The extraction of wind turbine condition related features using air-borne acoustic signals

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Abstract

Wind turbines vibration signals carry useful information about their conditions. However, such signals are usually very complex and comprise high number of vibratory signatures. Moreover, the cost of setting up vibration measurement systems using conventional accelerometers is very high especially in the case of multi-location measuring points are required.

This paper contributes towards developing an inexpensive and accurate condition monitoring method based on remotely measured air-born acoustic signals. Fault detection capabilities are assessed by determining its coherence with the well-understood vibration induced signals.

A new generation of recently improved condenser microphone used as input for the proposed coherence analysis algorithm. Special arrangement to eliminate reverberation problems associated with air-borne acoustic signals was designed. Consequently, coherence analysis is carried out to compare the information supplied by the accelerometer and the microphone of a three bladed horizontal wind turbine under different operating conditions. The air-borne acoustic signals exhibit good coherence with the vibration ones at rotating speed, gear meshing frequencies and fan passing frequency bands. More important, air-borne acoustic data was found to contain more pronounced information within wider spectrum compared with the vibration measurements.

The presented results open doors for deeper investigations on the diagnostic capabilities of such technique and probably lead to fully adoption by the wind turbine industry.

Keywords: Air-borne Acoustic; Vibrations, Wind Turbine, Condition Monitoring.

1. Introduction

Wind energy can be converted to electricity by rotating blades connected to drivetrains. The drivetrains have different assembly configurations so that can be companied together rotating blades to design wind turbines, as shown in Figure 1. Wind turbine drivetrains are categorized as the direct drive (DD) and geared type which depend on the gearbox system. It also consists of the hub that is connected with blades as the input, shaft, and the generator as the output. Different types of generators such as the squirrel cage induction generator (SCIG), the doubly-fed induction generator (DFIG), and the permanent magnet synchronous generator (PMSG) can be used in the wind turbine [1].

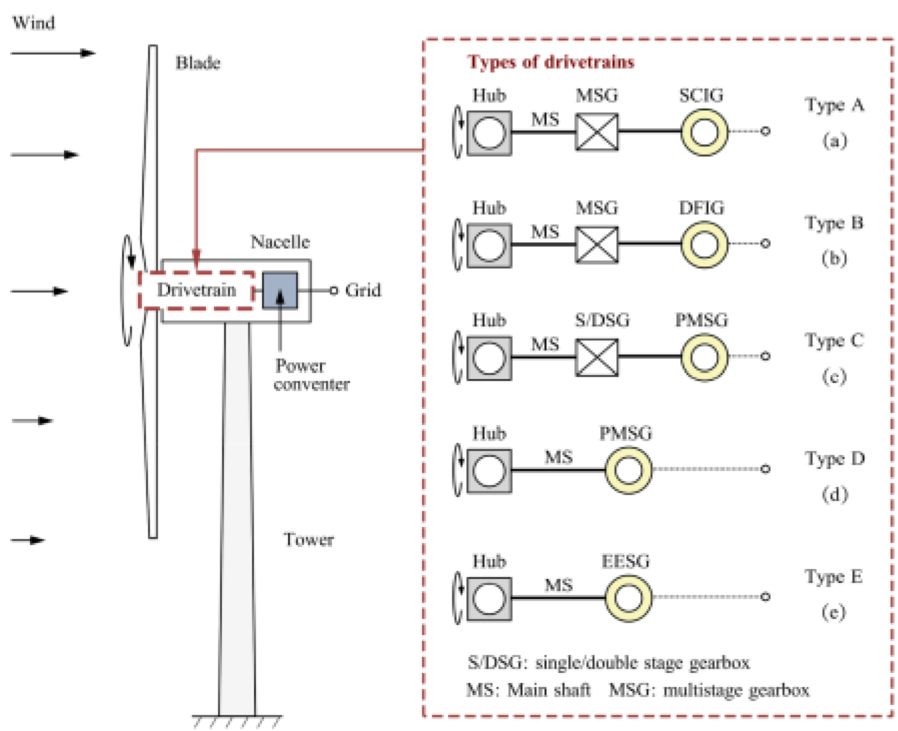

Figure 1 Configurations of wind turbine drivetrains [1]

Wind turbines act to extract energy as much as can from the wind via a larger rotor which is in fact a combination of blades and the hub. At the same time, a big issue will appear which is heavier loads will be induced, as illustrated in Figure 2 [1].

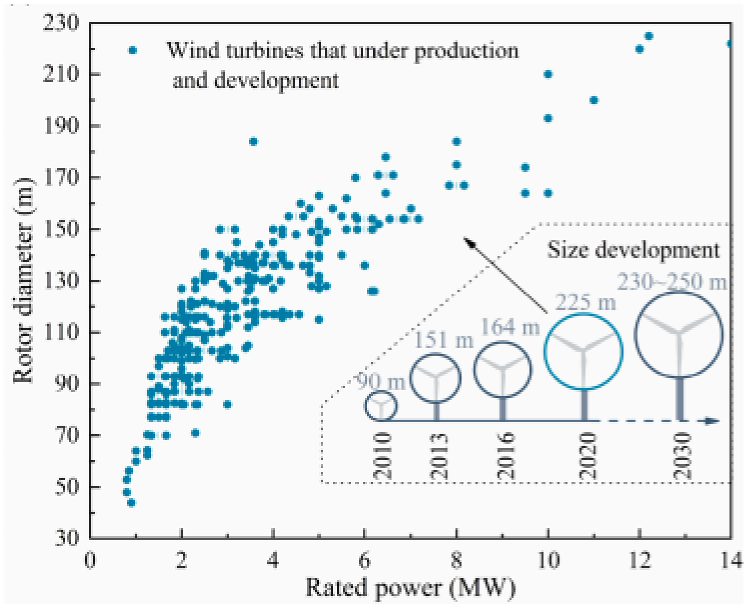

Figure 2 Wind turbines size that is under production and development up to 2030 [1]

Liu et al. employed acoustic emission (AE) analysis in their investigation for diagnosing low-speed wind turbine blade bearing. The blade bearing test rig illustrated in Figure 3 was adopted in their study. The sparse augmented Lagrangian was adopted by authors to build nonlinear auto-regressive (GLNAR) model and filter the AE signals. Their proposed algorithm was validated via different experiments under time-varying low-speed conditions [2].

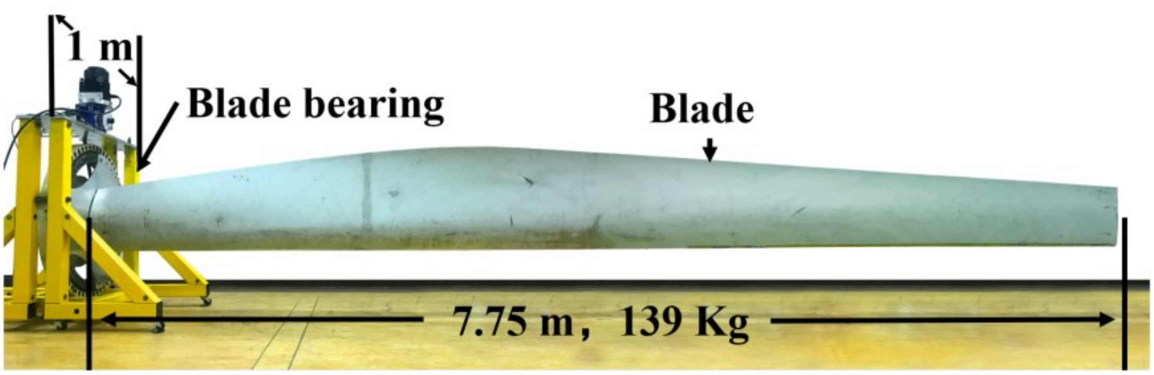

Figure 3 Blade bearing test-rig [2]

Xueli et al. [3] investigated a fault diagnosis model of a direct-drive wind turbine based on back propagation neural network parameters of the horizontal vibration and the vertical vibration of the wind turbine main shaft are comprehensively considered. A rotating wind turbine blade has been studied by Jung et al. [4] to obtain its vibratory characteristics. They derived a computational algorithm based on blade stiffness variation due to centrifugal inertia forces. Accelerometer was used to collect vibration signals from wind turbine to investigate the possibility of extracting wind turbine blades health related information based on EMD. Abouhnik et al. [5] presented a new and sensitive approach presented in order to detect faults in rotating machines; based on principal component techniques and residual matrix analysis (PCRMA) of the vibration measured signals. PCRMA method has been applied to vibration data sets collected from several kinds of rotating machinery using accelerometers. The result showed that the proposed approach successfully differentiated the signals for healthy and faulty conditions.

Wind turbine blades condition based on vibration measurements and the level of an empirically decomposed feature has been studied by Abouhnik et al. [6]. They proposed novel approach called empirically decomposed feature intensity level (EDFIL) that used to study the effects of faults on wind turbine blades. The results obtained by applying proposed approach on vibration data gave reasonable results and was in good agreement with the simulation predicted levels.

Jüngert et al. [7] used two different acoustic techniques for wind turbine blade inspection; local resonance spectroscopy and audible sound. Both methods were found to give information about the internal structure of the area being inspected. Albarbar et al. [8] employed adaptive filtering techniques to enhance diesel fuel injector needle impact excitations contained within the air-borne acoustic signals. Those signals are remotely measured by a condenser microphone located 25 cm away from the injector head, MatLab were used to filter and process band pass

Coherence based methods are usually applications of ordinary coherence function used in order to identify if two signals are linearly related. The benefits of existing Coherent Output Power techniques and of the directional acoustic measurements for a generic system was Studied by Moschioni et al. [9]. This method allows obtaining information about the coherence of two obtained signals using to different devices; accelerometer and microphone. Ning and Wei [10] used multichannel coherence analysis to examine the flight data of a four-blade helicopter for lateral and vertical vibrations at the center gravity and blade flap wise bending. They stated that the linear relationship between multiple harmonics of l/rev were clearly. Gavendra et al. [11] presented the degree of association of frequency spectra between the electrocardiogram or (ECG), (related to the heart signal) and Electroencephalogram (EEG), (related to the brain signal) at a particular frequency and analyzed the association of heart with mind signals by obtaining magnitude squared coherence and phase coherence parameters at a certain range of frequency. The relationship between vibration and current signatures considered for healthy and faulty induction motor conditions using the frequency response and coherence functions were investigated by Weidong and Mechefske [12]. The observation on the coherence behavior, for the detection of early contact, based on the simple laboratory experiments was presented by Suryam et al. [13]. It has been stated that such observation can be exploited for detecting early contact between two components. Solimine et al. [14] used internal microphones in the blade cavity to discover spikes in the sound signal and trends of the sound pressure level. They used internal microphones in the blade cavity to discover spikes in the sound signal and trends of the sound pressure level. They used an acoustics-based passive detection test with utility-scale∼50-m wind turbine blade subjected to fatigue loading. The blade root was built wall mount (concrete test stand) so that as a cantilever beam test as shown in Figure 4. A hydraulic oscillator was utilized to perform the fatigue testing.

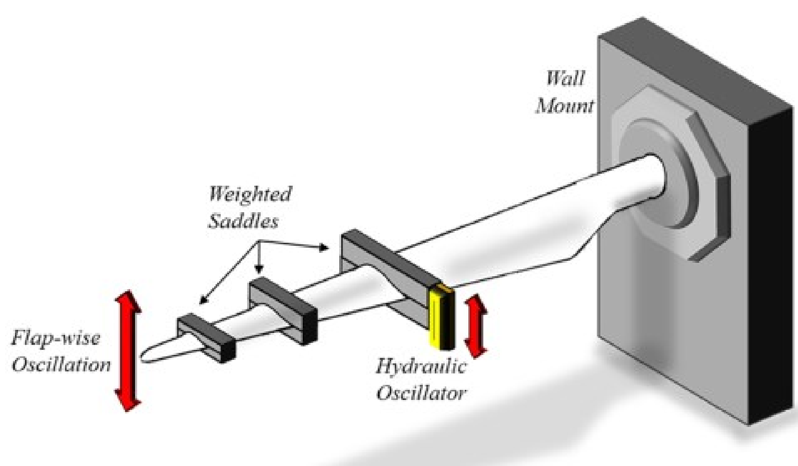

Figure 4 acoustics-based passive detection test [14]

To determine the corresponding relationship between vibrations signals collected using the accelerometer and airborne acoustic signal collected using the microphone, coherence was calculated and plotted for all expected frequencies from 0 to the highest frequency. Signal coherence analysis and confidence levels were accomplished with the software package MATLAB using its signal analysis and statistics toolbox.

This study focuses on using condenser microphones rather than mounted accelerometers to monitor wind turbines due to the high cost of accelerometers and the difficulty to mount those sensors on all wind turbines. Moreover the accelerometers are sensitive to thermal transients and base strain. As a measure of the degree of linear association between two signals the ordinary coherence function is widely used. It gives a measure of the degree of linear dependence between two signals, as a function of frequency.

2. Mathematical principal of coherence:

The coherence function is widely used; it is the degree of relationship or association of frequency spectra between two signals x(t) and y(t), at a particular frequency. The magnitude squared coherence (MSC) between two signals can be defined as:

$$Coh(\gamma) = \frac{[S_{xy}(\omega)]^2}{[S_{yy}(\omega)][S_{xx}(\omega)]} \qquad (1)$$

Where $S_{xy}(\omega)$ is the cross-power spectrum density at angular frequency (ω), while $S_{xx}(\omega)$ is the power spectral density of vibration signal and $S_{yy}(\omega)$ is the power spectral density of acoustic signal. Whilst the ω denotes the frequency of interest and where the complex cross power spectrum, and

$$S_{xy}(\omega) = \int_{-\infty}^{+\infty} R_{xy}(\tau) e^{j2\pi\omega\tau} d\tau \qquad (2)$$

Fourier transform of the cross correlation function

$$R_{xy}(\tau) = E[x(t).\,y(t+\tau)] \qquad (3)$$

where x, y are real; and E denotes the mathematical expectation. The coherence phase can be defined as:

$$\theta(\omega) = \tan^{-1}\left\{\frac{Im[S_{xy}(\omega)]}{Re[S_{xy}(\omega)]}\right\} \qquad (4)$$

Due to its mathematical definition, coherence function is unity if x(t) and y(t) are linearly related and higher the amplitude of the coherence spectra, the better the coherence between the signals. On the contrary, if $S_{xy}(\omega)$ is zero, i.e. the two signals are uncorrelated, then the coherence function is zero. If the coherence function is greater than zero but less than one, then both signals are partially linearly related. Possible departures from linear relationship between two signals or low values of the coherence function can derive from:

- Input or output or both signals measurements are corrupted by uncorrelated noise, which means that the noise may be present in the measurements of either or both signals.
- System non linearity which means that the input x (t) and output y (t) are not only linearly related, but they are may also be related nonlinearly.
- additional inputs present in the system
- leakage errors not reduced with windowing

If one of the previous reasons occurs, coherence assumes values lower than one, and is as much lower as higher is the effect.

3. Dynamic simulation analysis

The planetary gears are a type of coaxial transmission and they are distributed around the sun gear. Many advantages can be obtained of the using planetary gear train such as small volume and mass, large carrying capacity and transmission range, less running noise, high efficiency and high resistance of the fatigue load. Therefore, it plays an important role in wind turbine structure. Multibody dynamics model of wind turbine using ADAMS software based on Lagrangian equation method was created. The system dynamics equation, virtual kinematics and dynamics analysis of planetary gears are established. The dynamic characteristics of the planetary gear were obtained at different working conditions. The dynamics model analysis of the planetary gear is performed without and with loading, the response of planetary gears during meshing is shown in Figure 5. The coherence method was firstly examined on the obtained vibration signals from ADAMS model to investigate its effectiveness of diagnosing. Figure 6 shows the coherence has a powerful to determine the differences between the signals. Therefore the coherence method is applied to experimental data in the next sections.

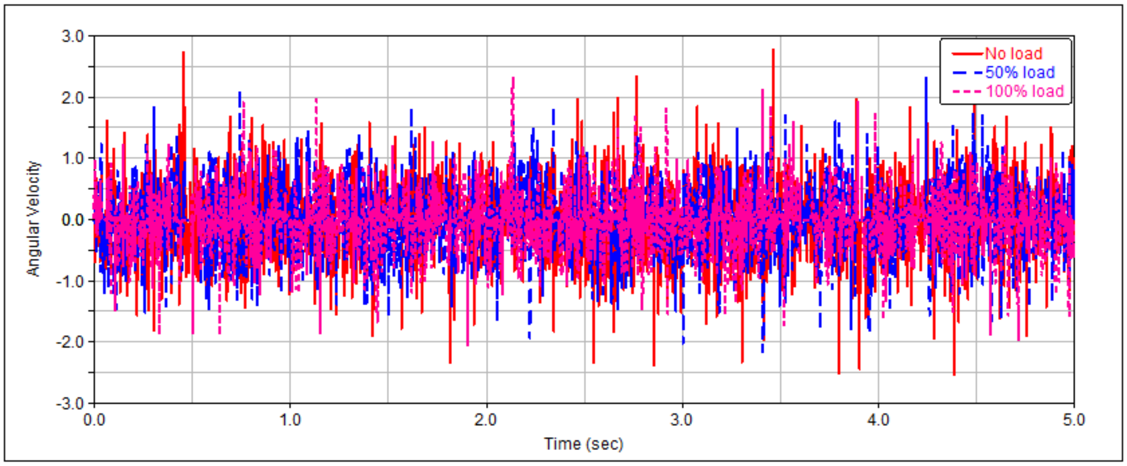

Figure 5 Response of planetary gears during meshing (ADAMS model)

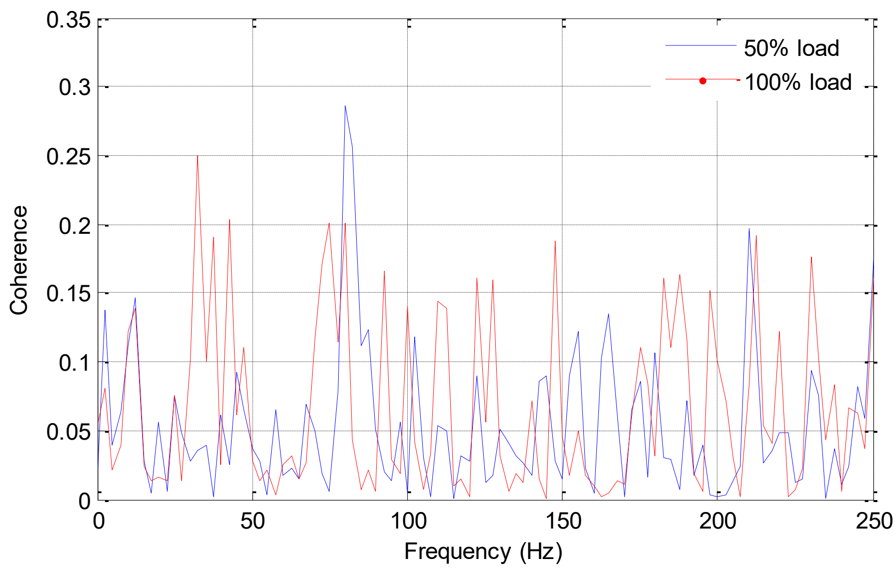

Figure 6 Coherence method applied on ADAMS model signal

4. **Test rig and instrumentation**

The test-rig used in experiment for the measurements of airborne acoustic and vibration consists of a 3 bladed horizontal-axis wind turbine as a source of signals; wind tunnel is an open-return wind tunnel; Condenser microphone type was YG-201 with frequency response characteristic up to 100 kHz; piezoelectric accelerometers were B&K type 4371 with sensitivity of 10mV/g; charge amplifier: A B&K type 2635 charge amplifier was used to convert the output of the accelerometer to mV; a national instruments data acquisition card (NI USB 9233) was connected between a PC and the charge amplifier to collect data; LABVIEW was the program has been used to collect data and then data analyzed using MATLAB. Schematic diagram for test rig is shown in Figure 7.

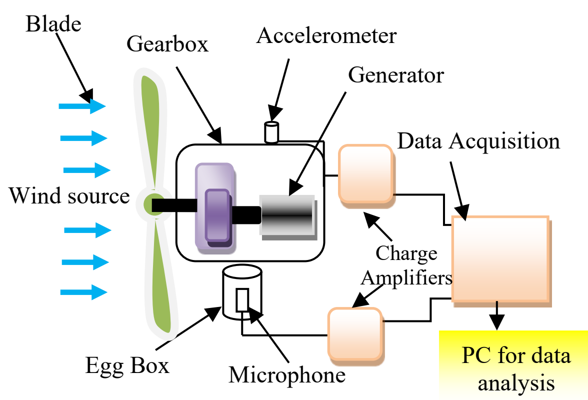

Figure 7 Schematic diagram of the proposed wind turbine monitoring system

5. **Methodology**

The experimental work was carried out on one of most complex of rotating machineries which is wind turbine. It used as a source of air borne acoustic and vibration data. Steps were taken as following:

A three bladed wind turbine was located in front of the wind tunnel; microphone was located away from the nacelle and connected to the charge amplifier and then connected to computer via data acquisition. Egg Box was used around the microphone to give noise reduction which is reverberating inside the lab to be dampened as well as to prevent echoing. Moreover windows were opening during the process of collecting data. Piezoelectric accelerometers mounted on the nacelle of the wind turbine, the output connected to data acquisition then to computer. The computer contains the LABVIEW software to acquire the data, store it and display the time or frequency domain signal. In this study all signals are sampled at 1 kHz with a sampling size of 3000 samples. Data sets of airborne acoustic and vibration measurements were taken at different rotation speeds 60, 120, 225 and 250 r/min.

6. Analysis and discussion

Datasets of airborne acoustic and vibration signals at different rotational speeds analyzed offline using MatLab program to understand the relationship between both signals, then the coherence between both signals were considered at three rotational speeds. Figure 8a represents the time waveform of the airborne acoustic signal at 250 r/min, while the time waveform of the vibration signal for the same condition is shown in Figure 8b.

Both signals exhibit complex sinusoidal signals superimposed on each other with substantial amount of noise. Clearly not much information could be extracted from such signals; therefore Fast Fourier transform (FFT) algorithm was used to show them in frequency domain. FFT was applied on both signals and the results as shown in Figure 9. Signals are generated from different components of wind turbine such as rotor including blades, shaft and gears. Thus shaft frequency signature, blade pass frequency (BPF) signature and mesh frequency will be taken into account during analyzing. The blade pass frequency (BPF) varies with number of blades and rotational speed, it can be expressed as:

$$BPF=nx/60 \qquad (5)$$

where BPF is blade pass frequency (Hz), n is rotation speed (r/min) and x is number of blades. While meshing frequency can be calculated as follows:

$$f_m = \omega_p N_P = \omega_g N_g \qquad (6)$$

Where *Np, Ng* are number of teeth on pinion and gear respectively. ω_p, ω_g are rotational speeds of the pinion and gear respectively.

To determinate coherence between vibration signal and airborne acoustic signal, power spectral density (PSD) for both signals calculated and plotted, the results are shown in Figure 10.

Coherence was calculated for both signals at different rotational speeds. In coherence's calculation the signal is squared, thus producing values from 0 to 1. Coherence was calculated and plotted for all expected frequencies from 0 to the highest frequency.

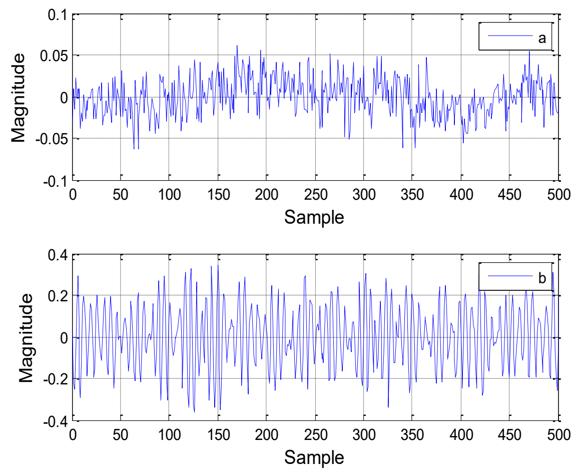

Figure 8 (a) airborne acoustic signals, (b) vibration signal at 250 r/min

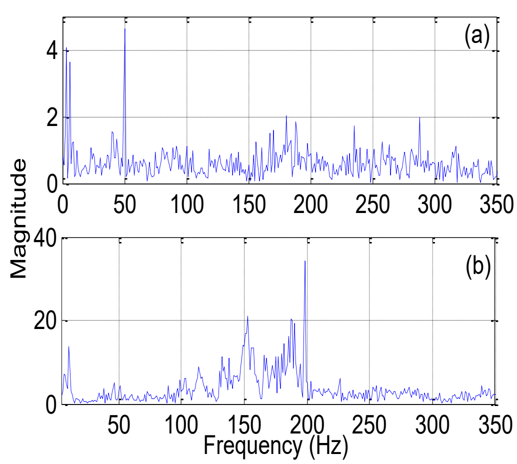

Figure 9 wind turbine frequency domain signals; (a) airborne acoustic, (b) vibration

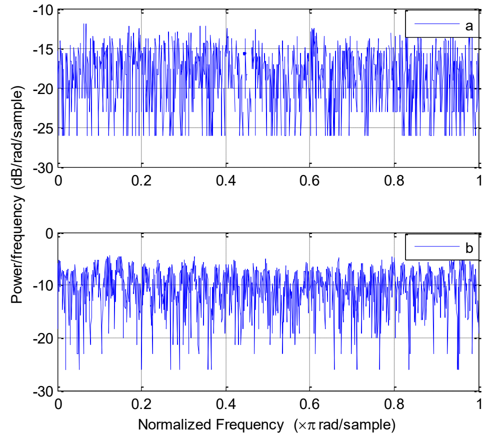

Figure 10 Power Spectral Density for: (a) airborne acoustic signal, (b) vibration signal at 250 r/min

The coherence between these signals at different rotational speeds were calculated. The coherence at 250 r/min was calculated and as can be seen from Figure (11-a) both signals have a common wave component with different frequencies. Moreover, there is change in coherence and values differ from zero to the highest value around 1; a large change.

By focusing on wind turbine components signature, the coherence seen in the frequencies 4.16 Hz which is induced by shaft, 12.5 Hz which generated by blade pass frequency and at 25 Hz which is associated with second harmonic of the blade pass frequency, while 125 Hz is associated with meshing frequency, whilst the large value which gives good coherence is 180 Hz and it is likely due to environmental noise, such as wind tunnel noise.

Although there are changes in coherence and values differ from zero to the highest value around 1; a large change due to noise, the result shows both signals are partially linearly related. From other side coherence phase, at different rotational speeds were calculated and plotted. It seems to be similar to the coherence. Figure (11-b) shows the phase coherence for signals at 250 rpm. The minimum phase coherence between both signals is -180 rad at the frequency 129 Hz. while the maximum phase coherence between the signals is 178.7 rad at 88 Hz.

The cross power spectral density function, defined as the Fourier transform of the cross covariance function, can be used similarly in the spectral domain. The cross power spectral density (cpsd) preformed for two signals. Both signals have 3000 samples long, the same number of sampling the Hanning window full width; and the amount of overlap in the subseries and the result is shown in Figure 12.

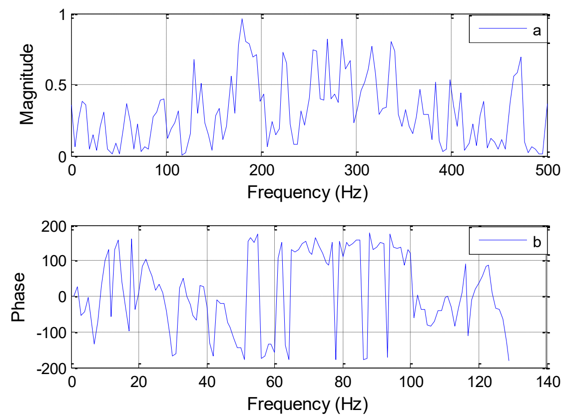

Figure 11 (a) Coherence Estimate via Welch, (b) Coherence phase at 250 r/min

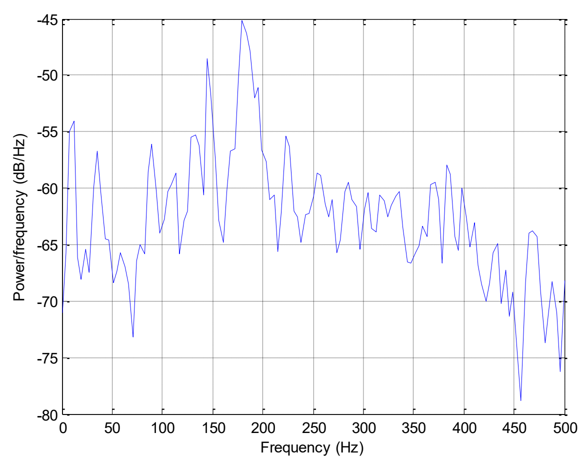

Figure 12 Welch Cross Power Spectral Density Estimate

Figure 13 shows wind turbine components frequencies at rotation speed 225 rev/min. as can be seen a good coherence between air borne acoustic and vibration signals. The shaft frequency is 3.75 Hz, whilst the blade Pass frequency at 11.25 Hz and the second harmonic of blade Pass frequency at around 22.5 Hz. Finally frequency associated with gear mesh frequency is shown at 112.5 Hz.

Figure 14 shows the same coherence for those components at rotational speed 120 rev/min. In this case obviously that the frequencies of those components can be determined, frequencies 2 Hz, 6 Hz and 12 Hz are associated with shaft, blade pass frequency and second harmonic of the blade pass frequency, respectively, whilst mesh frequency is shown at 60 Hz

As can be seen in figure 15 both signals have a common wave component with different frequencies at rotational speed 60 rev/min. A good coherence seen in the frequencies 1 Hz which generated by shaft follows by 3 Hz which is associated with blade pass frequency and 6 Hz is associated with second harmonic of the blade pass frequency, while mesh frequency and its sidebands at 30 Hz is, whilst there are coherence values due to environmental noise, such as wind tunnel noise.

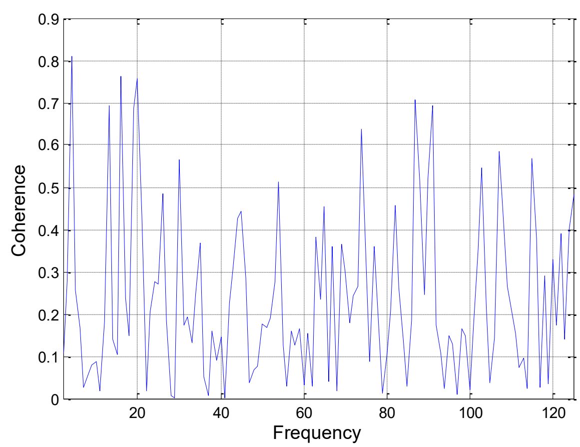

Figure 13 Coherence Estimate via Welch at 225 r/min

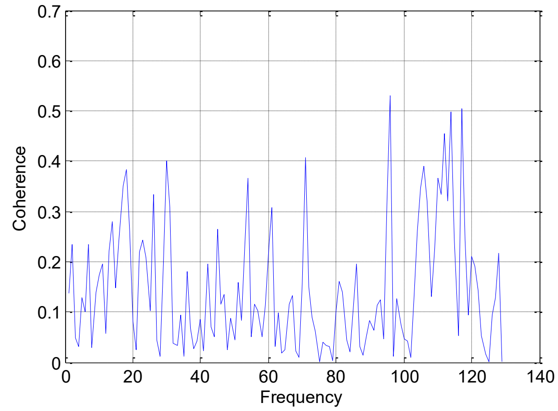

Figure 14 Coherence Estimate via Welch at 120 r/min

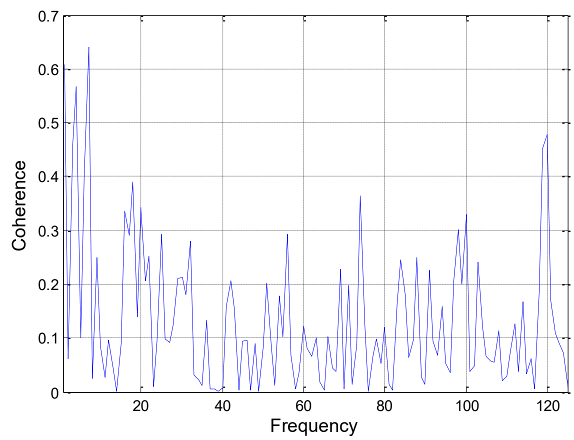

Figure 15 Coherence Estimate via Welch at 60rpm

7. Conclusion

Wind turbines have a number of vibration and acoustic sources and the emitted signals are very complex and corrupted by substantial amount of noise.

Accelerometers are usually used for measuring the vibration generated by each component of the wind turbine and, therefore a number of accelerometers are needed to monitor each of them and this increases the cost of sitting such systems.

This research proofs the visibility of using microphones to provide information similar to those contained within wind turbine vibration signals induced from wind turbines to reduce the high cost of monitoring. Good coherence between both signals found at frequency bands of, sound data was rotating speed, gear meshing frequencies and fan passing frequency. More important found to contain more pronounced information within wider spectrum compared with the acceleration measurement.

The achieved results pave the path to carry out more investigation into the capabilities of air-borne acoustic based monitoring techniques and probably lead to fully adoption by the wind turbine control and diagnostics industry.

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