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Evaluation of the Vibrational Spectrum of High Slim Towers with Wind Electrical Turbines

Johannes Fabiankowitsch [1], Heribert Kahmen [2], Philipp Matt [3]

[1] *Vienna University of Technology, Institute of Geodesy and Geophysics, Departement of Applied and Engineering Geodesy, Gusshausstraße 27-29, A-1040 Vienna, Austria*
[2] *Vienna University of Technology, Institute of Geodesy and Geophysics, Departement of Applied and Engineering Geodesy, Gusshausstraße 27-29, A-1040 Vienna, Austria*
[3] *Troie 3, A-6161 Natters, Austria*

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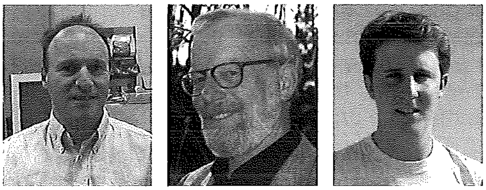

Abstract

To date, the movements of wind turbines during operational or idle periods have hardly been investigated at all. There is also little knowledge of the service lifespan of steel towers. Therefore extensive measurements were made, in cooperation with a power company, to arrive at new research results. The vibrational spectrum of high slim windmill towers were continuously and automatically recorded by a combination of accelerometer systems and point-positioning by satellite (RTK-GPS). Of particular interest were the movements of the tower during the rotor startup and braking phases and during full operation. An electronic measuring system, based on a PC, managed the signal conditioning, the measuring sequences and the evaluation.

Zusammenfassung

Bewegungen von Windkraftwerken außerhalb und während des Betriebes sind bisher noch wenig erforscht. Außerdem gibt es noch kaum Erfahrung für die Lebensdauer der Stahltürme. In Zusammenarbeit mit einem Energieunternehmen sind daher umfangreiche Messungen durchgeführt worden um hier zu neuen Forschungsergebnissen zu kommen. Die Bauwerksbewegungen an hohen schlanken Windgeneratortürmen werden durch eine Kombination von Beschleunigungssensoren und der Positionsbestimmung mittels Satellitenverfahren (RTK-GPS) kontinuierlich und automatisiert erfasst. Bei der Erfassung von Vibrationsspektren einer Windkraftanlage sind streng genommen verschiedene Betriebsphasen zu unterscheiden. Die Phase 1 ist gekennzeichnet durch den Stillstand der Rotorblätter, d.h., die Anlage ist abgeschaltet. In dieser Phase können vor allem die durch äußere Einflüsse (Sonne, Wind) hervorgerufenen Turmbewegungen, unabhängig von Anregungen durch die drehenden Rotorblätter, studiert werden. Es sind kurzperiodische Schwingungen auf Grund von Windeinflüssen und langperiodische Verformungen, die durch thermische Einflüsse (Stand der Sonne) hervorgerufen werden, zu unterscheiden. Von besonderem Interesse sind die Turmbewegungen während des Hochlaufes (Bremsens) des Rotors, welche als Phase 2 bezeichnet wird. Sie gilt als besonders kritisch, weil unter anderem dabei die sogenannte Eigenfrequenz des Turmes durchlaufen wird. Ein zusätzlicher Effekt kann eintreten, wenn vor dem Hochlaufen des Rotors oder während des Betriebes (Phase 3) die Gondel in eine neue Windrichtung nachgestellt werden muss. Dabei werden ja immerhin 63 Tonnen bewegt. Die Phase 3 betrifft den Arbeitsbetrieb. Durch die drehenden Rotorblätter ist eine Vielzahl von Vibrationen nachweisbar. Diese meist hochfrequenteren Schwingungen überlagern sich der Eigenschwingung des Turmes. Dank einer PC-Messelektronik, welche den Messablauf, die gesamte Signalkonditionierung und ein umfangreiches Auswerteprogramm bereitstellt, werden die Daten auf einem Laptop bearbeitet und ausgewertet.

1. Introduction

The use of natural sources of power has grown in importance significantly in recent years. Wherever landscape conditions combine to produce good, but more important, constant winds the temptation to use the prevailing winds as a source of energy is obvious. Consequently, by October 2002, one hundred boreal power stations had been erected in the federal state of Lower Austria alone.

As a consequence of their slim form, their height and their normally exposed locations, these towers are subjected to extreme influences, caused, either by the operation itself (rotation of the rotor) or by environmental conditions (wind, sun). To date, the cause and effect of induced tower movements have hardly been investigated at all.

Continuous recording of such tower movements put high demands on the measuring equipment. The circumstances of the tower to be studied, the environmental conditions and the wishes of the client had to be taken into account during the selection of the measuring-sensors.

The wind-generator-tower in question has a height of 60m, diameter at the base of 4.2m tapering to a diameter of 2.0m at the height of 60m. It consists of two hollow steel segments of

30m each, screwed together. The rotor-blades are 27m long. The rotor, including rotor-blades, weighs 25 tons. The rotatable gondola, including generator, weighs 38 tons. The rotor-blades are of the *"Active Stall"* type, meaning that they adjust their trim according to the prevailing wind velocity. This makes an even, steady rotation of the rotor possible during fluctuating winds. The gondola, which is detached from the tower, can follow the wind. This happens then, when the wind direction deviates from the direction of the rotor-axis more than ten degrees in the middle of a minute.

2. Assignment

The recording of the vibrational spectrum of a wind-generator-tower is to be strictly divided into different operational phases. With the help of suitable sensors, the goal is to measure these different operational phases.

Phase 1 is when the boreal power station is out of operation and the rotor-blades are still. This is the case when maintenance or repair work is carried out. During this phase, tower movements caused by environmental influences (sun, wind) can be studied independent of the influences of the rotating rotor-blades. Short-term vibrations caused by wind should be differentiated from the long-term deformations caused by thermic influences (position of the sun).

Phase 2 is characterised by the startup and acceleration or deceleration and shutdown of the rotors. This is considered to be especially critical because the so-called resonant frequency of the tower is passed through. An additional effect can occur when the gondola is adjusted to a new wind direction during startup or during operation (Phase 3). 63 tons are moved during this process.

Phase 3 is fully operational service. As a result of the rotating rotor-blades, a multitude of vibrations can be detected. These, mostly high frequency vibrations, are superimposed on the resonant frequency of the tower.

A combination of accelerometers and point positioning by satellite (RTK-GPS) were used to record the vibration spectrum of this tower. The RTK-GPS data was used as reference data.

3. Electronic control, sensor selection and synchronisation

The use of different sensors with varying physical operating principles make it neccessary to use a central controller. The data from the sensor and the positional data from the satellite receiver must also be synchronised to establish an unequivocal time definition. The measurement data was transferred from the central controller to a laptop where evaluation software, with a multitude of sub-programs ranging from data-recording through to the analysis of the data, make an online evaluation possible.

The electronic measuring system for PC *"Spider 8"* [1] was used as central controller. This system can be used to electronically measure mechanical dimensions such as movement, acceleration and speed. This system has four complete digital measurement-amplifiers using 4.8kHz carrier-freqency technology. It handles the complete signal-conditioning. This should be understood as the supply for passive reception, the amplification of the input-signal, the connector technology for maximal eight channels, a computer interface and the digitalisation. Each of the eight channels has ist own A/D converter allowing measurement rates of 1/second to 9600/second. These A/D converters are synchronised with each other, guaranteeing time-synchronised measuring through all channels.

With the selection of sensors, it is important to define whether movement or vibration is to be measured. A vibration measurement is concerned with the quadratic response of the object of investigation. A movement measurement is concerned with the speed or the shift of a static body (or part thereof). Three different sensors were used for this first projekt-study.

The accelerometer type B12 [2] works on the principle of induction, which, viewed mechanically is a highly-tuned spring-mass-system and viewed electrically is a passive supplier. Small dimensions (cylindrical form, 34 x 12.6mm) and minimal weight (17gr) are their characteristics. Two different types are to be used, the B12/200 and the B12/500. They differ in their assigned frequency and their measuring range. The B12/200 has a working frequency range of 0 Hz – 100 Hz, the B12/500 from 0 Hz – 250 Hz. As the name suggests, the B12/200 has a resonant frequency of 200 Herz, the B12/500 a resonant frequency of 500 Herz.

The accelerometer ISOTRON MODAL-63A-50 [3] is an active sensor that functions on the piezo-electric principle. It is characterised by low weight (20 gr), small exterior dimensions (cubes of 22.35mm), the integrated electonics but above all the capability to record accelerations in three, to each other, orthogonal axis simultaneously. From the specifications, we can take the resonance frequency as being approx. 15000 Hz and that the sensor can be used in the 1 Hz – 2000 Hz range.

The GPS System 530 from the Leica company was used as the third sensor. Point-positioning will be carried out with a frequency of 10 Herz. For this purpose, a fix reference point was established in the vicinity of the wind-generator-tower and two receivers were mounted on the roof of the gondola. An important advantage is that extremely low frequencies such as the natural vibration of the building and the generally expected vibrations of the tower can be recorded without phase displacement.

The measurements from the accelerometers were synchronised with each other on the basis of the CPU-time of the laptop. However, the position data is related to GPS-time, which has the characteristic, to deviate from Atomic-time by a constant integer value in seconds. At the time of the measurements this value was 13 seconds.

The synchronisation between CPU-time and Atomic-time was achieved using the programme *"Atomsync 115"*. Standard differences between CPU-time and Atomic-time after the synchronisation ranged from 0.01 – 0.05 seconds. These differences arose due to delays during the internet transfer.

The synchronisation was carried out before the measuring began and again after the measuring was finished to calculate the time-drift, which was then linear interpolated.

4. Measuring Setup

The RTK-GPS setup is described in paragraph 3. The three accelerometers were mounted together on a platform. The internal alignment of the sensors on this platform was so that the measurement-axis of the B12/200 and the B12/500 were perpendicular to each other. The ISOTRON 63A-500 was then orientated so that its x-axis was in line with and its y-axis perpendicular to the B12/500. Its z-axis was aligned vertically perpendicular.

The complete measuring system – the platform with the sensors, the measurement-amplifier for the ISOTRON 63A-500, the central controller *"Spider 8"* and the laptop – was assembled in the last chamber of the tower under the rotatable gondola. A geodetic orientation of the platform was not possible as there was no "line-of-sight" connection to outside.

Unlimited access to the wind-generator-tower was garanted for three days. Coincidentally, maintenance work was also carried out during this time, which allowed measurements of Phase 1 (see paragraph 2) to be made. Measurements of Phase 2 could be carried out three times. Un-

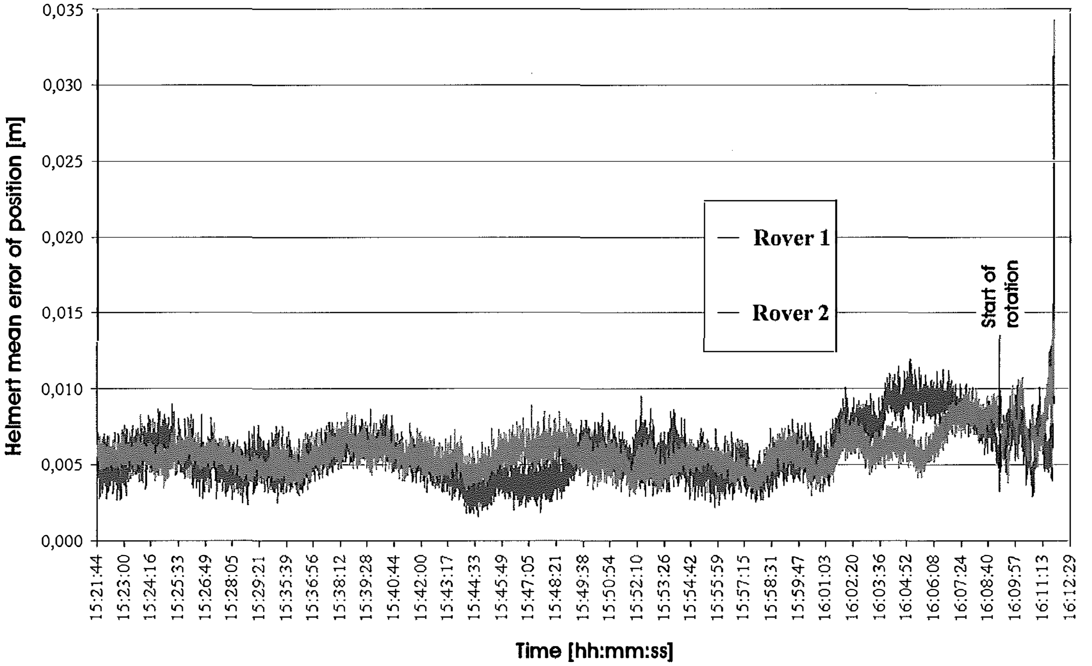

Figure 1: Helmert mean error of point position of both rovers (phase 1)

fortunately the wind was moderate during the three days and mostly from south-west.

5. Measurement results

In the calculation of tower movements in the frequency range, the resonant frequency of the tower takes a special place within the expected frequency spectrum. An estimate of the natural period of vibration T and the resonance frequency f under consideration of static wind energy [4] yields T = 2.73 seconds and f = 0.37 Herz.

5.1 Measurements with the RTK-GPS-system

Useful measurement data could only be obtained during Phase 1 (see paragraph 2), because only during Phase 1 were the obstructions and/or multipaths of the measuring signal negligible. Figure 1 shows the Helmert mean error of point position of both rovers.

It was shown that during machinery out of operation, the point-positioning determined with the RTK-GPS was accurate to approx. 5mm. There was a noticable reduction in positioning accuracy after 16:02. A reason could be the screening of the satellite signal for rover 2 by a stationary rotor-blade. The positioning accuracy of rover 1 is also reduced, but remains significantly better than rover 2. Similar causes can be assumed for the times 15:47 and 16:04 when the deviation of the positioning accuracy between the two rovers reach their maximum.

At about 16:08 the gondola begins to turn into the wind in preparation for operation (Phases 2 and 3). The accuracy of mean error of position of both rovers alternate quickly and deteriorate rapidly. As a result of the steady increase in rotation, the intervals between signal-reception and interruption become ever shorter. After about 16:11 the two rovers are no longer able to determine the ambiguities. With fewer than four satellites position determination is not possible. The amplitude spectrum of the RTK-GPS data shown in figure 1 is shown in the following figure 2.

Both rovers show a clear amplitude up to 3.6mm at a frequency of 0.413 Herz. A remarkable correlation to the resonant frequency that was estimated at the outset. Around 0 Herz amplitude values up to 3mm are seen. These values are a result of the mathematical approach and have nothing to do with the movements of the tower.

5.2 Measurements with the accelerometers

The analysis of the relevant data is not limited to Phase 1, but can be carried out from standstill

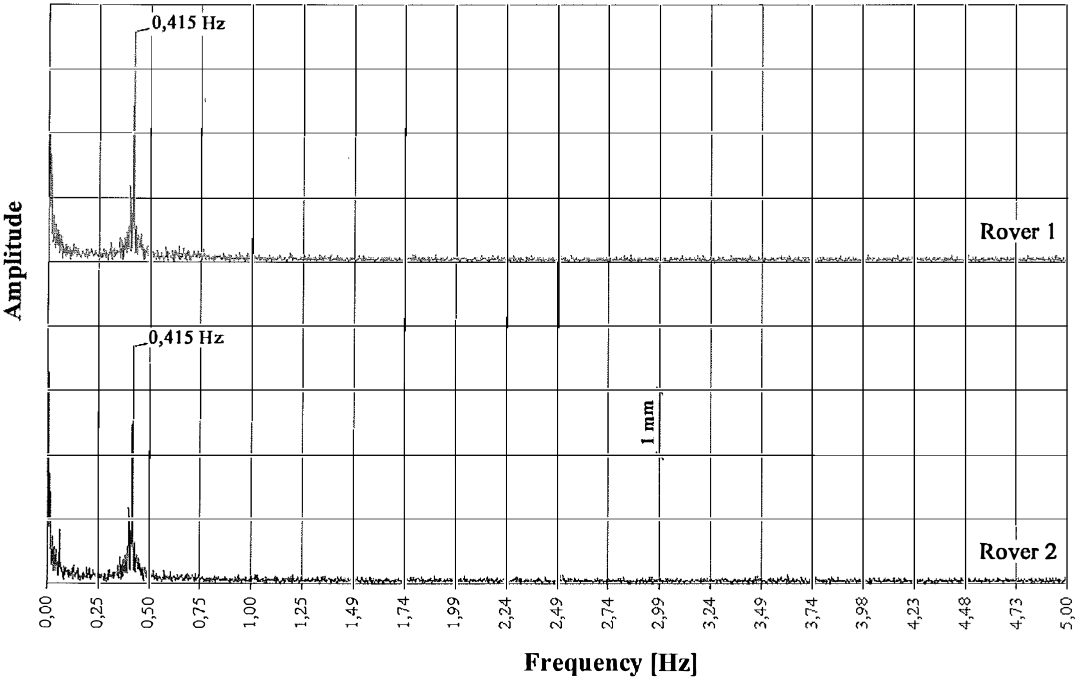

Figure 2: Amplitude spectrum of the RTK-GPS data (phase 1)

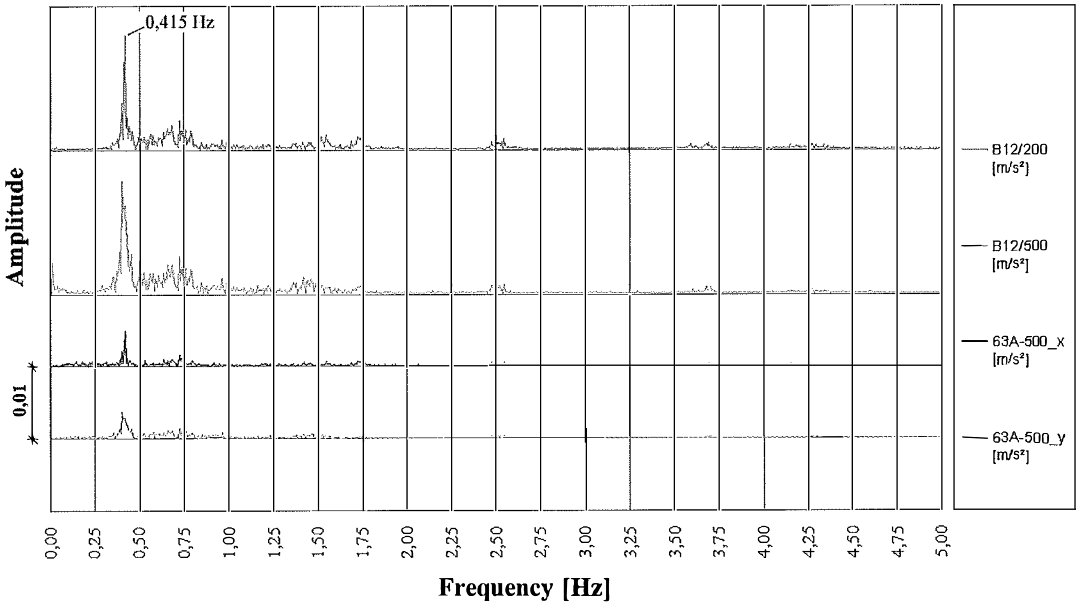

Figure 3: Amplitude spectrum of the accelerometers (phase 1)

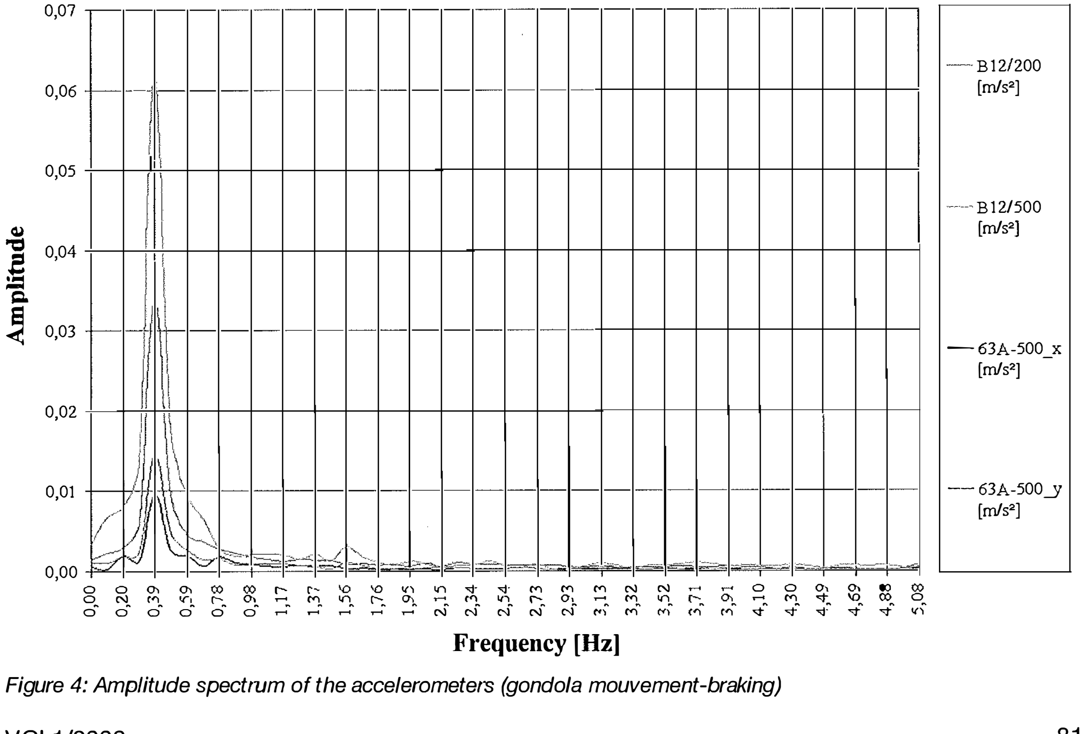

Figure 4: Amplitude spectrum of the accelerometers (gondola mouvement-braking)

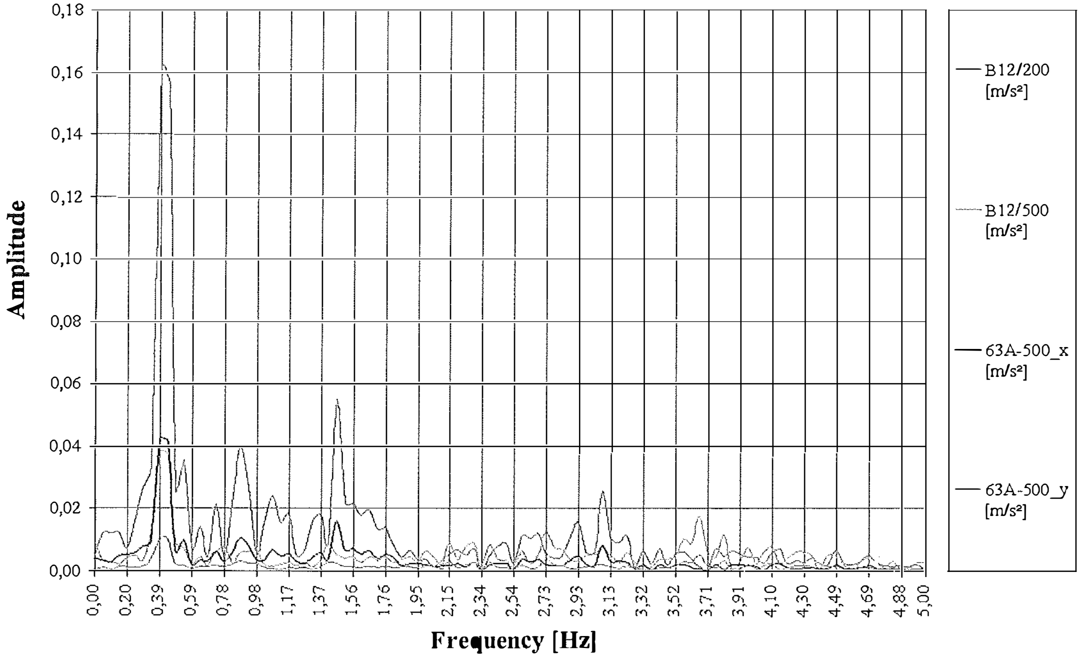

Figure 5: Amplitude spectrum of the accelerometers (startup phase)

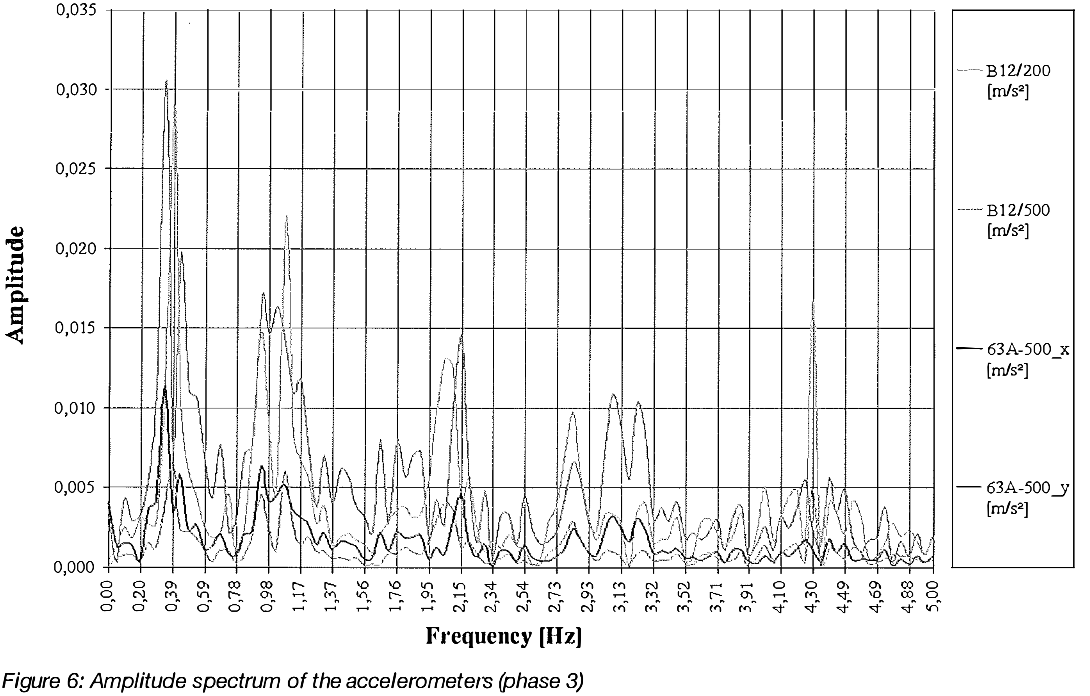

Figure 6: Amplitude spectrum of the accelerometers (phase 3)

through to fully operational service. The sampling rate is 200 Herz for all three sensors. The following figures 3, 4, 5 and 6 show the amplitude spectrums of the various service phases.

Figure 3 shows the same frequency range and time as Illustration 2. The largest amplitudes are supplied by the two acceleration-receivers B12. Generally speaking, the largest amplitudes are clearly at 0.415 Herz for all sensors. The GPS- and acceleration-measurements correlate very well concerning the resonant frequency. There are isolated higher frequencies, but with only very small amplitudes.

The turning of the gondola-axis into the wind was concluded with a very abrupt braking action. High acceleration values were recorded as a result of the large tower movements. The two sensors that were internally aligned to the y-axis measured higher acceleration values as those that were perpendicularly aligned.

Figure 4 shows that the largest amplitudes for all sensors are at 0.39 Herz and that the quickest acceleration was measured by sensor B12/500 at 0.062 m/s2.

The next diagramm shows an extract of the startup with the corresponding amplitude spectrums.

As would expected, there are more higher frequency moments recorded. Generally speaking, the largest amplitudes remain limited to the frequency range under 3 Herz. The amplitude maximum for all accelerometers is again to be found around 0.4 Herz. The quickest acceleration was measured by sensor B12/200 at 0.161 m/s2.

Several minutes pass from the beginning of the startup to fully operational service. At wind speeds around 5.5m/s, the active stall device allows the rotor to turn with approximately 14 rotations per minute.

Figure 6 shows that several clear amplitude-pikes appear across the frequency range. This is not really surprising, as the course of the measurement-signals in relation to time show fewer and fewer regularities. Further, the maxima of the accelerometers are clearly to be found under 1 Herz. The largest amplitudes for the B12/500 and 63A-500_y are at 0.39 Herz and for the B12/200 and 63A-500_x at 0.35 Herz. These amplitude values are partially considerably smaller than those recorded during startup (0.161 m/s2 against 0.031 m/s2 for the B12/200).

The vibration spectrum of the wind-generator-tower could be well recorded from standstill through to fully operational service. A general power-cut to the complete wind-generator-tower was the cause of the only data transmission failure.

6. Summary, Outlook

The problem, namely the recording and analysis of the tower vibrations as they occur by representation of the measurements of time and frequency range, that appeared to be easy at first glance, turned into a very complex one on closer inspection that also has an importance for further research.

As to the question which sensors can be used for such an assignment, it has to be said that the RTK-GPS-system can only be used within certain limitations. Obstructions and multipathing have shown clearly the limitations of this system. Especially disadvantageous was the fact that Phase 2, which was seen as being critical, could not be measured with the RTK-GPS-system. Figure 1 is an impressive example of these limitations.

The tower movements during standstill periods were very well recorded. With very few exceptions there were no obstruction problems. The long-term influences of the position of the sun could therefore be well measured. The time-frame that was available for these measurements was however insufficient. Besides, the main interest was in measuring the vibrations caused by the startup and during fully operational service.

The central controller proved to be highly suitable in all areas. Some limitations of the sensors had to be accepted as with the GPS.

The triaxiale accelerometer ISOTRON MODAL-63A-500 is a sensor that can be used in the higher frequency range (1 – 2000 Herz) and in the modal analysis. Nevertheless, it could also stand the test in the lower frequency range if one ignores the phase displacement in this frequency range. The measurement of the resonant frequency of the tower and the close correlation with the results of the other sensors verify this.

The best results came from the two B12 accelerometers. Thes highly-tuned spring-mass-systems (resonant frequency 200 and 500 Herz, attenuation constant D = 0.6, frequency ranges of 0 – 100 Herz and 0 – 250 Herz) are highly suitable in the lowest spectrum (close to 0 Herz). This was expected as the amplitude response, described as the relation of the amplitudes of the relative movements of the mass and their acceleration depending on the frequency, in the vicinity of 0 Herz is equal to 1.

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Contact

Dipl.-Ing. Dr. Johannes Fabiankowitsch: Vienna University of Technology, Institut of Geodesy and Geohysik, Departement of Applied and Engineering Geodesy, Gusshausstraße 27–29, A-1040 Vienna, Austria, email: jfabian@pop.tuwien.ac.at

Univ.-Prof. Dr.-Ing. Heribert Kahmen: Vienna University of Technology, Institut of Geodesy and Geohysik, Departement of Applied and Engineering Geodesy, Gusshausstraße 27–29, A-1040 Vienna, Austria, email: Heribert.Kahmen@pop.tuwien.ac.at

Phillip Matt: Troie 3, A-6161 Natters, Austria