REDUCING VIBRATION ISSUES AT SMALL VERTICAL-AXIS WIND TURBINES ON BUILDINGS

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Abstract

Small wind turbines (SWT) are rotating machines, therefore the rotor speed and its harmonics produce excitation frequencies leading to resonance issues if natural frequencies of the SWT, its sub structure and/or the building are in the operational frequency range. This is often not addressed during design and siting of SWT because of the complexity of rotor and structural dynamics and/or because natural frequencies of the building are unknown. The unexpected resonance issues threaten the SWT project by noise and vibration, accelerated wear and damages and production loss from standstill. At five recently installed vertical-axis SWT installed on buildings in Berlin, vibration measurements with 17 sensors and a root cause analysis was carried out to address resonance issues and building vibration. For vertical-axis SWT, the dynamics are far more complex than for horizontal-axis SWT, since more harmonics occur due to upwind and downwind blade-mast interaction. Therefore, resonance at SWT components and/or the building may occur even at low wind idling. It turned out that long braces, used to avoid periodic maintenance efforts for guy wires pretension control, had resonance frequencies in the same range as the steel framework building. Dampers installed to prevent generator vibration propagation into the tower formed an additional vibration system, and the damper's natural frequencies were excited by the harmonics. The heavy vibrations wore down the dampers fast. Rotor mass imbalances which had been several times the limit value were successfully reduced by advanced two-plane rotor balancing despite the strong rotor speed fluctuations.

Keywords

Vertical-axis small wind turbine, building vibration, vibration and load measurement, rotor balancing, resonance, root cause analysis

1. Introduction

When small wind turbines (SWT) are installed on buildings, not only the airborne noise emission but also the sound propagation of SWT vibration into the building is an important aspect, which may cause unexpected issues if not addressed. Mostly, the SWT manufacturer cannot afford an extensive 20 year's dynamic design simulation or prototype load measurements as required for certification of large wind turbines (WT). Therefore, fatigue and resonance issues of SWT are often underestimated. In addition, for installation often only request a static proof concerning the additional gravitational loads, and as well wind and ice loads on the roof to show that the installation is reasonably stable and safe. The dynamic issue of installing the SWT as a rotating machine on a building which has its characteristic natural frequencies is often not addressed, despite e.g. for steel framework structures and bridges excitation by traffic, tram, railway or subway is a known issue. The rotor and structural dynamics of SWT and the interference with the building create a complex total system. Moreover, the higher turbulence intensities from the strongly varying wind close to the ground and/or the complex urban terrain leads for a variable-speed SWT to a constantly changing rotor speed. Steady state operation is very rare. Every part of the SWT and its support structure is a potential source for resonance issues. If additional dampers for vibration reduction are installed they may have the desired positive effect for a certain frequency range but may create additional resonance issues for another frequency range.

Five Vertical-axis SWT of the type Venco Twister, Figure 1, had been installed on roofs in Berlin, Germany, by the Hochschule für Technik und Wirtschaft – University of applied Sciences (HTW) in cooperation with the Reiner Lemoine Institut gGmbH (RLI) in the course of a research and demonstration project "Application of SWT on buildings in urban areas of Berlin" [1] funded by the Berlin Senate

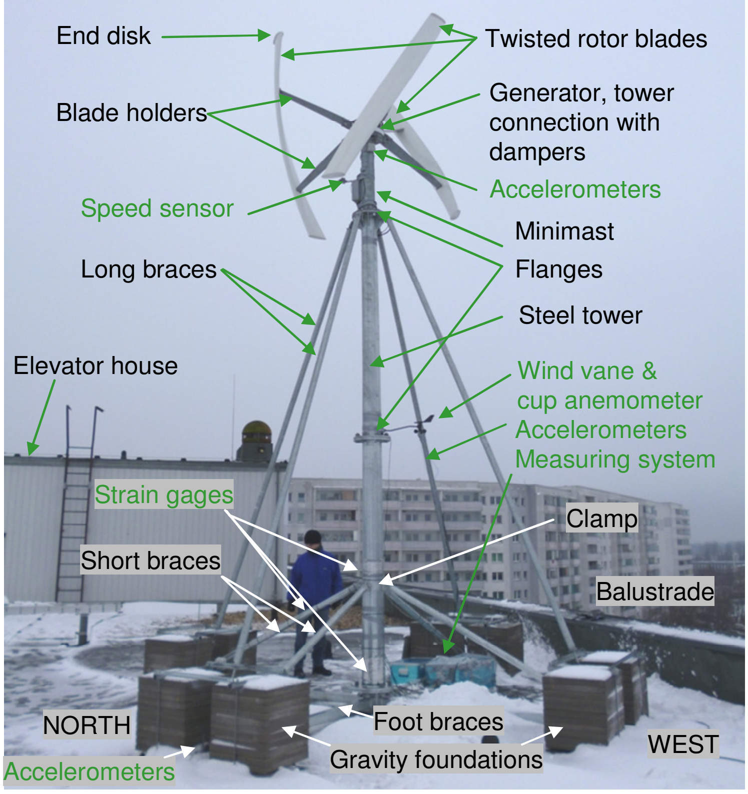


Figure 1: Vertical-axis small wind turbine Venco Twister 1000T (600 W) with 1.9 x 1.9 m rotor (older, smaller version), 6 m hub height on a Berlin roof top, tower stabilisation by long and short braces

Department for Urban Development and the European Regional Development Fund (ERDF).

Some of these SWT showed increased vibrations shortly after commissioning including a shaking of the gravitational foundations at some rotor speeds. Moreover, building vibrations and noise in the building occurred, reaching even some floors down. The excess vibrations wore down installed dampers between generator and mini mast within months and led to shut-down. It was obvious that a simple damper replacement would not cure the root cause. Due to noise and vibration a long-term operation could be questioned, moreover the acceleration of fatigue by the heavy vibrations would accelerate the lifetime consumption of the SWT and lead to early and costly damages. Moreover, loss of rotating parts is a potential hazard in urban areas which has to be avoided by all means. Together with Berlin-Wind's independent experts, vibration measurements, rotor balancing and a detailed root cause analysis was carried out in order to identify issues and propose measures to reduce vibrations.

2. Investigated small wind turbine and its site

The SWT with twisted rotor blades is shown in Figure 1. In the original configuration there are three dampers between the generator and the minimast to prevent noise propagation of rotor speed (*n*) dependent harmonics at 20 x *n*, origining from the 20 generator pole pairs, into the minimast and sub structure. Due to the twisted blades, the SWT starts to rotate at low winds. However, since every blade section has a different orientation to the wind, there will be an even more complicated 3D flow around each blade as for straight blades. For higher wind speeds, noise from stall effect was audible due to the blades rotating into and out of the wind every revolution.

The site is on a seven-floor building with the main wind direction from the nearly undisturbed area in the South-West where trees and other smaller buildings are at some distance. However, two elevator houses on the same roof in the South-eastern and North-western direction are significant obstacles with wake effects which are potential site-related causes for increased vibration. In the original research and demonstration project, a basic permanent monitoring of rotor speed and power of the SWT and meteorological data from a separate mast (not shown in Figure 1) with a 3D ultrasonic anemometer (UA), temperature sensor and humidity sensor are installed. The latter two sensors are used for SWT shut down during periods with potential ice throw hazard, too.

A general static proof was calculated to determine the required mass of the gravity foundation for the extreme wind forces according to IEC 61400-2 [2], and as well the additional roof loads. The four gravity foundations, of approx. 660 kg each, are placed directly above the steel girders of the roof, and there is a gap between tower bottom and roof because the roof is not very stable at this position.

Several variations of the tower guying were tested: All variations included the short braces, Figure 1. Instead of the shown pre-tensioned long braces, long braces without pre-tension and manually pre-tensioned guy wires were tested as well. Basically it was intended to avoid O&M costs for the periodic control of the wire pre-tension. The unexpected strong SWT and building vibrations required a detailed root cause analysis with vibration measurements to propose solutions for the issues.

3. Measurement system

The BerlinWind measurement system installed at the SWT in Figure 1 was tailored specifically for the planned measuring campaign's needs. It consisted of:

- 2 accelerometers (at right angles) at the minimast to monitor tower top vibration
- 2 accelerometers at the middle of a long brace (at right angles) to monitor brace vibration
- 2 accelerometers at one foundation for horizontal and vertical vibration
- 1 rotor speed sensor
- 2 strain gauges at the tower above the clamp (at right angles)
- 2 strain gauges above the tower base (at right angles)
- 2 stain gauges at two short braces
- A low-cost wind speed and wind direction measuring device at the tower (later correlated with the UA) mounted in the main wind direction
- Temperature and ambient pressure sensor
- USB-based multi-function data acquisition system BalancingBox with adapter module
- Strain gauge amplifier
- Notebook with in-house developed software for load measuring campaigns and wind turbine balancing
- Power supply module to provide, at 3 different DC voltage levels, the required total power (30 W) drawn from the 24 VDC UA heating power supply

For special measurements, e.g. determination of the Eigenform of the tower, up to eight accelerometers were installed. Data from the 17 sensors was generally recorded with 300 Hz sample rate, for balancing measurements with a higher sample rate to have sufficient data points per revolution.

3. Measurements

The measuring campaign consisted of the following parts:

1. Determination of natural frequencies of the SWT and its sub structure
2. Optical photometric measurements to investigate blade angle and rotor partition differences
3. Vibration measurements for 2-plane rotor balancing
4. Operational vibration measurements including measurement of the building vibration for several days
5. Vibration measurements during SWT operation with modification of the SWT structure:
   - damper below generator blocked (yes/no),
   - long braces bent towards the tower in their middle by additional tension belts to shift their natural frequency (yes/no)

Five SWT were balanced, the detailed investigations were carried out at the older, smaller SWT version shown in Figure 1 and as well at two of the newer, larger SWT version on different building and roof types.

4. Evaluation

The data evaluation was performed at several levels:

1. On-site and off-site evaluation of the natural frequencies and the rotor balancing measurements using BerlinWind's in-house developed evaluation software for large turbine rotor and drive train balancing with up to three balancing planes [3, 4].
2. Off-site evaluation with tailored BerlinWind software for investigation of resonance issues by evaluation of shorter measurement sections. Because of the strongly changing rotor speed, the implementation of a sliding window evaluation was required to produce the vibration amplitude values dependent on the rotor speed and the harmonics without falsifying the amplitudes by averaging over a too long section.
3. Off-site evaluation for load spectrum calculation in cooperation with the Technical University of Berlin where in the course of a doctorate scholarship, funded by the Reiner Lemoine Stiftung, an evaluation and assessment strategy for the remaining service life estimation of wind turbines is developed [5].

Since the entire measuring data amount from the several days of measurement exceeds 40 GB, the entire evaluation, especially of the longer operational measurements is still under process. Especially the problematic operating states with strongly increasing vibration amplitudes currently have to be identified by visual checks. The correlation with wind speed and wind direction to evaluate e.g. the wake effects from the elevator houses is presently done manually. In addition, the first results showed the necessity of the implementation of further techniques in the evaluation software. Especially the evaluation by a sliding window for obtaining the amplitudes of the rotor speed dependent harmonics for a smaller number of revolutions, e.g. 8 or 16, showed to be essential because else the averaging in the evaluation leads to under-estimated amplitudes. Therefore, the entire measuring campaign serves as well as a basis for the development of a new load measuring system and load assessment software for SWT.

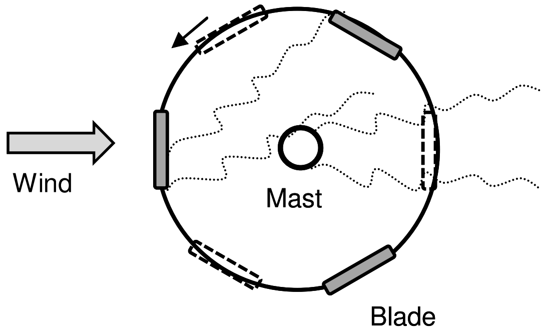


Figure 2**:** Schematic top view of blade-mast interaction 3 x 120° (3 x n, filled blades) and 6 x 60° (6 x n, filled and dashed blades), dotted lines: schematic wake of blade and mast

5. Results

5.1 Preliminary remark

In addition to the described SWT, four more SWT of the same design were investigated, as well some of a newer version with a larger rotor diameter. Since the resonance issues and the findings from the measurements were similar, the following results aim on a general discussion independent of the SWT size.

5.2 Basics on resonance investigations

When a rotating machine like a WT is designed it is important to compare

- the occurring excitation frequencies (EF) of the rotor speed and its harmonics, e.g. from blade-mast interaction, Figure 2 with
- the existing natural frequencies (NF) of the machine and structure [6, 7].

For EF = NF, the operating point is critical because **resonance** occurs and periodic excitation leads to strongly amplified vibration which has to be avoided or minimized. Therefore, it is an important part of the design process to identify potential resonance issues by forming a so-called Campbell diagram, which is shown in Figure 3 and Figure 4 for the older and newer version of the SWT discussed below.

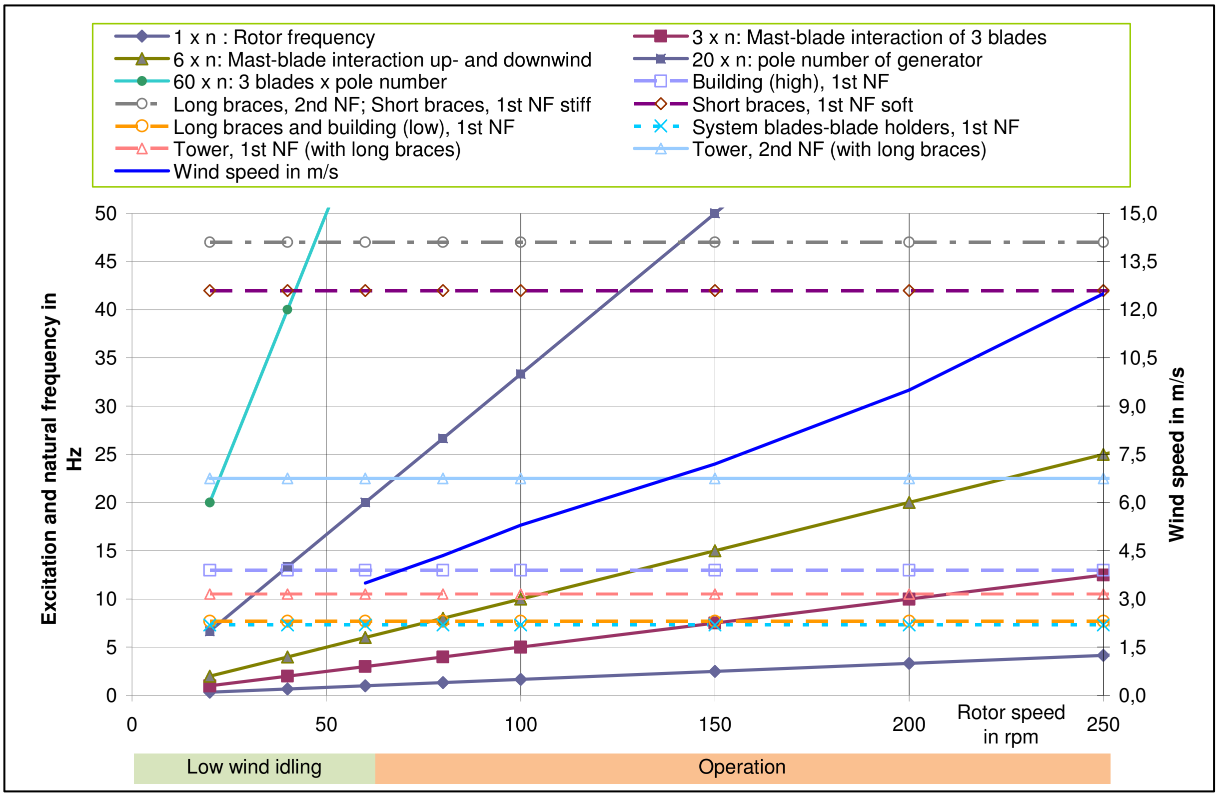


Figure 3**:** Campbell diagram for older version of vertical-axis SWT. Rotor speed, harmonics and natural frequencies (1st and some 2nd)

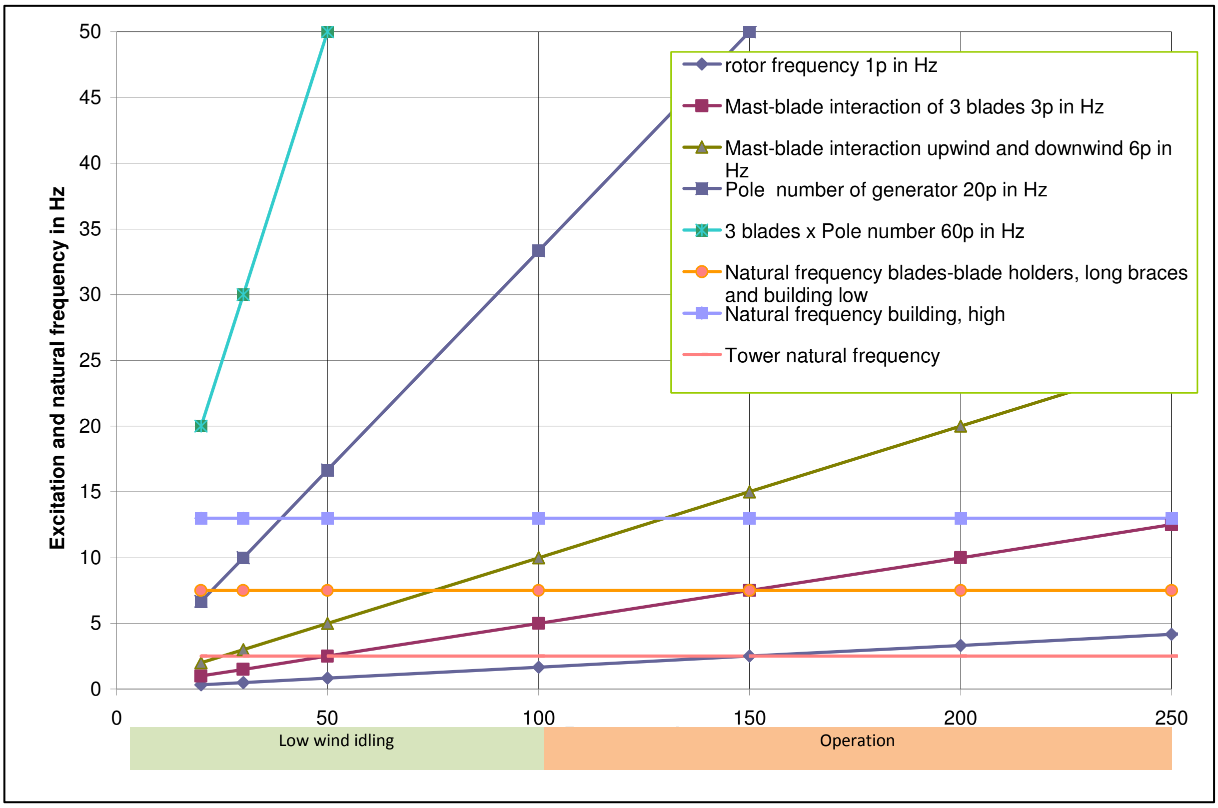


Figure 4: Campbell diagram for newer, larger version of the vertical-axis SWT with similar tower structure. Rotor speed, important harmonics and some 1st natural frequencies. For newer version resonance issues already at low wind idling

For a **constant-speed WT** design there is harmonic excitation only from a single rotor speed and its discrete harmonics. Avoiding resonance is quite simple, only the effect of slip, increasing the rotor speed slightly with rising load, has to be considered as well . Accordingly, for a constant-speed WT with generator pole switching there are the discrete rotor speeds and their harmonics as EF.

In contrast to that, for the **variable-speed WT**, the entire operating range from low wind idling to maximum rotor has to be considered in the Campbell diagram, Figure 4. The rotational frequency and its harmonics give the curves linearly increasing with the rotor speed. The natural frequencies are mostly independent of the rotational speed, therefore they are horizontal lines. Every intersection of an excitation curve with a natural frequency line is a critical point where structural resonance occurs and leads to strongly amplified vibrations if the WT runs for a longer period at this operating point. In the following, the resonance issues more specific to the investigated SWT are described.

5.3 Resonance issues at the variable-speed vertical-axis SWT

The rotor dynamics of vertical-axis SWT with three blades are far more complex than for horizontal SWT. Due to flow conditions alternating permanently per revolution and more blade-mast interactions there are more harmonics of the rotor speed present. There are at least the following **excitation frequencies** for the investigated SWT:

- 1 x n excitation from rotor speed n
- 3 x n excitation due to the periodical alternation of blade's orientation relative to the wind, causing periodical variation of angle of attack and relative velocity
- 3 x n excitation due to upwind blade-mast interaction 3 x 120° (Figure 2, filled blades)
- 3 x n excitation due to the passage of the lower downwind blade part through the mast wake 3 x 120° (dashed blades). This provokes as well periodic nodding moments because not the entire blade is hit by the mast wake.
- 6 x n excitation due combination of upwind and downwind blade-mast interaction, i.e. 6 x 60°
- *20* x *n* excitation by the generator due to the pole pair number (here p = 20)
- *60* x *n* excitation by due to 3 blades and generator pole pair number (here p = 20)

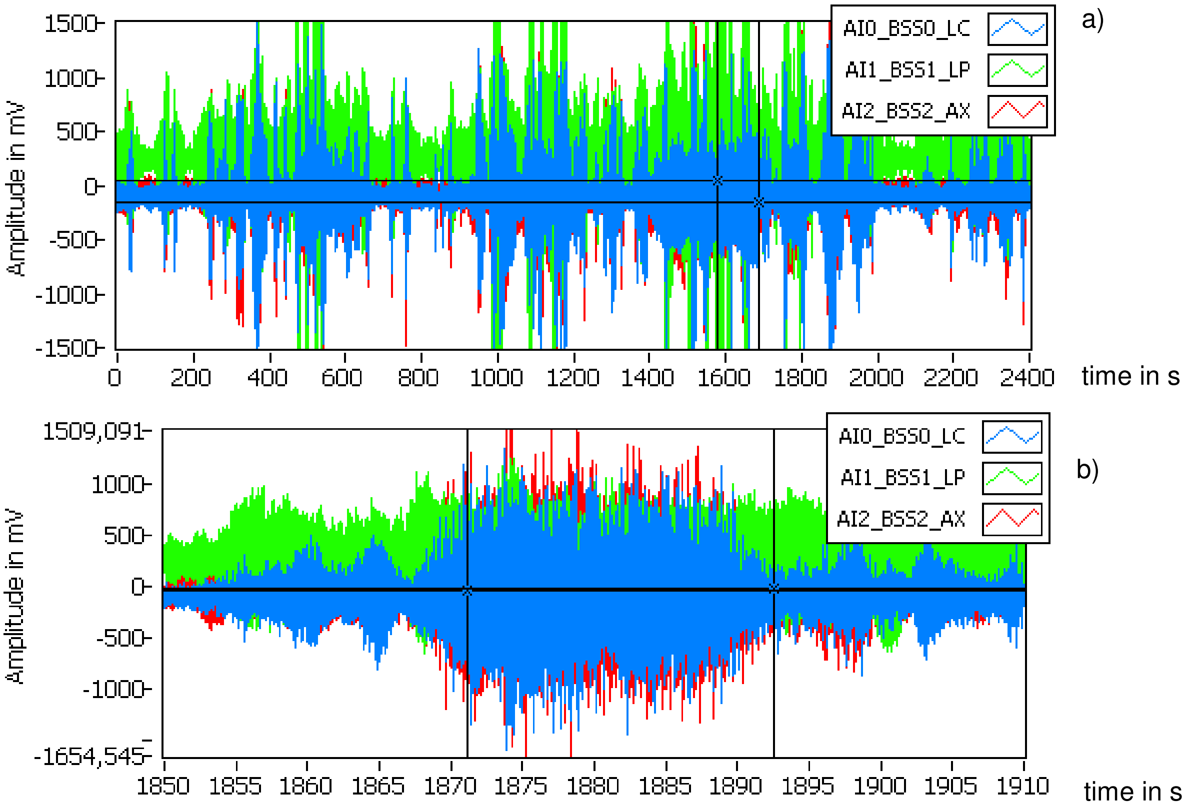


Figure 5: 40 min measurement under operation with n = 80 to 220 rpm at older version of SWT: a) Horizontal acceleration signal at minimast (LC, AX) and at middle of long brace (LP) with heavy horizontal vibrations exceeding +/- 1 g (unit: 1 mV = 1 mg = 1/1000 g = 1/1000 * 9.81 m/s²);
b) detail: heavy vibration amplification due to resonances at rotor speed above 180 rpm

For the older SWT version with a smaller rotor and power production start at 60 rpm, Figure 3, the rotor frequency (1 x n) is always below the **natural frequencies** (NF). However, there are more than 10 critical intersections of the NF with the harmonics of the rotor speed, six are already at low wind idling range. The tower's first NF is around 10.5 Hz for the structure with pre-tensioned long braces, which produces during operation resonance around 100 (resp. 200) rpm due to 6 x n (resp. 3 x n). For the building's NF, two lines are drawn, at 7.7 and 13 Hz, for different buildings showed different natural frequencies.

For the newer, larger SWT version and power production start at 100 rpm, Figure 4 bottom, more resonance issues appear already during low-wind idling with the natural frequency of the long braces of the SWT, and some of the buildings, which are excited by harmonics. Figure 5 shows for the older SWT version horizontal **acceleration amplitudes** measured at the minimast (LC: blue and AX: red) and at a long brace (LP: green) during operation between 80 and 200 rpm.These amplitudes temporarily exceed the range of the gravitational constant g, at the long brace even 1.5 g. Due to the oscillating top mass of approx. 130 kg (rotor and generator) the horizontal inertia forces of approx. 1280 N exceed the assumed maximum operational design loads of 1080 N. However they are below the extreme wind loads for standstill of 1650 N used for static foundation design with 38,75 m/s extreme wind according to IEC 61400-2 [2]. Extreme winds are rare conditions whereas the fatigue relevant operational loads occur with every rotor revolution. To illustrate the **vibration of the minimast and the long braces** in the variable-speed operation in a range between 30 and 220 rpm and the corresponding rotor speed harmonics Figure 6 shows the results from analysing the measured acceleration by order analysis using a sliding window of 8 revolutions. The three sensors are coded by the different colours. The harmonics of the same order have the same symbol. It is clearly visible how the harmonics excite several natural frequencies, and that for several discrete frequencies the corresponding amplitudes nearly reach 0.5 g = 500 mg. For comparison, at large WT the typical amplitude range during normal operation or balancing measurements are in the range below 50 mg.

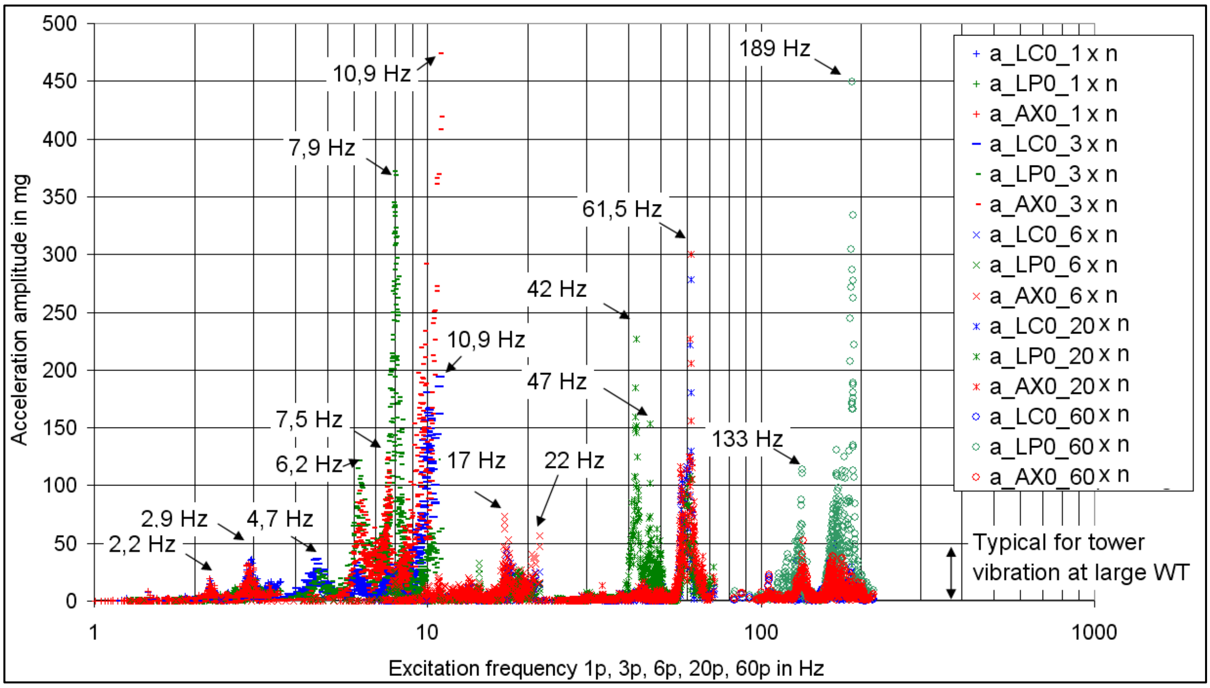


Figure 6: Acceleration amplitude versus excitation frequency for rotor speed range n = 30 to 220 rpm obtained by order analysis using sliding window size of 8 revolutions. Longer measurements at minimast and long brace for the older SWT version. Various resonance issues due to rotor speed harmonics and natural frequencies marked. Unit: 1 mg = 1/1000 * 9.81 m/s²

The observed excessive operational vibrations caused vibrations of the SWT, its structure and gravitational foundations, and as well strong vibration immission into the building.

Despite the three **special dampers** between the generator and the mast which were installed to prevent sound propagation from the generator harmonics into the mast (20xn, from the generator pole pair number), these harmonics were measured, sensible and audible in the SWT structure. Dismantling the dampers showed that the excess vibration had worn down the rubber. The admissible horizontal forces for the three dampers between generator and tower were exceeded in operation and hence wearing down the rubber within months. In addition, the damper's natural frequency was excited by harmonics, and the system of rotor mass and damper showed a natural frequency around 2.6 Hz, like the tower's natural frequency for the newer, larger version of the SWT. Attempts to find a more suitable damper or have a special damper designed failed due to the high horizontal forces from vibration and the wide rotor speed range. Simulation showed that resonance effects of the rotor-damper system would always be an issue as there would be always a resonance frequency in the operating range.

Since without the dampers the vibration issues reduced, they were permanently removed. Moreover, the system of **blades and holders** showed a vertical movement with a NF around 7.5 Hz, unfavourably three times the tower's NF and very close to the NF of the long braces. There are four long bars with slightly varying natural frequencies, therefore **beat frequencies** were observed meaning that vibration builds up at one brace and then decays again while it builds up at the next brace. These vibrations even made the gravity foundations vibrate. Moreover, evaluating sensors applied at the braces at rectangles revealed that each brace had slightly different natural frequencies for the perpendicular vibration directions due to their design.

5.4 Building vibration issues

As expected, vibration measurements at the foundations and on the roof top showed less noise and vibration problems for a **concrete roof** which has a better damping. Nevertheless, the harmonics from the generator (20xn) transmitted by the foundation were visible as waves in water puddles on the roof. For some buildings and roof tops in **steel framework construction** the natural frequencies of the building were found in the range between 7 and 12 Hz as drawn in the Campbell diagrams Figure 3 and Figure 4. As a consequence, these buildings were significantly excited by the rotor speed harmonics, for the larger SWT version already at low wind idling when the SWT was not even producing power. The vibration of the long braces with a NF around 7.5 Hz amplified the problem.

Figure 7: Test masses temporarily fixed at the blade holders for 2-plane balancing measurement at older SWT version

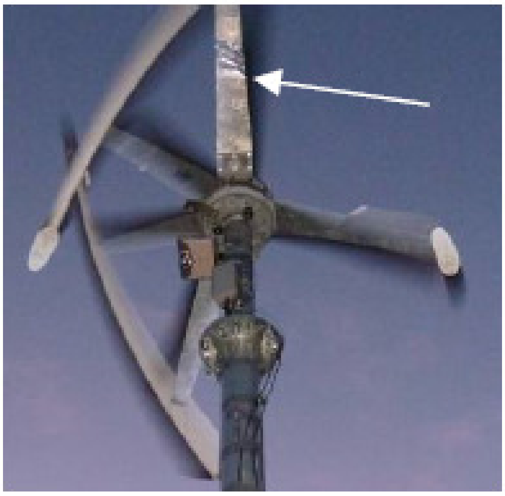
Temporarily fixing the long braces in their middle by additional tension belts towards the tower significantly lowered the building vibrations and showed that the long braces amplified the vibration issues. Tests with pre-tensioning the long braces showed that due to the brace mass this is not possible to shift their natural frequency above the problematic frequency range around 7 to 15 Hz. Therefore, it was recommended to use guy wires properly designed, pre-tensioned and periodically inspected despite the increasing O&M efforts. However, the significantly higher natural frequencies of the wires will avoid the vibration amplification as caused by the long braces. In addition, it would be an option to introduce adequately designed or chosen dampers between SWT and roof. However, the newly created system of entire SWT and damper with its additional natural frequencies then has to be investigated.

5.5 Rotor imbalance issues

Typical root causes for increased WT vibrations are **rotor imbalances** from

- mass imbalance (MI): an uneven Mass distribution in the rotor and/or
- aerodynamic imbalance (AI): deviations of the aerodynamics at the blades lead to uneven thrust and driving forces.

For AI, **blade erosion, blade angle differences and rotor partition differences** have to be investigated. The latter means that the blades are not evenly spaced at 3 x 120° with respect to the rotor axis meaning a torque imbalance of the three blades. To measure AI, optical blade angle and rotor partition measurements were performed by evaluating photos taken from below the rotor with a software for AI measurements at large WT.



Due to the twisted blades and end disks, the blade angle measurements were not successful. This means that this potential issue can be measured only by other advanced methods, e.g. the laser-based measurement system ContourBox a distance laser-scanner. However, for the SWT in Figure 1 the photos revealed a significant rotor partition error of 0.5° which was also verified by manual measurement of the blade distances. At a newer version of the SWT type, the improved design and production prevents these partition issues.

Due to the axial length of the vertical SWT rotor, only **two-plane balancing** is the appropriate method to determine the MI in the upper and lower rotor section. For calibration temporal test masses had to be taped to the blade holders, Figure 7, or realized by nuts and washers at the blade bolts for the newer SWT version. Due to the strongly fluctuating wind and rotor speed, Figure 8 ,there are only very short periods with a suitably low rotor speed standard deviation during a measurement run.

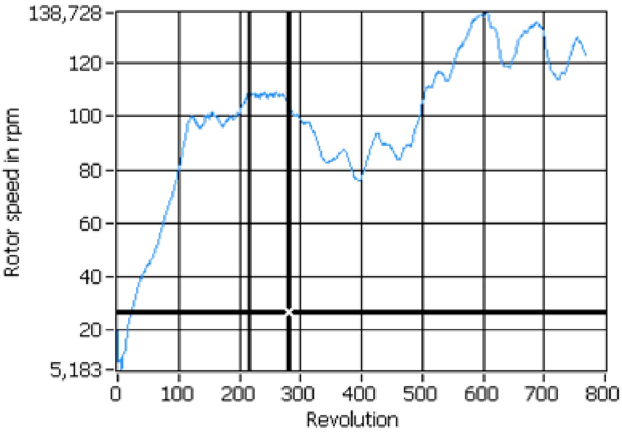


Figure 8: Rotor speed versus recorded revolution: Typical rotor speed fluctuations during rotor balancing measurement with only small section of nearly constant rotor speed (approx. 108 rpm) suitable for balancing evaluation

Two-plane balancing requires at least four runs:

- one run for recording the initial state,
- two calibration runs with test mass and
- one validation run after fixing the determined counter weights.

All balancing evaluations have to be done for the same rotor speed (here 108 rpm) and with the same speed standard deviation, because the centrifugal forces from imbalance depend on the squared rotor speed. The measured amplitudes are influenced in addition by the frequency ratio of rotor and natural frequency. If this is not observed, speed variations falsify the balancing result. Since it is unknown how strong the wind will be in the next runs, a quite long measurement time is needed. Therefore, balancing SWT takes as much time as for large WT.

Order analysis is imperative to prevent falsification of the MI determination by the residual speed fluctuations in the chosen evaluation section. The total initial imbalance was successfully determined.

For all five measured SWT the admissible limit value of 12 g*m, derived from a required balance quality grade of G 2.5 for the generator (according to ISO 1940-1, [8]), was exceeded significantly by a factor of 5 to 10. The calculated correction masses were installed and lowered significantly the 1 x n vibrations measured in the validation run, which proved the correctness and relevance of SWT balancing. Nevertheless, for the older SWT version due to the falsification by AI (partition error), the attained 1 x n level was not as low as for typically reached for a pure MI.

For some of the SWT located at one and the same site, it was found by the MI measurement, that blades from different rotor sets were accidentally mixed during assembly because the sets were not marked. Hence, despite a static balancing below 5g by the manufacturer during production the MI occurred.

6. Conclusions and outlook

The vibration measurements at the vertical-axis SWT and root cause analysis showed the following:

1. Variable-speed vertical axis SWT show complicated rotor and structural dynamics due to harmonics of the rotor speed which are relevant for resonance issues of the SWT and the building.
2. The design of SWT rotor, support structure and foundation should include the structural dynamics over the entire rotor speed range and for all planned structure variations to prevent resonance issues.
3. The degree of building vibration issues strongly depends on the roof type and building structure.
4. SWT design, production and installation requires high quality standards as the specific investment per kWh is higher than for large WT and the costs of unexpected issues threaten the project economics fast. Detailed assembly instructions and experienced installation staff are recommended.
5. Despite increased O&M efforts of pretensioned guy wires, for their defined pretensioning and inspection, the benefit on reduced resonance issues and defined natural frequencies of the structure is a relevant benefit compared to the braces.
6. Dampers should preferably be installed between foundation and roof to minimize resonance issues with the building. Design should take damper resonance, periodic damper inspection and eventual replacement into account.
7. Aerodynamic and mass imbalance is a potential issue at SWT. Design, manufacture, quality control and professional erection should prevent it at best. Defined easy accessible locations for test and correction masses are necessary. Dynamic balancing of the assembled rotor is required especially for variable-speed SWT.
8. Due to the strongly fluctuating winds and rotor speed balancing SWT is quite time consuming and requires for vertical-axis SWT two-plane balancing. Nevertheless, the applied method was very successful.
9. Vibration issues of SWT, especially when installed on buildings, increase significantly wear and damages of the SWT threatening the project profit by increased O&M costs and stand still - and the costly root cause analysis. Additional costs for later vibration analysis and SWT modifications are estimated to reach easily 10-20% of the SWT initial costs (depending as well on the SWT size) but lie below the minimum repair costs of vital components if the issues are not addressed.
10. For a detailed vibration analysis of SWT with strongly changing rotor speed, advanced measurement and evaluation techniques are required. Order analysis and sliding evaluation window methods are

necessary to prevent under-estimation of the real amplitudes which occurs when averaging over too long periods.

11. As a consequence of the works, a mobile, robust and flexible load measuring system is being developed to provide a system for investigation of SWT vibration issues. It will be able to measure power characteristics as well. It will be tested in 2013 in a measuring campaign of several weeks.
12. In parallel, the evaluation software will be improved to provide reliable tools for easy and efficient root cause analysis in the case of SWT vibration issues.

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