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DYNAMIC RESPONSE OF THE STUTTGART TV TOWER MEASURED BY CLASSICAL INSTRUMENTS AND GPS TECHNOLOGY

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This paper compares the measurement results of dynamic characteristics, including natural frequencies, damping ratio, and wind-induced responses of the Stuttgart TV Tower (TV Tower), obtained by Lenk in 1959 using classical instruments with those obtained by the authors a few decades later using Global Positioning System (GPS). The objective of this paper was to monitor the response of the TV Tower under wind loading, which is an important tool for the validation of its design, construction, and structural health. During the authors' GPS measurements, weak and moderate wind speeds occurred most of the time. Only in 2007, the stronger wind observed ($90 < V < 100$ km/h) at the head of the TV Tower (H=157 m), which caused displacements in the decimetre range. Further measurements in 2011 were carried out, using additional GPS receivers with a higher data rate. The results achieved by the GPS prove that the cross-wind response was larger than the along-wind component for all ranges of wind speed, which occurred during the measurement periods, i.e. from 2002 to 2015. The authors of this paper extended Lenk's results, by the static and along-wind components, confirmed the first natural frequency, and damping ratio, evaluated by the Random Decrement technique. Mounting a GPS receiver, on the steel antenna mast tip, enabled detection of the second natural frequency fs2 = 0.800 Hz, which is the frequency of the mode shape of the TV Tower steel antenna mast. Lenk did not measure this frequency.

Keywords: Stuttgart TV Tower, GPS measurements, wind-induced response, natural frequency, damping ratio

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1. INTRODUCTION

The Stuttgart TV Tower (TV Tower – see Fig. 1) is the reinforced concrete structure constructed as a concrete shell. After 20 months of construction on the 5th of February 1956 was opened. It consists of two parts: (a) a concrete shaft with the TV Tower head 161 m high and (b) a steel antenna mast, which is 56 m tall. The total height of the TV Tower is 217 m. The concrete shaft diameter is 10.8 m at the ground, and 5.04 m at the bottom of the head of the TV Tower. The wall thickness of the concrete shaft decreases from 60 cm (80 cm at the entrance door) to 30 cm at the shaft height of 10 m, and to 19 cm below the TV Tower head.

In 1953-1954, Leonhard proposed the concept and project of the TV Tower. Pieckert's design office designed a structural system. The concept of the TV Tower, its structural system, all the assumptions for the static calculations, costs, and the first measurements of the foundation settlements are given in Leonhardt's paper [1]. In this paper, there is a suggestion that the wind response of the TV Tower should be measured. This was achieved in 1959 by Lenk [2].

In 1977 and 1995 vertical cracks were discovered in the concrete shaft of the TV Tower [3], which were subsequently repaired. These cracks were analysed as a consequence of solar radiation and daily air temperature variation acting on the TV Tower shaft resulting in a deformation of its circular cross-section. These thermal stresses created a systematic time-dependent "ovalization" of the Tower shaft, which over the years led to fatigue of the concrete tensile strength, which is noticeable by longitudinal cracks on opposite sides of the concrete TV Tower shaft.

The authors are not aware of measurements of the dynamic properties of the TV Tower in connection with the remediation of the cracks which have occurred. In 1999, the authors introduced a new series of measurements on the displacements at the head of the TV Tower. Some results of these measurements have been published [4,5,6].

The methodology of the authors' measurements is similar to that of other researchers [7,8,9,10]. The authors of these papers have confirmed that GPS is suitable for monitoring static, quasi-static and dynamic displacements, and to detect dynamic characteristics (natural frequencies and damping ratios) of full-scale large structures, such as high-rise buildings, tall industrial chimneys, tall towers, and short-span and long-span bridges [11,12,13,14,15,16].

The authors continued to monitor the TV tower until 2015. However, despite a concerted effort in 2013 and 2015 to collect additional data, unfortunately, the TV tower did not encounter strong wind during those two measurement campaigns. Nevertheless, the authors were able to monitor reliable data collected in 2002, 2005, 2006, 2007, 2008, and 2011 which covered a range of low to high wind speed. On January 18-19, 2007, at the head of the TV Tower, a gust wind speed of 26 m/s was recorded. In this paper, these data are presented in a statistical format in terms of the mean along-wind, peak along-wind, and peak cross-wind displacement response. Specifically, the objectives of the paper are as follows:

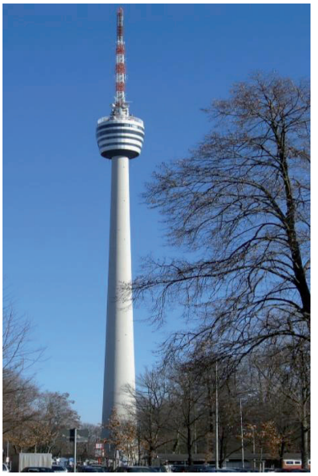

Fig. 1. The Stuttgart TV Tower

(i) to present the excitation and response characteristics of the along-wind, and cross-wind displacement response of the TV Tower, based on different GPS campaigns

- January 18 – 19, 2007, (data rate 2 sps),
- April 28 – 30, 2011 (the data rate 10 sps);

(ii) to identify the magnitude of the along-wind and cross-wind response of the TV Tower as a function of the mean wind speed, based on the measurements in 2002, 2005, 2006, 2007, 2008, and 2011, and

(iii) to detect the structural dynamics characteristics, i.e. natural frequencies and damping ratios of the field test conducted on the TV Tower by GPS on April 28–30, 2011, and compare them with Lenk's results [2].

The application of the GPS technology for the wind-induced response of the Stuttgart TV tower and its dynamic characteristics offered new and novel contributions to relative Lenk's results [2] achieved by classical instruments. There are as follows:

- Mounting the GPS 1200 Rover receiver (2011), on the steel antenna mast tip, enabled detection of the second natural frequency fs2 = 0.800 Hz (at a sample rate of 10 sps), which is the frequency of the mode shape of this steel antenna mast of the TV Tower. This second natural frequency was not detected by Lenk.
- Lenk's result for the dependence of the cross-wind response of the TV Tower, as a function of wind speed, has been enriched and extended by the static, and along-wind response of the TV

Tower. The sum of the static displacement and the along-wind component is comparable to the magnitude of the cross-wind component.

- The dynamic characteristics, i.e. first natural frequency and damping ratio, determined by Lenk [2] (applying the free vibration measurements), are quite a good agreement with those quantities detected many years later by authors using the GPS technology (applying power spectral density and Random Decrement technique). So, the TV Tower stiffness is comparable to the as-built condition on 5th February 1956 which is important for structural health monitoring of the TV Tower after 60 years of use.

2. TV TOWER AND ITS RESPONSE AS MEASURED BY LENK IN 1959

The first quasi-static displacements, due to solar radiation and daily air temperature variations, of one point of the TV Tower shaft, located 125 m above ground and 11 m below the TV Tower head, were carried out in August 1956. The measurements were made using a conventional geodetic plumb-method inside the TV Tower shaft. The exact day and weather conditions are not given in the paper [1]. The path of this point described an ellipse with the longer axis equal to 8 cm in the east-west direction and 4 cm in the south-north direction.

Measurements of free vibrations and the wind-induced response of the TV Tower were carried out by Lenk in 1959 [2]. The measurements of the wind-induced response were done continuously from 10th June to 22nd December. In the first series of tests, Lenk investigated the free vibration response of the TV Tower. Two instruments, known in German as a Lemag – Seismo –Schwingschreiber, were installed at the height of 156 m. They were able to measure and record on a strip of paper the TV Tower response in two directions, i.e. east-west and south-north. The TV Tower was disturbed from its equilibrium position by a rope with a diameter of 24 mm fixed to the top of the TV Tower and then pulled by an auto crane on the ground. The rope was cut and the free vibration was recorded. In the first series of Lenk's tests, the free vibration measurements repeated four times. Based on these measurement records, Lenk determined the two natural periods of vibrations with results as follows: $T1= 5.18$ s ($f1 = 0.193$ Hz), $T2 = 0.72$ s ($f2 =1.27$ Hz), and the logarithmic decrements $\delta 1 = 0.039$, $\delta 2 = 0.021$ according to the mean values determined from four records.

In the second series of tests, Lenk measured the wind speed, its direction, and the wind-induced response of the TV Tower. The wind speed (10 minutes average) measured at a height 165 m above the ground. His electric universal wind speed sensor fixed on a 4 m long horizontal steel girder attached to the steel antenna mast and aligned to the south-west. His measurements lasted over half a year. He stated in his paper [2] that the second half of 1959 was warm with relatively moderate winds. For such conditions, he was able to draw a diagram that illustrates the dependence of the cross-wind response as a function of the wind speed shown in Fig. 2. Lenk also drew a graph for the wind pressure distributions measured at three heights: 61.0 m, 104.8 m, and 140.4 m. At these levels, 6 pressure sensors equally distributed around the TV Tower. Based on these measurements, he was able to compile a wind speed profile and a wind pressure distribution profile.

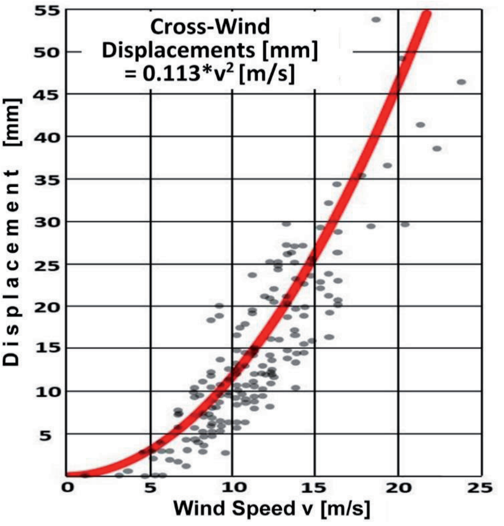

Fig. 2. Cross-wind induced displacements of the head of the TV Tower, diagram based on Lenk's data [2]

3. Measurements of TV Tower wind response using GPS

3.1. GPS measurements on January 18 – 19, 2007

3.1.1 Meteorological Data

For the analysis of the GPS measurements recorded in January 2007, the wind data obtained from the official meteorological station (Deutsche Wetter Dienst - DWD) at Echterdingen Airport, located 9 km south of the TV Tower. Also, locally measured wind data, which measured above the TV tower head, were read every half an hour from the electronic display and recorded at the TV tower headquarters. For both stations, the wind direction specified within the range of 0°-360° in increments of 10 degrees.

The reported GPS campaign took place from 18th until 22nd January 2007. During these days, a maximum wind speed up to 26 m/s occurred on the night of 18th - 19th January 2007. Since the local weather data at the TV Tower were recorded only between 08:00 and 22:30, for the period of strong wind after midnight, only the records of the official station Echterdingen were available (see Fig. 3). Since it was of interest to obtain an approximate value for the wind speed at the top of the TV Tower, the measured wind speeds at the meteorological station Echterdingen were multiplied by a correction factor 1.7. This factor determined by a comparison between the continuous wind recording at the meteorological station Echterdingen and the manually read values (18:21:30, 18:22:00, 18:22:30, and 19:08:00, 19:08:30, 19:09:00) at the TV Tower head (157 m above ground).

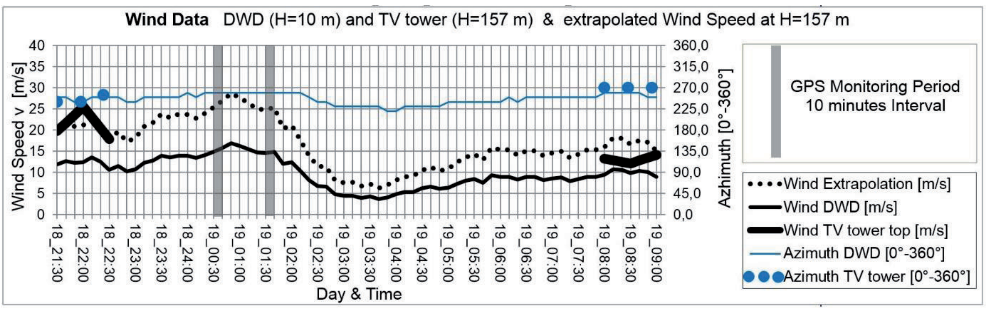

Fig. 3. January 18 – 19, 2007, wind data from the meteorological station Echterdingen and local data from the TV Tower, with extrapolation to the head of the TV Tower

In the following sections, two 10-minute intervals of the GPS measurements are evaluated, whose intervals marked in Fig. 3. In Fig. 3 for both intervals, an identical wind speed recorded at the reference height (H = 10 m), as well as the extrapolated height of GPS-Rover (H = 157 m). In the following analysis for both intervals, one assumed the occurrence of an identical wind speed of v = 15 m/s (54 km/h) at Echterdingen and v = 26 m/s (94 km/h) at the top of TV Tower, respectively. Based on Fig. 3, the authors assumed that the maximum wind speed occurred at 19_00:50 (19th of January 00:50 a.m.), i.e. between the two GPS marked intervals. The following analysis is limited to these two marked observation intervals (19_00:30 and 19_01:30).

3.1.2 GPS MEASUREMENTS

The GNSS (Global Navigation Satellite System) includes several national navigation systems. During the reported measurements, only the American system of GPS (Global Positioning System) used.

The accuracy of positioning (x /y /z) by satellite signals depends on the available receiver types (single- or dual-frequency receiver), the homogeneity of the ionosphere, and the selected observation method. In these campaigns, two dual-frequency receivers from Leica Geosystems (type GPS1200) and the so-called baseline method were applied, which largely eliminated the influence of ionospheric and atmospheric disturbances for baselines <10 km.

For the use of the baseline method, two receivers are needed to define the baseline (3D vector). The reference station was placed at a solid, unchanging position, while the over station fixed to the variable object. The 3D vector between the reference and rover monitored. Its change indicates a displacement of the rover antenna. The baseline mode represents the relative positions (dx/dy/dz) versus the stable reference station. During an observation interval of 3 to 10 minutes, an accuracy of approximately 5 mm can reach in the ground sketch (dx/dy). During longer observation intervals, a change may occur in satellite availability and/or in the geometric satellite configuration, thereby generating a more intensive signal noise followed by a possible systematic variation in position.

A condition for the application of GPS technology is a clear and unobstructed view to the sky for both antenna positions to receive signals from identical navigation satellites without any disturbances. For evaluating a baseline static mode, the availability of 4 satellites is necessary. For processing the trace of a moving point in the kinematic baseline mode, the availability of 5 satellites required. The number of available satellites is not constant for 24 hours. If there are no local obstacles preventing satellite signal reception, the number of available satellites very rarely falls below the number needed. Indeed, under favourable conditions, 10 to 12 satellites are often available.

For kinematic positioning, to track the rover antenna’s sequential displacements, it is necessary to monitor the 3D vector continuously. In the actual measurements, the GPS-positions recorded at a sampling rate of 2 Hertz. Since the oscillation period of the TV Tower is expected to be approximately 5 seconds, that sampling rate delivers about 10 records for every oscillation period. The continuous registration of the GPS data did not take place over 24 hours, but at half-hourly intervals with a limited monitoring period of 10 minutes each. Within this 10-minute interval, 1200 GPS positions recorded. Every 10 minutes data series provides a sufficient basis for the evaluation in kinematic mode and meaningful frequency analysis.

The GPS measurements also aimed at determining the quasi-static displacement of the TV tower over the day due to the unilateral warming of its facade by sun radiation. Evaluating the previously described half-hour observations in the static mode, a sequence of individual positions is achieved, from which the course of the deflection correlated with the time of day can read.

In this campaign, processing the kinematic baseline mode was restricted to intervals with strong wind. Recording the wind speed above the TV Tower head does not meet the standard of a meteorological data collection. However, the local measurements offer the advantage of time-definite assignment of the wind event, since the wind events are always location and time-dependent. Furthermore, the wind speed is influenced significantly by the topography of the surrounding area. At the top of the TV Tower, the airflow is less turbulent, but the average wind speed is higher than at 10 m above ground. As discussed in Section 3.1.1, the measured wind speed at the top of the TV tower is about twice (factor =1.7) the value at 10 m above ground.

During the reported measurements, the Reference station was set up in the valley of Stuttgart on a stable complex of a University building. The Rover station installed at the south facade of the TV tower situated on the hills above the valley. The GPS rover antenna was fixed on the balcony above the viewing platform 157 m above ground, close to the end of the concrete shaft of the TV Tower, as shown in Fig. 4. The horizontal distance between Reference and Rover was about 3000 m, the vertical difference about 365 m. The maximum wind speeds at the TV tower head varied between 26 m/s and 29 m/s (94 - 104 km/h).

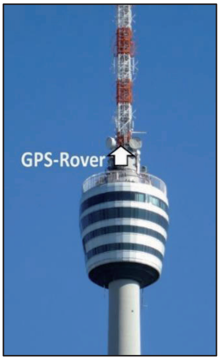

Fig. 4. The head of the TV Tower, GPS Rover position 157 m above ground

3.1.3. WIND-INDUCED OF THE TV TOWER HEAD RESPONSE

During 5 days of GPS measurements on January 17-21, 2007, a period with strong wind occurred, which marked in Fig. 3. Subsequently, the wind response within two selected GPS monitoring intervals was analysed:

- January 19th, 2007, 00:32 to 00:42 a.m., wind speed 26 m/s (at the top of the TV Tower), from the west,

- January 19th, 2007, 01:32 to 01:42 a.m., wind speed 26 m/s (at the top of the TV Tower), from the west.

During both periods, the wind direction kept relatively stable even at the relatively high wind speed. The following analysis restricted to the plot of the dominant transverse vibration component versus the time axis. This component is orientated orthogonal to the wind direction (here the west wind). In the case of the west wind, the direction of the main vibration corresponds closely with the variation of the coordinate component south-north. Figs. 5 and 6 present the component of the lateral vibration and the associated FFT-analysis (Fast Fourier Transform) for each of these two observation intervals. Fig. 5 presents the results for the component of lateral vibration during the first observation interval over 10 minutes and a local wind speed of 26 m/s. The left graph shows the varying amplitudes of the transverse vibration versus the time axis. The vibration reaches the maximum displacement of approximately 21 cm (peak to peak). The right graph shows the result of the FFT analysis. The natural frequency peak is visible at f1 = 0.193 Hz.

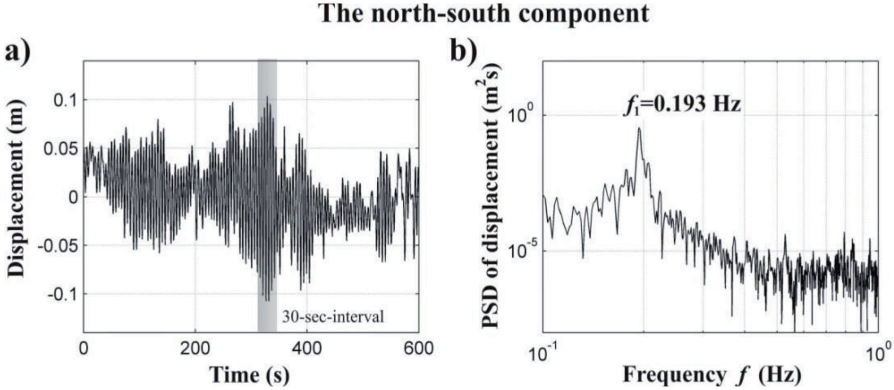

Fig. 5. a) The TV Tower head, north-south component of the wind response during wind of 26 m/s over 10 min, 19th of January 2007, 00:32 to 00:42 am, b) and FFT frequency analysis

Fig. 6 refers to the second observation interval over 10 minutes, with the same wind speed of 26 m/s. The diagram shows the same two components, as in Fig. 5. The maximum peak-to-peak-oscillation diameter is 24 cm. The natural frequency is evaluated to be f1 = 0.194 Hz, which is consistent with the previous frequency analysis almost the same.

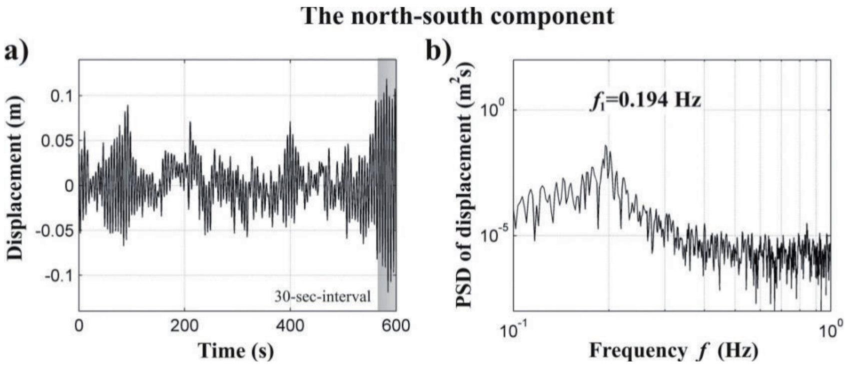

Fig. 6. a) The TV Tower head, north- south component of the wind response during wind of 26 m/s over 10 min, 19th of January 2007, 01:32 to 01:42 am, b) and FFT frequency analysis

A visualization of the vibrations in the horizontal plane for the entire 10-minute interval produces a confusing cluster of 1200 recorded points. For better clarity within the diagram, the visualization was limited to 5% of the total cluster. For each observation interval, a significant section with strong amplitude fluctuations was selected within the interval of 30 s. They are marked in Figs. 5 and 6 (grey colour). Each segment contains 61 positions of the observation chain at the separation of 0.5 seconds. Consequently, around 6 full vibration loops can be displayed within the selected interval. The GPS positions in the plain-plot (Figs. 7 and 8) have been connected by an arrow line in a time-depending order. In both graphs, an elliptical vibration that runs clockwise is recognized. The major axis of vibration is orientated to the north-south direction. The orientation of the oscillating tracks during 30 seconds varies slightly. The peak to peak oscillation displacements in the ground sketches is 21 and 24 cm, respectively.

Depending on the oscillation phase, the points have a mutual separation of approximately 1-6 cm. Based on the distance and the time interval of 0.5 s, the speed of the TV Tower displacement can be estimated: at the zero crossings of oscillation around 12 cm/s, at the reversal points < 2 cm/s.

In the background of every plan, the so-called "zero-spot area" is marked. The zero-spot area was defined by the authors [5] as the location of the TV tower during the night or cloudy day, when no displacement occurs, due to the absence of solar radiation and daily temperature variation. The diameter of this spot is estimated to be around 4 cm. This term ”zero spot area” was selected by the authors to indicate the area in which the top of the TV Tower is close to its upright position. The distance between this zero-spot area and the marked oscillation centre in Figs. 7 and 8 indicate the static component of the wind-induce response, which is equal to about 7 cm on both graphs. The pattern of measured displacements, as shown in Figs. 7 and 8, describes the total response for the specified time.

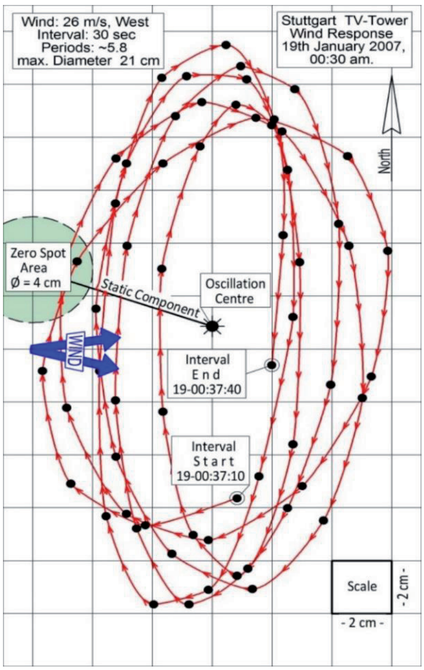

Fig. 7. The TV Tower, static and dynamical components of the wind response on the horizontal plane, 30 s detail, 00:37:10 a.m., a west wind of 26 m/s

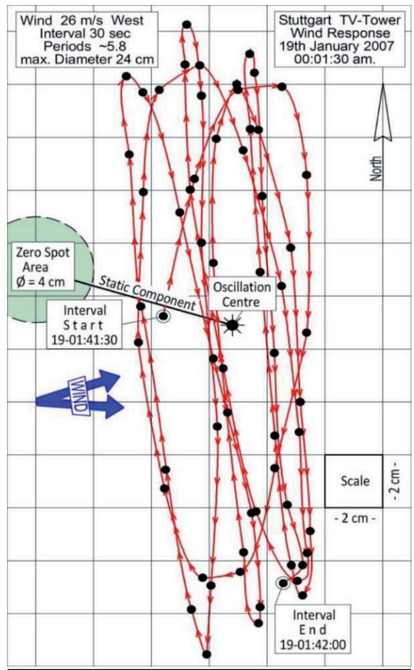

Fig. 8. The TV Tower, static and dynamical components of the wind response on the horizontal plane, 30 s detail, 01:41:20 a.m., a west wind of 26 m/s

3.1.4. Along and cross-wind responses for different wind speeds

As presented and discussed in Figs. 7 and 8, the west wind with a speed of 26 m/s caused a displacement of the oscillation centre to the east (azimuth ~ 110 °) of around 7 cm. This distance refers to the centre of the zero-spot area, for which the position and the diameter of about 4 cm were estimated from the results of 96-hour monitoring. From the graphs in Figs. 7 and 8, the lengths of the visualized vibration loops of the major axis were taken manually and were summarised in Table 1 together with other key data.

Table 1. Characteristics of vibration samples from Figs. 7 and 8 (H=157 m above ground)

Date Time	Interval length [s]	Number of periods	Wind		Loop diameter		Static component [cm]
			Azimuth [°]	Speed [m/s]	Cross-wind [cm]	Along-wind [cm]	
19th Jan. 2007 00:30 a.m.	30	~6	~270	~26	16-21	6-11	~6
19th Jan. 2007 01:30 a.m.	40	~8	~270	~26	17-24	3-7	~5

3.2 GPS MEASUREMENTS ON APRIL 28-30, 2011

3.2.1 ARRANGEMENT OF GPS RECEIVERS

In 2011, 2013, and 2015 renewed efforts were initiated to monitor the TV Tower with a higher GPS-sampling rate.

Two of the GPS receivers Leica 1200 mounted as Rover stations and two Leica 500 installed as Reference stations in April 2011, as shown in Fig. 9. The almost 60 m high steel lattice tower rising above the TV Tower head had to be climbed only by trained personnel and per under an increased level of safety. This temporary antenna installation was only possible by the courtesy and the interest of the SWR (Südwest Rundfunk / Southwest Broadcasting).

The second the GPS Rover receiver installed on the beacon-balcony, 157 m above the ground. Four devices, designated in terms of their types with 501 and 502, alike with 1201 and 1202 respectively, as shown in Figs. 9-11 for internal use. Two GPS receivers, i.e. 501 and 502 as reference stations, were mounted on the geodetic observation deck of the University of Applied Sciences (HFT) down in the valley of Stuttgart. The horizontal lengths of the baselines between Reference and Rover amounted to about 2980 m, the height difference to 364 m and 423 m. The arrangement of Rover and Reference stations shown in Figs. 10-11. Another innovation in our series of tests was the data registration with a higher frequency than so far, namely with a data rate of 10 Hz. The GPS measurements in previous years recorded at a data rate of 1 s or 0.5 seconds, which is sufficient for the analysis of vibration regarding the low natural frequency of the tower of around 0.2 Hertz. The increase in the registration frequency aimed at detecting some natural frequencies of higher modes.

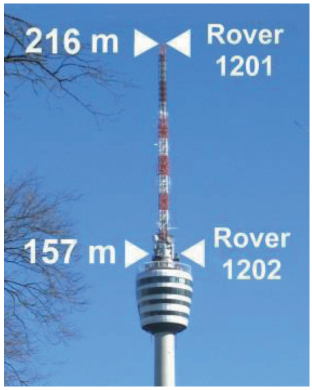

Fig. 9. The upper part of the TV Tower with two GPS Rovers

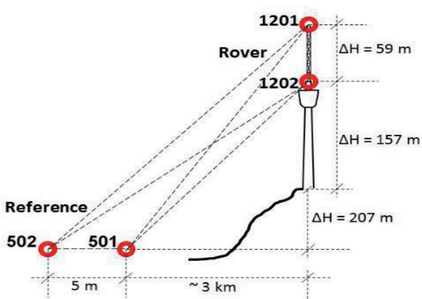

Fig. 10. Sketch for the arrangements of base lines with Reference and Rover receivers

Fig. 11. Positions of two receivers on the TV tower at different levels above ground

3.2.2 GPS MEASUREMENTS STRATEGY

The duration of the GPS measurement was extended to three days to attain two goals. The first goal of a longer observation period was to document the diurnal cycle of displacement caused by solar radiation and daily air temperature variation. The second goal of a longer observation increased the chance of the occurrence of stronger wind. The possible duration time of the measurement campaign limited by the capacity of the memory card in the GPS receiver. The memory card requirement is proportional to the frequency of data recording, which set in this example at 10 sps. For economical use of storage capacity, the GPS data recorded only at certain periodical instants of time, over a limited time interval. Starting monitoring, for an observation interval of two hours, the subsequent observations limited to intervals of 10 min, taken every 30 min, as sketched in Fig. 12. The damping estimation of the TV Tower required two hours of measurements. The intended monitoring strategy implemented by applying the so-called "Wake Up" function, which was available in both receiver types.

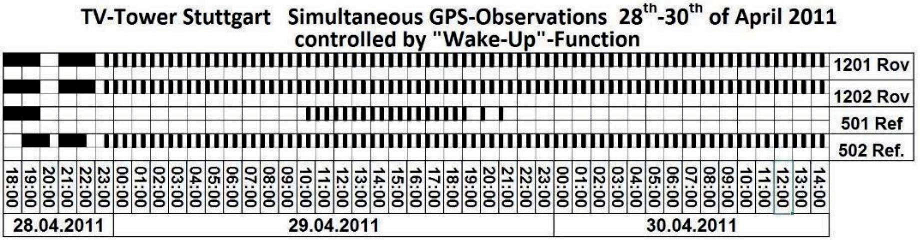

Fig. 12. Scheme of simultaneous GPS measurements at two Rover and Reference stations

The strategy, which shown in Fig. 12, allows extending the measurements with the GPS 1200 receivers to approximately 80 hours. The Leica GPS 500 receivers are equipped by standard with 32 MB memory cards. Since the length of the data sets in device type GPS 500 is significantly shorter than in type GPS 1200, a memory card of equal capacity in the GPS 500 can store the data over a much longer period. Applying the "Wake-up-Function" for simultaneous data recording on both receiver types, it must note that the device GPS 500 requires a warm-up-time of about 70 seconds before data registration starts. For an economical use of the GPS 1200 memory card, the unit GPS1200 should start one or two minutes later than GPS 500. The common observation period for simultaneous data recording fixed exactly at 8 minutes. This observation period usually is sufficient for the baseline solution both in Static as well as in Kinematic Mode.

The capacity of the internal batteries of the GPS devices is limited to a few hours. Several days of measurements are not possible. Therefore, the devices should provide an external 12-Volt battery with at least 32 Ah (Ampere hours). Otherwise, the device should connect the local 220-Volt-network via a transformer. At the reference stations 501 and 502, the planned observation times were not able to be fully realized, because some external problems occurred. At station 501, after 11 hours because of heavy rain, the 12-Volt transformer was damaged by water spray. At station 502, after 39 hours because of external intervention, the data registration was canceled. Despite the described reduction of the planned observations schedule, there remains a 39-hours-long simultaneous observation interval for simultaneous data recording with 2 GPS units of the TV Tower. For the redundant measurements, based on two Reference stations, four simultaneous baselines exist a time interval of 11 hours.

3.2.3 Meteorological Data

Fig. 13 shows the measured wind data at the television tower 157 m above ground. A maximum wind speed of 18 m/sec (65 km/h) occurred on the 29th of April between noon and 1 p.m. For this time interval, there exist simultaneous baseline observations based on two GPS reference stations (Fig. 12). In that way, due to the availability of 4 baselines, the evaluation of the GPS positions was carried out, with redundancy and the reliability of the Kinematic GPS Mode. During the other times of the GPS campaign, there was only a moderate wind of 2-8 m/sec (7 - 28 km/h). The wind direction, at higher wind speeds, tends to keep relatively stable, whereas, at low wind speeds, the wind azimuth was indeterminate.

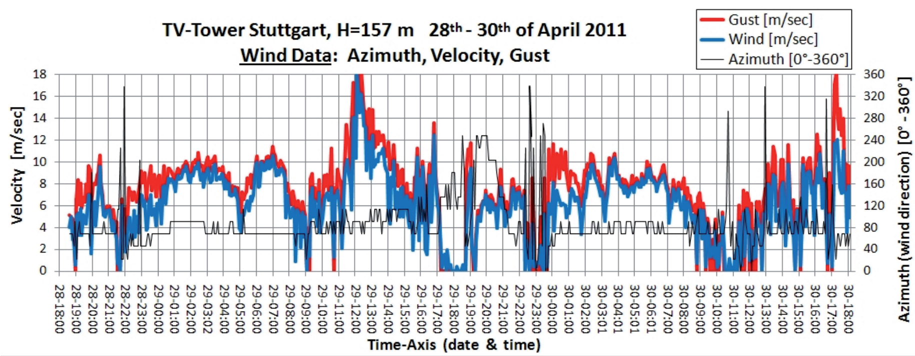

Fig. 13. Recorded wind data above the TV Tower head at the altitude 157 m above ground

3.2.4 Baseline solutions in GPS Static Mode – daily drift of the TV Tower tip due to solar radiation and daily air temperature variation

During the three days of GPS measurements, two Reference stations (501, 502) and two Rover stations (1201,1202) were active, delivering several simultaneous quadruple baselines from Reference to Rover. Based on Reference 501, there are 20 baselines available, based on Reference 502, a series of 81 baselines were available. Table 1 presents a list of the measured baselines and shows the success of the ambiguity solution using the Leica LGO Software in Static GPS Mode.

Table 2. Observed GPS baselines and resolved ambiguities in static mode

Baselines Reference-Rover	Session number	Program controlled LGO-baseline solutions		Outliers (scratched solutions)	Individual solutions achieved by manual post processing	Available baselines solutions	
		Ambiguity YES	Ambiguity NO			Number	Percent
501-1201	20	20	0	1	0	19	95 %
501-1202	20	18	2	1	1	18	90 %
502-1201	81	81	0	1	1	81	100 %
502-1202	81	77	4	9	6	74	91 %

As can be seen in Table 2, the most successful solutions of the baseline were those with the endpoint on the top of the steel lattice mast (Rover 1201). This success was predictable, because at the top of the lattice mast, a rather free sky view was prevailing, and no satellite signals were blocked off. For these baselines, a success rate of the ambiguity resolution was achieved at 95% up to 100%. For the other baselines, with the endpoint 1202 (beacon balcony), a success rate of around 90% was obtained. Figs. 14 and 15 show a plan view of the diurnal course of the Rovers 1201 and 1202 concerning the References 501 and 502 in intervals of 1 hour. Each one-hour-position was formed as a moving arithmetic average of 3 adjacent sessions in 30-min-intervals. This averaging enabled a continuous sequence of positions in 1-hour intervals, despite some unresolved baselines. In Fig. 14, as well in Fig. 15, a significant course deviation of about 3 cm, and 2 cm respectively, occur towards north-west between the time markers 30-00:00, and 30-07:00. This deflection represents the quasi-static component of the wind load, which expected, referring to Fig. 13 (east wind with a speed of 6-11 m/s).

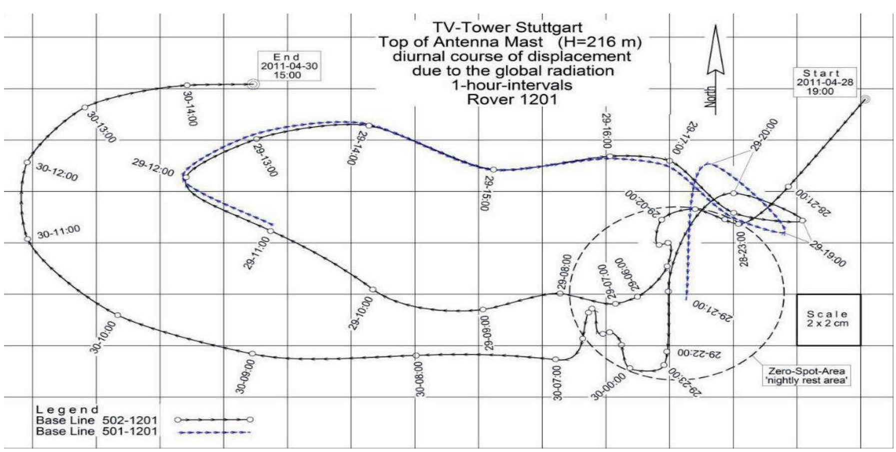

Fig. 14. Rover positions 1201 at the steel antenna mast tip (216 m above ground) related to two reference stations 501 and 502 during 44 h

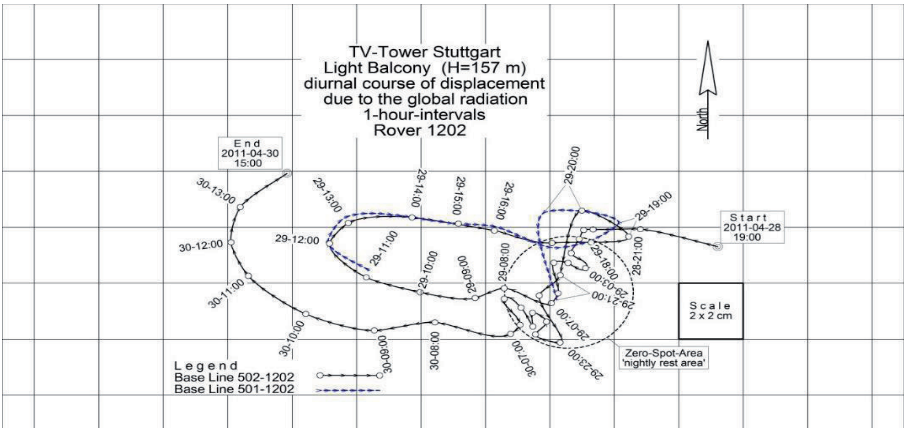

Fig. 15. Rover positions 1202 at the end of the concrete TV Tower head (157 m above ground) related to two reference stations 501 and 502 during 44 h

3.2.5 BASELINE SOLUTIONS IN GPS KINEMATIC MODE

Of particular interest are those observation intervals during which a maximum wind speed occurred. Fig. 13 indicates for the registered wind data a unique maximum at 29-12-00 (29th of April 0:00 p.m.). The associated GPS session covers the time interval from 00:02 p.m. until 00:10 p.m. For this 8-minute-interval, simultaneous measurements exist for all four GPS units. The corresponding baselines 501-1201, 501-1202, 502-1201, 502-1202 successfully resolved in the Static Mode that giving a good prognosis for the evaluation in the Kinematic Mode.

The subsequent analysis applying the Kinematic Mode restricted to this selected time interval with four simultaneous baselines. The originally recorded data sets in Static Mode had to be adapted first to the Kinematic mode by manual editing. It is worth pointing out, that each of the four KOF-chains with 4800 GPS positions has been resolved successfully, as an uninterrupted sequence of individual antenna positions at intervals of 0.1 s. This achieved to a favorable observation window with 8-9 available satellites and a high level of accuracy of $1.7 \leq \text{GDOP} \leq 2.4$.

3.2.6 WIND-INDUCED RESPONSES AND NATURAL FREQUENCIES OF THE TV TOWER

Figs. 16 and 17 depict the noisy along and cross wind-induced components the steel antenna mast tip (H=216 m) during 480 s, interval 12:02 pm until 12:10 pm (April 29, 2011) related to the baselines 501-1201 and 502-1201 respectively and the corresponding FFT analysis. The diameter of the cross wind-induced component reaches about 12 cm. A short interval for later analysis of 5 vibration loops is marked.

Figs. 18 and 19 depict the noisy along and cross wind-induced responses of the TV Tower head (H=157 m) during 480 s, interval 12:02 pm until 12:10 pm (April 29, 2011) related to the baselines 501-1202 and 502-1202 respectively and the corresponding FFT analysis. The diameter of the cross wind-induced response reaches about 7 cm. Table 3 summarizes the key data of the TV Tower head wind-induced response.

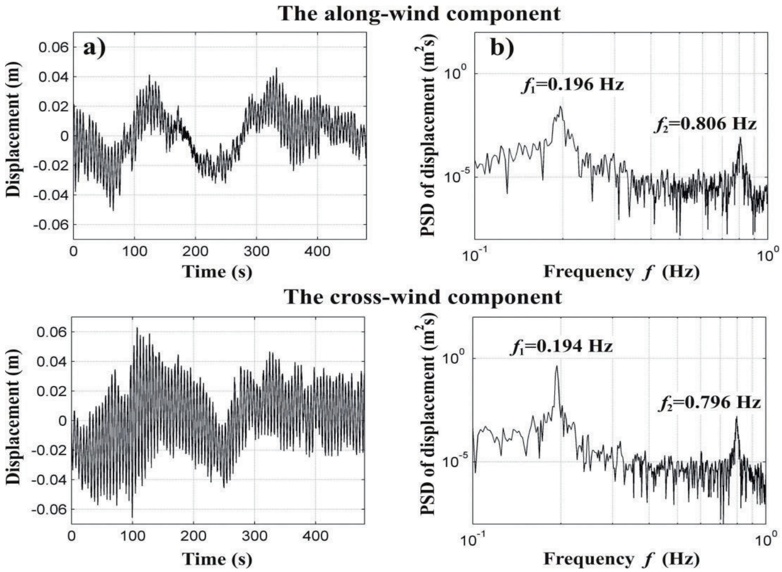

Fig. 16. a) The response of the steel antenna mast tip at the level of H = 216 m (along and cross-wind components), start: 29/04//2011 – 12:02:00, interval 480 s, baseline 501 – 1201, b) Power spectral densities for both components

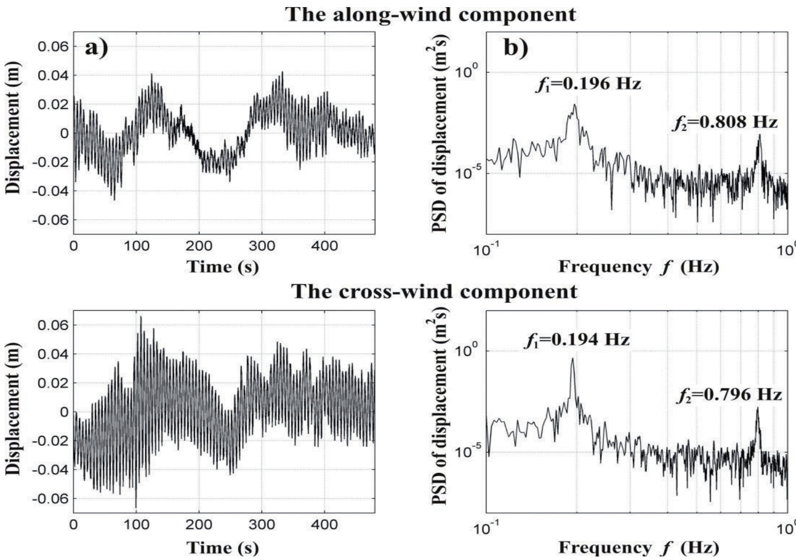

Fig. 17. a) The response of the steel antenna mast tip at the level of H = 216 m (along and cross-wind components), start: 29/04//2011 – 12:02:00, interval 480 s, baseline 502 – 1201, b) Power spectral densities for both components

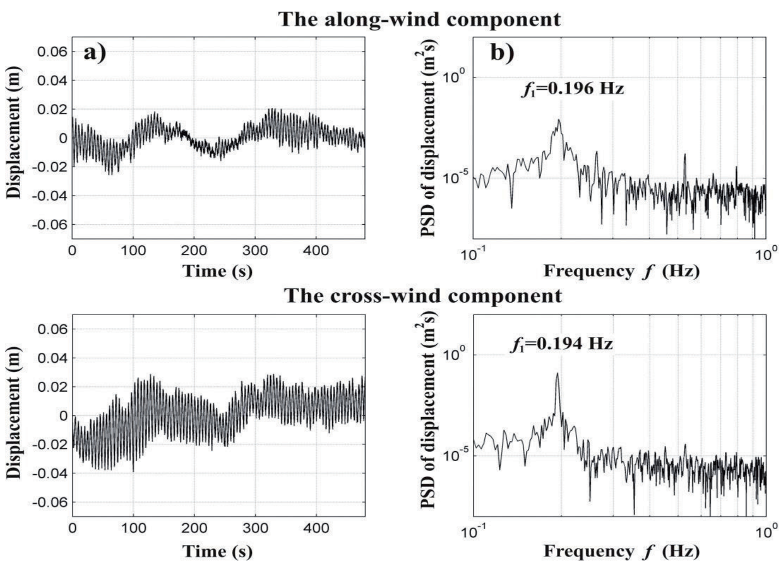

Fig. 18. a) The response of the TV Tower head at the level of H = 157 m (along and cross-wind components) start: 29/04//2011 – 12:02:00, interval 480 s, baseline 501 – 1202, b) Power spectral densities for both components

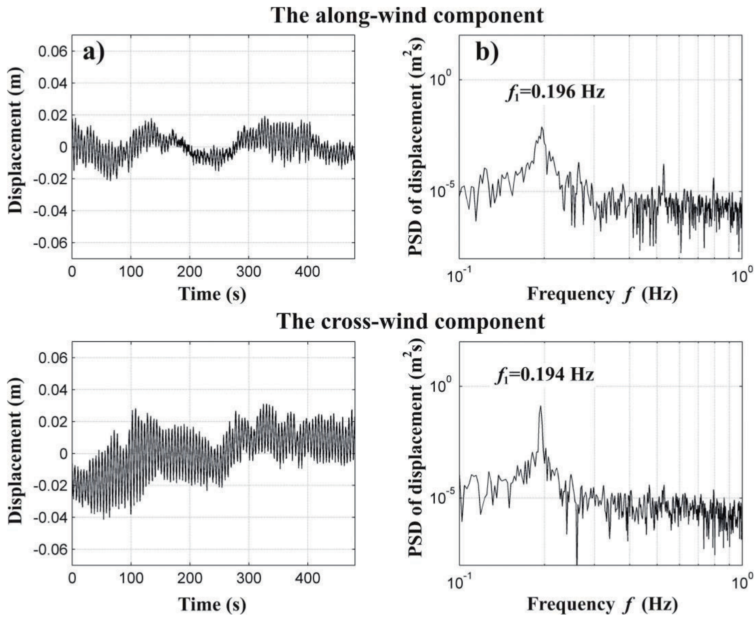

Fig. 19. a) The response of the TV Tower head at the level of H = 157 m (along and cross-wind components) start: 29/04//2011 – 12:02:00, interval 480 s, baseline 502 – 1202, b) Power spectral densities for both components

Table 3. Characteristics of vibration samples from Figs. 18 and 19 (H=157 m above ground)

29th Apr. 2011 Start 12:02:53.4	Interval length [s]	Number of periods	Wind		Loop diameter		Static Component undefined
			Azimuth [°]	Speed [m/s]	Cross-wind [cm]	Along-wind [cm]	
Baseline 501-1202	26	~5	~70	~18	4-7	2-3	overlaid by thermic deformation
Baseline 502-1202	26	~5	~70	~18	4-7	2-3	

For exemplifying the process of vibration, it’s useful to have a look at the course in the plane sketch. Focusing on a more comprehensible visualisation, the recorded data series of 480 sec with 4.800 data points was shorted to an interval with 5 five oscillation loops over 26.5 sec with 265 data points. The selected time interval has been marked by a red arrow in Figs. 16-19. Derived from 4 baselines, Fig. 20 shows the selected 5 vibration loops presenting the wind response of the steel antenna mast tip (H=216 m) and at the head of TV Tower (H=157 m).

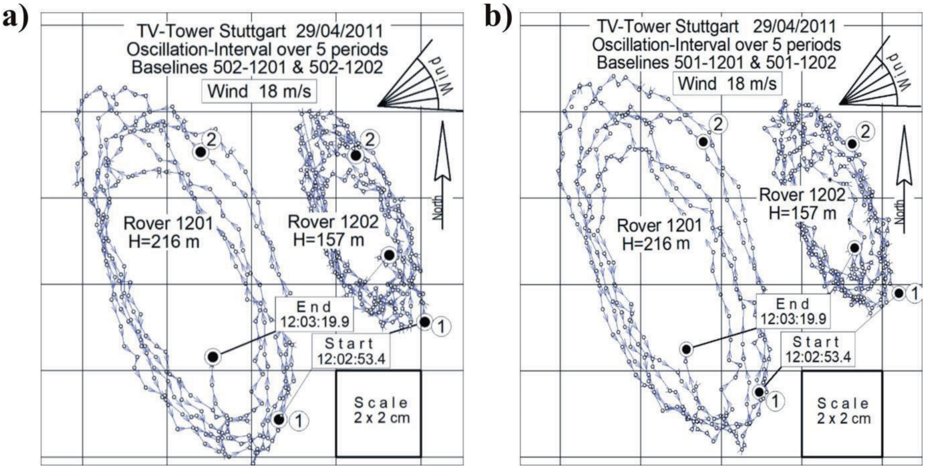

Fig. 20. Dynamical components of the wind response on the top of steel antenna mast and the TV Tower head, five vibration loops

Based on Figs. 16-19, a comparison of measured natural frequencies by authors and Lenk presented in Table 4. A good agreement is between the first natural frequency fc1 of the TV Tower concrete shaft determined experimentally by Lenk in 1959 and by authors of this paper in 2011. Based on Figs. 16-17, it is determined the second natural frequency fs2 of the steel antenna mast tip measured by the GPS measurements, which was not measured by Lenk. Based on the data of Table 4. one can state that the first three frequencies were detected by Lenk and authors of this paper:

fc1 = 0.195 Hz (average) for the first mode shape of the whole TV Tower,

fs2 = 0.800 Hz (average) for the second mode shape of the TV Tower (only steel lattice part vibrate),

fc2 = 1.27 Hz for the third mode shape of the TV Tower.

Table 4. Comparison of measured natural frequencies by Lenk (1959) and authors (2011)

Along-wind component		Cross-wind component		Lenk's results	
f_{c1} [Hz]	f_{s2} [Hz]	f_{c1} [Hz]	f_{s2} [Hz]	f_{c1} [Hz]	f_{c2} [Hz]
0.196	0.806	0.194	0.794	0.193	1.27
0.196	0.806	0.194	0.794		
0.196	-----------	0.194	-----------		
0.196	-----------	0.194	-----------		

4. DAMPING ESTIMATION BASED ON GPS MEASUREMENTS

The damping ratio values ξk, as a fraction of critical damping, of the considered TV Tower were evaluated using the Random Decrement (RD) technique, based on the TV tower head displacements, measured by the GPS in a horizontal plane, due to the weak wind. The field measurement was carried out on April 28, 2011, during the time interval of 104 min, i.e. from 18:15:58 to 20:00:00, with the sampling rate of 10 Hz. Fig. 21 (a) and (b) depicts the horizontal displacements of the TV tower, decomposed into two orthogonal directions, i.e. in the east-west and north-south. The recorded displacements analyzed by the Fast Fourier Transform. The obtained Power Spectral Density (PSD) functions of the time series of displacements depicted in Fig. 21 (c) and (d). Because of the limited measurement accuracy of the GPS, only the first natural frequency of the TV tower detected in both directions. On all the PSDs, there is one peak with f1 = 0.195 Hz, which corresponds to the natural period T1 = 5.128 s.

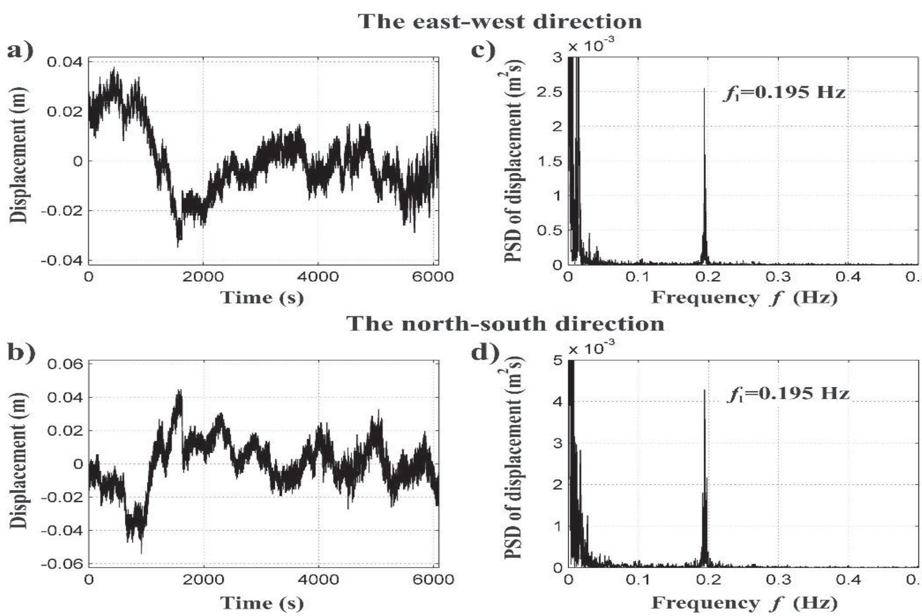

Fig. 21. Displacements of the TV Tower head due to the weak wind, measured on April 28, 2011, over 104 min, from 18:15:58 to 20:00:00, and the PSD of displacements for: (a and c) the east-west direction and (b and d) north-south direction, respectively

The RD technique was introduced by Cole [17], and then developed among others, by Ibrahim [18], Vandiver et al. [19], Jeary [20, 21], and Tamura et al. [22, 23] as one of the time domain signal processing methods used in an output-only modal analysis. The method is appropriate to obtain the natural frequencies and corresponding damping ratios using the RD signature ranked by the peak amplitude of a measured response (displacements or accelerations). Such an RD signature defined as the auto-correlation function of the structural response of a single degree of the freedom viscous-damped system. It is noteworthy that the RD technique can be applied for structures, which response characterized by the narrow spectral-band function, while the excitation of a structure is a relatively wide spectral-band process.

To extract the appropriate time series of the displacements for damping ratio estimation, the filtering procedure using the second-order Type 1 Chebyshev band-pass digital filter, with band 0.192–0.199 Hz, and pass-band ripple 1 dB were adopted. Figs. 22 (a) and 23 (a) depict the calculation results of the RD signatures in two perpendicular horizontal directions. The damping ratio values ξk estimated by approximation of these RD signature, containing only the contribution of the first natural mode, using the least square curve fitting method regarding four unknown parameters, i.e., the natural frequency f1, the damping ratio ξ1, the initial acceleration of the modal decay x1, and the phase shift φ1. The approximation of the RD signature performed by the damped free oscillation function according to the following equation:

$$RD = \frac{x_1}{\sqrt{1-\xi_1^2}} e^{-2\pi\xi_1 f_1 t} \cos\left(2\pi\sqrt{1-\xi_1^2}\, f_1 t - \varphi_1\right) + m(t) \tag{1}$$

where m(t) is the function of approximation inaccuracy, depicted in Figs. 22 (b) and 23 (b).

In Figs. 22 (c) and 23 (c) are given the approximating functions (function expressed on the right side of Eq. (1) and the damping ratio values of the TV Tower obtained in two considered directions.

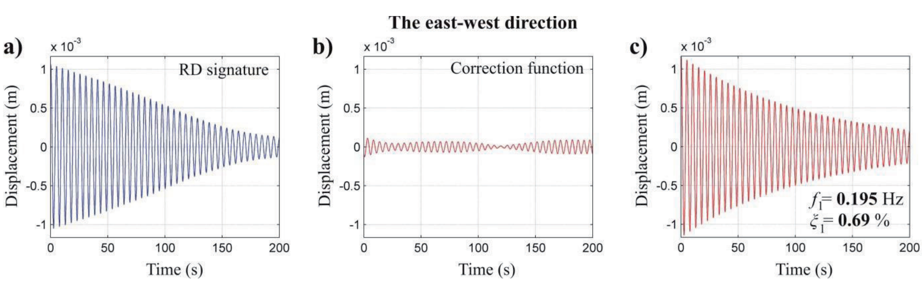

Fig. 22. In the east-west direction: (a) RD signature, (b) function of approximation inaccuracy, and (c) approximating function with an obtained damping ratio value

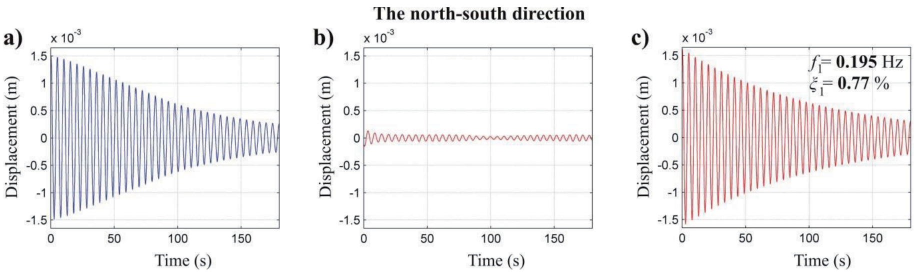

Fig. 23. In the north-south direction: (a) RD signature, (b) function of approximation inaccuracy, and (c) approximating function with an obtained damping ratio value

The estimated damping ratios are compared using the RD technique with those reported by Lenk [2]. Lenk did four free vibration tests on the TV Tower in 1959. In Table 5 are given his and the authors' results. There is good agreement between them.

Table 5. Comparison of damping data between Lenk (1959) and authors (2011)

Test number by Lenk	Damping by Lenk		Damping ratio ξ_1 by authors	
	Log. decrement	Damping ratio ξ_1	East-west	South-north
1	0.045	0.72	0.69	0.77
2	0.039	0.62		
3	0.033	0.52		
4	0.040	0.69		

5. Along and cross-wind responses for different wind speeds for all authors' campaigns

It is interesting to compare the values of the wind-induced response given in Table 1 and Table 3 with the former results of Lenk [2], obtained with the use of classical instruments (Fig. 2). Between 1999-2011, the authors made several kinematic measurements at different lower wind speeds. These further evaluations were documented in previously published papers [4,5], while some other results are new. All these results included in Fig. 24 (a), (b), and (c). These drawings show the results of several measurements at different wind speeds, concerning the static displacements and the maxima displacements of the along, and cross-wind responses. In Fig. 24 (c), the parabolic function formula for the cross wind-induced response, proposed by Lenk, was also plotted. It is noteworthy that the sum of the static displacement and the along-wind component is comparable to the magnitude of the cross-wind component. The Lenk's results enriched and extended by the static and along-wind response of the TV Tower.

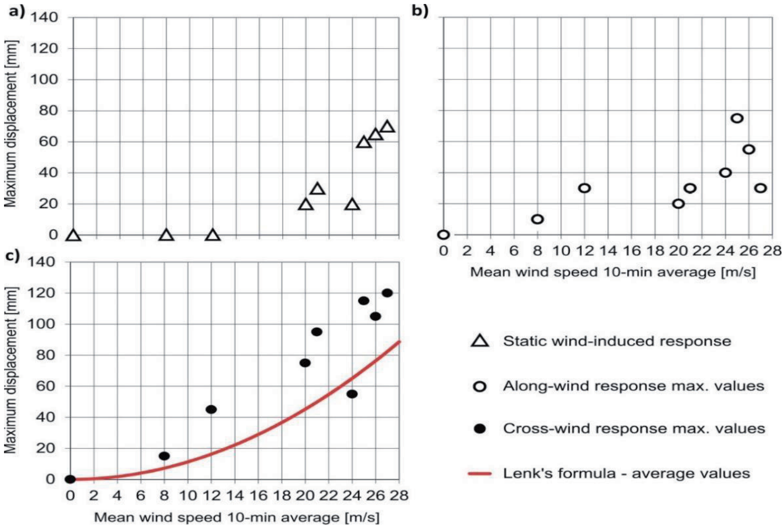

Fig. 24. Synopsis of the measured maximum values of TV Tower head displacements compared with Lenk's formula for cross-wind component

6. CONCLUSIONS

From our GPS measurements and analysis, we draw the following conclusions.

a) The dynamic characteristic, i.e. first natural frequency, measured by Lenk [2], are quite a good agreement with those quantities measured many years later by authors with the GPS. The TV Tower stiffness, up to a displacement of around 150 mm, is comparable to the as-built condition on 5th February 1956, despite the vertical cracks on the outer surface of the TV Tower detected and repaired in 1977 and 1995.

b) The GPS was able to measure the first natural frequency f1 = 0.194 Hz for wind-induced response measured at a sample rate of 2 sps in 2007. Mounting the GPS 1200 Rover receiver (2011), on the steel antenna mast tip, enabled detection of the second natural frequency fs2 = 0.800 Hz (at a sample rate of 10 sps), which is the frequency of the mode shape of this steel antenna mast of the TV Tower. Based on the data of Table 4, together, the first three frequencies were detected by Lenk and the authors of this paper. Due to the low wind-induced TV Tower response (displacement by a few cm), the introduction of advanced GPS in 2011 with a sampling frequency of 10 sps, did not allow the measurement of the third natural frequency of the TV Tower concrete shaft.

c) The damping ratios $\xi 1$ estimated by Lenk in 1959 are in good agreement with the authors' value (Table 5).

d) The results show clearly that the cross-wind response of the TV Tower is larger than the along–wind response for all ranges of wind speed occurring during the GPS measurements, as shown in Fig. 24. The cross-wind response is stimulated due to the combined action of the cross-wind turbulence component and vortex–shedding excitation.

e) The sum of the static displacement and the along-wind component is comparable to the magnitude of the cross-wind component.

f) The dependence of the cross-wind response of the TV Tower, as a function of wind speed, proposed by Lenk in 1959, confirmed in several measurements since 2002. The results achieved by several years of the GPS measurements shown in Fig. 24. The Lenk's results have been enriched and extended by the static, and along-wind response of the TV Tower, as shown in Fig. 24 (a) and (b).

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LIST OF FIGURES AND TABLES:

Fig. 7. The TV Tower, static and dynamical components of the wind response on the horizontal plane, 30 s detail, 00:37:10 a.m., a west wind of 26 m/s

Rys. 7. Wyniki pomiarów statycznych i dynamicznych przemieszczeń wierzchołka trzonu wieży w płaszczyźnie poziomej spowodowanych zachodnim wiatrem o średniej prędkości 26 m/s w czasie 30 sek. o godz. 00:37:10

Fig. 8. The TV Tower, static and dynamical components of the wind response on the horizontal plane, 30 s detail, 01:41:20 a.m., a west wind of 26 m/s

Rys. 8. Wyniki pomiarów statycznych i dynamicznych przemieszczeń wierzchołka trzonu wieży w płaszczyźnie poziomej spowodowanych zachodnim wiatrem o średniej prędkości 26 m/s w czasie 30 sek. o godz. 01:41:20

Fig. 9. The upper part of the TV Tower with two GPS Rovers

Rys. 9. Widok ogólny górnej części wieży telewizyjnej i punkty zamocowania dwóch odbiorników ruchomych GPS

Fig. 10. Sketch for the arrangements of base lines with Reference and Rover receivers

Rys. 10. Sposób określania długości linii bazy pomiędzy odbiornikami referencyjnymi i ruchomymi GPS

Fig. 11. Positions of two receivers on the TV tower at different levels above ground

Rys. 11. Lokalizacja dwóch odbiorników GPS na wieży telewizyjnej na różnych wysokościach nad poziomem terenu

Fig. 12. Scheme of simultaneous GPS measurements at two Rover and Reference stations

Rys. 12. Schemat cykli pomiarowych dwóch odbiorników ruchomych i referencyjnych GPS

Fig. 13. Recorded wind data above the TV Tower head at the altitude 157 m above ground

Rys. 13. Zarejestrowane dane dotyczące wiatru w punkcie nad wierzchołkiem trzonu wieży telewizyjnej na wysokości 157 m nad poziomem terenu

Fig. 14. Rover positions 1201 at the steel antenna mast tip (216 m above ground) related to two reference stations 501 and 502 during 44 h

Rys. 14. Ruch wierzchołka stalowej anteny wieży zarejestrowany odbiornikiem ruchomym 1201 na wysokości 216 m nad poziomem terenu względem dwóch odbiorników referencyjnych 501 i 502 w czasie 44 godzin

Fig. 15. Rover positions 1202 at the end of the concrete TV Tower head (157 m above ground) related to two reference stations 501 and 502 during 44 h

Rys. 15. Ruch wierzchołka żelbetowego trzonu wieży telewizyjnej zarejestrowany odbiornikiem ruchomym 1202 na wysokości 157 m nad poziomem terenu względem dwóch odbiorników referencyjnych 501 i 502 w czasie 44 godzin

Fig. 16. a) The response of the steel antenna mast tip at the level of H = 216 m (along and cross-wind components), start: 29/04//2011 – 12:02:00, interval 480 s, baseline 501 – 1201, b) Power spectral densities for both components

Rys. 16. Przemieszczenia wierzchołka stalowej anteny wieży na wysokości 216 m w kierunku wiatru i w kierunku poprzecznym, początek pomiarów w dniu 29.04.2011 o godz. 12:02:00, w czasie 480 sek., linia bazy 501-1201, i b) funkcje gęstości widmowej mocy zarejestrowanych drgań

Fig. 17. a) The response of the steel antenna mast tip at the level of H = 216 m (along and cross-wind components), start: 29/04//2011 – 12:02:00, interval 480 s, baseline 502 – 1201, b) Power spectral densities for both components

Rys. 17. Przemieszczenia wierzchołka stalowej anteny wieży na wysokości 216 m w kierunku wiatru i w kierunku poprzecznym, początek pomiarów w dniu 29.04.2011 o godz. 12:02:00, w czasie 480 sek., linia bazy 502-1201, i b) funkcje gęstości widmowej mocy zarejestrowanych drgań

Fig. 18. a) The response of the TV Tower head at the level of H = 157 m (along and cross-wind components) start: 29/04//2011 – 12:02:00, interval 480 s, baseline 501 – 1202, b) Power spectral densities for both components

Rys. 18. Przemieszczenia wierzchołka trzonu wieży na wysokości 157 m w kierunku wiatru i w kierunku poprzecznym, początek pomiarów w dniu 29.04.2011 o godz. 12:02:00, w czasie 480 sek., linia bazy 501-1202, i b) funkcje gęstości widmowej mocy zarejestrowanych drgań

Fig. 19. a) The response of the TV Tower head at the level of H = 157 m (along and cross-wind components) start: 29/04//2011 – 12:02:00, interval 480 s, baseline 502 – 1202, b) Power spectral densities for both components

Rys. 19. Przemieszczenia wierzchołka trzonu wieży na wysokości 157 m w kierunku wiatru i w kierunku poprzecznym, początek pomiarów w dniu 29.04.2011 o godz. 12:02:00, w czasie 480 sek., linia bazy 502-1202, i b) funkcje gęstości widmowej mocy zarejestrowanych drgań

Fig. 20. Dynamical components of the wind response on the top of steel antenna mast and the TV Tower head, five vibration loops

Rys. 20. Przemieszczenia dynamiczne wierzchołka stalowej anteny i trzonu wieży telewizyjnej spowodowane wiatrem w czasie odpowiadającym pięciokrotności okresu drgań podstawowych wieży

Fig. 21. Displacements of the TV Tower head due to the weak wind, measured on April 28, 2011, over 104 min, from 18:15:58 to 20:00:00, and the PSD of displacements for: (a and c) the east-west direction and (b and d) north-south direction, respectively

Rys. 21. Przemieszczenia wierzchołka trzonu wieży telewizyjnej spowodowane słabymi podmuchami wiatru w dniu 28.04.2011 r. w czasie 104 min, w godz. 18:15:58 do 20:00:00 i funkcje gęstości widmowej mocy zarejestrowanych drgań w kierunkach: (a, c) wschód-zachód i (b, d) północ-południe

Fig. 22. In the east-west direction: (a) RD signature, (b) function of approximation inaccuracy, and (c) approximating function with an obtained damping ratio value

Rys. 22. W kierunku wschód-zachód: (a) funkcja losowego dekrementu, (b) funkcja niedokładności aproksymacji i (c) funkcja aproksymująca wraz z oszacowaną wartością liczby tłumienia drgań

POMIARY ODPOWIEDZI DYNAMICZNEJ WIEŻY TELEWIZYJNEJ W STUTTGARCIE ZA POMOCĄ KLASYCZNYCH PRZYRZĄDÓW POMIAROWYCH I TECHNOLOGIĄ GPS

Słowa kluczowe: *wieża telewizyjna w Stuttgarcie, pomiary systemem GPS, odpowiedź spowodowana wiatrem, częstotliwości drgań własnych, liczba tłumienia drgań*

STRESZCZENIE:

Wieża telewizyjna w Stuttgarcie została oddana do użytkowania w dniu 5 lutego 1956 roku. Konstrukcja wieży składa się z dwóch części: (a) trzonu żelbetowego z głowicą o wysokości 161 m i (b) stalowego masztu antenowego o wysokości 56 m. Całkowita wysokość wieży to 217 m. Średnica zewnętrzna trzonu żelbetonowego wynosi 10,8 m u podstawy trzonu i 5,04 m w górnej części trzonu (poniżej głowicy trzonu). Grubość ściany trzonu zmienia się od 60 cm do 19 cm.
W latach 1953-1954 Leonhard zaproponował koncepcję i projekt wieży telewizyjnej. Biuro projektowe Pieckert zaprojektowało system konstrukcyjny. Koncepcję wieży telewizyjnej, jej układ konstrukcyjny, wszystkie założenia do obliczeń statycznych, oszacowanie nakładów finansowych i pierwsze pomiary osiadań fundamentów podane zostały w jednej z prac Leonhardta. W tej pracy zasugerowano także potrzebę pomiaru odpowiedzi wieży telewizyjnej na działanie wiatru. Jako pierwszy dokonał tego Lenk w 1959 roku.

W latach 1977 i 1995 stwierdzono pionowe pęknięcia w żelbetowym trzonie wieży, które następnie zostały naprawione. Przyczyny tych pęknięć wyjaśniono jako konsekwencje promieniowania słonecznego i dobowych zmian temperatury powietrza działających na trzon wieży telewizyjnej, wywołujących deformacje płaszcza trzonu. Naprężenia termiczne spowodowały zmienną w czasie „owalizację" trzonu wieży, która z biegiem lat doprowadziła do zmęczenia materiału, czego skutkiem były wyraźnie widoczne podłużne pęknięcia po przeciwnych stronach trzonu wieży telewizyjnej.

Autorom niniejszego artykułu nie są znane wcześniejsze pomiary charakterystyk dynamicznych wieży telewizyjnej związane z naprawą powstałych pęknięć. W związku z tym, w 1999 roku autorzy przeprowadzili pierwszą serię pomiarów przemieszczeń wierzchołka wieży telewizyjnej z zastosowaniem techniki satelitarnej GPS. Metodologia pomiarów była podobna do metodologii stosowanej przez innych badaczy. Na tej podstawie autorzy potwierdzili możliwość zastosowania systemu GPS do monitorowania przemieszczeń statycznych, quasi-statycznych i dynamicznych oraz do określania podstawowych charakterystyk dynamicznych (częstotliwości drgań własnych i współczynników tłumienia drgań) istniejących dużych konstrukcji w skali naturalnej.

Autorzy cyklicznie monitorowali przedmiotową wieżę telewizyjną do roku 2015. Jednak pomimo podjętego wysiłku w celu zebrania dodatkowych danych pomiarowych, niestety w 2013 i 2015 r. nie było możliwości pomiaru przemieszczeń wieży telewizyjnej pod wpływem silnego wiatru. Niemniej jednak autorzy dokonali analizy danych pomiarowych zgromadzonych w latach 2002, 2005, 2006, 2007, 2008 i 2011, które obejmowały pomiary w zakresie prędkości wiatru od małej do dużej. W dniach 18-19 stycznia 2007 r. w pobliżu wieży zarejestrowano porywy wiatru o prędkości 26 m/s, co spowodowało jej przemieszczenia w zakresie decymetrów.

Najważniejsze cele niniejszego artykułu są następujące:

(i) przedstawienie danych meteorologicznych dotyczących głównie prędkości wiatru i przemieszczeń wieży w kierunku wiatru i w kierunku poprzecznym do kierunku wiatru na podstawie dwóch serii pomiarowych wykonanych w dniach:

• 18 - 19 stycznia 2007 r., (częstotliwość próbkowania danych 2 Hz),

• 28 - 30 kwietnia 2011 r., (częstotliwość próbkowania danych 10 Hz),

(ii) badanie zależności przemieszczeń wieży telewizyjnej w kierunku wiatru i w kierunku poprzecznym jako funkcji zależnej od średniej prędkości wiatru - na podstawie pomiarów wykonanych w latach 2002, 2005, 2006, 2007, 2008 i 2011,

(iii) eksperymentalne określenie charakterystyk dynamicznych wieży, tj. częstotliwości drgań własnych i współczynników tłumienia drgań na podstawie pomiarów w skali naturalnej za pomocą techniki GPS w dniach 28–30 kwietnia 2011 r. i porównanie ich z wynikami otrzymanymi przez Lenka.

W wyniku przeprowadzonych prac badawczych stwierdzono, że zastosowanie techniki GPS do monitorowania odpowiedzi wieży telewizyjnej spowodowanej wiatrem i jej charakterystyk dynamicznych wniosło nowatorski wkład o charakterze poznawczym w porównaniu z wynikami otrzymanymi przez Lenka za pomocą klasycznych przyrządów pomiarowych. Zakres nowych dokonań jest następujący:

a) zamontowanie dodatkowego odbiornika ruchomego GPS 1200 Rover (2011 r.) na wierzchołku stalowego masztu antenowego umożliwiło identyfikację drugiej częstotliwości drgań własnych fs2 = 0,800 Hz (przy częstotliwości próbkowania 10 Hz), która jest częstotliwością modalną tego masztu. Ta druga częstotliwość drgań własnych nie została wykryta przez Lenka,

b) wyniki Lenka z 1959 roku w zakresie odpowiedzi wieży telewizyjnej w kierunku poprzecznym do kierunku wiatru jako funkcji prędkości wiatru zostały rozszerzone o przemieszczenia statyczne i składową przemieszczeń dynamicznych w kierunku wiatru. Suma przemieszczenia statycznego i składowej przemieszczeń dynamicznych w kierunku wiatru jest porównywalna z wartością przemieszczeń wieży w kierunku poprzecznym,

c) charakterystyki dynamiczne wieży, tj. pierwsza częstotliwość drgań własnych i współczynnik tłumienia, określone przez Lenka (analizując drgania swobodne konstrukcji) dość dobrze zgadzają się z wielkościami wyznaczonymi wiele lat później przez autorów niniejszego artykułu z zastosowaniem systemu GPS (analizując drgania wymuszone wiatrem wieży). W ten sposób potwierdzono, że sztywność wieży telewizyjnej jest porównywalna ze stanem wyjściowym, tj. z dnia 5 lutego 1956 r. Jest to istotna informacja w zakresie monitorowania stanu konstrukcji wieży telewizyjnej po 60 latach użytkowania.

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