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Monitoring of tall slender structures by GPS measurements

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Abstract. A method is applied for the estimation of structural damage of tall slender structures using natural frequency and displacements measurements by GPS. The relationship between the variation in the global stiffness matrix (or in the stiffness of each finite element) and the change in the natural frequencies of the structure is given. In engineering practice the number of frequencies which can be derived by GPS measurement of long-period structures will be equal to one, two or three first natural frequencies. This allows us in initial studies to detect damage with frequency changes based on forward methods in which the measured frequencies are compared with the predicted analytical data. This idea, of health monitoring from possible changes to natural frequencies, or from a statement of excessive displacements is applied to the Stuttgart TV Tower.

Keywords: full-scale measurements; GPS; monitoring; the Stuttgart TV Tower; wind.

1. Introduction

Many civil engineering structures in their service life are subjected to deterioration and damage due to factors, such as operating actions (i.e. wind load, live load), fatigue, environmental corrosion, etc. Their structural failure could be catastrophic not only in terms of financial loss, but also in terms of social impact. This is the main reason that structural damage detection is becoming an important research problem in engineering. Current nondestructive testing techniques may be divided into two subsets:

a) visual or local experimental methods such as: radiological, optical, electromagnetic, ultrasonic and thermal field method; or
b) a vibration – based method that either examines the difference between numerically predicted results and measured amplitude displacements of the harmonic response of structures; or, the changes of vibration characteristics (i.e. natural frequencies, mode shapes and damping) of structures. These two methods are based on the fact that local damage usually causes a decrease in structural stiffness, which produces changes in the global vibration characteristics of the structure, that is, in its harmonic response or modal characteristics.

The disadvantages of the experimental methods mentioned in the subset a) are as follows: they are time-consuming, costly, the location area must be accessible and the location of the damage must be known a priori. The advantage of the vibration-based method is that it is not necessary to know the

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damage location before measurements are taken.

This paper presents an attempt to identify damage to tall long-period structures, such as TV towers and industrial chimneys. The purpose of this study is to use dynamic wind response measurements by GPS as a health monitoring tool. Measurement may provide data to show significant changes in the dynamic characteristics such as natural frequencies and damping or to show excessive displacements of structures mentioned above. With the development of GPS measurement equipment the vibration properties of these types of structures can be measured more accurately and conveniently, so this method is being rapidly developed and has been applied in monitoring of civil engineering structures in the last two decades. In order to help to a solution to this problem the GPS antennas have been temporarily installed on the top of the Stuttgart TV Tower. This paper presents field tests conducted on this tower in January 2007 to measure the displacements at the tower top caused by wind during thunderstorm. These measurements provided data indicating that there has been no change in the first natural frequency of the tower since it was estimated experimentally by Lenk in 1959 (Lenk 1966), by authors of this paper in 2006 (Breuer, *et al.* 2008) and 2007, and also no excessive displacement. So, it was confirmed twice, that the Stuttgart TV Tower after more than 50 years in service life seems to be structurally undamaged.

2. The relationship between the variation in the global stiffness matrix and the natural frequency changes

The eigenvalue problem of the free vibration of an undamped structure with n degree of freedom is described by the equation

$$(\mathbf{K} - \lambda_i \mathbf{M})\{\phi_i\} = \{0\}, \quad i = 1,2,...,n \tag{1}$$

where [**K**] is the $n \times n$ symmetric stiffness matrix, [**M**] is the $n \times n$ symmetric mass matrix, λ_i and $\{\phi_i\}$ are the ith eigenvalue and mass-normalized mode shape, respectively.

Damage of the structure is defined as the change of its stiffness matrix by an amount $\Delta\mathbf{K}$. It is also logical to assume that damage is not accompanied by a change in mass (Xia and Hao 2003). Further, a change in stiffness produces changes in the eigenvalues, denoted here as $\Delta\lambda_i$, and changes in the mode shapes, $\Delta\phi_i$. Then the eigenvalue problem of the damaged structure can be similarly written as

$$[\mathbf{K} + \Delta\mathbf{K} - (\lambda_i + \Delta\lambda_i)\mathbf{M}]\{\phi_i + \Delta\phi_i\} = \{0\}, \quad i = 1,2,...,n \tag{2}$$

Expanding Eq. (2) and neglecting the higher order terms it can be written as

$$\mathbf{K}\{\Delta\phi_i\} - \lambda_i\mathbf{M}\{\Delta\phi_i\} = -\Delta\mathbf{K}\{\phi_i\} + \Delta\lambda_i\mathbf{M}\{\phi_i\} \tag{3}$$

After premultiplying Eq. (3) by $\{\phi\}^T$ gives

$$\{\phi\}^T(\mathbf{K} - \lambda_i\mathbf{M})\{\Delta\phi_i\} = -\{\phi\}^T\Delta\mathbf{K}\{\phi_i\} + \Delta\lambda_i\{\phi_i\}^T\mathbf{M}\{\phi_i\} \tag{4}$$

Noting that $\{\phi_i\}^T(\mathbf{K} - \lambda_i\mathbf{M}) = 0^T$ the relation between the change in the global stiffness matrix and the change in the eigenvalues is given by

$$\Delta\lambda_i = \{\phi_i\}^T \Delta\mathbf{K}\{\phi_i\}, \quad i = 1,2,...,n \tag{5}$$

In the FE method, [**K**] is obtained by assembling the contribution of all $\mathbf{K}_j^e$, $j = 1,2,...,m$ elements. To relate changes in the natural frequencies $\Delta\lambda_i$ to the change in the stiffness of local structural element denoted by $\Delta\alpha_j\mathbf{K}_j^e$, the global stiffness of the damaged structure can be written as

$$\mathbf{K} + \Delta\mathbf{K} = \sum_{j=1}^{m} \mathbf{K}_j^e(1 + \Delta\alpha_j) \tag{6}$$

where $\Delta\alpha_j$ is the proportional change in the stiffness of element or in other words it is the "elemental stiffness reduction parameter". Thus the change of the global stiffness matrix can be written as i.e. the change to the global stiffness matrix depends on changes in the element stiffness matrices

$$\Delta\mathbf{K} = \sum_{j=1}^{m} \Delta\alpha_j\mathbf{K}_j^e \tag{7}$$

Substitution Eq. (7) into Eq. (5) gives a set of algebraic equations in the form of

$$S\{\Delta\alpha\} = \{\Delta\lambda\} \tag{8}$$

Where $\{\Delta\alpha\}$ and $\{\Delta\lambda\}$ are the elemental stiffness reduction vector and the natural frequency change vector, respectively, and [**S**] is the sensitivity matrix whose elements are

$$\mathbf{S}_{ij} = \{\phi_i\}^T\mathbf{K}_j^e\{\phi_i\} \tag{9}$$

for and $i = 1,2,...,n$ and $j = 1,2,...,m$, where n is the number of available frequencies in testing.

The Eq. (8) relate the change in the stiffness of each element to the changes in the frequencies of the structure. When the initial FE model of the structure is known and the frequencies in the damage state are measured accurately, Eq. (8) can be uniquely solved when the number n of available changes in frequency is equal to the number of unknown elemental stiffness reduction. But in engineering practice, the number of measured frequencies n is usually less than the unknown changes in all the elements, i.e. n<m. This is an underdetermined problem in mathematics, which means that it has infinite solutions. It can be solved uniquely only after the introduction of an optimality criterion (Hassiotis and Jeong 1995).

3. Assessment of structural damage from possible changes in natural frequencies

It is assumed that an computational model of a tall long-period structures exist that correctly describes the structure before damage. It means that Eq. (1) is satisfied exactly for an n-degree-of-freedom system, i.e. after solution of Eq. (1) the set of the eigenvalues λ_i is determined. It can be also assumed that a few first eigenvalues λ_i for a given structure may be determined experimentally after construction of that structure. So, it is assumed that the natural frequencies λ_i describing the intact state of the structure are known.

The structures after many years of service life, can be structurally damaged due to many deterioration processes or by accidental actions. In the damage state of the structure its stiffness will be decreased and changes of natural frequencies $\Delta\lambda_i$ will be observed. These changes of the vibration data can be examined by the vibration-based method, i.e. by GPS measurements of the structure by a free vibration test or by forced-vibration test due to week or strong wind. The natural frequencies of the damage state of the structure are denoted by $\tilde{\lambda}_i$, which means that $\tilde{\lambda}_i = \lambda_i + \Delta\lambda_i$. It is assumed that similar tests on the eigenvectors $\{\phi_i\}$ for the intact state and the eigenvector $\{\tilde{\phi}_i\}$ for the damage state of the structure are not available. This is a result of the assumption that the natural frequencies can be measured even at one point of the structure. So, an inverse approach namely model updating method can not be applied to identify damage. The damage location and its magnitude can be identified by other methods, for example by the visual method.

4. GPS health monitoring of long-period structures from measurements of natural frequencies and displacements

In the last fifteen years Global Positioning System (GPS) with 10-20 Hz sampling rates has become a useful tool for measuring static, quasi-static and dynamic displacements in long-period civil structures exposed to wind, traffic, earthquakes or temperature variation, and to derive their natural frequencies, usually up to 1 Hz, but even to 4 Hz using high frequency GPS receivers 20 Hz (Psimoulis, *et al.* 2008). So in practice the number of frequencies derived by GPS measurements will be equal to two or three first natural frequencies. The natural frequencies are the global properties of the structure and thus they can be derived by measurement at a few locations or even at one point. This allows us in initial studies to detect damage with frequency changes based on forward method in which the measured frequencies are compared with the predicted analytical data (based mainly on a finite element (FE) mode). This forward technique can only give a rough estimate of the damage and only be practical for a single damage scenario.

The biggest advantage from GPS measurements of wind-induced dynamic responses is that one can measure displacements directly, i.e. a static component and a dynamic fluctuating component. This information may be made available to managers whenever a predetermined displacement threshold is reached. The structure managers can asses the response of the structure according to: (a) changing dynamic characteristics, (b) different threshold displacements (e.g. A and B as shown in Fig. 1). The value of the Treshold B for along and cross-wind may be estimated theoretically according to the

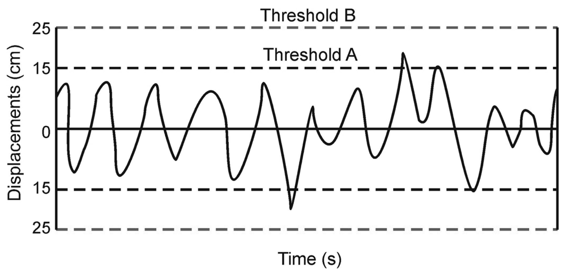


Fig. 1 Assumed hypothetical thresholds of displacements shown to demonstrate how GPS data can provide warning at different displacements values (e.g. Threshold A may refer to the serviceability limit state, and Threshold B to the ultimate limit state for a structure), the same approach as in our paper by Breuer, *et al.* (2008)

methods presented in the paper(Gorski, *et al*. 2008). In the case of serious situation, the management can make decisions for additional inspection (e.g. visual inspection) of the structure to secure its safety. In such an approach a structural health monitoring system will be created. For tall slender structures, at least two GPS units are required to monitor a TV tower or industrial chimney: one of the unit will serve as a reference ground station, the second unit should be deployed on the top of the structure to detect translational wind-induced response, and to evaluate relative displacements. Both units require good sky visibility.

5. The Stuttgart TV Tower and its dynamics characteristics

The Stuttgart TV Tower, shown in Fig. 2, was constructed as a concrete tube in 1953-1955 as the first television tower in the world. Its fundamental dimensions are as follows: the concrete shaft is 161 m tall, the diameter is 10.8 m at the bottom and 5.04 m at the end, the wall thickness decreases from 60 cm to 19 cm, above the tower head the steel antenna mast is mounted, it is 51 m tall. In 1955 the total height of the TV Tower was 212 m. Its absolute height above sea level is 700 m.

The information about a structural system of the Stuttgart TV Tower, details of the construction, costs, assumption for the calculations and wind response, the first measurements of the settlement of the foundation and quasi-static displacements of the shaft of the tower due to solar radiation and daily air temperature variation are given in the paper by Leonhardt (1956). The synopsis of its dynamic characteristics as previously calculated and measured are given in paper by Breuer, *et al.* (2008).

The Stuttgart TV Tower has been temporarily monitored by the authors of this paper since 1998. The Rover Antenna was always tightly fixed on the handrail of the southern light balcony, as shown in Fig. 3. The stiffness of the frame is very high because of its case-formed diameter. As it was written in our paper (Breuer, *et al.* 2008), the free vibration of the handrail was measured on 4th March 2008 and found to have a first natural frequency of about 11 Hz. That frequency is of a different order from the first natural frequency of the tower which is approximately equal to 0.2 Hz. Therefore a possible vibration of the handrail should have no influence on our interpretation of wind response.

Fig. 2 The Stuttgart TV Tower with a tower head

Fig. 3 The Stuttgart TV Tower with GPS-Antenna (Rover Station) mounted on the hand-rail of the balcony, 5 meters above viewing platform

6. Response to stormy wind

In January 2007 it was forecasted that during 2 weeks bad weather with wind velocity up to 100 km/h might happened. In this time GPS equipment was available for the temporary installation and the Stuttgart TV Tower was accessible. Therefore the wind response of the top of the tower was measured during two GPS sessions – everyone lasting about 100 hours.

In the night of 19th of January, 2007 a thunderstorm occurred from 00:00 to 04:00 h. The wind velocity is shown in Fig. 4, where during the time (00:00-02:00) a maximum wind velocity of 16 m/s was observed. The wind speed was recorded at the meteorological station of the Airport Stuttgart–Echterdingen, located at a distance of 7 km southwest of the tower. The anemometers of all meteorological stations are mounted 10 m above ground, an extrapolation of data is needed to the altitude of the top of the tower (161 m), i.e. at the end of the concrete shaft. According to the power low, an average velocity of 24.5-26.0 m/s at the top of the tower can be estimated.

The displacement of the tower's top due to wind action is related to the tower's upright position.

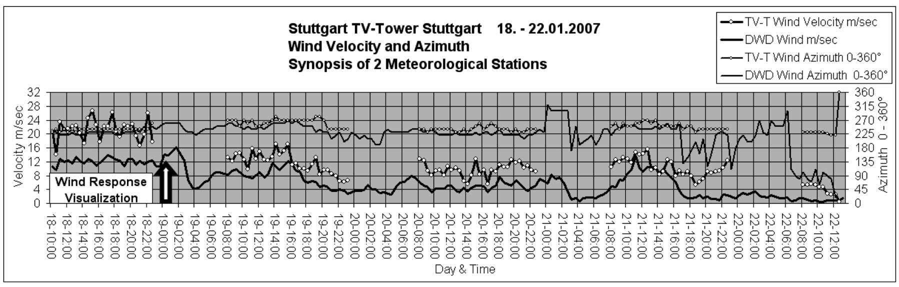


Fig. 4 The wind velocity and its direction recorded during GPS session (Stuttgart, 18th – 22nd January 2007), where: DWD means the German meteorological station of the Airport Stuttgart-Echterdingen (10 m above ground), and TV-T means the anemometer of the TV-Tower which is mounted above the head of the tower (161 m above ground) at the base of the steel girder mast. Reading of data is possible during the operating hours of the lift only

This position is not always identical with the vertical axis of the structure, but with the tower's position due to a combined influence of solar radiation and daily air temperature variation. Before analyzing the wind response, the daily drift of the tower due to this influence should be known in advance. Fig. 5 presents the results of this daily drift of tower's top in a 2 x 2 cm grid. The hourly positions of the tower are plotted and labeled with time marks. Consecutive positions are connected by an arrow line. These data were measured in winter 2007 (18th – 22nd January) when the Stuttgart TV Tower was monitored by GPS for about 100 h. The same procedure was applied as in summer 2006 (4th – 8th July, Breuer, *et al.* 2008), i.e. every 30 min a data series was registered covering 10 min with a data rate of 0.5 s. Since the equipment Leica GPS 500 has a start up delay of 90 s before it can track satellites, each data series was restricted to 1020 data sets. The positions of the daily drift were calculated applying the so-called Static Mode and post processing. For every hour a moving average was calculated based or 3 values of half-hour positions.

The daily winter drift of the top of the tower shown in Fig. 5 is much smaller than the daily summer drift shown in Fig. 8 in the paper by Breuer, *et al.* (2008). The daily summer drift occurs in Fig. 8 (Breuer, *et al.* 2008) as several elliptical loops with long axis in the West-East direction (17 cm) and a shorter axis in the South-North direction (9 cm). In Fig. 5 this drift occurs of about 6 cm in the North and in the East direction only. The difference between both Figs. is caused by the difference of solar radiation and daily air temperature variation between summer and winter. In

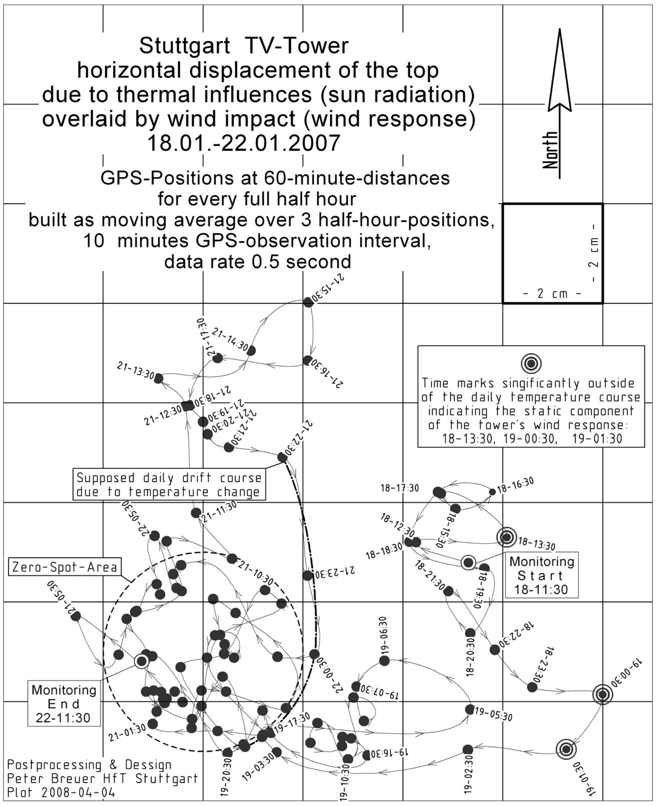


Fig. 5 The Stuttgart TV Tower, daily drift of the top due to solar radiation and daily temperature variation with hourly positions and time marks (18th - 22nd January 2007)

winter these both influences are strongly reduced. In Fig. 5 there is a unique day with a 5 cm displacement out of the zero-spot area directed to the North. This event is caused by a short sunny period of time on 21st of January 2007 during noon when the sun was in the South only. The displacement of 6 cm (or 8 cm from the center of the zero-spot) are in the East direction, shown in Fig. 5, is the static wind response component during the thunderstorm of that time (midnight 19th of January 2007).

An example of wind response of the top of the tower is shown in Fig. 6. Only a sequence of 30 s (60 positions) is taken to preserve clearness of drawing, i.e. Fig. 6 illustrates the wind response between 00:37:10 – 00:37:40 (h:min:s). The background of Fig. 6 shows the path of the daily temperature drift. In the foreground a selected 30 s time of the dynamic component of wind response is drawn in the form of 6 elliptical loops. The graphic design shows two components:

· The static component = the displacement to the East of about 6-7 cm from the zero-spot area.

· The dynamic component = the vibration in along-wind direction with the maximum amplitude about ± 5.5 cm, and in cross-wind direction with the maximum amplitude about ± 11 cm.

Besides the path in the ground plan shown in Fig. 6, the vibrations are designed over the time

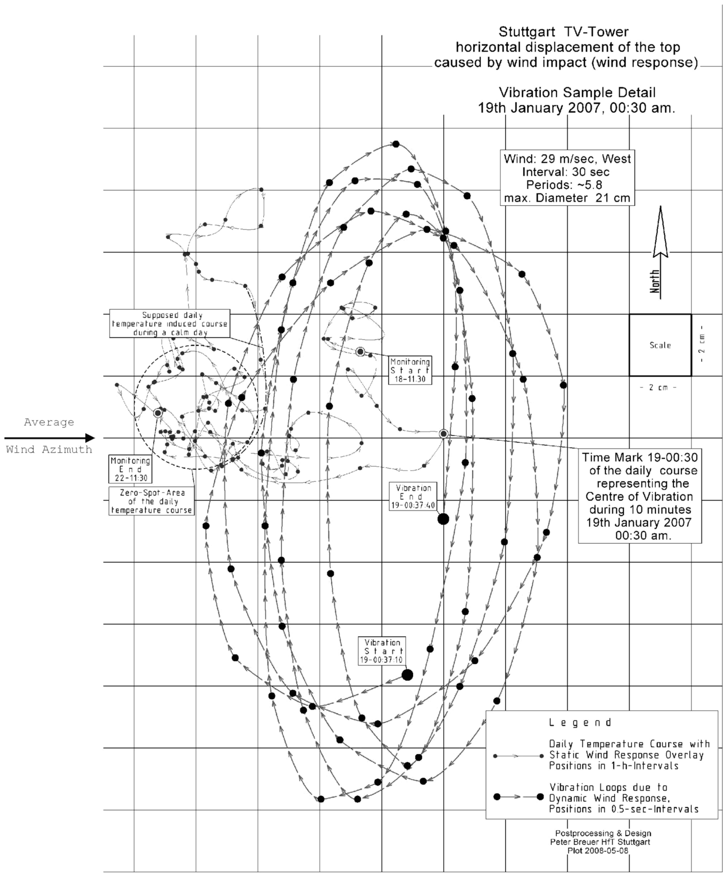
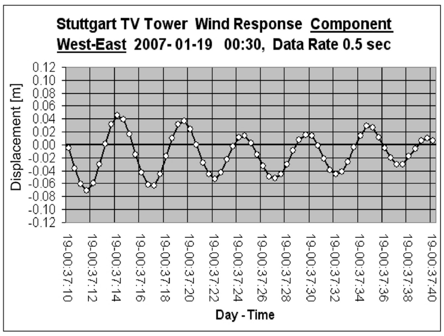


Fig. 6 The Stuttgart TV Tower, static and dynamic components of the wind response during a thunderstorm and the daily temperature response for comparison. The wind from the West with a velocity of about 16 m/sec causes a the East displacement (static component) of about 6 cm



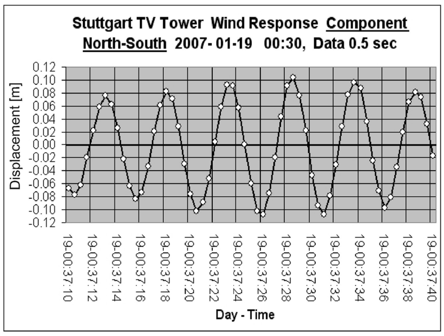


Fig. 7 Stuttgart TV Tower - oscillation of the top of the tower during Westerly wind of about 16 m/s: (a) along-wind component (West-East) of the vibration over 30 seconds, (b) cross-wind component (North-South) of the vibration over 30 seconds

axis shown in Fig. 7. The zero axis of displacement is fixed by the centre of the 60 positions (measured during 30 s). At that time the wind came from the West direction and had a maximum velocity of about 20 m/s (at the top of the tower). The West-East is the along-wind component, and the North-South is the cross-wind component (Fig. 7).

7. Information for the process of GPS data

During the referred GPS sessions Dual-Frequency-Receivers type Leica GPS 500 and GPS 1200 were used as well as the belonging software LGO (Leica Geo-Office). In field the data have been recorded every half hour with a data rate of 0.5 second during recording intervals of about 10 minutes. After start the receiver unit GPS 500 needs about 75 seconds until satellite tracking. Therefore data recording is limited to a period of about 8 minutes and 45 seconds, achieving about 1050 data records. The more modern equipment GPS 1200 uses the full 10 minutes interval for recording delivering 1200 data sets. Applying the so called “wake-up-function”, all data recording is adapted to “static post processing mode”. To process a “kinematic chain” later on, the rough data have to be complemented by an additional parameter applying RINEX format and manual editing.

Since satellite signals have no reliable quality when received from satellites in the vicinity of the horizon (elevation angle =0°), it is recommended to cut off satellite signals which have an elevation angle less than 10° or 15°. Furthermore buildings and trees in the vicinity of the reference antenna on the ground form obstacles and prevent signal reception. During the described GPS campaigns an elevation angle or cut-off angle of 10° was introduced.

The number of available GPS satellites during 24 hours and during GPS campaign is not constant. In middle Europe this number may change between 3 and 12. The number of available satellites defines the quality of geometrical condition for the resection of receiver position. In general a big number of available satellites improve reliability of positioning. On the other hand 4 satellites is the minimum number for “static” GPS positioning and 5 satellites is the minimum number for “kinematic” GPS positioning. Because of the fluctuating number of satellites, there is no guarantee that GPS positioning during 24 hours is possible permanently.

Professional GPS application tries to avoid local obstacles preventing satellite signal reception by a careful selection of antenna positions. Since in Europe in the northern hemisphere occurs a lack of satellite tracks, it is useful to place the antennas in a way, that obstacles appear only in the north sector where are no satellites. In reality obstacles will not be avoidable completely. During the GPS observation referred in the presented paper a number of about 5 - 10% of GPS base lines were not able to be resolved.

Another problem in static base line ambiguity resolution appears during storm. Static GPS mode requires a stable position for reference and rover station. If the rover antenna's vibration during storm causes amplitude with a magnitude > 10 cm, the "static mode" solution is prevented, unless the number of available satellites is close to ten. When a 'static mode' solution is impossible, a 'kinematic chain' solution may be tried successfully. The average of chain's coordinates is able to replace the 'static mode' solution.

The recorded data can be processed later on applying the so-called "static mode" or applying the kinematic mode". "Static mode processing" produces a single coordinate triple for the antennas position, i.e. an average position during the observation interval. A kinematic chain (KOF = Kinematic on the Fly) delivers a series of coordinate triples for the antenna whose number corresponds to the selected data rate, for instance one GPS position every 0.5 seconds. - Static processing mode has been used to evaluate the daily temperature induced horizontal displacement course of the structure which moves with a maximum velocity of about 4 cm per hour. The "kinematic chain mode KOF" (Kinematic on the Fly) has been adapted for those time intervals only when significant wind occurred. Until now the maximum velocity of in horizontal vibration loop appeared with a displacement of about 12 cm/second.

Drawing the drift of rover's temperature induced displacements in ground sketch, the hourly positions have been marked and labelled. Every hourly position was built as an average of three neighbouring positions in half-hour-distance. Thus one or two unresolved baselines in series could be spanned and compensated. In this way a continuously order of hourly positions has been composed.

Analyzing vibration due to wind impact can be done only when ambiguity for the KOF chain has been solved. To preserve clearness in the diagrams, for presentation only a partial time interval had been selected which had sufficient satellites and a favourable DOP (Dilution Of Precision). For this purpose in the presented paper some small time intervals have been selected with 6-7 satellites and a GDOP=2-3. These quantities have been noted in figures and captures of the presented paper.

8. Health monitoring of the Stuttgart TV Tower

As it was written in the paper by Breuer, *et al.* (2008), the Stuttgart TV Tower in its more than 50 year service life can be structurally damaged due to many determination factors such wind load, environmental erosion, sun radiation and daily air temperature variation, fatigue, etc. In the damage state of the tower the changes of natural frequencies will be observed. In our second approach (first was described in the paper by Breuer, *et al.* 2008, based on GPS measurements in July 2006) to detect damage to the Stuttgart TV Tower, we also assumed that the changes in the first natural frequency as a global property of the tower may be used as a measure of potential damage. The first two natural frequencies of the Stuttgart TV Tower were derived in 1959 by Lenk (1966). So, it is assumed that the first natural frequency f_1 describing the intact state of the tower is known.

Fig. 8 shows the power spectral densities of the top of the tower as calculated by the FFT method for along and cross wind responses for the time series measured during time from 00:32 to 00:42 on

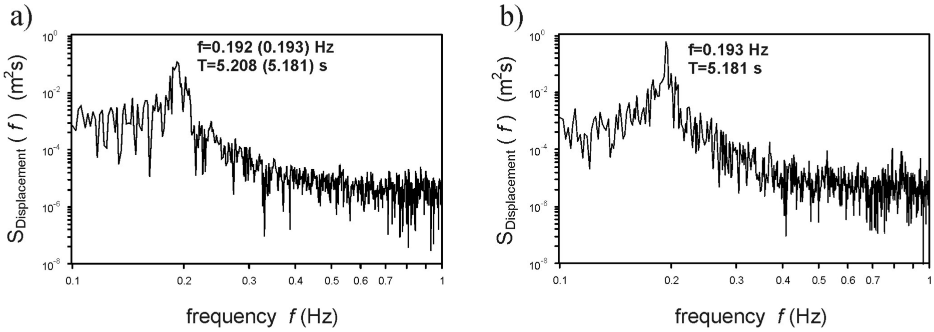


Fig. 8 The Stuttgart TV Tower, power spectral densities of tower responses: (a) for the along wind component, (b) for the cross wind component (19th January 2007), calculated by FFT from the time series measured during time from 00:30 to 00:40 on January 19, 2007

Table 1 The comparison of the first natural frequency as estimated experimentally

Structure	Lenk's test f_1 [Hz]	Breuer's, *et al.* test f_1 [Hz]	Chmielewski *et al.* test f_1 [Hz]
The Stuttgart TV Tower	0.193	0.191	0.192 / 0.193

19th of January 2007. For these power spectral densities one peak is at 0.192 Hz, and the second at 0.193 Hz, corresponding to the lowest natural frequency of the tower.

The comparison of the first natural frequency estimated by Lenk (1966) in 1959 and twice by authors of this paper in 2006 and 2007 is presented in Table 1.

There is no change between the first natural frequency as estimated experimentally in 1959, and next in 2006 and 2007. Therefore, as it was written by Breuer, *et al.* (2008), the Stuttgart TV Tower after 50 years of service life seems to be structurally undamaged. Its structural stiffness has not decreased.

In the original study wind-induced responses in January 2007 were measured for 10 minute intervals only with sample rate equal 2 sps. This interval was insufficient for us to estimate the damping ratio using Random Decrement technique. To do this it would be necessary to measure the wind response continuously for approximately 2 hours. The sample rate equal 2 sps did not allowed us to identify higher vibration frequencies except the first natural frequency.

9. Conclusions

From our measurements we can draw the following conclusions:

1) The results show clearly that it is possible to measure the total wind response, i.e. a static and dynamic components in tall structures like the Stuttgart TV Tower using GPS units. These measurements allow us to examine both displacement levels and also changes of vibration characteristics such as natural frequencies (up to 4 Hz), all of which provide information about potential damage to the structure.
2) For wind response and for a sample rate equal to 2 samples per second (2sps), GPS was able

to measure only the first natural frequency (0.192 Hz, 0.193 Hz) of the Stuttgart TV Tower.

3) There is no apparent change (within the accuracy of the tests) between the first natural frequency as estimated experimentally by Lenk in 1959 and as measured by Breuer, *et al.* in 2006 and 2007. So, the Stuttgart TV Tower after 50 years of service life seems to be structurally undamaged. Its structural stiffness is not decreased.
4) The monitoring system with GPS units which may be temporary installs on a tall slender structure such as the Stuttgart TV Tower or an industrial chimney facilitate rapid assessment of the structure integrity.
5) The total displacement of the top of a tall slender structure due to the strong wind or/and possible changes in its natural frequencies are related to the damage conditions of the structure. These data are enough to facilitate informed decision making process.

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