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Automated wind farm noise measurement systems with feature analysis

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Summary

The measurement of noise immissions at typical residential neighbours to wind farms offers challenges not ordinarily found in other environmental noise measurements. These include the need to measure noise levels which are relatively low, often comparable to the residual noise in the absence of the turbines, and under windy conditions. Furthermore, the variability of noise levels is crucially dependent on the changes in the weather conditions. The requirement to establish these dependencies means that noise measurements often extend over periods of months. Finally, the measurements are frequently undertaken in remote rural locations which can prove difficult or time-consuming to access.

The noise monitoring process ordinarily requires the deployment of a logging system followed by regular site visits to manually download data. The downloaded noise data is then analysed against separately acquired operational/meteorological data from the wind farm. The need to manually download noise data is driven by size of the audio data required for subsequent acoustic feature analysis.

This paper will discuss the development of a remote noise monitoring and analysis system designed to assist in the management of the large amounts of data that may result. The design philosophy is believed to be unique in two respects. First, the objective analysis of acoustic features, including for example tones and amplitude modulation, is objectively implemented, thereby greatly reducing the effort required to post-process data. Second, the system can be directly linked in to operational/meteorological data potentially allowing an ongoing and constantly updated analysis of data as it is gathered, rather than the more conventional approach of only undertaking analysis following download of the relevant data for specific preceding periods. These features combined mean that real time feedback on noise in terms of both overall levels and features can be provided to involved parties in real time, thereby allowing for more efficient and cost-effective analysis of

wind turbine noise in practical situations and the potential to more quickly develop effective mitigation strategies.

1. Introduction

The rapid evolution in technology of sound measurement and analysis systems has meant that the capabilities of modern sound level meters have expanded dramatically. A wide range of measurement indices as well as audio recordings can now be acquired with standard units. In tandem with this, improvements in mobile and landline data networks have enhanced the options available for remote communications and allowed the development of advanced automated and autonomous noise measurement systems. The present paper will discuss the advantages of these systems. It will also consider the specific challenges involved with the applications of these systems to wind farm noise measurements, setting out some examples of actual applications and current developments being progressed.

2. Prior experience of automated measurement systems

2.1 Remote monitoring system.

The authors have extensive experience of developing bespoke noise-monitoring solutions. Compared to standard, “off-the-shelf” systems, these dedicated systems are custom-designed to fulfil a specific combination of tasks, such as measuring a number of different environmental pollutants, including noise. Measured data can be acquired, processed, stored and published in a number of ways depending on the application required.

Figure 1 shows a long-term construction noise monitoring system which is typical of the type of systems which have been operational for several years. Noise measurements are made at one second resolution at two locations (one on the border of the site and another located further away at a noise sensitive receptor). Other systems also measure vibration and dust using dedicated sensors. In addition to standard noise indices, continuous audio recordings are made and stored using an on-site data server. The different components of the system are connected using ‘bridge’ wireless antennas. A mobile data connection is used to transmit essential noise data to an external server every five minutes. This server is connected to a dedicated public web interface [1] which can be used by members of the public.

Similar capabilities have been developed for a site where data for both noise and vibration were presented [2]. Here the web interface allows measured noise and vibration data to be interrogated, both for the current time period as well as historical records. Raw measured data can be displayed in both tabular and graphical format, and again interrogated in a number of interactive ways. This allows transparent display of information which any interested party can interrogate.

Figure 1 – a dedicated construction noise, dust and vibration monitoring solution developed by the authors (circled in red)

home | historical data | help

Current Day - Summary

Current date and time:	Monday 18 Aug 2014 16:07:19			
Latest LAeq,5min	62.0 dB	Calculated from 5 values: 18/08/2014 16:00:00 to 18/08/2014 16:04:00 inclusive (times period start)		
Latest 5 min PPVs (mm/s):	0.0214	0.0343	0.0258	Calculated from 5 values: 18/08/2014 16:00:01 to 18/08/2014 16:04:01 inclusive (times period start)
Noise LAeq (08:00 to 18:00)	60.5 dB			

Noise - Intensive Periods		**Vibration - Intensive Periods**			
Period	LAeq (dB)	Period	PPVx (mm/s)	PPVy (mm/s)	PPVz (mm/s)
08:00 to 10:00	62.4	08:00 to 10:00	0.0449	0.0269	0.0578
12:00 to 14:00	58.7	12:00 to 14:00	0.0507	0.0235	0.1002
16:00 to 18:00	62.0	16:00 to 18:00	0.0214	0.0343	0.0258
Total	*60.9*	*Maximum*	*0.0507*	*0.0343*	*0.1002*

Noise - Less Intense Periods		**Vibration - Less Intense Periods**			
Period	LAeq (dB)	Period	PPVx (mm/s)	PPVy (mm/s)	PPVz (mm/s)
10:00 to 12:00	59.7	10:00 to 12:00	0.0641	0.0306	0.0739
14:00 to 16:00	60.3	14:00 to 16:00	0.0519	0.0583	0.0673
Total	*60.0*	*Maximum*	*0.0641*	*0.0583*	*0.0739*

Figure 2 – example of a monitoring system public web interface

2.2 Specific challenges of automated wind farm noise monitoring

By the very nature of wind farm design, wind farm noise levels at residential properties are often comparable with the level of naturally occurring noise that would be present regardless of the presence of the wind farm. The measured noise levels will necessarily include contributions from both the wind farm noise and also any sources of extraneous noise that may be occurring during the measurement period. It can therefore be challenging to determine the exact contribution of the specific source, wind turbine noise, from what is referred to as the 'residual background' noise.

The variability of noise levels from wind farms must also be recognised. This poses some significant challenges. First of all, wind farm noise is specifically and strongly dependent on weather conditions, to an extent which sets it apart from many sources such as the construction noise considered in the previous section. This dependence is mainly with regard to wind speeds, which are, to the frustration of both acoustic practitioners and operators, outside of our control. But wind direction is also a key variable, particularly in the case of far-field measurements. At some locations the wind directions of interest may only occur infrequently, particularly if these desired wind directions correspond to non-prevailing conditions. At some sites variations in atmospheric stability may also be relevant. Furthermore, complex propagation effects, as well as variations in various other sources of noise in the environment, introduce additional variability.

Capturing this variability and minimising uncertainties requires in practice extended measurement of weeks or months rather than hours. As wind farm sites are often situated in remote areas, this means that if disturbance is reported measurement equipment can take some time to deploy and similar conditions may take a long time to manifest themselves, requiring several weeks or more data gathering being required to obtain a suitable range of data. This can lead to frustration for the affected residents or communities.

The measurement durations involved introduce key issues, particularly with regards to data storage requirements. Audio recordings are often captured both for source identification through playback and also for undertaking narrow-band analysis of tonality. The necessity to undertake objective analysis for tonality means that uncompressed audio recordings are required. Limiting audio recording to a maximum of two minutes duration every ten minutes is standard practice, but this still amounts to large amounts of data which are challenging to handle. Even if limited to a reasonable audio sampling rate, uncompressed audio recordings can represent a rate of data capture of approximately 60 Mb/hour.

Measurements are of course required in the windy conditions in which the wind turbines operate. In some cases [3], the measurement location can be sheltered from the wind by forestry or the terrain but in other cases, the location may be relatively exposed. In order to minimise the contribution of wind-induced noise on the microphone, it is necessary to use enhanced windshield systems. Most environmental noise monitoring solutions available on the market are equipped with standard microphone windshield system, consisting in a single foam ball of

less than 100 mm diameter. These will not be sufficient in exposed, windy conditions [4].

The authors have regularly used a custom design 2-layer system based upon the advice given in the report Noise Measurements in Windy Conditions [5]. Measurements of the relative reduction in wind-induced noise undertaken using a rotating boom system [6] suggest that such two-layer, secondary windshield systems offers a supplementary reduction of the order of 10 dB(A) compared to a smaller traditional windshield over the wide range of wind speeds that are of interest when measuring wind turbine noise. Other systems developed have used a secondary system, as considered in a separate paper [7].

Given the variability experienced, time-synchronisation of all the different elements of the monitoring chain is essential. This is best accomplished through the use of a single time reference for all noise and weather measurement systems, which should also ideally match that used by the wind turbine control system (Supervisory Control And Data Acquisition or SCADA). The latter often adopt Universal Coordinated Time (UTC) as a reference.

2.3 Example implementations of wind farm noise monitoring

The first implementation of an autonomous wind farm noise monitoring system described in this paper was installed in relative proximity of the turbines at a secure location as seen in Figure 3. This was at the request of a site operator wishing to monitor aspects of the noise output by the turbines under different conditions due to external operating restrictions. The system is based on 01dB DUO sound level meter, with supporting backup power regulation and connectivity infrastructure. It transfers the measured data automatically and periodically at scheduled intervals to a dedicated server within a nearby building. The server includes a fault-tolerant ‘mirrored’ disk system for long-term storage of data, and an uninterruptable power supply.

Raw data are separated into contiguous periodic ten minute data periods with 100 millisecond values of L_{Aeq} and L_{AF} ‘Fast’ time-weighted values recorded as well as $L_{eq,100ms}$ values within each one-third octave band. This allows the calculation of noise metrics such as $L_{Aeq,10min}$ and $L_{A90,10min}$ which are commonly referenced in the UK. In addition, a simple Ethernet remote control can be remotely accessed to initiate audio recordings on a continuous and contiguous ten minute basis. A permanent connection to the server was also provided via the Internet.

Figure 3 – Automated wind farm monitoring - example 1

Scheduled service visits are still required, for instance to maintain the performance of the system on at least an annual basis, for instrument checking, physical inspection of the installation to look of signs of deterioration and remedy any issues and to carry out external laboratory calibration. Most of the specialist tasks, such as adjustment of instrument measurement parameters, can be done remotely through an Internet connection. This means that more regular tasks such as interim calibration checks can be undertaken by local site operating staff following suitable training.

Figure 4 shows another example of a monitoring system installed in proximity to a residential property neighbouring a wind farm. The architecture of the system developed was similar. However this system undertakes regular audio recordings of two minute duration which are spaced every ten minutes to enable objective analysis for tonality. Measured noise data and audio recordings are pushed to a remote server after each ten minute period via a fixed landline connection. This allows post-processing of data for analysis of overall noise levels and tonality.

The inclusion of rain logging is necessary to obtain data on rainfall which may corrupt measurements, but these data are generally not captured by wind turbine control or meteorological systems. This is accomplished by use of a tipping bucket rain gauge installed near the noise measurement location. Bespoke software running on an embedded PC automatically transfers data from the rain logger to the data server via FTP at the end of each ten minute period.

Similar systems have also been developed to monitor onshore noise from construction of off-shore windfarms, where extended periods of pile driving, sometimes during the night, are required to build the turbine foundations.

Figure 4 – Long-term wind turbine monitoring system - example 2

3. Further developments

3.1 Continuous – automated level analysis

The examples above have shown practical systems which allow the long-term measurement of the various indices necessary for the analysis of wind turbine noise. The data acquired are captured robustly and transmitted through a communications network to a remote server for analysis. But to date, such systems have mainly relied on subsequent manual data analysis. This involves manually filtering and post-processing these data and then plotting results as a function of wind speeds and/or turbine operational parameters, these latter items generally

being obtained separately prior to their import into the assessment process. After this is completed, results are reported in the traditional way, but this can take time.

The analysis comprises many processes that can be automated, with specialist user supervision. Furthermore, the data produced by the wind farm control system can be imported and used directly to relate noise levels to the wind farm operating conditions. The authors are currently developing and testing an architecture which would allow live analysis of these data. The potential is there for implementing a ‘smarter’ system which would pre-process the acquired data and send only the necessary information to a central storage server. Communication, however, continues to represent a key challenge, including establishing the necessary links with the turbine control system in order for the direct acquisition of necessary turbine operational parameters. Current experience shows that this element of the system in particular must be determined in practice on a case by case basis accounting for installation-specific constraints and challenges.

In addition to the automated processing and storage of data, consideration must also be given to the presentation of the results and access to these data. The goal is to provide ‘live’ versions of charts of noise against wind speed or other relevant parameters. This allows determining the suitability of the acquired data and provides continuous feedback on the progress of the measurements. Ultimately this information can be provided on a website such as [2]. The ability to manage access rights to such websites means that results of the measurements could be made available either to the general public or specific groups, such as site operators, local authorities or third parties. Those having access to the information would be provided with the means to easily and quickly review overall noise results and/or specific recorded instances and their characteristics. This could allow a faster investigation and analysis of any complaints, thereby minimising the survey length and response times.

The first main output of the analysis would be the evolution of measured noise levels with wind speed. In order to better isolate wind farm noise from the background noise, it is common practice to filter acquired datasets using criteria such as time of day, exclusion of rainfall periods, and selection of key wind directions. This requires a detailed site knowledge and a review of the data. However, with some experience, basic filtering can be implemented to provide a preliminary filtered result. Figure 5 shows a representation of what such a filtered output could look like. Weather conditions and the amount of valid data collected could also be displayed.

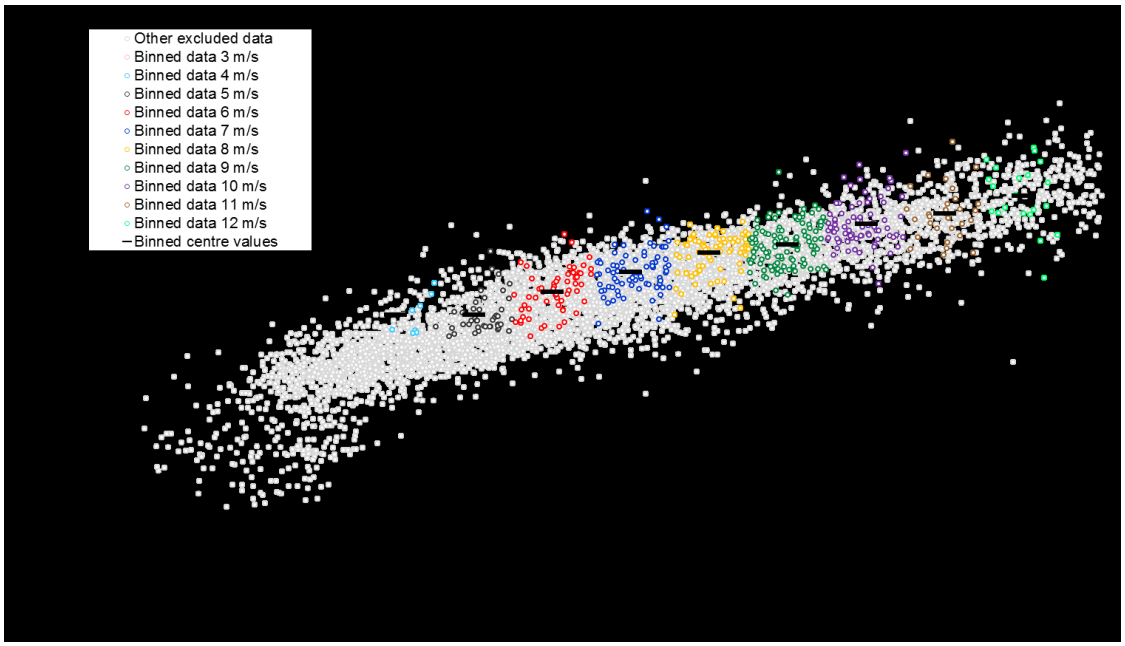

Figure 5 – representation of a 'live' analysis of measured noise levels, based on a selection of filters, with L_{A90} noise levels binned in integer wind speed categories. The un-filtered data are represented in grey.

3.2 Tonality analysis

Several methods are currently available for the analysis of tonality. Many of these lend themselves well to automated implementation [8,9]. Figure 6 below shows the output from a procedure developed by the authors, which implements the ETSU-R-97 methodology [9].

The narrow-band analysis required needs to be undertaken on the uncompressed raw measured audio. This can be done locally within the noise meter control system or at the data server, and subsequently stored, thus avoiding the need for transfer of large datasets which are then subsequently processed and analysed back in the office.

It is nevertheless important to be able to review individual recordings for subjective evaluation and for undertaking due diligence checks on the automated analysis process. For this purpose, suitably compressed audio formats can arguably be sufficient, thereby reducing the amount of data to store and transfer by approximately a third, which would be significant.

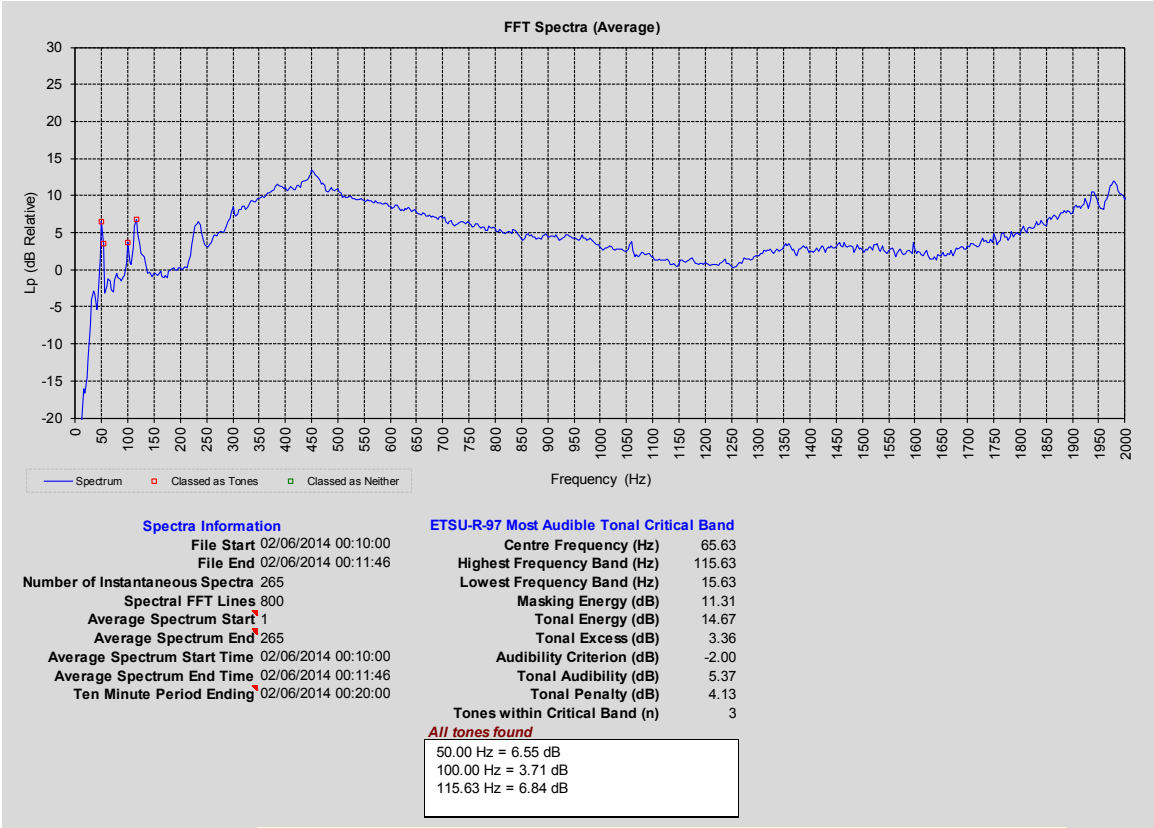

Figure 6 – Result of an automated ETSU-R-97 tonal analysis process developed by the authors – tones are highlighted in red in the spectrum, with the tonal audibility and indicative penalty displayed.

Whilst automated analysis has some risks, such as the identification of false positives (for example tones caused by vehicle movements), this can be compensated by the analysis of large datasets and filtering which will tend to average out spurious results. An automated process allows such bulk data processing to be undertaken. Site specific filtering could also be implemented: if for example a specific range of tonal frequencies could be identified, then detection of tones and rating of their audibility could be focused using a predetermined site-specific criteria.

3.3 AM analysis

The issue of amplitude modulated noise (often referred to as ‘blade swish’ or ‘AM’) arising from the operation of wind turbines currently represents a key area of research and discussion in the UK. The main difficulty is that at present there is no universally accepted objective methodology to quantify AM, nor is there any criteria against which the output result of an objective methodology can be tested.

A large number of publications have nonetheless presented results using techniques based on the frequency analysis of the acoustic A-weighted signal envelope, using different Fast Fourier Transform techniques (FFT), to produce a modulation spectrum. For example, the method produced by Lundmark [10] was

used successfully in a study looking at long-term variability of AM in different weather conditions [3]. Research such as that commissioned by RenewableUK [11] has shown that these techniques allow the automated identification of the presence of modulation in wind turbine sound to be identified, characterised and studied.

Figure 7 shows the results of the implementation of such a technique by the authors. This represents the evolution of the modulation spectrum with time. Using such outputs, the continued presence of modulation at a rate consistent with the rotational speed of the turbines could be readily identified.

Implementing these techniques with a remote monitoring system allows a fast response time and rapid analysis of this feature when it arises in different weather conditions. This could also possibly allow direct feedback of the effectiveness of mitigation techniques, such as those described in [12].

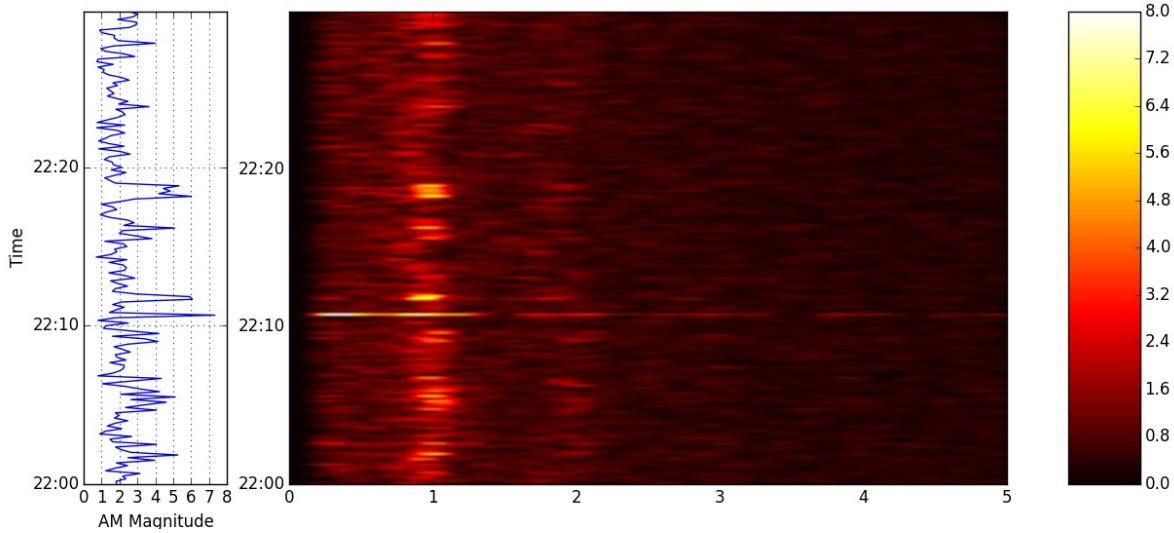

Figure 7 – Results of an automated modulation analysis for a 30 minute sample (200 Hz 1/3 octave band) – the coloured chart shows the modulation spectrum with time, and the value in blue the magnitude of the modulation at 1 Hz.

4. Conclusions

The measurement of wind turbine noise presents unique challenges when compared with monitoring other sources of environmental noise which must not be underestimated or overlooked. In particular, the variability of this source and the need to acquire a sufficient range of weather conditions translates to extended measurement periods, often in remote areas. This means that automated permanent or semi-permanent noise measurement systems can have great value in undertaking such surveys. It is however necessary to have dedicated systems which are adapted to the specific requirements of such measurements, including measuring in windy conditions. Monitoring results can be acquired and stored

locally and transmitted through the network for review and analysis but transfer and storage of audio recordings is a key challenge.

The authors have developed and installed several such systems in the UK. Techniques for the semi-automated analysis of noise levels and acoustic features are being developed. This could allow 'live' analysis results to be available to practitioners or interested parties. The availability of such information in real time would potentially reduce the delays associated with data collection, transfer and analysis, and allow a prompt reaction to any issues at the locations studied, including monitoring of the effectiveness of noise mitigation measures. It is hoped that further results can be presented at the conference.

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