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“Acoustic Maintenance Management Employing Unmanned Aerial Vehicles in Renewable Energies”

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Acoustic Maintenance Management Employing Unmanned Aerial Vehicles in Renewable Energies

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Abstract.

Nowadays, wind energy is one of the most important renewable energy sources for covering the current electrical demand. The sophistication and the complexity of the wind energy systems are constantly growing. Therefore, new maintenance management techniques are required for ensure the efficiency and rentability of these systems. This paper is focused on the extraction of information from the noise generated by wind turbines. The main causes of noise generation by wind turbines are analyzed in this paper. The noise information allows some types of failures to be detected incipiently and, consequently, preventive and corrective maintenance tasks can be improved. In this field, the use of unmanned aerial vehicles (UAV) can be very useful and facilitate the execution of the inspections. This paper presents a collection of methods for detecting failures through the processing of wind turbine noise. In addition, the possibility of employing UAVs for implement those methods is studied.

Keywords: Acoustic Condition Monitoring, Operation and Maintenance, Faults Detection and Diagnosis, Wind Turbines, Drone, Unmanned Aerial Vehicles (UAV).

1. Introduction

Wind energy, as a source of electricity generation, has grown exponentially in the last two decades worldwide. This growth is around 700% in the last decade. Currently, the global installed capacity is more than 480 MW [1]. Figure 1 shows the cumulative global capacity during the last decade.

Fig.1. Wind energy cumulative global capacity 2001-2016. Source [1].

The wind energy cumulative global capacity growth is accompanied by a sophistication of the wind turbines (WT) and their components [2]. Consequently, more complex manage and maintenance tasks are required to ensure the viability of wind farms. The operation and management (O&M) are usually 12% and 23% of total costs, depending on several factors, such as the location of the wind farm, the environmental conditions, the size of the wind farm, etc. [3].

The companies are managing the maintenance based on the Supervisory Control and Data Acquisition (SCADA). There are a large number of approaches employed in SCADA systems [4,5]. The operators take decisions according to analytics methods [6-8], where in fault detection and diagnosis have been studying novel techniques in the last few years [9-11]. In order to improve the O&M process, condition-based maintenance systems are widely employed for the wind energy systems [12-14]. These systems allow useful information about the condition of the WTs to be extracted. This information can be used to check the status of equipment, identify potential problems before failures occur, minimize downtimes, schedule relevant repairs and maximize the efficiency of the conversion processes [15-17]. Since the number and the complexity of the components are growing, it is crucial to employ new technologies in the development of maintenance management strategies [6,18].

This paper proposes the combination of two modern technologies in order to develop a new condition monitoring system (CMS) [3,19]. On one hand, the system will receive the noise generated by the WTs through a noise receiver system. On the other hand, an unmanned aerial vehicle (UAV) will transport this receiver system as close to the WTs as possible and the collected signal will be sent by a wireless transmitter to the operators [20]. This paper is intended to study the viability of the system according to the existing literature. For this purpose, a review of the literature about WT noise, fault detection and applications using UAVs is carried out.

As aforementioned, the fault detection methods based on the noise emitted by WTs are studied in this paper. These methods are complementary to the conventional monitoring

techniques, such as the vibration analysis systems. Sometimes, the vibration analysis is not sensitive to certain failures, however, the components do not sound normally [3,21]. Experienced mechanics can identify the cause of some engines malfunctions only by listening to the noise they emit. This evidence shows the relationship between the operating status of mechanical components of machinery and noise.

Besides of the rotatory components, failures in the blades can be also caused by faulty manufacture or adhesion of foreign objects, e.g. insect debris, dirt, mud or ice, etc. which alter the aerodynamic profile of the blade and creating an imbalance. Consequently, the power and performance of the WT is affected. These factors change the normal movement of the blades and, therefore, the noise is also altered [22].

Nowadays, several data acquisition processes are aided by UAV, due to their multiple advantages [9], for example, as visual inspection and thermography of WT. But these processes have their limitations. The use of UAVs for additional monitoring and maintenance processes would lead to apply several techniques at once. In this way, maintenance costs can be minimized.

The main contribution of this paper is the exhaustive analysis of the state of the art about the acoustic maintenance management employing unmanned aerial vehicles in renewable energies. The paper presents in Section 2 the main noise sources in wind turbines. Fault detection from wind turbine noise is shown in Section 3. Section 4 analyses the wind turbine inspection using unmanned automatic vehicles.

2. Wind turbine noise sources

The noise of WTs has been widely studied from different points of view [23,24]. Some researchers have studied the acoustic impact on the people, the environment and the buildings. For example, F. Van den Berg [25] studied the acoustic impact on the people who lived close to a wind farm, such as annoyance and sleep disturbance. P. Lindkvist, et al. [26] demonstrated that the noise of WT causes low frequency vibrations on near buildings or structures. However, this paper is not focused on the consequences, but rather the causes of noise. Noise will not be treated as an inconvenient but as a source of information for fault detection.

Noise emissions in WT can have two different sources: mechanical noise from rotating mechanical components and aerodynamic noise from blade movement. The noise level increases proportionally with the size of the rotor and the rotational speed. The noise level, measured close to the rotor ranges from 96 to 107 dB(A), depending on the power and the rotational speed [27].

2.1 Mechanical noise

The mechanical noise is generated by the rotative components, i.e. the gearbox, the transmission system, the generator, etc. [27]. The mechanical noise tends to be tonal, however, some broadband components can appear at frequencies lower than 1.000 Hz. The noise can be emitted directly through the air or indirectly through components that are around the source. The mechanical noise is transmitted through the hub and the tower, and finally, through the blades. The blades act as a loudspeaker of the mechanical noise [28]. This noise transmission process is shown in Figure 3. The main sources of the mechanical noise are listed below:

- *Gearbox*: the gearbox is composed of different type of gears and bearings. The gearbox works under considerable loads and, therefore, it is the component that generates the highest noise level.
- *Generator*: the noise of the generator is caused by the vibration due to coil flexure.
- *Auxiliary Equipment*: some components such as the cooling system or the yaw drives are noise sources. For example, the cooling system can comprise a cooling fan as a noise source. The hydraulic components and the compressors of the yaw drives can also generate noise.

Fig. 1. Sound power level of the wind turbine components. The noise transmission process can be: through the structure (s/b) or directly through the air (a/b) [27]

2.2 Aerodynamic noise

The aerodynamic noise is generated by the interaction between the blades of the WT and the air. This is the dominant noise of the WTs. Nowadays, the blades are becoming increasingly large due to the size of blades is directly related to the productivity [13]. The larger blades are usually louder than the small ones. Moreover, the modern gearboxes are increasingly noiseless. Therefore, the aerodynamic noise level is higher than the mechanical noise.

The predominant aerodynamic noise is generated by the turbulences caused by the blades. These turbulences are due to the rotatory movement and are located in the trailing edge of the blades [27]. The aerodynamic noise level depends on several factors such as the size of the blades, the aerodynamic design, the rotational speed, the position of the rotor and the tower, the wind speed, etc [29]. The main sources of aerodynamic noise are:

- *Leading-edge interaction noise*: this noise is generated by the impact of the air with the leading edges of the blade.
- *Trailing edge noise*: it is produced by the turbulence of the boundary layer and the trailing edge of the blade. This is the dominant noise of the WT.

- *Blade tower interaction noise*: it is generated when the blade goes through the turbulent flow created by the tower.
- *Tip noise*: it is generated by the interaction of turbulences with the tip of the blades.
- *Airfoil tonal noise*: the interaction of the turbulent flow of the boundary layer generates a resonant vortex. This type is less relevant than the trailing edge noise.

As aforementioned, the noise generated by aerodynamic causes is predominant with respect to the mechanical noise. In this field, Oerleams et al. [30] studied the noise sources of the WTs showing the noise at low frequencies (1-4) and high frequencies (>500 Hz). Schepers et al. [31] demonstrated that the noise is mainly generated during the downward movement of the blade. This noise is louder in the tip, due to the speed is higher and the turbulences are more important. The noise emission is also measured according to three different conditions of the blades: Clean blade; untreated blade, and; tripped blade. Figure 3 shows the noise generated in the three scenarios. It can be concluded that the tripped blades generated higher noise levels.

Fig. 3. Noise generation under different scenarios [14]

Reference [31] also demonstrated that the power of the WT is directly proportional to the area of emission. Figure 4 shows that the noise generated during the whole movement of the blade is louder when the power of WTs is higher. The blade tower interaction noise is also more significant when the power of the WTs increases.

Fig. 4. Noise generation in WTs with different power. Gamesa G58 850 kW (left) y GE 2500 kW (right) [14]

Oerlemans *et al.* [32] and Doolan *et al.* [33] demonstrated that the noise is mainly transmitted in a predominant direction. This direction is perpendicular to the rotor and opposite to the air flow. An important characteristic of the trailing edge noise is the cardioid directivity pattern (see Figure 5).

Fig. 5. Directivity pattern of the trailing edge noise [33]

Fazenda [29] studied the fault detection through condition monitoring of the WTs noise. He affirmed that the aerodynamic noise is broadband noise and transmitted through the axis of turbine, whereas the mechanical noise is radiated orthogonal to the turbine axe.

3. Fault detection from wind turbine noise

WTs often are exposed to inclement conditions (high speed wind, sudden changes of wind direction, turbulences, etc) that cause cyclical loads and gradients of temperature on the blades during their rotational movement. These loads cause fatigue in the different components of the WTs, and consequently, the wearing of the components. Some failures can be also caused by a defective fabrication process or the adherence of foreign objects, e.g. insects, dirt, mud, ice, etc. that affect to the aerodynamic airfoil of the blades. All these factors generate an abnormal vibration of the affected component. According to Yongyong *et al* [34], the changes of the natural vibrations show an unbalance of the components. Therefore, the noise emitted by these components is altered.

The main failures of the mechanical rotative components are: unbalances; misalignment, scuffing wear, backlashes, eccentricity, clearance, partial fractures, deflection, cracks, paint chips, pitting, etc. These failures can cause knockings, hissings, ratcheting noise, vibration frequency variations, etc.

The faults that affect aerodynamically to the blade are located in the loaded areas. The most common defects are cracks, delamination, structural faults and fibre fractures. Additional failure causes are: defects of fabrication, adherence of foreign objects such as insects, dirty, mud or ice that modify the aerodynamic features of the blades. These factors generate variations of the normal noise and affect to the power of the WTs.

The fault detection and diagnostics through noise is commonly carried out by analysing in detail the spectrum of the acoustic signal. For this purpose, Mario E. Munich [35] combined systems based on Mel-frequency cepstral coefficients, Gaussian mixture models, hidden Markov models and Bayesian subspace methods. The author applied these methods to detect failures in military vehicles. An accuracy of 83% was obtained. In this field of vehicle fault detection and diagnostics, Huadong Wu *et al* [36]. employed the eigenfaces method, also known as an extension of the Korhunen-Loeve or the principal component analysis. They obtained satisfactory results from the pattern recognition of the noise signals. Ortega *et al.* [37] analysed and classified the noise of a motor for fault diagnostics. The used Linear Prediction Cepstral Coefficients for the extraction of the main acoustic features, and Principal Component Analysis and Neural Networks for the pattern recognition. An accuracy of 95.83% was obtained for the detection of three common faults.

Baydar *et al.* [22] employed the wavelet analysis for the fault detection in gearboxes. Failures such as teeth fractures or cracks are detected by comparing vibrations and acoustic signals. The results show that the acoustic analysis is an effective method for early detection of faults in gearboxes.

Fazenda *et al.* [22] studied the accumulation of dirt or ice on the WT blades through the noise emitted by them. For this purpose, they employed rotational frequency spectral magnitude based methods combined with fuzzy logic. Two inputs were employed in this model: spectral peak and the rotational peak variation. The results showed that this model is suitable for determine the severity of the accumulations.

4. Wind turbine inspection using UAVs

Nowadays, UAVs are employed in multiple fields such as agriculture, public safety, security, construction, surveying, mappings, inspections, etc. The industrial applications are aimed to maximize the benefits by aiding the maintenance management. This paper is focussed on the inspections of WTs carried out by UAVs. For this purpose, the main advantages of this technology are:

- Complete and accurate inspections in locations that are difficult to access.
- UAVs can provide real time data and therefore, decisions can be made during the inspection
- There are multitude of UAV types that can be used according to the specific conditions of the inspection.
- The costs are reduced compared with other methods. Figure 6 shows the service platforms employed for the maintenance of a WT. The costs of this platforms are very high.

Fig. 5. Service platforms employed for WT inspections [38]

- The risks associated to the inspections are reduced compared with other methods. Figure 7 shows the risks that suffer the operators working at heights.
- The inspection time can be reduced.
- Multiple inspection techniques can be applied simultaneously (noise analysis, thermography, etc).
- The UAVs can follow GPS coordinates and, therefore, the inspection can be automatically routed. Figure 8 shows a UAV approaching to a WT blade for inspection.

Fig. 2. Hydraulic crane(left) and climber (righth) during blade inspections [38]

Fig. 3. Blade inspection developed by a UAV [39]

Nowadays, the main monitorization techniques for UAV based inspections are visual inspection and the thermography. However, these techniques do not allow hidden components to be monitored. For this purpose, the noise analysis can be suitable technique. A brief review of some researches in this field is presented in this paper.

Anne Jüngert [40] researched the suitability of ultrasound-echo technique in order to detect some internal defects of the WT blades. This technique is demonstrated to be an ideal solution for knowing the state of the laminations. The author also employed the local resonance spectroscopy for the detection of internal defects in blades. This technique analyses the noise generated when an impulse hammer crashes with a blade. Each defect is supposed to generate a characteristic noise. It is demonstrated that this technique can detect internal delamination. The required devices can be easily equipped on a climber or a robot in order to carry out more reliable inspections. Simon Kleppevik [41] demonstrated that internal failures, e.g. delamination, can be detected using a UAV through the pulse echo technique.

Furukawa *et al.* [42] employed the sound source localization for people and animal detection out of visual range. This methodology employs UAVs for detecting people screaming, gunshots, explosions, etc. A Gaussian process regression is used to estimate the noise correlation between the pitch-roll-yaw tilt angles, the rotor speed and the control values of the UAV. The method is demonstrated to be very efficient under high signal to noise ratio conditions. This study concludes that the sensors equipped in the UAV can collect noise that is not generated by the own drone.

Paulson [43] patented a monitoring system for leaks detection in superficial pipelines. This system employs acoustics together with temperature monitorizations. The author proposed the continuous acoustic monitorization and periodical visual and thermographic inspections using a UAV. Loud *et al.* [44] patented an acoustic inspection method for industrial machinery using UAVs. This method included the collection of acoustic information of WTs. A filtering process is proposed in order to discard irrelevant data, such as the wind, or the propulsion system of the UAV. This author proposed to identify the location of the noise sources through their characteristic noise.

Murphy *et al.* [45] patented an inspection system for WTs in order to locate multiple non-destructive devices on a remotely operated aerial platform (ROAP). This system could be used to evaluate the noise level of a wind farm and determine its impact on the environment. This system also could study the distribution of the noise sources. This information is useful to achieve aerodynamic designs that allow WTs to be noiseless. It is based on the idea of Oerlemans *et al.* [32] but with the help of a UAV. This system could be also used for detecting debris or ice accumulation by equipping the UAV with an acoustic receiver [22].

The aforementioned techniques only could be implemented by a UAV if the system meets the following compatibility requirements [41]:

- The weather is suitable for the UAV operation (wind speed, humidity, etc)
- There is not any legal restriction (restricted areas)
- The characteristics of the UAV are completely reliable and there is not risk of impact on the WTs
- The UAVs is approved to carry the total weight of the equipment.

5. Conclusions

The noise generated by wind turbines (WTs) has been demonstrated to be useful for the early detection of some faults or abnormal conditions. This information can be employed for improving the maintenance management of a wind farm. This paper proposes a novel system for acquiring this information efficiently, quickly and reducing the risks and costs associated to the conventional WTs inspections. The proposed system consists of an unmanned aerial vehicle (UAV) fitted with a noise receiver. The viability of the system has been evaluated through different research studies. Firstly, the main noise sources of the WTs have been analysed. Secondly, a collection of methods to interpret noise data from different industrial machines has been presented. In third place, the main advantages of using UAVs has been studied. Finally, some compatibility requirements have been identified to ensure that the proposed system is suitable for WT inspections.

According to this literature review, this paper concludes that scheduled WTs inspections could be performed using the proposed system. Some experimental analysis will be carried out in future works in order to demonstrate the real viability of the proposed system.

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