

## WHERE IS THE NOISE COMING FROM?

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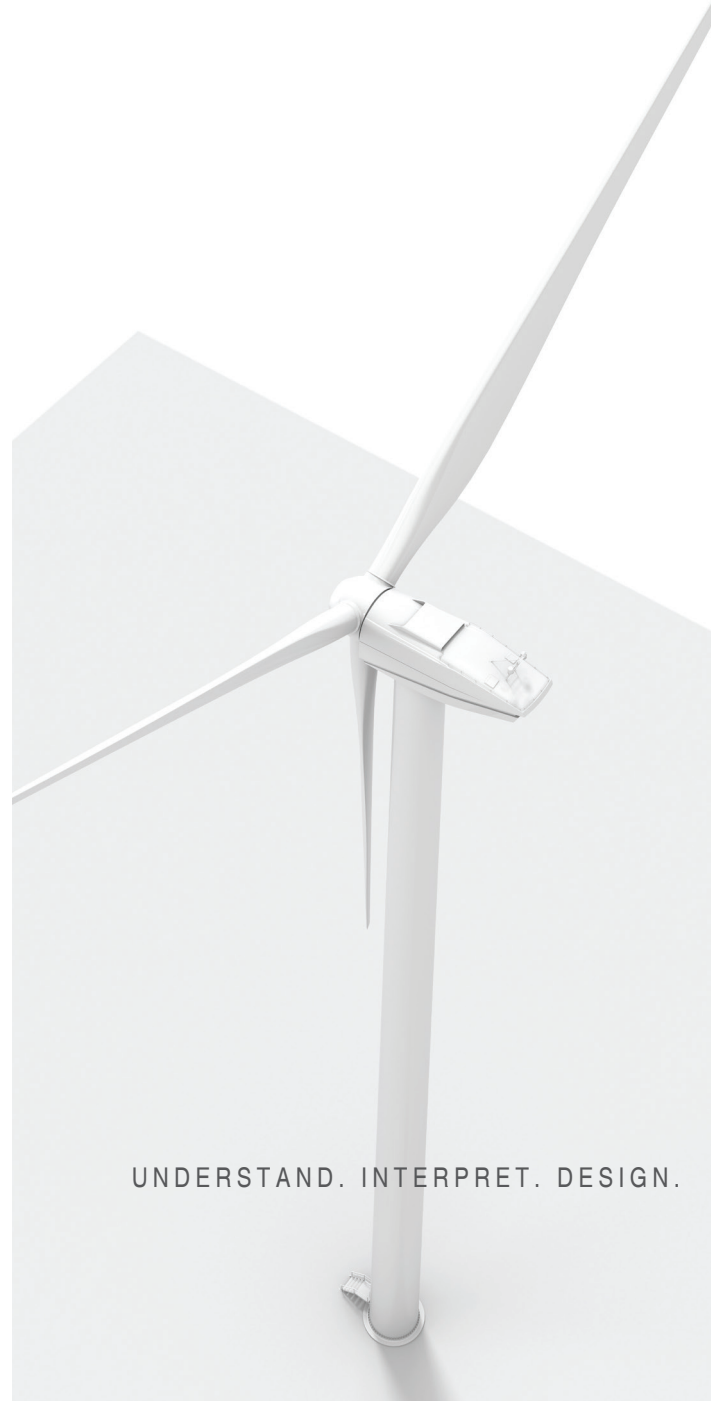
### Efficient vibroacoustic measurements on wind turbines

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#### 1. INTRODUCTION

In the transition from nuclear to regenerative energy sources, wind energy is frequently considered as a key factor. As turbines require wind to operate, environmental conditions have a direct effect on the turbines' functionality. Possible inland locations are limited and often situated near a populated area. This can cause residential disturbance due to the noise of the turbines. The emitted noise has to be kept as low as possible and is governed by various standards, such as the IEC61400-11 [1] in Europe. These standards usually stipulate the measurement method, applied sensors, sensor positions, and the analysis required. Currently the focus is on sound power, 3<sup>rd</sup> octaves and tonalities calculated at different wind bins. Various environmental conditions, topography and setup challenges add to the complexity of the measurement task. Especially when large distances need to be covered, the measurement setup can be costly and time-consuming. A fixed setup is not recommended due to environmental conditions, such as wind direction, wind speed and gondola position. All analyses require a certain amount of data for each wind bin and each possible operational mode. This leads to a flexible and efficient system enabling quick setup changes and smart data management.

While standard measurement provides valuable information about the wind turbine status, it does not provide any information on where the noise is coming from and how it is distributed through the turbine structure. Therefore it seems reasonable to add more measurement positions with a wide range of different transducers and additional analyses. In order to acquire further sensor signals, the measurement setup has to be flexible enough to address the specific measurement task while at the same time considering the large structure and environmental conditions. Hence, a wireless solution is needed for the acquisition of the noise, vibration and rotational data. This data can be used for a wide range of analyses. These include simple correlations and comparisons of individual measurements and signals or for the analysis of individual components. Individual disturbing components are located using a microphone array and applying beamforming algorithms. The entire structure or the individual components can be analyzed further through structural analyses based on frequencies or eigenfrequencies (e.g. impact or shaker based measurements besides classic operational measurements). Captured results



are visualized using Operational Deflection Shape analysis (ODS). For more detailed analyses, Transfer Path Analysis is suggested. Transfer Path Analysis ranks the contributions of different sources in the case individual response positions are investigated.

## 2. STANDARD MEASUREMENTS ACCORDING TO IEC64100

The IEC61400 [1], [2], especially the current 3rd edition, requires a specific measurement setup for the applied sensors, sensor positions, and dedicated analysis. As the analysis usually requires the operating noise to be measured, a correction of the according background noise at the same microphone position must be made. In this way, the operating noise is acquired and separated from the background environmental noise.

### A. Measurement Setup and Method

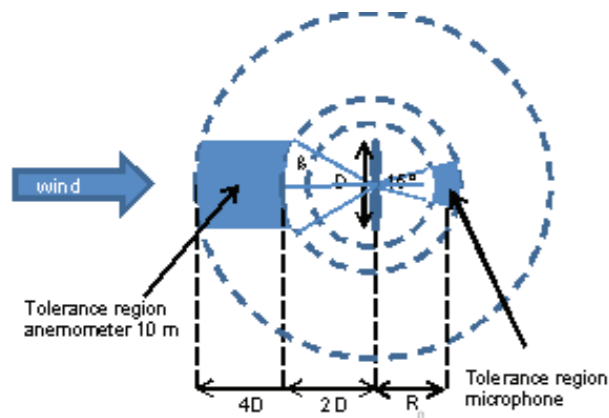
The measurement setup is illustrated in **Figure 1**. The microphone and anemometer positions depend on both the hub height  $H$  and the diameter of the rotor  $D$ . The optimum distance between tower and microphone is given by

$$R_0 = H + \frac{D}{2}, \pm 20\%, \quad (1)$$

where the microphone is positioned at a 15% corridor behind the gondola. In cases where the wind direction or the gondola position changes, the microphone then has to be rearranged to acquire a new background noise. The anemometer is located at a distance in between  $2D$  and  $4D$  within the corridor

$$\beta = \frac{z-z_{ref}}{H-z_{ref}}(\beta_{max} - \beta_{min}) + \beta_{min} \quad (2)$$

in a height of apx.  $z=10$  m if possible and  $z_{ref}=10$  m. Furthermore, data monitored by the wind turbine itself, e.g. weather data at hub height, rotational speed, pitch, gondola position and produced electrical power have to be taken into account.



**Figure 1:** Top view of the standard measurement setup in accordance to IEC64100. Possible locations for microphone and anemometer are indicated in blue

Even though it seems obvious to record the noise while the turbine is operating (ON – operation noise), an additional background noise (BG), recorded at the same position while the turbine is switched off, is required in order to eliminate environmental influences such as turbines located nearby, streets, wind, rivers, etc. These influences have not to be taken into account within the analysis sequence.

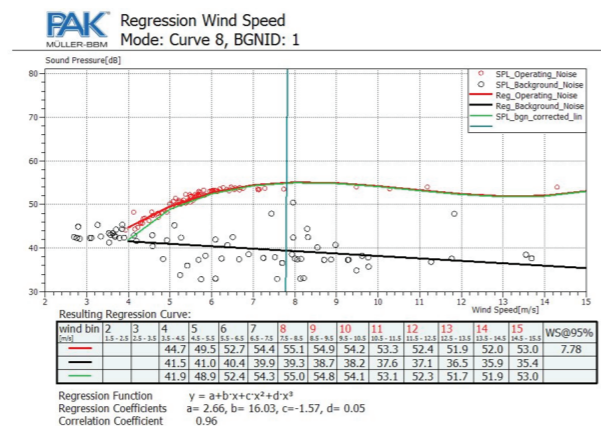
### B. Required Analysis

Prior to analysis in PAK software, the normalized wind speed is calculated by applying a regression curve with coefficients derived from the power curves. The normalized speed is based on the power produced. This is valid up to 95% of the maximum power. Larger values are calculated using the measured wind speed and the factor  $\kappa$  reflecting the ratio between the measured and calculated wind speed. The acquired sound pressure and the normalized wind speed are subsequently averaged with an averaging time of 60 s. The sound pressure level is classified into so-called wind bins, where the wind speed is divided into bins with 1 m/s width and centered at integer values, according to the synchronously measured/calculated wind speed. Regression curves are calculated for the operating and background noise. The level of the recorded noise  $L_{s+n}$  is subsequently corrected by the level of the background noise  $L_n$  at the same microphone position with

$$L_s = 10 \lg[10^{0.1L_{s+n}} - 10^{0.1L_n}], \quad (3)$$

This results in the operating noise  $L_s$  for differences larger than 6 dB between operating and background noise. The correction is otherwise performed by subtracting 1.3 dB. The result is illustrated in **Figure 2**. The corrected sound pressure level is used to calculate the emitted sound power  $L_w$  with

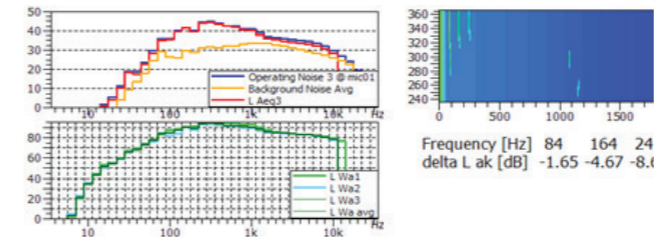
$$L_w = L - 6 + 10 \lg \left[ \frac{4\pi R_0^2}{1} \right], \quad (4)$$



**Figure 2:** Regression curves and resulting sound pressure levels for operating noise, background noise and the corrected sound pressure level depending on the current wind speed

Only selected data has been applied to calculate the regression curves and will be used for further analyses. It is now possible to calculate the 3<sup>rd</sup> octaves and the tonality as both the sound pressure and the wind speed are already classified into wind bins. A correction of the background noise is performed to eliminate frequencies from other sources at selected time stamps where the averaged wind speed is close to the wind bin center. This is in contrast to DIN 45681 [3]. In both cases multiple operating noises are used and corrected by the assigned background noise. The sound power is calculated based on the corrected 3<sup>rd</sup> octaves. Exemplary analyses are illustrated in **Figure 3**.

In order to achieve reliable results, the analyses should not only be performed at time stamps with averaged wind speeds near the wind speed center. On the one hand extreme values are frequently represented by outliers which would alter the resulting sound power. On the other hand the difference between operating and background noise should be at least 6 dB in order to limit the influence of the background noise.



**Figure 3:** a) Shows 3rd octave levels for operating and background noise and the resulting correction  $L Leq$  b) Sound powers of all three required time stamps and the resulting average c) Tonality as spectrum over time for two minutes. Averaged tones are illustrated in the table below

## 3. UNDERSTANDING THE WIND TURBINE BETTER

From the previously described analyses it is only possible to decide whether a turbine fulfills legislative regulations or not. In order to design a quiet and efficient turbine, additional information is required to describe the behavior of the turbine both in operation and in idle mode when wind excites the turbine. This makes it possible to look into further details as well as to visualize and to solve occurring problems.

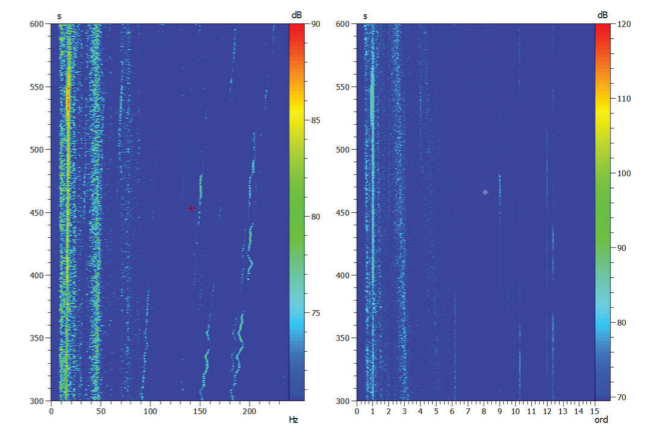
### A. Rotational Analysis

Wind turbines can cause undesirable noises and vibrations. In the case below, a turbine's gearbox was monitored as this is the main source for the rotating sound besides the rotating blades. While blades usually reach only low rotational speeds, both the generator and the gearbox can reach high rotational speeds which results in annoying high frequencies. These can either be heard or inducted into the structure resulting in disturbing vibrations. Therefore it seems reasonable to try to correlate rotational speed with both airborne and structure-borne sound. To assign annoying noises and vibrations to single components, users utilize different rotational analyses. A basic requirement for analyzing rotational systems is an exact recording of the rotational speed using high-resolution tachometer inputs.

### B. Order Analysis

It is possible to only use an ordinary FFT for analysis purposes. In this case, the rotational speed is usually shown as a specific line including the harmonics as side lines. This can be effective for quasi static signals and constant rotational speeds. Run-ups and run downs have to be considered more carefully. The most crucial areas are fast changes within the FFT window resulting in a smearing of individual lines.

An order analysis with digital resampling of the measurement data, allows the noise sources of rotating components to be matched with the harmonics of the rotational speed. As such, it seems reasonable to measure the rotational speed and apply a so-called digital resampling. While FFT usually has a fixed window size based in the time domain, the window size in the case below is based on the number of rotations, resulting in shorter windows during fast rotations or changes. In this way the signal and the actual rotation can be correlated more precisely to the acoustic or vibrational data.



**Figure 4:** Order tracking at the gearbox

### C. Sound Localization

As the dimension of a turbine makes the localization of possible sound sources difficult, a more advanced estimation of the sound source of a turbine is usually required. Complex microphone arrays are frequently applied [6] to narrow down possible sound sources. Currently various different algorithms are used to analyze the acquired data [7]. Usually beam forming and deconvolution algorithms are employed to calculate possible sound locations based on run time and phase differences.

The first step is the design and construction of a microphone array that addresses a specific predefined frequency range. A rule of thumb is that the maximum and minimum wave lengths are limited by the distances of the microphones. An array has to be large enough to cover low frequencies. The spatial resolution  $R$  of the localization capabilities is limited by both the distance  $r$  from the object of interest and the size  $D$  of the array with

$$R = \frac{a * r * \lambda}{D} \quad (5)$$

where  $\lambda$  is the wavelength of the emitted noise. It seems reasonable to design various arrays for different applications. With desired frequencies as low as 100 Hz and distances of apx. 100 m, it becomes obvious that a conventional layout is not possible due to the size of the array. The solution is to place microphones horizontally, as illustrated in **Figure 4**. The individual microphones are placed directly on the ground using wooden plates and wind shields. A distributed measurement setup as shown in section 5 is suggested due to the distance that has to be covered and the large amount of applied microphones required.



**Figure 5:** Principle setup of array and turbine





Figure 6: A localized sound emitted by the generator of a wind turbine

## D. Structural Analysis

Wind turbines are not only affected by static forces but also by dynamic excitations. These excitations are usually caused by both wind and rotating parts (e.g. gearbox) whereas imbalances could be the source of excitation. Each structure has its own specific vibrational characteristics, where especially the so-called eigenfrequencies have to be considered as standing waveforms. The following modal parameters describe the structure:

- Eigenfrequency
- Eigenwaveform
- Eigendamping.

The parameters are calculated with a matrix of transfer functions where both Impact Measurements [8] and Shaker Measurements can be performed to calculate the transfer functions. A special case occurs when the excitation frequency equals the eigenfrequency of a part or the structure. Depending on the damping of the structure, high amplitudes can be reached. Potential damage can occur from resonance.

Two approaches to optimizing the structure are available:

- Reducing the dynamic excitation, which is not always possible due to external limitations; and
- Changing the eigenfrequencies so that they do not match the excitation frequencies.

The simplest task is usually Impact Measurement. Here, an impact hammer is used to excite the structure while multiple accelerometers acquire data at the response position. In this way, the transfer function between the excitation (force) and the response positions can be calculated, see Figure 7, and then used for modal analysis. The dynamic stiffness of a structure is determined when the excitation and response position are equal.

Shaker Measurement calculates transfer functions between the force measured at the shaker and the acceleration measured at the response position. Different to impact measurement, excitations can be performed over a longer period of time. Even highly damped structures can be excited by a high signal-to-noise ratio at high frequencies. This results in a high frequency resolution. Therefore more precise results within the Modal Analysis can be achieved.

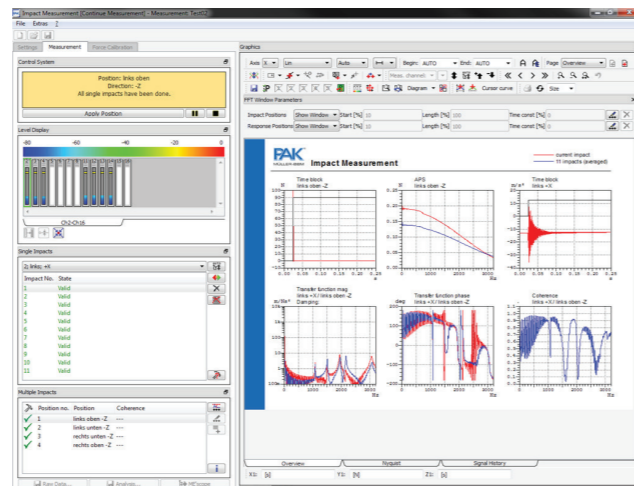


Figure 7: Exemplary transfer functions of an impact measurement

The PAK system can be used to conduct the measurement in various modes at different excitation and response positions, while calculating transfer functions at the same time.

By acquiring operational data or data excited with an impact hammer or shaker at different sensor positions, makes it possible to determine the vibrational pattern of a structure using Operational Deflection Shape Analysis (ODS). The vibration pattern is then shown as an animated geometry illustrated in Figure 8 a). In the presented case below, two different options are available. On the one hand it is possible to animate the time domain where all available frequencies are included. On the other hand it is possible to analyze the vibration pattern for a specific frequency or order. In this approach the desired frequency line is specified in an APS as illustrated in Figure 8 b). A highly precise order tracking or digital resampling should be performed in order to avoid smeared orders extracted from the FFT spectrum.

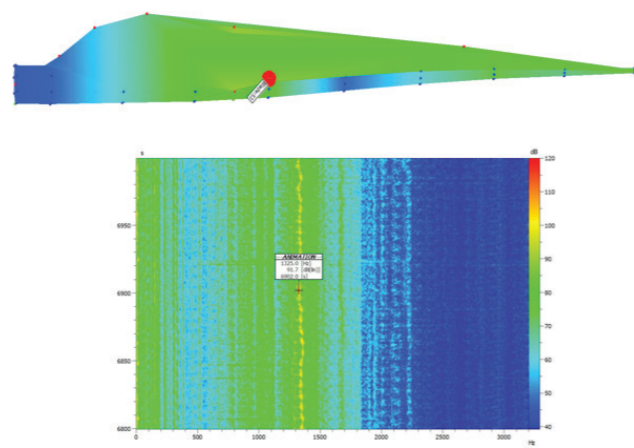


Figure 8: a) Exemplary ODS with Campbell colors indicating the amplitude  
b) Exemplary APS for the selection of frequencies to be animated

## E. Transfer Path Analysis

As wind turbines are rather complex and huge structures, it is quite difficult to find specific sources and transfer paths of both airborne and structure-borne noises observed at a predefined receiver location. Hence, Transfer Path Analysis (TPA) [9] is applied. This analysis method traces vibration or noise through a set of known transfer pathways to the receiver. It aims to provide further insight into the structure and identifies components that need to be altered in order to solve a concern. It is possible to set the receiver location to the microphone position specified in IEC64100. In this way, possible sources and paths from the wind turbine to the observation point are determined.

TPA describes the system by

$$X_i * H_i = Y_i \quad (6)$$

where  $X$  represents both the airborne and structure-borne source signals,  $Y$  represents air-borne response signals and  $H$  is the transfer matrix, describing the paths through the structure to the receiver. The matrix dimensions are thereby given by the number of source signals, acquired throughout the testing process. As a result it is now possible to rank the contribution of different sources along different paths. In this way, it is possible to determine the influence of a source position for each individual receiver position. As illustrated in Figure 9, each individual source signal contributes to the overall signal, illustrated for 2 gearbox positions as well as the generator. It is possible to use the acquired data and simulate modifications at source positions and the transfer paths. This results in a Response Modification Analysis (RMA) where the effects of changing or altering components (e.g. a different stiffness) or the elimination of resonances can be evaluated.

In order to describe the entire structure efficiently, a vast number of different source positions must be captured and refined through the actual analysis. Data acquisition systems must be able to handle large amounts of data.

The TPA itself can be applied during the design process for acoustic optimization and helps to match overall acoustic targets to the various individual components. TPA is frequently used for troubleshooting, when problems are discovered late in the development process or when components are changed, e.g. the gearbox. Using this method, it is possible to detect the positions where changes can be performed effectively.

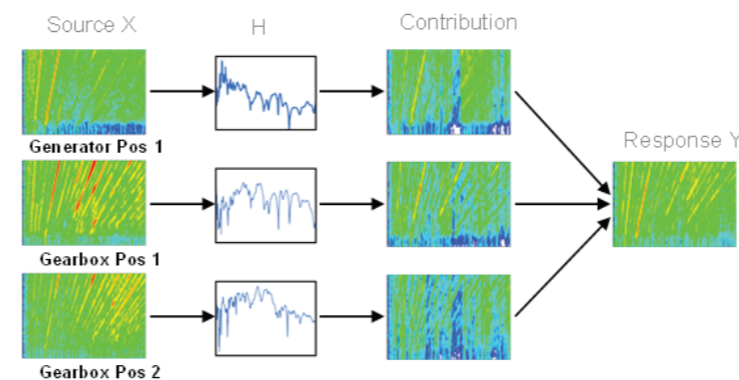


Figure 9: Exemplary contributions of the generator and gearbox to the overall observed signal.

## 4. CHALLENGES DURING THE MEASUREMENT

Although the measurement task described in IEC64100 seems simple, it requires a complex setup and an experienced measurement team. If not, it is almost impossible to collect enough meaningful data in a short amount of time.

### A. Collecting a sufficient amount of data in a short amount of time

The IEC 61400 describes the measurement procedure for one specified power curve from one microphone position. Multiple power curves and microphone positions are omitted. Both factors are obstacles to a fast, reliable and easy data acquisition. For each wind bin (in the case below the bins 2-15), at least three averaged points are required to fulfill the demands of the regulation. In order to receive meaningful results, especially when calculating regression curves and determining the subsequent sound power, the acquisition of more data is required. The common approach to collect both sufficient and meaningful data for a single power curve is to acquire data over a long period of time. The PAK system provides a more flexible approach. As an engineer cannot influence wind speed and hence the current emitted power, it is important to monitor the amount of collected data for each bin and operating mode online, instead of in the subsequent post-processing. It is recommended that the elements within each wind bin during the measurement are counted. As soon as a bin is considered full (more than ten elements per wind bin are suggested) and the wind speed as currently constant, another power curve for the wind turbine can be set. The PAK system automatically adjusts the data management to the selected power curve. The same procedure is performed when the microphone position needs to be adjusted. This procedure uses only one background noise for each microphone position and all modes that speed up data acquisition. As soon as the wind speed changes, the power curves can be once more adjusted, and data collected for other bins.

### B. Challenges of the measurement setup

While systems with high channel counts are frequently employed on standard test benches, measurements on wind turbines face engineers with additional challenges. These are usually related to the distances which have to be covered during sensor placement.

**Technical Issues** Cabling is a critical technical issue as the distance between sensor and measurement frontend has to be kept as short as possible. In order to achieve high signal quality and a high signal-to-noise ratio (SNR), cables must be of a high quality. It is laborious to apply sensors at distant positions and connect these with a centralized frontend. Thereby the signal quality has to be taken into account. Many sensors can have a maximum cable length. Although ICP® sensors and microphones can be driven with long cables; others, e.g. charge and strain gauges, have shorter ranges. Regardless, the average length is less than an average wind turbine with its hub height of approximately 100 m and an average blade with 73 m length. A suitable solution for each applied sensor must be found.

It is also often not possible to apply cables, e.g. between hub and nacelle, due to its moving parts in-between and OEMs usually do not install a loop through for a wide range of signals.

**Practical Issues** Cable setup is time consuming. The standard setup requires more time than the actual measurement when all sensors are attached to a centralized frontend and all cables have to be laid neatly.

**Environmental Challenges** As wind turbines are usually located in or around public regions; environmental conditions must be taken into account. These are primary influenced by the surrounding topology, illustrated in **Figure 10**. Here trees, rivers, streets, buildings or even animals present obstacles. All these factors compound the need for direct cabling with a centralized data acquisition system. As wind turbines are usually built in farms, where noise emitted by neighboring plants influences the acoustical analysis. Other objects may also disturb the measurement. Possible sensor positions must also take wind speed and direction into account. The IEC61400 requires the recording of a so-called background noise at each microphone position. This will be used to correct the recorded operating noise according to the corresponding wind speed. For this to take place, the measurement setup must be flexible enough to cover all possible combinations of power curves, wind directions and wind speed. As such, both the hardware setup and the management of data must be user-friendly, with very little effort required to change the relevant settings.



**Figure 10:** Possible environmental challenges can be animals, streets, trees or other background noises such as cars or other wind turbines nearby

## 5. DISTRIBUTED DATA ACQUISITION - THE TAILOR-MADE TECHNICAL SOLUTION

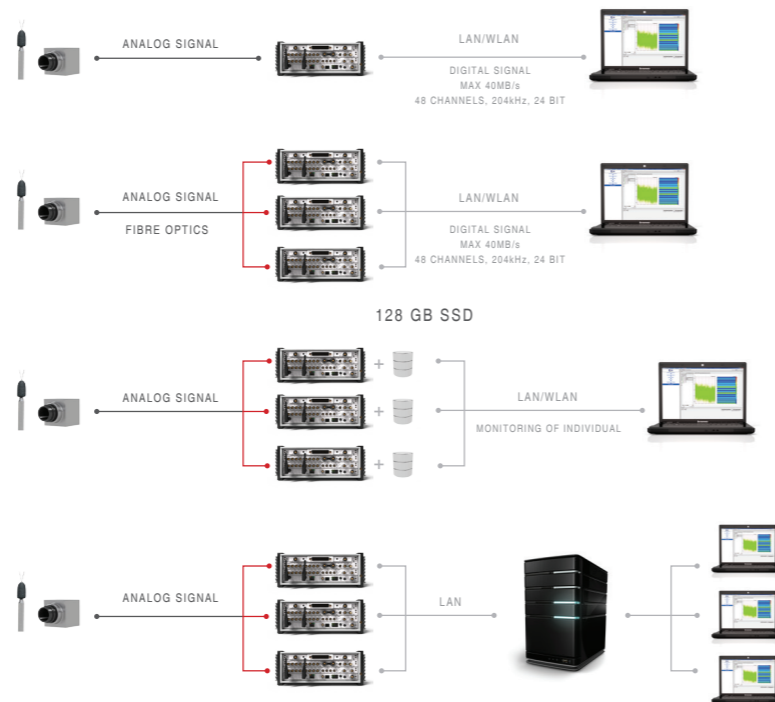
Limitations for data acquisition in complex environments, such as on wind turbines, require a specialized system in order to acquire data from distributed positions close to the relevant points of interest. Such a system not only has to overcome the difficulties presented but must also acquire correct data at a reasonable effort and cost. A few possible solutions, based on the works of Arsić et al [4] are presented as follows.

### 5.1 Common Approaches

Within the last few years various approaches for distributed data acquisition have been implemented and applied to a wide range of applications. **Figure 11** illustrates possible setups with varying scope and level of performance.

The most common setup is shown in **Figure 11 a)**. Here, the analog signals from a wide range of sensors are collected and digitalized by one central PAK MKII frontend. Data is then transferred to a workstation or laptop via LAN or WLAN and is stored at a maximum rate of 40 MB/s, corresponding to 48 channels sampled at 204.8 kHz in 24-bit mode. The main advantage of a direct link to a PC is the

ability to monitor the measurement and in this case the wind turbine online. Users can conduct analyses, such as spectra, psychoacoustics and order tracking online, allowing for immediate conclusions and troubleshooting. As the length of cables, especially for sensors, is crucial, a first step for reliable, distributed data acquisition is achieved by using multiple PAK MKII frontends. This is illustrated in **Figure 11 b)**. All frontends are placed close to the required sensor positions, while keeping the cable lengths short. The distance between frontends is limited by the network connection used for the data transfer. Covering distances of up to 1 km by fiber-optic cables has been proven under operating conditions. This increases the channel count without the need to upgrade to more powerful controllers. Data digitalized by each frontend is transferred to a central PC at a maximum transfer rate of 40 MB/s. While a wide range of analyses is not dependent on phase-synchronization (e.g. alignment of averaged values or the overall level), especially transfer functions can only be determined correctly when data is aligned even in phase information. A centralized clock distributed over fiber-optics synchronizes PAK MKII frontends with a phase error of 0.2%, at a frequency of 10 kHz. This setup is highlighted in red in **Figure 11 b)** below. With a growing amount of sensors and the need for higher sampling rates, the current maximum data rate of 40 MB/s limits few measurement tasks. The approach illustrated in **Figure 11 c)** is applied for high channel counts and large amounts of data. Each PAK MKII frontend can contain an optional internal SSD for Local Storage. A selected amount of channels can be transferred to a PC for monitoring and analysis purposes. Each individual frontend is able to store 40 MB/s on the internal hard drive, allowing more than enough channels with sampling rates of up to 204.8 kHz to be stored and synchronized. Due to the system's stability and the limited amount of data that has to be transferred to the PC, a direct link using WLAN is also possible. Once the measurement campaign is complete, the data stored on the single frontends is transferred to a PC via the network and merged into one large dataset. In this way, users can work with a single dataset with no further effort on data management required.



**Figure 11:** Overview of different approaches for distributed data acquisition a) A centralized frontend and immediate data transfer to a PC b) Multiple synchronized frontends and centralized data storage on a PC c) A cluster of synchronized frontends with local storage and a monitoring system d) A cluster of frontends within a Server-Client setup, allowing data distribution to selected clients without interference to the current measurement campaign.

### 5.2 A Server-Client based topology

To analyze the details of a wind turbine, not only a large amount of sensors is required but also a long period of data acquisition is needed. All possible wind speed and power curves have to be captured. The recommended setup is described in **Figure 11 c)**. Here the PAK system enables users to monitor and record data from distributed measurement points over a long period of time. Additionally, data must often be accessed for other purposes, e.g. when providing data to other departments such as aerodynamics; when acquiring data only at predefined events or even when the measurement setup must be changed without interrupting the monitoring or recording of data. Server-Client technology enables the fast and reliable access of selected data. This is illustrated in **Figure 11 d)**. A central server manages the data acquired by the individual frontends. The server's main tasks include monitoring the measurement, managing changes in the measurement setup and distributing data to attached clients. Each client can be connected during any time period; either at the measurement start or even during the measurement. In doing so, clients can record and analyze the entire data set or only selected channels of interest. The server can fulfill or deny the clients' requests and provide only a specified data selection. This is important, as not all users should access all relevant operational data of the wind turbine. A consultant for blade design for example does not necessarily need the currently emitted electrical power and the current rotational speed of the gearbox. Hence, data access is limited to predefined user groups.



**Figure 12:** An exemplary wireless distributed data acquisition system for wind turbines

### 5.3 A Wireless Solution

The previously described approaches for data acquisition require at least one cable to each frontend. These are usually Ethernet cables for transferring data and fiber-optics for phase-synchronization. In some situations however an entirely wireless solution is preferred. Such a wireless solution is illustrated in **Figure 12**. All PAK MKII frontends are placed directly at the points of interest, while keeping the sensor cables as short as possible. Local storage enables users to set up a WLAN network, as the amount of data transferred is negligible. Only control commands, such as start/stop or automated range detection, are transmitted. Should some channels need to be monitored; only the selected channels are transferred without interfering with the measurement. Even in the case that the wireless network fails, the measurement will continue and full data integrity preserved. GPS is used for synchronization. Consequently wiring is limited to an absolute minimum.

### 5.4. A standalone solution

All solutions require qualified operators, capable of monitoring the system and confirming signal integrity. PAK provides powerful tools for online analysis that are not needed for every task. Additionally, the required windows based PC or laptop is not suitable for every environment. An easy to configure and easy to handle standalone solution is required and found in PAK capture suite. The PAK MKII frontend is now equipped with additional intelligence. After installing the sensors and switching the frontend on, it is already in live mode, waiting for a trigger condition to record data. A possible solution is to use an iOS® or Android™ based smart device to start and stop the recording. The connection for this is established via WLAN or any other IP based connection. Users are able to configure the measurement, control the current levels and view completed measurements. In this way, it is possible to equip the public with smart devices and let them record disturbing noises with no additional training required. Residents have not only the possibility to record disturbing noises, themselves, they also feel that their voice has been heard and that they are included into the process.

This standalone approach introduces other possible applications. Wind turbines can now be easily monitored over a long period of time, as the only requirement is a stable, standalone data acquisition system. Users are now able to access their measurement at any time to see what has happened and is currently happening. Over time, all environmental conditions can be captured and easily analyzed.



**Figure 13:** Exemplary setup of PAK capture suite with an iPhone as monitoring and configuration device



## 6. CONCLUSION

An overview on current state of the art data acquisition for acoustic analysis of wind turbines has been provided. While the setup required by the IEC61400 is only used to evaluate a wind turbine in terms of electrical power, wind speed and sound pressure at predefined positions, an extended setup addressing a wide range of additional sensors is required. This collected data can be subsequently used within the R&D process in order to determine the reasons of possible disturbing sounds or high sound power levels. This is usually performed by considering rotational speed, acceleration and sound pressure. As the distances between desired sensor positions are large and cabling complex, a distributed data acquisition system is recommended. PAK MKII frontends can be placed close to the sensor, guaranteeing a high quality signal and reliable internal storage. If required, phase-synchronization is achieved with only one additional fiber-optic cable.

Further development and research continues with the aim of simplifying the measurement setup and enhancing measurements. An entirely wireless solution, where even phase-synchronization is granted, must be found. Therefore synchronization, even over large distances, has to be established. Such synchronization can be performed over GPS, which is highly precise, and can be used to trigger at the exactly same time stamps while providing low phase error.

Current setups are fast and flexible but require experienced users, as various error sources must be monitored. Designed as "One man Operating System", one operator can setup and monitor the measurement. This operator is equipped to observe and detect unusual events that require the measurement to be triggered. As the monitoring of a measurement is especially exhausting and experts are expensive, a remote solution is required. An alternative is to empower the population in the vicinity to trigger the measurement should unusual events occur.

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