Using Ground Radar Interferometry for Precise Determining of Deformation and Vertical Deflection of Structures

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Abstract. The paper describes possibilities of the relatively new technics – ground based radar interferometry for precise determining of deformation of structures. Special focus on the vertical deflection of bridge structures and on the horizontal movements of high-rise buildings and structural objects is presented. The technology of ground based radar interferometry can be used in practice to the contactless determination of deformations of structures with accuracy up to 0.01 mm in real time. It is also possible in real time to capture oscillations of the object with a frequency up to 50 Hz. Deformations can be determined simultaneously in multiple places of the object, for example a bridge structure at points distributed on the bridge deck at intervals of one or more meters. This allows to obtain both overall and detailed information about the properties of the structure during the dynamic load and monitoring the impact of movements either individual vehicles or groups. In the case of high-rise buildings, it is possible to monitor the horizontal vibration of the whole object at its different height levels. It is possible to detect and determine the compound oscillations that occur in some types of buildings. Then prevent any damage or even disasters in these objects. In addition to the necessary theory basic principles of using radar interferometry for determining of deformation of structures are given. Practical examples of determining deformation of bridge structures, water towers reservoirs, factory chimneys and wind power plants are also given. The IBIS-S interferometric radar of the Italian IDS manufacturer was used for the measurements.

1. Introduction

By looking for methods of some contactless observation of deformations and vertical deflections of the structures, we need to define other requirements for these methods as well. One of these requirements might be the ability to observe deformations and deflections in real time for both, short and long time span. For example, in the case of bridges they are passing of the vehicles or stress tests, in the case of high buildings they are wind gusts. As well dynamically observe and measure frequencies and amplitudes of observed object's oscillation in range for example of 50 Hz. Ability to determine the size of deflections with accuracy in 0.01 mm, because the size of the deflections is usually in range from 0.1 mm to 10 mm. Ability to simultaneously determine deflections on multiple points of the observed object, so that is possible to get both, detail and whole information about deformations of the structure during dynamic stress.

To all of these requirements fits the method of measurement based on principles of ground-based radar interferometry. The big capability of this method is the simultaneously measurement of multiple deflections on multiple points on one observed object with range resolution at least of 0.75 m. For example, on bridge with length of 100 m, we can simultaneously observe and measure roughly 100 points. To show the possibilities of the radar interferometry technology, this article will focus to determining of deformations and deflections of few different object types. It will be measurement of vertical deflections of concrete bridges and horizontal movements of water towers reservoirs, factory chimneys and wind power plants. The measurements are done by interferometry radar IBIS-S (IBIS-FS) of IDS – Ingegneria Dei Sistemi Company.

2. Principles of using radar interferometry

Basic principles of radar interferometry with IBIS-S are described below. The IBIS-S products are based on two well-known radar techniques:

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

2.1. Stepped Frequency Continuous Wave

The continuous stepped frequency wave serves to measure the distance from radar to observed object. It resolves the scenario in the range direction, detecting the position in range of different targets placed along the radar's line of sight. Microwave radiation is sent out in short high-power pulses and the distance to object is calculated from time correlation between sent and received signal. Utilizing this technology IBIS constructs a one-dimensional image called range profile. The illuminated area is divided into circular segments (range bins = resolution cells) of constant distance from radar. All targets in a given segment contribute to the observed values (amplitude and phase) of the segment. The segments' width is called range resolution ΔR. The distance from radar to target is calculated from formula

$$R_0 = \frac{cT_o}{2} \;, \tag{1}$$

where T_0 is delay in response. The range resolution can be calculated from

$$\Delta R = \frac{c\tau}{2} \;, \tag{2}$$

where τ is pulse width. This means the radar is able to discern two distinct targets only if $\Delta t > \tau$ and thus $\Delta d > \Delta R$. Range resolution is limited by pulse width.

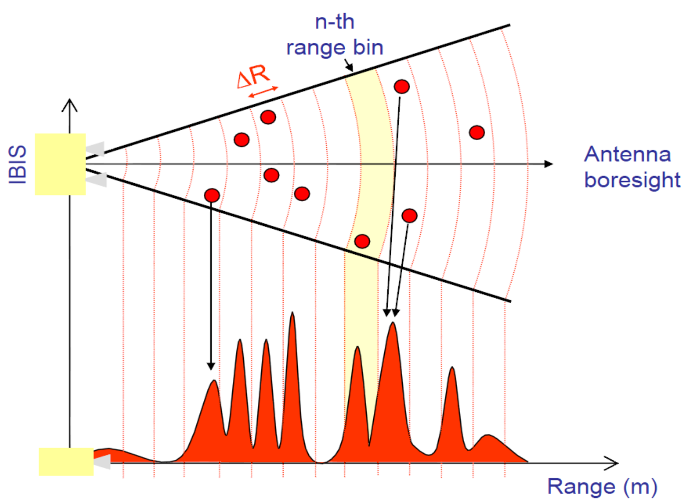

Figure 1 - Range resolution concept, [1]

Figure 1 shows range resolution. X axis is distance from radar. The IBIS-S radar can distinguish targets only in one direction (in the line of sight). If there are more targets in the same range bin (single cell), these cannot be told apart and movements of individual targets are averaged. Y axis shows signal to noise ratio of received signal.

2.2. Differential interferometry

After resolving the scenario in the range direction and detecting the position in range of different targets placed along the radar's line of sight we can start to compute movements of individual targets by the differential interferometry method. In this case the range bins are obtaining individual targets and representing parts of observed object. This method uses differences in phase values about range bin from two (or more) acquisitions to determine their relative movement. The principle is shown on figure 2. The computed movements *d* are in the line of sight of the radar (LOS) direction. There is a limit value of movement d_{max} between two acquisitions caused by ambiguity of observed phase. For IBIS-S this maximum movement is 4.38mm.

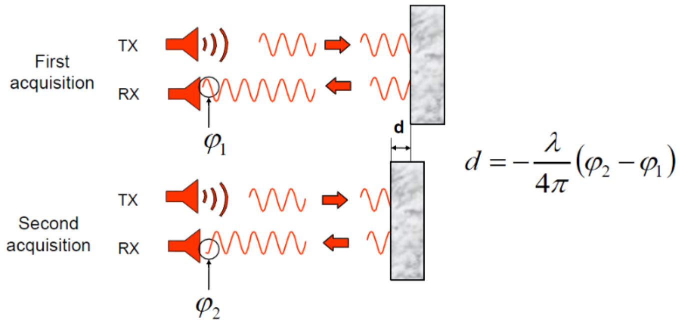

Figure 2 - Radar differential interferometry principle, [1]

2.3. Computing of real movements

All movements are measured in line of sight. 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 3. The situation of measurement is usually as in the figure 3. The distance *R* is measured by the radar, the height difference *h* is necessary to determine with additional geodetic measurement.

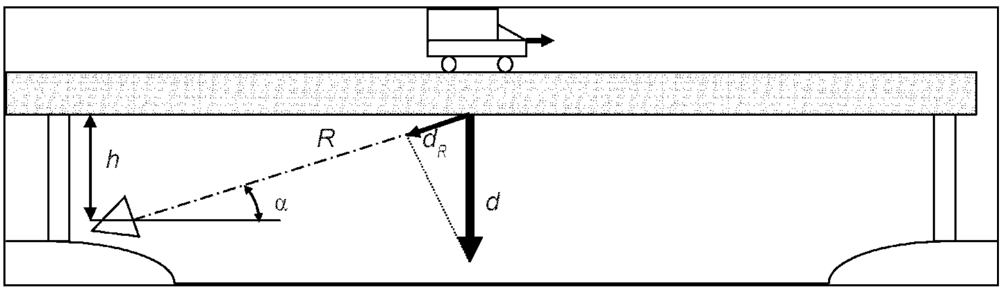

Figure 3 - Line of sight movement (*dR*) and real movement (*d*), [1]

2.4. Instrument characteristics

All measurements presented in this contribution are done by interferometry radar IBIS-S (IBIS-FS) of IDS – Ingegneria Dei Sistemi company. IBIS-S is a terrestrial coherent radar interferometer [2]. 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 is 0.75 m in range direction.

3. Possibilities of using technology in practice

Technology of the ground based radar interferometry can be successfully used to determine the deformation of a wide range of different types of objects. Above all, it is the determination of vertical deflections of bridges (metal or concrete), horizontal movements of various kinds of high-rise buildings and deformation of a variety of special objects such as for example floodgates. Specific usage examples and results will be shown on each particular example.

3.1. Monitoring vertical deflections of the concrete bridge

An example of monitoring vertical deflections of concrete bridge is shown on a road bridge near town Pelhřimov, Czech Republic [3, 4]. The monitoring was done during usual traffic.

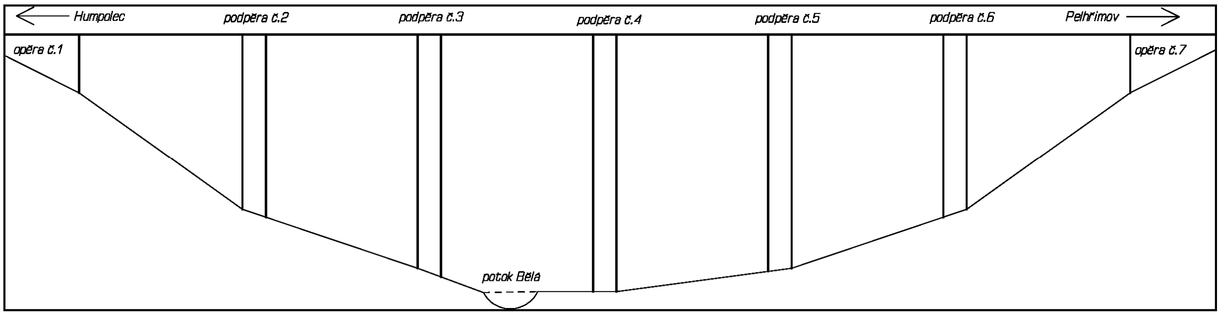

Figure 4 – Schema of the bridge

The way of measurement and placement of corner reflectors are obvious from figure 5 and figure 6. After evaluation of quality of measured data, it is possible to proceed whole measurement to get deflections of the bridge. The resulting vertical deflections of observed corner reflectors are shown in figure 7 and figure 8.

Figure 5 – Measurement situation and corner reflector mounted on the bridge railing

In the figure 7 the vertical deflections of the bridge by vehicles passage during 10 minutes' period of the measurements are shown. The biggest deflections are caused by fully loaded lorries passing in northern lane, where the corner reflectors are attached. The lower deflections are caused by lighter vehicles or vehicles passing the other lane. The detail evaluation covering the biggest deflection in time span between 170 s and 200 s is shown in the figure 8.

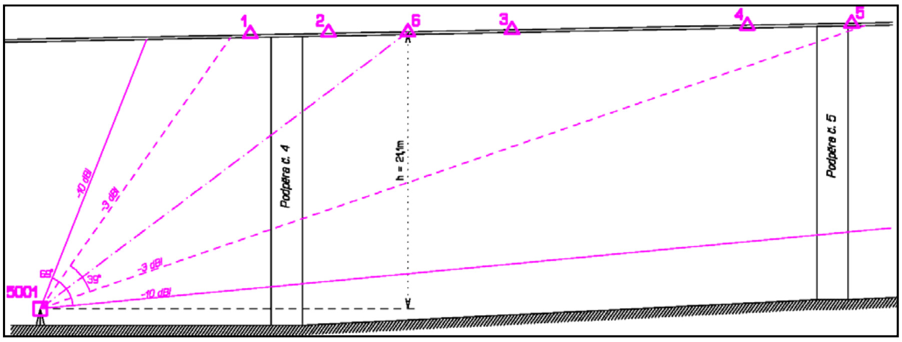

Figure 6 – Placement and orientation of radar and corner reflectors

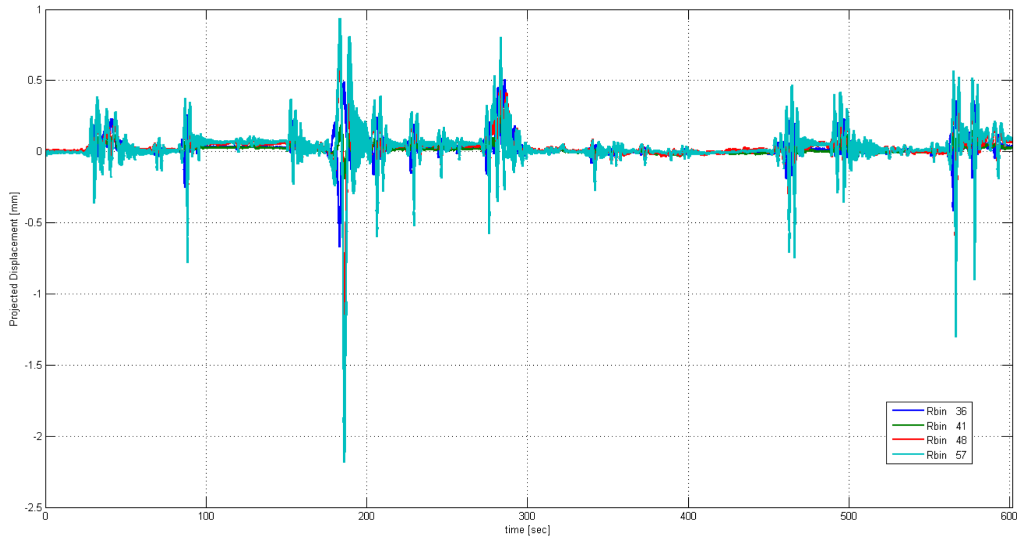

Figure 7 – Vertical deflections of points No. 1, 2, 6 and 3 during 10min measurement

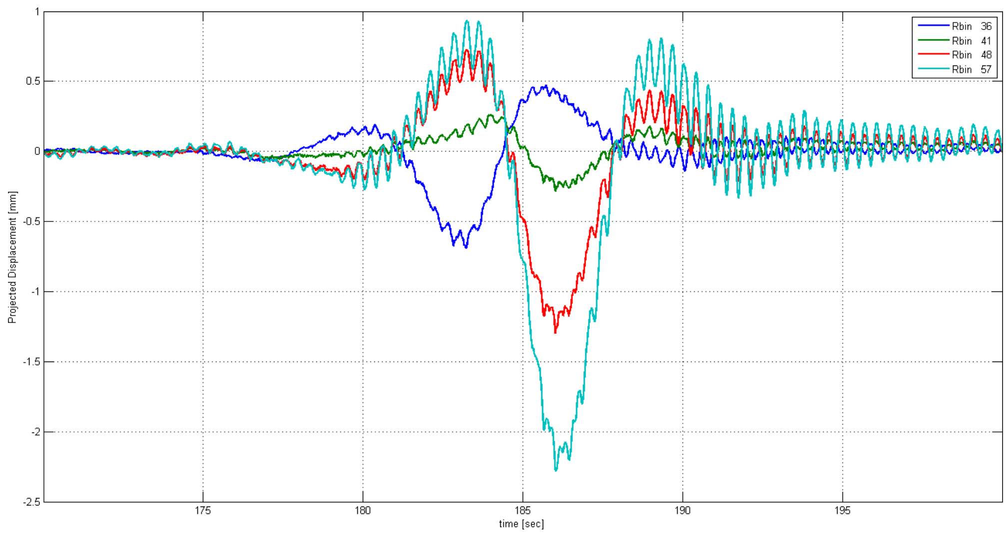

Figure 8 – Detail of vertical deflections of points No. 1, 2, 6 and 3 at time span between 170s and 200s

The basic frequency of the bridge deflections during vehicle passage is shown in the periodogram of the frequencies on the figure 9. In this case the main oscillation frequencies is 2.671 Hz (cca 5 vibrations per 2s).

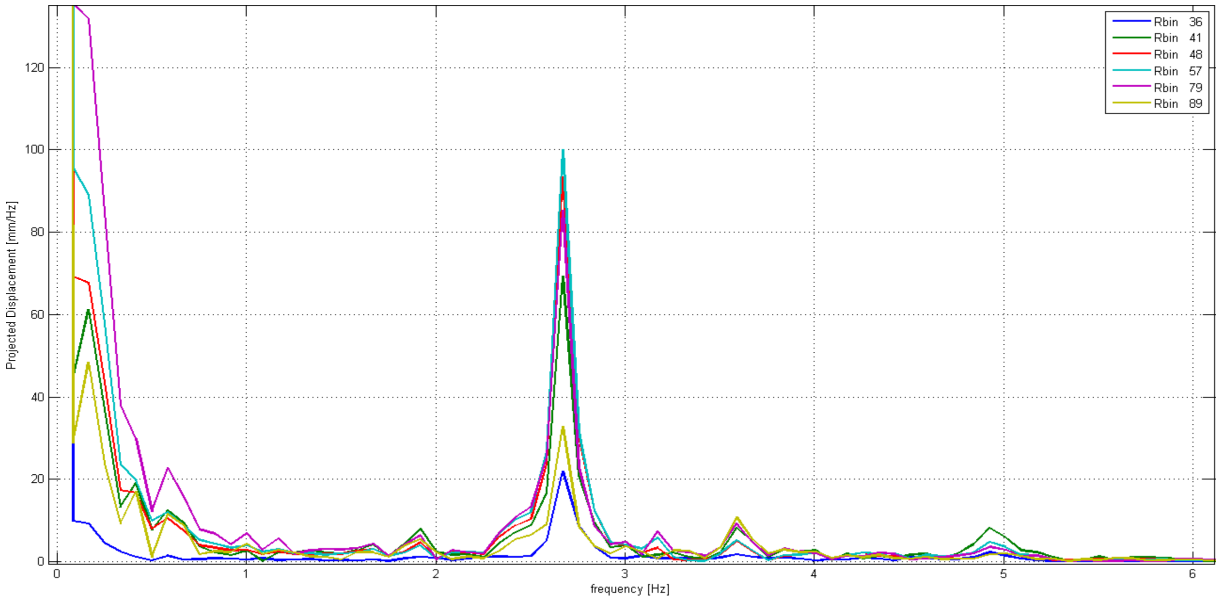

Figure 9 – Periodogram of vertical movements at time span between 188s and 200s

3.2. Monitoring horizontal movements of the water tower reservoir

As the example of monitoring horizontal movements of the water tower reservoir, was chosen water tower in the Klecany town near Prague, Czech Republic. Water tower is composed by carrying the cylindrical pylon and spherical tank. The carrying pylon is composed by three sections, each section is composed by a few annuli. All the section joints are raised which makes them natural reflectors of the radar signal. The annuli joints are much softer, but there is still no need to install corner reflectors.

Figure 10 – Water tower reservoir, section and annuli joints, schema of measurement

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During the measurement there was very weak northwest wind and radar was stationed in the direction of the wind to the water tower. Movements of three points corresponding with section joints are shown in figure 11. High frequency and variable amplitude of the oscillation of the water tower pylon is clearly detectable. The resulting vibration is the sum of two simple vibrations. In the periodogram of the horizontal movements are detectable three basic frequencies. The most one is 0.24 Hz.

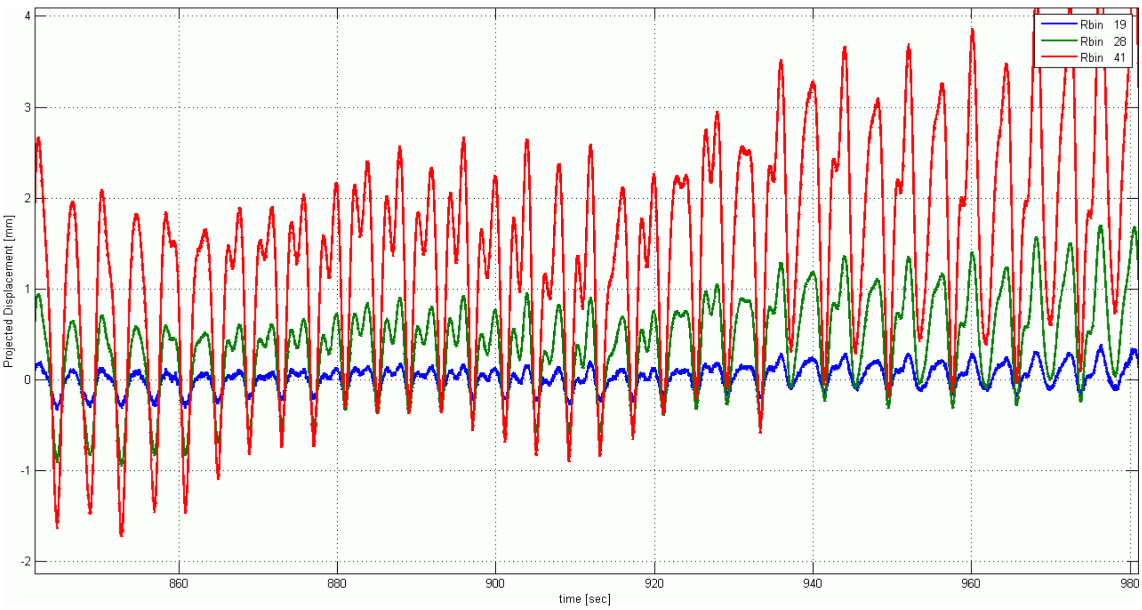

Figure 11 – The resulting vibration is the sum of two simple vibrations

3.3. Monitoring horizontal movements of the factory chimneys

The monitoring of the horizontal movements of the brick factory chimney of Novodur Ltd. company was done [6]. It is a brick ca 100 m high chimney. On the southeast and northwest side of the chimney is a metal ladder. This metal ladder was used as a natural reflector of the radar signal. The situation is on the figure 12.

Figure 12 – View of the chimney from the northwest and detail of the metal ladders

Monitoring horizontal movement of the chimney was carried out on 18 October 2012 at moderate northeast wind. The radar position was approximately in direction of the wind from the chimney. The metal ladder on the northeast side of the chimney was oriented to the radar. The monitoring was performed in dynamic mode with 100 Hz sampling frequency. The measurement took 10 minutes.

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The measurement results are the horizontal movements of the monitored points on the chimney in the direction radar – chimney, see figure 13. The figure shows the oscillation of the monitored points on the chimney during the whole measurement period. The amplitude and midrange are variable. It depends, apparently, on the varying strength and direction of the wind acting on the chimney. All the monitored points on the chimney oscillate at the same frequency. The magnitude of the oscillation amplitude increases with the height of the spot on the chimney. Frequency of oscillation is 0.36 Hz, i.e. about 7 vibrations in 20 seconds.

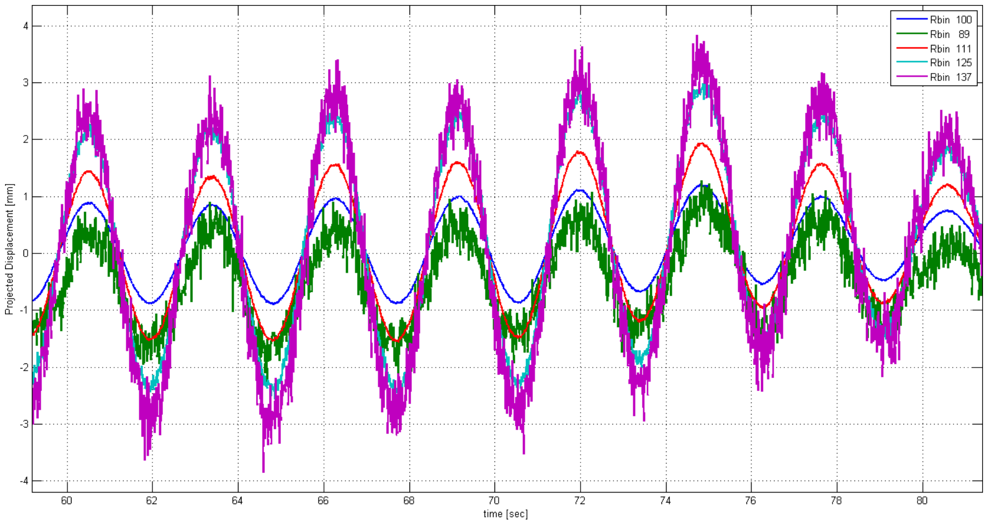

Figure 13 – Horizontal movements of the monitored points on the chimney

3.4. Monitoring horizontal movements of the wind power plant pylons

For wind turbines, the biggest influence, of course, apart from the wind, is whether or not a rotor is running. The largest mast tilt occurs when the rotor is running. The reason is that the blades of the power plant are exposed to the greatest wind resistance. In addition, there are some shocks when starting and stopping the rotor. These can be very well monitored. The size and character of the resulting movement is shown in figure 14.

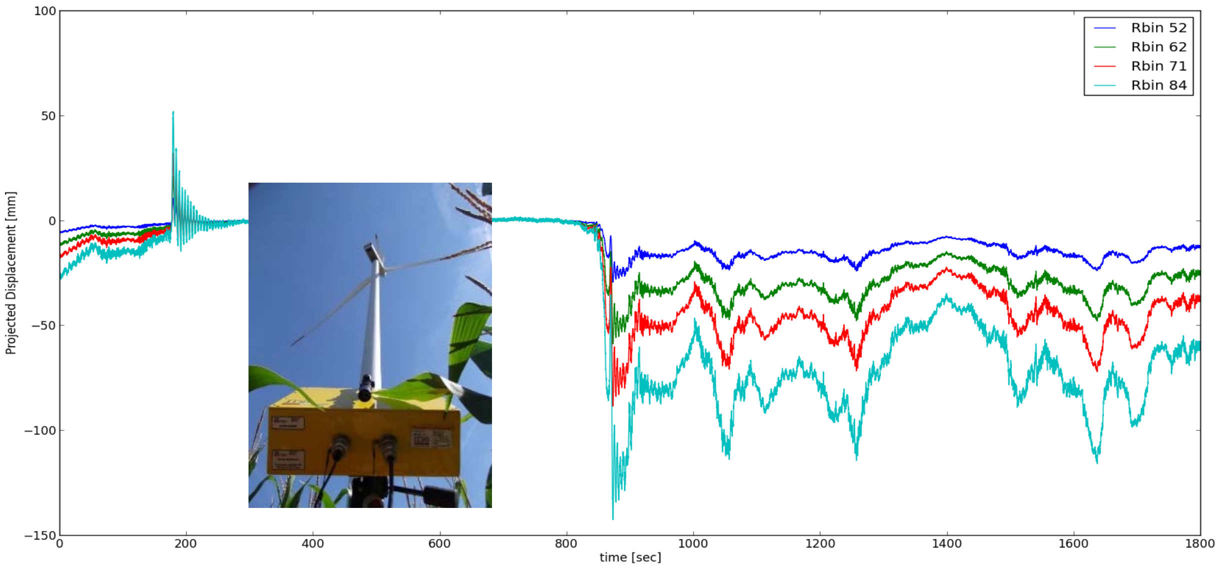

Figure 14 – Horizontal movements of the monitored points on the wind power plants

First, there are depictions of movements when the rotor is running during the downward force of the wind. Followed the situation after stoppage of the rotor at the time of 180s. Furthermore, movements when the rotor is off which are negligible compared to the movements during operation. The following is a moment when the rotor is switched on at time of 840s and the power plant moves up to 140mm depending on wind power. More details are in [7].

4. Results and discussions

The purpose of the article is to describe possibilities of the relatively new technics – ground based radar interferometry for precise determining of deformation of structures. An example of several different types of building structures has shown how to use it. However, certain usage policies must be followed to successfully deploy this technique in practice. 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 behavior 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 [3]. 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.

Next examples, advantages, limitations and possible applications are for example in [8], [9] and [10].

5. Conclusions

Presented technology of ground-based radar interferometry provides determining of deformations and deflections/movements of many different objects. Only because of the need to reduce this article, the results of other measured objects are not presented (e.g. horizontal transversal movements of flood-gate sides, horizontal movements of high-rise buildings, horizontal movements of tower transmitters). Technology provides determining of the deformations and deflections/movements of structures with high relative precision (up to 0.01mm) in real time simultaneously on multiple points of the observed object. From the results we can obtain new information about behavior of some structure types. It is recommended to repeat measurement with a certain interval to get information about observed object‘s behavior depending on its senescence, external conditions or the season.

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