Investigations of low- and high-frequency movements of wind power plants using a profile laser scanner

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Abstract. This paper examines the possibility of contactless monitoring of wind power plants with a 2D profile scanner. Before measuring real wind power plants the concept was tested under laboratory conditions. With simulated oscillations between 0.1 Hz and 10 Hz the qualification to detect movements of artificial structures with the measurement system was proven. The measurement campaign (still in progress) was carried out at two different wind power plants south of Darmstadt. The two wind power plants are quite contrary, they differ from each other in the following points: age, hub height, speed, power control and power output.

The data acquisition and data handling is presented together with problems and an outlook how to overcome them with the combination of profile scanning and an image assisted total station (IATS). The first analysis of the measured data was realized with the discrete Fourier transformation (DFT). In the following, the limitations of this method in this particularly application are shown and an alternative is proposed with the discrete wavelet transformation (DWT).

Keywords. Laser scanning, 2D, wind power plant, eigenfrequency, DFT, DWT, IATS

1 Motivation

According to an evaluation of BerlinWind GmbH (2013), 45 % of 1000 examined wind power plant turbines have an imbalanced rotor. The results are harmful centrifugal forces and increasing oscillations, thereby the lifespan of the wind power plant is shortened. In a worst case scenario this can lead to fatigue breaks and a possible destruction of the wind power plant.

The monitoring of wind power plants is mainly done with sensor systems attached to the wind power plant, like inclinometer or accelerometer, see for example Neuner (2008) or Schaumann (2000). These methods are quasi standardized and accepted by different fields of study. But they have three main disadvantages: access to the object is needed, data coverage is ensured only where the sensor is attached and the installation of the sensors is an extremely technical and time-consuming work.

Laser scanning offers an alternative without those disadvantages, due to the fact that it is a contactless measurement method. But using a 3D laser scanner has limiting factors as well. For an effective application the long acquisition time and the big data volumes present problems.

Fortunately the spatial progress of a deformation pattern at artificial structures often shows a uniform behavior over the entire surface and varies only in its amplitude, for example the bending from the bottom of the pillar to the top. For wind power plants mechanical models exist, which describe the expectable deformations and their main directions. Therefore, measuring profiles instead of full 3D point clouds may be a representative alternative.

With this reduction we can overcome the above mentioned limitations by decreasing the dimension of the acquisition method using a 2D laser scanner. The repetition rate can fairly be increased up to 200 Hz. Consequently, higher moving rates or more precisely fast changing deformation patterns and oscillations up to 100 Hz can be detected. This paper concentrates on monitoring wind power plants in 2D profile mode, based on the pioneering works mentioned in section 2. With the advancement in hardware (measurement rate up to 200 Hz, accuracy and measurement range improvements) the extraction of more information is possible.

An interesting approach to extend the understanding of wind power plant deformations is the combination of a profile scanner with other sensors, e.g. image assisted total station (IATS) to capture the movements of the pillar in wind direction and across simultaneously.

2 Previous works

The main focus of using a terrestrial laser scanner (TLS) in profile mode nowadays is on mobile mapping applications, which are not discussed here any further.

But there are also scientific adaptations for modal and movement analysis. Hesse et al. (2005 and 2006) made use of a laser scanner to investigate wind power plant oscillations. In this context the problems that can arise at wind power plants and how to overcome them are shown in Neuner (2008). In Paffenholz et al. (2008), Kutterer et al. (2010), Liebig et al. (2011) and Neitzel and Niemeier (2012) a laser scanner is used in 1D-, 2D- or 3D-mode to analyze bridges and the results are compared with other measurement technologies.

Literature related to the discrete wavelet transformation (DWT) is for example Percival and Walden (2000) or Bäni (2005). They present a practical access to the whole thematic and the application of the DWT. The usage of the DWT for deformation modeling is shown in Neuner (2008).

3 Sensor system

3.1 Profile scanner

The scanner used for the investigations in this paper is the Zoller+Fröhlich Profiler 9012, a sole 2D scanner designed for the use in mobile mapping applications, depicted in Fig. 3. Equipped with a GPS receiver, it is possible to calculate a time stamp for every measured point. The maximum measurement range is specified with 119 m and the data acquisition rate is 1 million points per second, with a rotation speed of 50, 100 or 200 revolutions per second (rps).

3.2 Laboratory test configuration

The interferometer laboratory at the TU Darmstadt is located in the subbasement of the Institute of Geodesy, directly on the building foundation. The thermal conditions are nearly constant. The oscillation table (shown in Fig. 1) consists of a servo motor with different planetary gears and a movable platform with guided linear bearings on a steel rail. The reference of the oscillation table is an Agilent laser interferometer, with a resolution of 1 nm and a typical accuracy of < 1 µm. The whole setup is mounted on a solid concrete wall. The mounting of the laser interferometer is uncoupled from the oscillation table. The oscillation table supports frequencies from 0.1 to 10 Hz, with amplitudes from 1 to 8 mm.

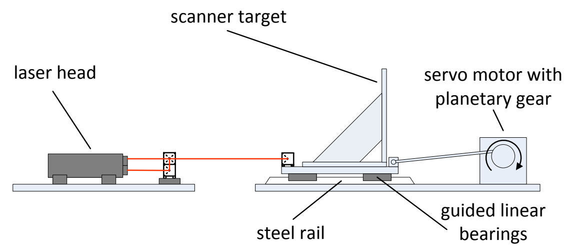

Fig. 1 Diagram of the oscillation table

To evaluate the qualification of the profile scanner for modal analysis of wind power plants, the expected frequencies (see section 4.1 and 4.2) were simulated with the oscillation table. The movement of the oscillation table is recorded simultaneously with the interferometer and the profile scanner. The preprocessing of the scans is similar as specified in section 4.4. Both data sets were analyzed with the same iterative workflow, as described in the following:

1. transformation of the measured dataset in the frequency domain with a discrete Fourier transformation,
2. least-square adjustment of the main frequency,
3. subtraction of the result of the adjustment from the measured data,
4. analysis of the residues in time (autocorrelation) and frequency domain,
5. if a significant systematic remain, repeat steps 1.-4., using the residues as the new dataset.

With the knowledge of the significant number of frequencies in the signal and the derivation of the approximate values, it is possible to customize the adjustment model to the individual signal. A new adjustment with those parameters provides the final results.

3.3 Laboratory test results

The analysis of the laser interferometer measurements has shown that the oscillation table generates the predefined frequencies with an accuracy of 10^{-5} Hz. The accuracy of the reference amplitude is 0.3 µm and is derived from measurements with different frequencies in between 0.125 and 1 Hz.

Table 1. Results of test setup

Reference value [Hz]	Mean frequency difference [Hz]	Mean amplitude difference [µm]
1.000	↑	-11
0.750		-18
0.500	$< 10^{-4}$	-4
0.250		-2
0.125	↓	-7

As seen in Table 1 the frequency estimation shows no difference within the measurement accuracy between the reference value and the measurements of the Profiler 9012. The amplitude shows deviations, caused by a higher signal to noise ratio. Altogether those results are quite satisfactory and show clearly that the Profiler 9012 is qualified for modal analysis of artificial structures.

4 Monitoring wind power plants

4.1 Wind power plant design

An operating wind power plant experiences dynamic excitation from different sources, seen in Bhattacharya (2014). Especially important are:

- wind turbulences,
- periodic excitation with single number of revolutions („1p excitation"), for example from an imbalanced rotor,
- periodic excitation from rotor blade passing, with threefold number of revolutions („3p excitation").

For the design of wind power plants those effects are crucial, because the first eigenfrequency must not be located in an area were dynamic excitations occur. Therefore only three narrow sectors are possible. In Fig. 2 these sectors are numbered consecutively from 1 to 3.

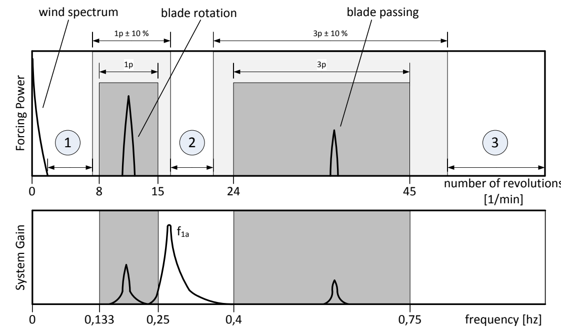

Fig. 2 Forcing power and system gain

The position of the first eigenfrequency (f_{1a} in Fig. 2) is the most important design parameter and therefore the classification of the stiffness of a wind power plant is based on this position.

If the eigenfrequency is below the blade rotation (1p) the wind power plant is "soft-soft", between the blade rotation (1p) and the blade passing (3p) the wind power plant is "soft-stiff" and above the blade passing (3p) the wind power plant is "stiff-stiff".

Theoretically a "stiff-stiff" design has the advantage that the first eigenfrequency never lies within a dynamic excitation area. But with today's hub heights such stiff plants are uneconomic. Nearly all newly built wind power plants are designed "soft-stiff", therefore the blade passing (3p) excitation frequency passes through the first eigenfrequency in the booting process.

4.2 Wind power plants (technical data)

The examined wind power plants are located south of Darmstadt on the Neutscher Höhe.

In Fig. 3 the Tacke TW600 is shown, built in 1994. The typical operational live span of a wind power plant is 20 years. The TW600 has reached its typical operational life span already. The hub height is 50 m and the expected first eigenfrequency is $f_{1a} \approx 0.69$ Hz. The blades are fixed and the system is stall regulated with a rotational speed of 18 or 27 revolutions per minute. Therefore the excitation frequencies are:

- blade rotation: $f_{1p} = 0.3$ or 0.45 Hz („1p-excitation"),
- blade passing: $f_{3p} = 0.9$ or 1.35 Hz („3p-excitation").

In Fig. 4 the second examined wind power plant is shown (Repower MM92), built in 2011. The hub height is 92 m and the expected first eigenfrequency is $f_{1a} \approx 0.27$ Hz. In Fig. 2 the excitation areas of the MM92 are shown. The rotational speed can vary between 8 and 15 revolutions per minute, the system is pitch regulated. This means the pitch of the blades can be changed to get the maximum power output at each wind velocity. The excitation frequencies are:

- blade rotation: $f_{1p} = 0.133 ... 0.25$ Hz („1p-excitation"),
- blade passing: $f_{3p} = 0.4 ... 0.75$ Hz („3p-excitation").

Both wind power plants could be classified as „soft-stiff".

Fig. 3 Tacke TW600

Fig. 4 Repower MM92

4.3 Measurement configuration

As mentioned in the section 4.1, the movement of a wind power plant and its amplitude depend mainly on one external factor: the wind and its variations. All forcing powers acting on the wind power plant can be directly or indirectly traced back to the wind. The wind pressure acts as a forcing power directly on the whole system in wind direction. The rotational speed is indirectly connected to the wind and its direction, but its forcing power acts perpendicular to the wind direction. Therefore two measurement directions were chosen, as shown in Fig. 5: one in rotor plane (position 1) and the other perpendicular to the rotor plane (position 2).

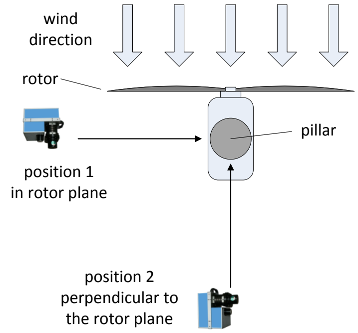

Fig. 5 Measurement configuration, top view

4.4 Data preprocessing

In order to reduce the data volume and improve the signal to noise ratio a spatial block filter was applied to each profile. The block width was set to a fixed angle range. As a result the spatial extent of the classes are widening from the bottom to the top of the pillar, as seen in Fig. 6, while the number of points in each class is constant. The output of this filtering is a dataset with i x j cells, where i is the number of profiles and j is the number of classes. On those time series an adaptive Hampel filter was applied for outlier detection and removal. So far the filtering was implemented only in the time domain, future implementations will be done in the frequency domain using the discrete wavelet transformation.

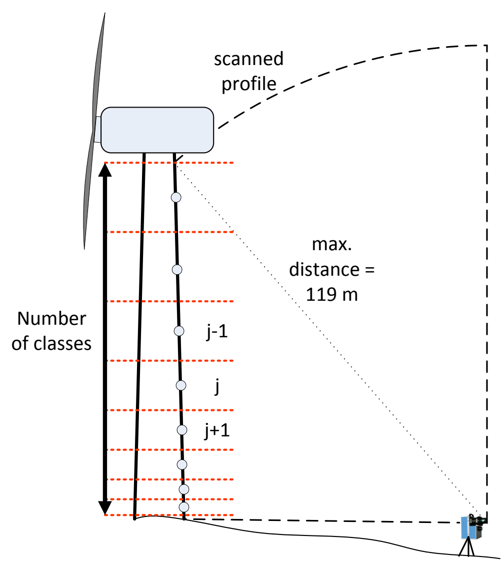

Fig. 6 Measurement configuration, side view

4.5 Measurements

Until now 5 days with more than 150 scans were carried out in a time span of six weeks. The external conditions varied over this time span significantly. The following section concentrates on the measurements from 09.11.2015. On account of the high wind speed up to 8 m/s, the deformations and oscillation are the most meaningful.

In Fig. 7 a filtered time series of one class (height: 44 m) of the TW600 wind power plant is shown (not synchronized), perpendicular to the rotor plane (position 2) and in the rotor plane (position 1). Fig. 8 shows the same for the MM92 (height: 72.5 m). The length of all four data sets is 10 minutes and they were recorded with 50 rps.

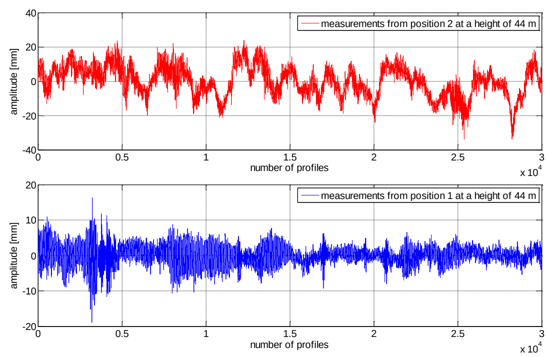

Fig. 7 TW600 time series from position 2 (red) and from position 1 (blue); upper : lower y-axis scaling of 2 : 1

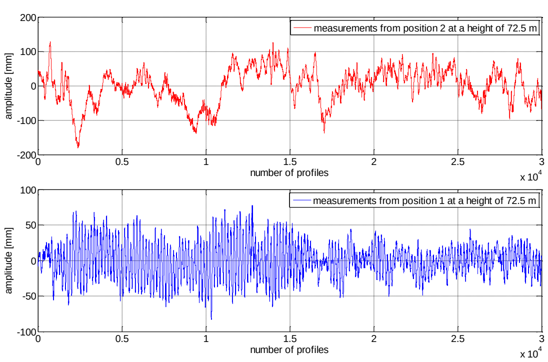

Fig. 8 MM92 time series from position 2 (red) and from position 1 (blue); upper : lower y-axis scaling of 2 : 1

The time series measured from position 2 are non-stationary. The time series have an inhomogeneous variance distribution and a changing mean value, due to the turbulence of the wind. Further analysis in the frequency domain appears not to be useful. Therefore the analysis in the frequency domain will concentrate on the measurements from position 1.

Those measurements are also non-stationary over longer periods, and thus not completely suited for the use of a discrete Fourier transformation. But to get a first idea especially of the frequencies of the wind power plants it should suffices.

One effect leading to a non-stationarity of the measured time series from position 1 is due to the curved surface of the pillar, as discussed in the next section. It overlays the periodic effects of the measured wind power plant with a changing mean value.

4.6 Problem due to measured surface

The target of all measurements was the curved surface of the pillar. This leads to the problem that movement of the pillar in wind direction change the measured point on the pillar from position 1. Due to those changes the measured distances in the rotor plane are falsified with Δd, as seen in Fig. 9. The effect of the pillar curving could be determined if the movement of the pillar in wind direction would be known.

The amplitude of Δd depends on two factors: the radius of the pillar and the amplitude of the movements in wind direction. As seen in Fig. 8 those movements can easily exceed some centimeters.

The accuracy of the mean value of the spatial block filter is less than 1 mm. Therefore effects over 1 mm should be compensated. If the movement in wind direction reaches 0.05 m the effect of the curved surface exceeds 1 mm, as seen in Table 2.

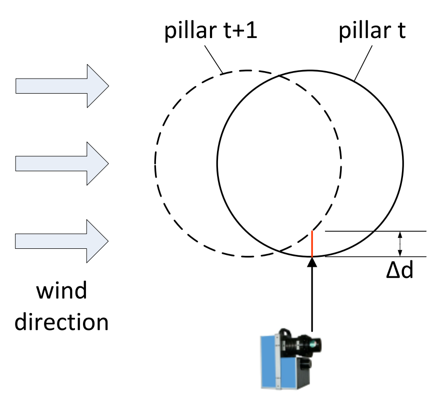

Fig. 9 Cross section pillar, time t and time t+1

Table 2. Falsification of distance measurement due to curved surface

Movement in wind direction (Fig. 9) [m]	Δd of TW600 (radius 1.15 m) [mm]	Δd of MM92 (radius 2.15 m) [mm]
0.01	0	0
0.05	1	1
0.10	4	2
0.50	114	59
1.00	582	247

The compensation could be done for example with the measurements from a second scanner on position 1 or with a camera system on the same position. Because of this advantage the combination of the Profiler 9012 with a camera system is one future goal.

Regardless of the effect based on the curved pillar surface, measuring a wind power plant in both directions simultaneously could bring insights, which could not be reached by measuring the two directions in sequence.

4.7 Data processing in the frequency domain

In Fig. 10 and 11 the power spectra for both wind power plants are shown. The power spectrum of the Tacke TW600 shows the main peak at 0.688 Hz with an amplitude of almost 2 mm, matching the theoretical first eigenfrequency. The rotation speed was approximately 27 rpm, which should correspond in peaks at 0.45 Hz and 1.35 Hz. Both peaks are clearly visible, especially the 1p excitation frequency with an amplitude of nearly 0.5 mm. The small ratio between the amplitude of the first eigenfrequency and the amplitude of the 1p excitation frequency could indicate an unbalanced rotor.

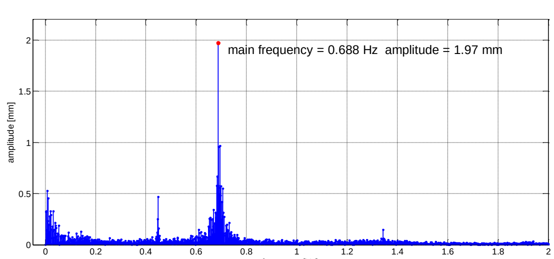

Fig. 10 Amplitude spectrum of TW600 at a height of 44 m

The power spectrum of the Repower MM92 shows one peak at 0.275 Hz with an amplitude of almost 23 mm, matching the theoretical first eigenfrequency. The rotation speed was approximately 15 rpm, which should correspond in peaks at 0.25 Hz and 0.75 Hz. They are not so easily discernible: for one thing the frequencies are closer together and the 1p frequency is in the frequency rise caused by leakage effects. Apart from that the ratio between the amplitude of the first eigenfrequency and the amplitude of the 1p frequency is bigger. One explanation could be the different years of construction. The MM92 was built only 4 years ago and is therefore probably in a better condition.

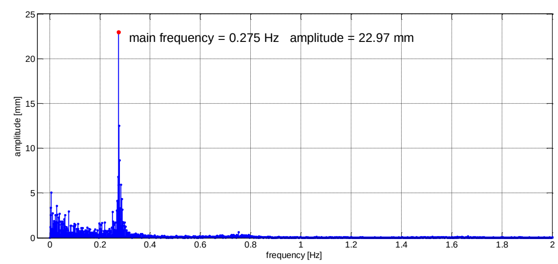

Fig. 11 Amplitude spectrum of MM92 at a height of 72.5 m

These results were reproduced with different measurement speeds (50 and 100 rps) and durations (10 and 30 minutes). All classes along the pillar were analyzed, confirming the expectation of a homogenous oscillation with decreasing amplitude from top to bottom of the pillar. The TW600 was modeled with 20 classes, the MM92 with 30 classes. With the amplitude of the first eigenfrequency for every

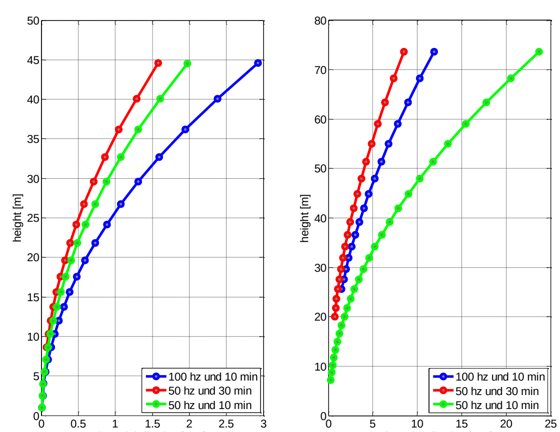

Fig. 12 and Fig. 13 Bending lines TW600 and MM92 class the first eigenform could be derived, as shown in Fig. 12 and 13.

It was assumed that a class is valid as long as the amplitude of the first eigenfrequency was the dominant frequency in the spectrum. If the signal to noise ratio drops below 1 the class was sorted out.

Due to the variation of external conditions like the wind, the different realizations represent a snapshot in time, leading to bending lines with different amplitudes. Therefore the bending lines were normalized with its maximum amplitude. The residues between those normalized bending lines are less than 10^{-2} mm.

As pointed out in section 4.5 the measurements are non-stationary. In the upper part of Fig. 14 the changing mean value is represented by the thick line, leading to low frequencies in the spectrum. In the lower part of Fig. 14 the changing mean value is subtracted to get a better visualization of the variation of the amplitude.

This variation leads to an averaging in the frequency domain and the result is an average over all amplitudes of the respective frequency. Therefore the amplitudes determined with the discrete Fourier transformation are not representative for the whole time series.

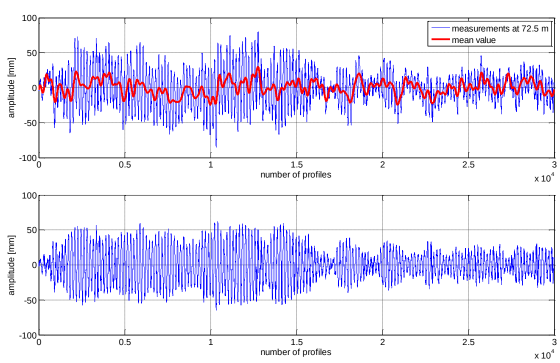

Fig. 14 Time series with mean value and difference

This is problematic when estimating parameters with a global adjustment model. Therefore an extended deformation model is proposed by Neuner (2008) with the usage of a discrete wavelet transformation (DWT).

Due to the mechanisms of the DWT as high- and low-pass filters, the different signal components are represented on different scales. The low frequencies caused by the changing mean value are contained in the scaling coefficients and the high frequencies are contained in the wavelet coefficients on different levels of decomposition. Therefore the separation of those effects is succeeded automatically.

The problem of changing amplitudes is counteracted with separating quasi stationary parts of the time series. For example the first and the second half of the lower time series in Fig. 14. Every part is evaluated in a separate adjustment process and put together again after the adjustment. Neuner (2008) uses the wavelet transformation for the compensation of this effect only as a preliminary stage to separate the stationary parts of the signal from the non-stationary parts.

A further approach will be the use of wavelet packages, to refine the frequency resolution of the DWT to the expected frequencies and in this way separate them in different wavelet coefficients on the same level of decomposition.

5 Profiler 9012 vs. image assisted total station (IATS)

The used image assisted total station was a combination of a Leica TCA 1100 with an AVT Guppy PRO F-031B. The camera was mounted as an ocular camera and uses the tachymeter only as an objective. The full resolution of the camera is 656 x 492 pixels.
The focus of the combination of Profiler 9012 and IATS measurements at the MM92 wind power plant was not to analyze it, but to compare the two measurement systems (shown in Fig. 15). For this reason a measurement configuration was chosen were both systems measure the movement of the pillar in wind direction. In order to enable a direct comparison the profile scanner was located at position 2 and the IATS at position 1 (see Fig. 5).

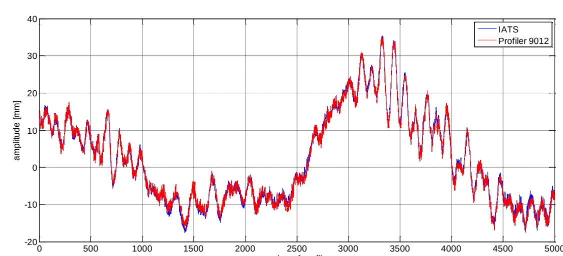

Fig. 15 Comparative measurement Profiler 9012 and IATS

The passive measurement target of the IATS was the pillar edge against the sky in the same height

(72.5 m) as a profile scanner class. The edge detection in the recorded pictures was done with a prewitt operator, afterwards all extracted edge pixels where averaged. First tests with both systems show promising results. But future works in this direction will have to concentrate on time synchronization and different image processing algorithms, as seen e.g. in Ehrhart (2015).

6 Conclusion and outlook

In this paper a contactless modal analysis of two different wind power plants is shown. The used measuring system was mainly a profile scanner with the addition of an image assisted total station (IATS).

The analysis of the recorded time series in the frequency domain showed the dominant frequencies matching the expected theoretical values. Especially the results from Tacke TW600 wind power plant were applicable. Not only the first eigenfrequency but also the 1P and 3P frequencies could be clearly detected. Indicating at a possible imbalanced rotor, planned measurements at other wind power plants of the same type and construction time will bring clearer statements.

One main advantage of profile scanner measurements is that the whole pillar profile is recorded simultaneously. As a consequence the realized analyses are not constricted to a single point. Therefore not only the eigenfrequency could be derived, but also the bending line of the pillar.

The recorded time series feature non-stationary effects, caused by the variation of the wind, especially in the measurements perpendicular to the rotor plane. Because of the curving of the pillar these effects can also be seen in the measurements in rotor plane. To overcome this problem a simultaneous measurement of both main directions is important. With this additional information a correction function could be derived to compensate the effect. The proposed and tested addition is an IATS. Future works will concentrate on a new IATS (Leica TS60), time synchronization and other image processing algorithms.

Due to the non-stationary effects in the time series the conducted investigation displays the need to find an alternative to the discrete Fourier transformation for this application. Using a discrete wavelet transformation as proposed by Neuner (2008) could solve those issues.

It can be concluded that wind power plants are a suitable outdoor laboratory for modal analysis, the expected frequencies are known and mechanical models of the structures exist. It can be expected that with a profile scanner based multi sensor system and the use of improved algorithms (DWT or wavelet packages) the mentioned problems can be overcome

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