11:56 pm.

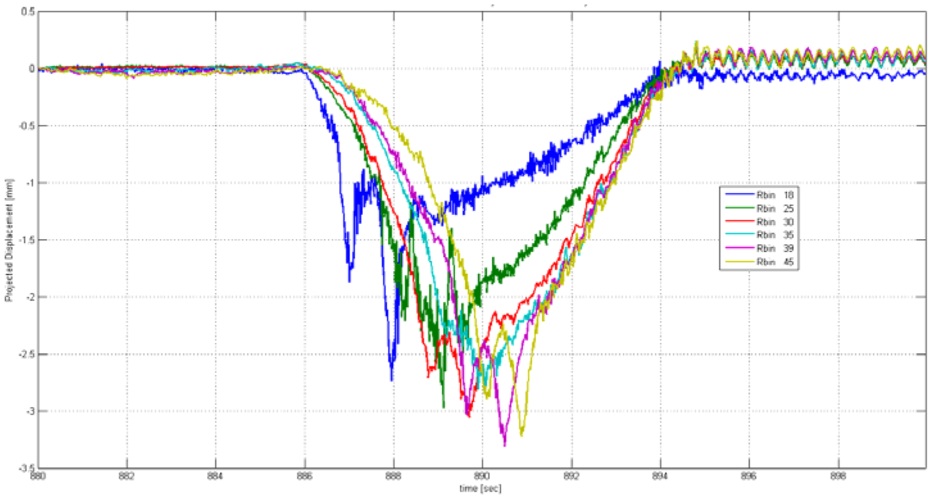

Figure 7 – Deflections caused by train passage in radar view, 6:58am, 20.0 and 16.0 °C

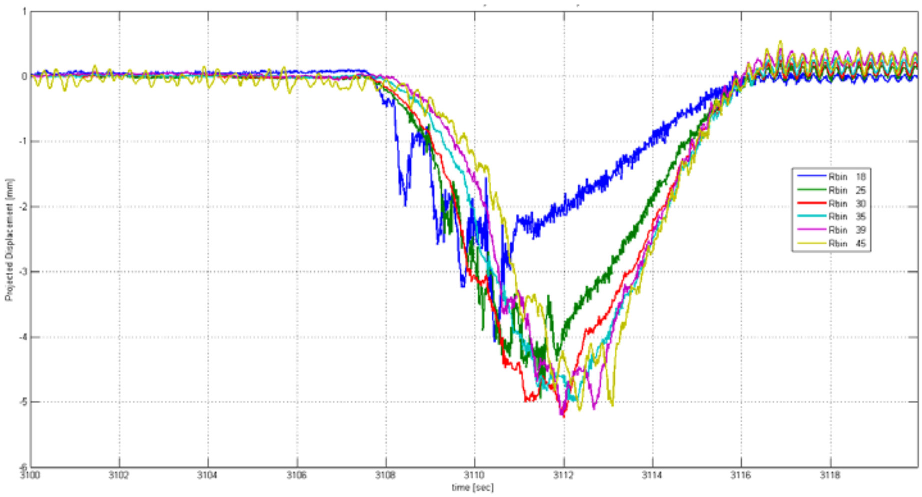

Figure 8 – Deflections caused by train passage in radar view, 7:36am, 25.0 and 17.8 °C

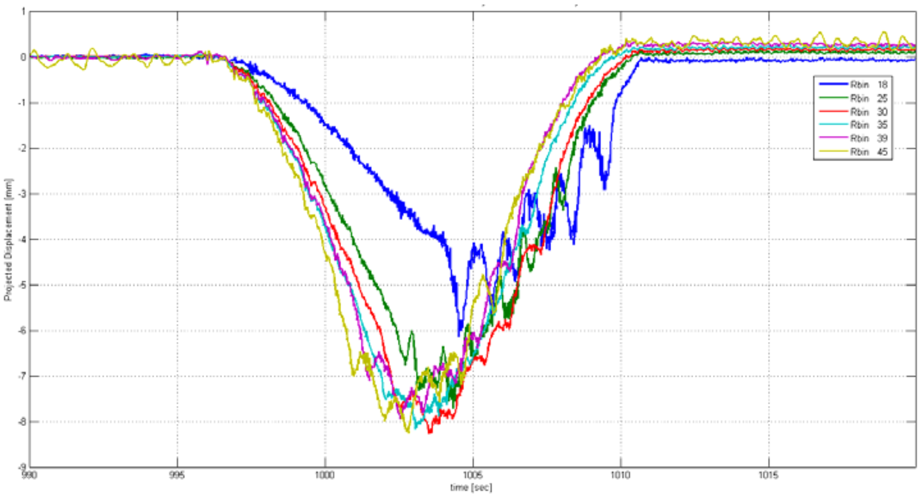

Figure 9 – Deflections caused by train passage in anti-radar direction, 9:01am, 35.7 and 22.7 °C

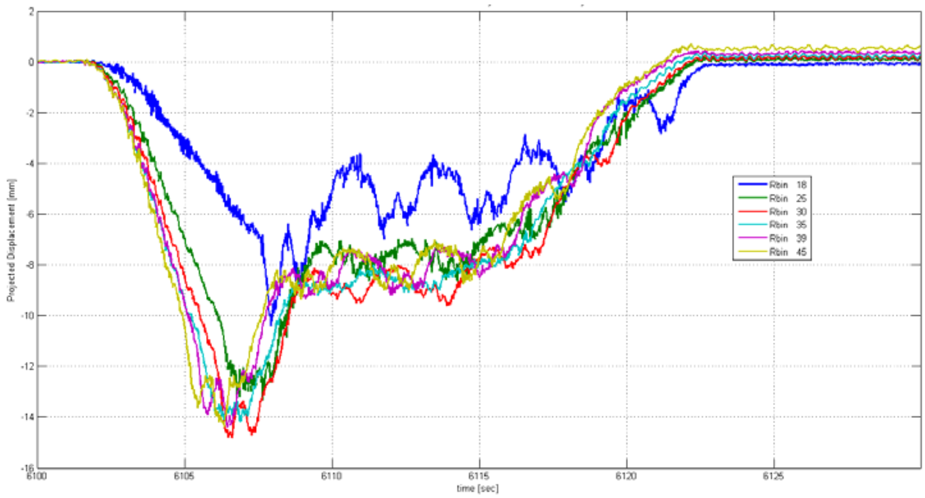

Figure 10 – Deflections caused by train passage in anti-radar direction, 10:26am, 39.2 and 27.6 °C

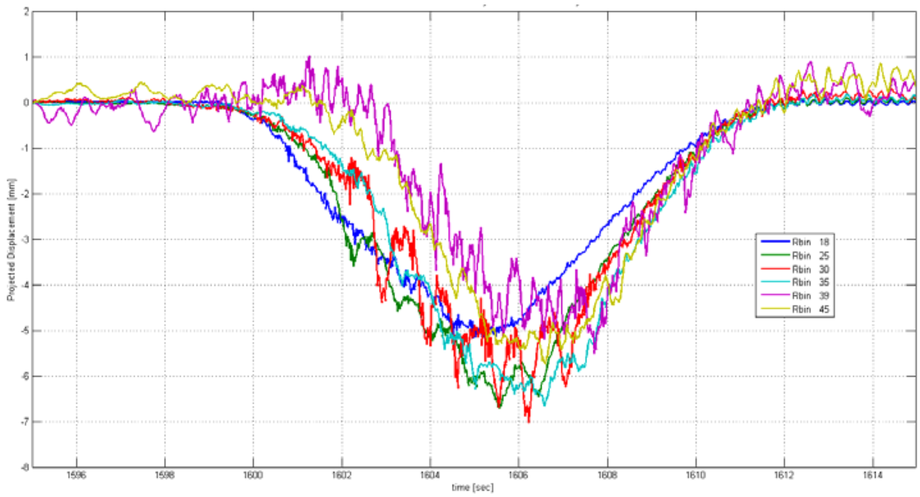

Figure 11 – Deflections caused by train passage in radar view, 1:48pm, 35.8 and 40.8 °C

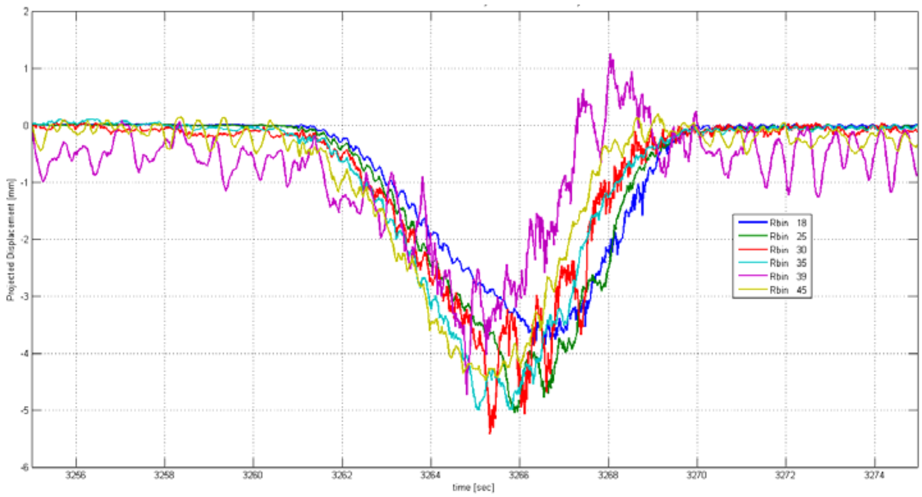

Figure 12 – Deflections caused by train passage in anti-radar direction, 2:16pm, 32.9 and 38.3 °C

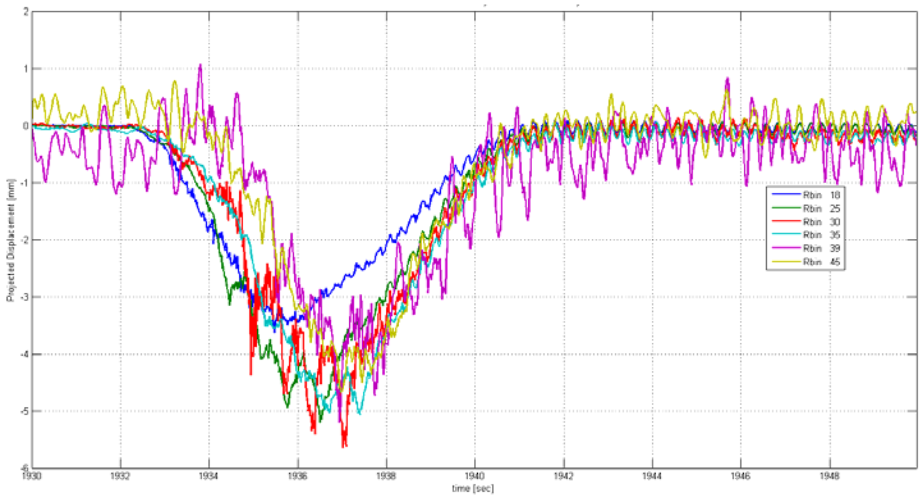

Figure 13 – Deflections caused by train passage in radar view, 3:53pm, 32.8 and 39.7 °C

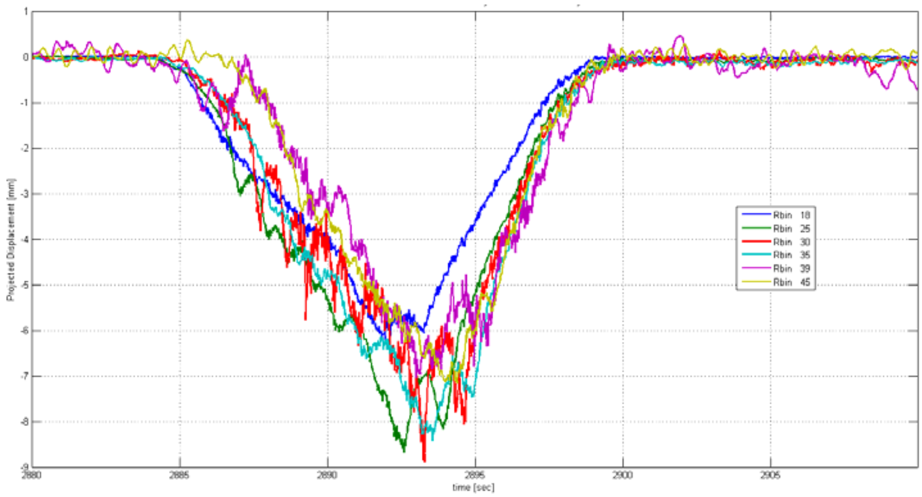

Figure 14 – Deflections caused by train passage in radar view, 4:11pm, 32.7 and 43.0 °C

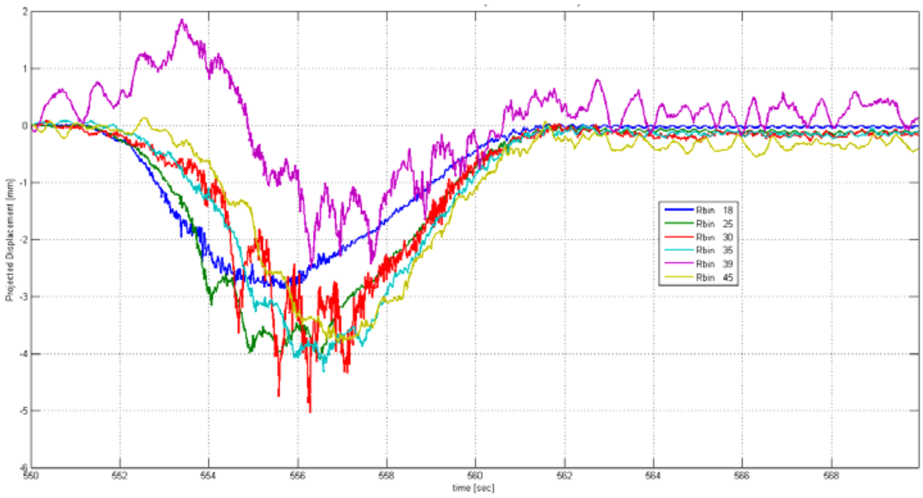

Figure 15 – Deflections caused by train passage in radar view, 8:12pm, 27.2 and 27.2 °C

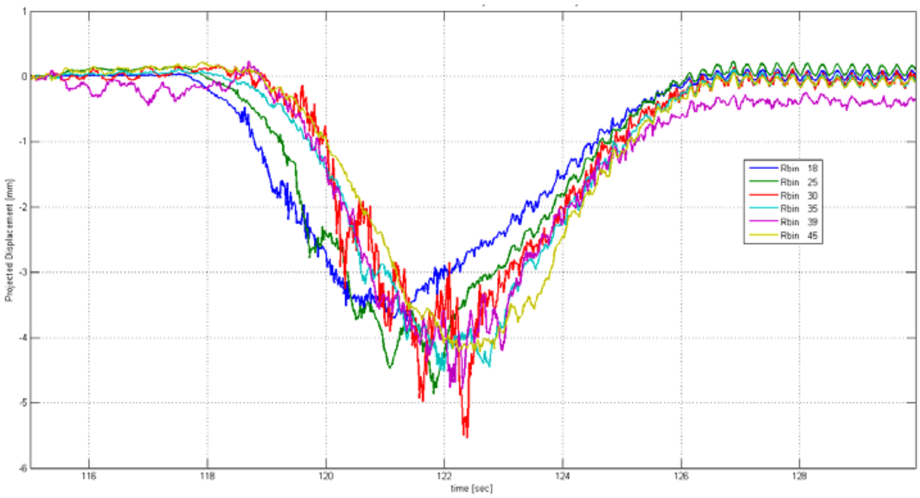

Figure 16 – Deflections caused by train passage in radar view, 11:56pm, 18.1 and 18.3 °C

Further measurement results are the **vertical deflections** of the bridge construction at the locations of the selected crossbeams **due to thermal longitudinal expansion**. By measuring, it was found that it was the lifting of the whole construction during increasing of the temperature. During cooled it was the descent. During the morning continuous measurement from 4:42 am to 12:16 pm, the first crossbeam was lifted by about 5mm and all other crossbeams approximately 10mm. The course of the individual crossbeams lifting due to temperature increase is shown in figure 17. Here you can see data with frequency 1 Hz (instead of the originally measured 100 Hz). The picture also shows the effect of the passage of individual trains. It can be assumed that the temperature does not cause arc-shaped deflection of the bridge, but that almost the entire bridge is lifted together on a few peripheral crossbeams. Of these peripheral crossbeams, only one (Rbin 18) was in the radar range - see figure 4.

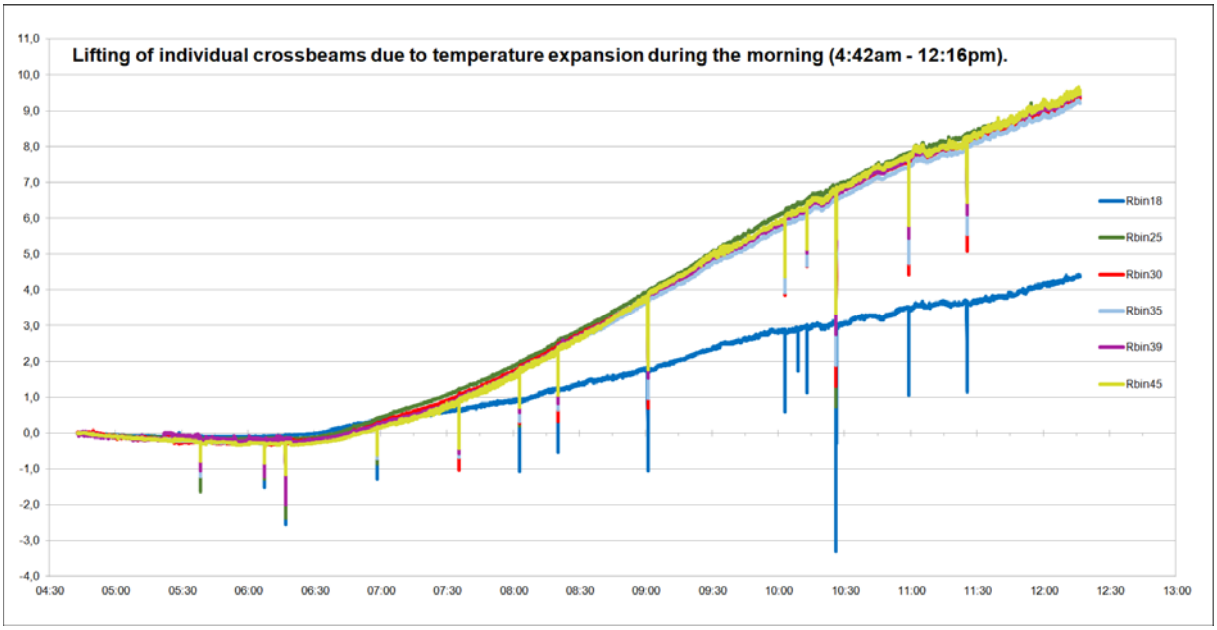

Figure 17 – Lifting of individual crossbeams due to temperature expansion

Figure 18 shows the development of temperature changes throughout the measurement on July 19, 2014. Compared to Figure 17, it can be seen that the temperature changes of the construction in a given time interval from 4:42 am to 12:16 pm are in accordance with the specified lifting of the individual crossbeams.

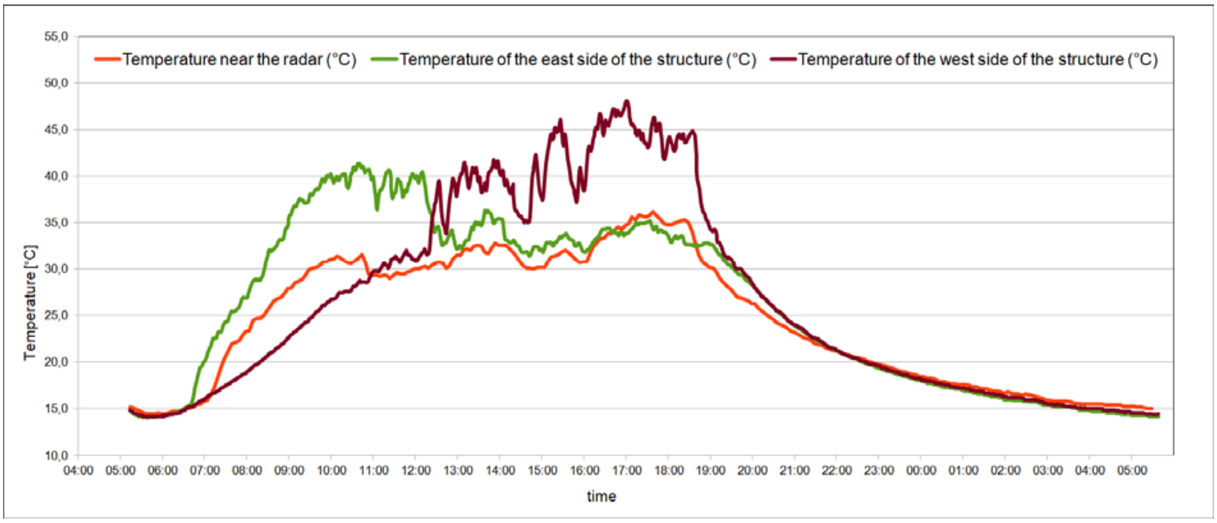

Figure 18 – Temperature changes during July 19, 2014

5. Conclusions

By experimental measurement it was proved that the principles of terrestrial radar interferometry can be used in practice for the quick contactless determination of vertical deflections of railway bridge structures with accuracy up to 0.01 mm in real time. Deflections were determined simultaneously at the locations of individual cross beams. There was thus obtained both total and detailed information on the behaviour of the structure both in its dynamic load due to the passage of trains and the influence of temperature changes on the expansion of the metal structure of the bridge.

The deflections due to the dynamic load during the passage of a train of 3 to 14 mm have been proven, depending on the type (weight) of the passing train. The influence of temperature changes on these deflections caused by dynamic loads during the passage of trains has also been demonstrated. At higher temperatures of the construction, the bridge in the centre area was vibrating rapidly with amplitudes of 1 to 2 mm.

It was also proven the bridge deflection due to slow temperature changes during the day. The temperature of the construction changed during measurement from 14.1 °C at 4:42am to 41.0 °C at 12:16pm. In accordance with this change the bridge was lifted by about 10 mm during this time.

Acknowledgments

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