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ACOUSTIC BASED CONDITION MONITORING OF TURBINE BLADES

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An initial investigation into the performance of acoustic condition monitoring in the detection of structural faults in turbine blades has been carried out. The focus is to design a non-contact condition monitoring method which might allow the detection of incipient faults in the turbine blades therefore preventing major breakdown and potentially reducing maintenance downtime. Such systems, may be deployed remotely from the turbine and provide a non-fixed and thus more economic solution for operation and maintenance of wind turbines.
An initial investigation into the performance of an acoustic monitoring system has been carried out both in laboratory as in-situ. A number of signal analysis methods are evaluated against structural faults in turbine blades. A lab measurement was obtained using a 3 blade small fan of constant speed. The in-situ measurements were carried outdoor on a 5 blade micro wind turbine with speed dependent on wind speed.
Faults were planted on a single blade for each test system, in the form of added weights and delaminations near the tip of the blade. Acoustic data acquisition was obtained by placing a single microphone close to the blades. Time synchronous analysis (TSA), ensemble empirical mode decomposition (EEMD) and spectrum of individual intrinsic mode functions were investigated as feature extraction and fault finding methods.
Results show that the effect of faults is to shift energy in the IMFs, particularly around the harmonic frequencies of the system. Faults can also be detected in terms of increased harmonic energy, observable through magnitude spectra determined from individual valid IMFs.

1. Introduction

1.1 Wind turbine operation and management

Wind farms are now ubiquitous as a sustainable method for harvesting wind energy. Due to the availability of adequate area and levels of nuisance to Human environment, these are commonly deployed in remote sites and off-shore locations where monitoring and maintenance of units is typically costly.

Modern industrial wind turbines may operate for longer than 13 years almost always unattended. Since the cost of downtime far supersedes that of component replacement, turbine availability, access and maintenance are considered a critical aspect in the operation and management of wind turbines and wind farms[1].

The SCADA (supervisory control and data acquisition) system, a vital element of the wind farm, acts as a nerve centre for the wind farm development, connecting individual wind turbines, the substation and meteorological stations to a central control. The SCADA provides a comprehensive supervision of the condition of the wind farm as a whole. Traditionally the SCADA is designed and provided by wind turbine manufacturers during commissioning. However, a market is emerging for independent SCADA systems, which may further integrate condition monitoring methods such as the one being proposed here.

1.2 Rotor blade faults

The rotor blade is one of the key components of wind turbines. There has been a substantial effort placed into the development of materials and design approaches for rotor blades. The ever increasing size and consequent problems with handling and transport have led some manufacturers to consider approaches such as jointed blades[1].

Condition testing has become a crucial part of blade manufacturing concentrating primarily on their structural integrity. The most common forms of blade damage reported are to do with faults in adhesive joints, delaminations and rupture of fibres in laminate composites. Measurement and certification against these faults may be based on various methods - acoustic emission, fibre optics or inertial sensors able to detect cracks through emission, variation of structural density and alteration to structural modes, respectively.

This certification is typically carried out prior to mounting and commissioning. In operation, the rotor blade is particularly likely to fail due to such problems during the initial years of deployment[1]. Furthermore, due to its exposure to atmospheric elements, other faults develop over the life of a turbine blade. These are more commonly associated with collection of debris, ice forming and physical damage due to collision with birds and flying debris. It is thus obvious that blade condition monitoring will become critical in the wind energy industry.

Whilst there are a number of reports on condition monitoring of turbines, these have mainly focused on vibration sensors to detect faults in rotating machinery (gearbox, generator, associated bearings, etc); electric signal monitoring devices that flag a fault if there is a power decrease; and video cameras inside and outside the nacelle allowing a visual control of structural integrity. Hitherto, and to the knowledge of the author, there have been no publications on the use of acoustic technology for the condition monitoring of wind turbines.

1.3 Turbine acoustic condition monitoring

Turbines are noise sources which has become a problem for large scale development, particularly near urban areas[2]. In general wind turbine noise is generated mainly from aerodynamic and mechanical sources[3]. Measurement data is influenced by factors such as blade size and aerodynamics; drive-train operation; orientation of rotor with respect to tower; and wind parameters such as force and turbulence. Low frequency, narrow band noise components are commonly associated with cyclical rotation and blade tip passing frequency. Mechanical noise components are also tonal in nature and are generally associated with elements such as the gearbox (teeth meshing), the generator (electro-mechanical poles interaction), and system hydraulics equipment.

Broadband noise sources are commonly associated with aerodynamic loading fluctuations caused by inflow turbulence interacting with the rotating blades; turbulent boundary-layer flow over the airfoil surface interacting with the blade trailing edge; and vortex shedding caused by the bluntness of the trailing edge.

Measurements carried out on the radiation patterns of wind turbines have shown that aerodynamic noise radiates mainly along the axis of the turbine, whereas mechanical component noise radiates orthogonal to this. Standards specify that all measurements are normalised to wind speed which in turn dictates wind turbine rotation speed and levels of background noise.

The work proposed here aims to investigate methods to extract wind turbine acoustic signature and determine blade condition from variations of this in comparison with a known, healthy condition .

2. Measurement

The following section describes the measurement process for each of the systems studied. The simplest system is introduced in 2.1. This measurement has been carried out in a semi-anechoic room which is a closed, controlled environment, ensuring high S/N ratio. The aim here is to detect planted faults in a constant blade-pass-frequency system. The measurement of varying speed rotating blades poses a higher challenge and this is detailed in 2.2. In this case, a micro wind turbine was measured in situ.

For both systems described, the acoustic measurement was carried out using a fixed position microphone mounted close to the blade tip. This position was chosen out of a number of possible locations since it provides the best S/N ratio for the specific faults planted.

2.1 Scale turbine measurements in lab

To study the behaviour of fan blades a simple experiment was set up in a semi anechoic room. At this stage it was also important to ensure that blade pass frequencies were kept constant to allow extraction of simple features.

In most studies of periodical, rotating machinery, the generic behaviour is well established using Time Synchronous Average (TSA). TSA requires the extraction of tachometer information from the data (in cases where it is not available from other sensors) but is useful in obtaining a definite periodic signal and reduce influence from noise. A TSA time series for a small vibrating fan system with 20Hz rotating frequency (RF) and 60Hz blade pass frequency (BPF) has been transformed into a magnitude spectrum and plotted in Figure 1 (grey line). The RF and BPF at 20Hz and 60Hz are evident. The data also shows weak harmonic content at 40Hz, 80Hz, 100Hz, and 120Hz.

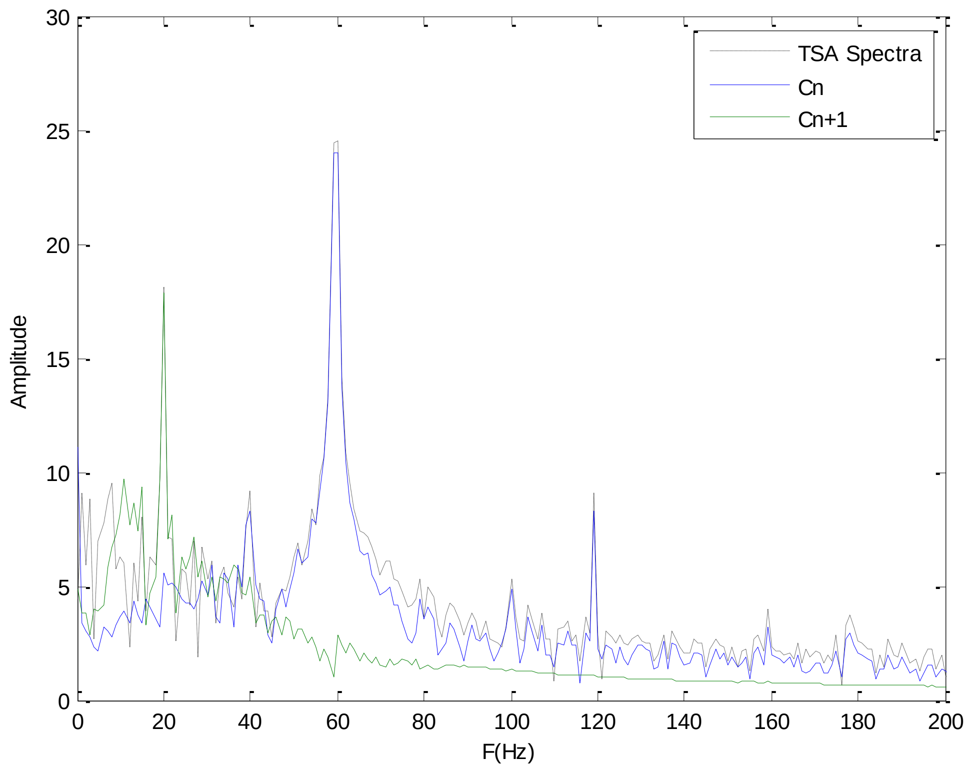

Figure 1. Magnitude spectra for healthy 3 blade fan obtained from TSA. Magnitude spectra for IMF 4 and IMF 5 for healthy 3 blade fan.

Whilst TSA is useful in characterising periodic systems, its averaging process tends to obliterate some of the non-linear and non-stationary data that may be generated by incipient faults. The work presented here uses the Empirical Mode Decomposition method (EMD), first proposed by Huang[4] and now very common in condition monitoring methods. The EMD extracts underlying modes of vibration directly from the recorded time series data. The signal is decomposed into a series of functions, named intrinsic mode functions (IMF), from the highest to the lowest frequencies. the IMFs are obtained following two main criteria: any IMF must have the same number of zero crossings and extrema and; must be symmetric with respect to the local mean. The EMD process acts as an adaptive filter and, as it is derived from the input data, it has proven to be quite versatile in extracting signals from nonlinear and non-stationary processes [5-7].

One of the issues with the original EMD process is that, in the presence of noise, it is possible for sections of the signal to be split between two neighbouring IMFs therefore producing less reliable results - this has been referred to as mode mixing [(eg. in 10)]. Huang et al. [9] later proposed the *ensemble empirical mode decomposition* to try to overcome this issue. This approach introduces uncorrelated noise during the mode decomposition process and obtains the IMF from the mean of an ensemble of trials.

IMFs obtained from the EEMD analysis of a healthy 3 blade fan system are presented in Figure 2. It is evident that the higher frequency is retained in the higher order IMFs and the components of the signal in decreasing frequency range follow. The first few components have relatively small amplitude, indicating weak high frequency content. The periodicity of components c4 and c5 is evident and corresponds to the blade-passing- and rotational-frequencies respectively. A magnitude spectrum for each if these two IMFs is plotted in Figure 1. Amplitudes for components of order lower than 3 and higher than 8 are, in this case negligible and no longer used in the discussion.

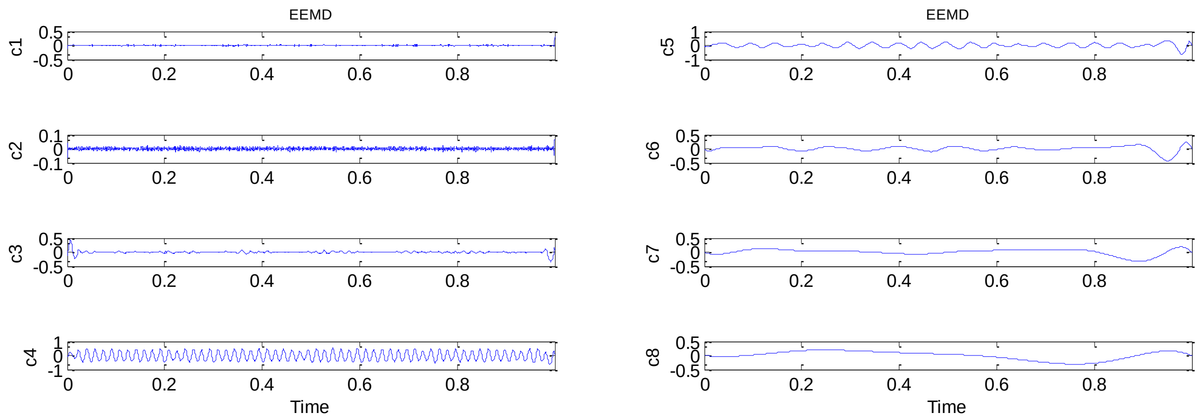

Figure 2. Intrinsic Mode Functions for a healthy blade system.

One monitoring feature that may readily be extracted from the individual IMFS is their amplitude calculated as the root mean square value. The results shown in Figure 3 have been obtained using the EEMD method and converting each IMF into rms amplitude. The data plotted corresponds to the ‘healthy’ blade case. It is clear that IMFs 4 and 5 have strong energy, corresponding to rotational and blade passing frequencies. Figure 3 also shows a relatively high level of energy in IMFs 6, 7 and 8 but observation of the data in Figure 2 reveals that this is associated with residual energy in frequencies lower than the rotational frequency. The resulting conclusion is that analysis of data using a single method (such as IMF rms) may not be sufficiently revealing to support the detection of a fault.

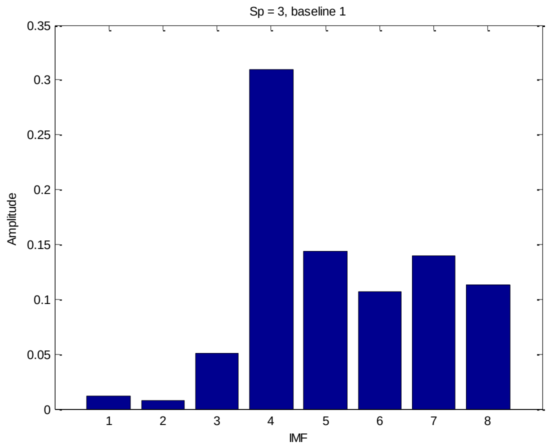

Figure 3. Intrinsic Mode Function amplitude (rms) for healthy blade system.

In order to test the capability of detecting incipient faults in the blade, two different types of faults were planted: the addition of a small amount of material in weights of 0.5g, 1g and 2g, to the tip of a single blade and; three different attachments of adhesive tape, flat, flapping and tripped, also placed on the blade tip. These conditions have been chosen merely due to their predicted small effect of the acoustic radiation of the system rather than a direct emulation of common blade faults. It is however interesting to note that ice-forming, delaminations and blade tripping, commonly found in wind turbine blades, are somewhat analogous to the cases studied here.

The results in Figure 4 show significant changes in the amplitude of IMFs when compared to the healthy case (see Figure 3). It is clear that the as the amount of added weight in the blade tip increases (top row in Figure 4) there is a shift of energy towards the higher IMFs and particularly from IMF 4 to IMF 5. There is also a decrease in energy contained in the higher IMFs (6,7 and 8).

In the case of faults related to 'tape' configurations (bottom row) the trends in the results are less clear. This is not surprising since the tape fault cases do not follow a simple progression of an added feature as is the case for the weights. Thus, extracting a monotonically varying feature such as a shift from one IMF to the other is less likely.

Nevertheless, when compared to the 'healthy' system, all faulty cases reveal clear differences.

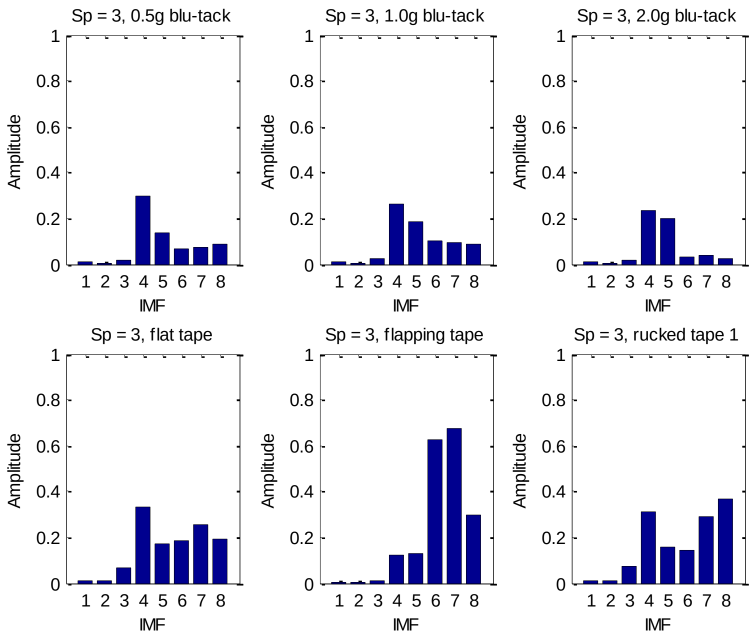

Figure 4. Intrinsic Mode Function amplitude (rms) for all 'faulty' systems.

The data for the 'best' IMF candidates in condition monitoring (IMFs 4 and 5) has been further examined by generating the magnitude spectral content for each IMF.

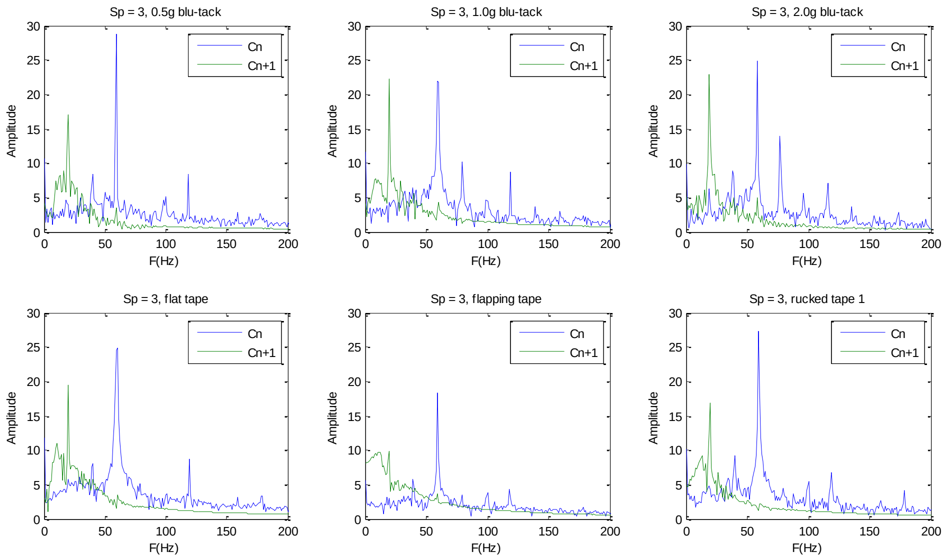

Figure 5. Magnitude Spectra for IMFs 4 and 5 across all faulty systems.

The rotational and blade passing frequency can be clearly seen in all plots, at 20Hz and 60Hz respectively (Figure 5). The effects of the added weight (top row) can also be detected as an increase in harmonic content of the IMFs, especially at 80Hz. Clearly this is harmonic energy ($4f_o$) introduced from the passing of the faulty blade. The effects of the tape faults (bottom row) are somewhat more difficult to detect from this representation. The main effect appears to be in the magnitude of the rotational frequency, the 20Hz component. The author has not yet found a physical explanation to this effect.

2.2 Micro wind turbine measurements

A micro wind turbine has been measured on site. The turbine radius is approximately 56cm and it has 5 blades. Turbine rotation due to wind direction tracking was prevented by fixing the turbine nacelle to the housing and mounting post. This is an attempt to fix the physical distance between the microphone and the rotation area of the blades. Some residual movement of the turbine could not be prevented for these measurements. The microphone in this case was mounted directly behind the blade face and fitted with a basic windshield. All ‘faults’ introduced to the turbine were applied towards the tip of a single blade. The details for the faults tested are presented in Table 1:

Table 1 - Test condition and filenames for micro wind turbine measurement

Filename	Blade Defect	Notes
baseline1	N/A	Wind intermittent, with no real high speed operation
baseline2	N/A	Strong wind
tape1	Ridged flap of gaffa tape ≈ 7.5×100mm running parallel to the blade along the leading edge and extending virtually to the tip	Wind intermittent, though with occasional higher speed gusts (e.g. ≈ 3:00). Noisy van pass at ≈ 1:25-1:45
tape2	Ridged flap of gaffa tape ≈ 7.5×50mm running across the blade ≈ 50mm from the tip	Fairly average, winds, though notably gusty at ≈ 4:27
blutack1	3g blu-tack – ≈ 80×10mm sculpted along the leading edge and extending virtually to the tip	
blutack2	6g blu-tack – ≈ 80×10mm sculpted along the leading edge and extending virtually to the tip	Forklift truck at ≈ 1:10-1:40. Two large single event bangs at ≈ 2:07 and 2:30

The main difficulty in the analysis of this system is the rapidly varying speed of the turbine. Figure 6 below shows a spectrogram for three cases. Plots from left to right: healthy blades; 6g of added weight; tape flapping.

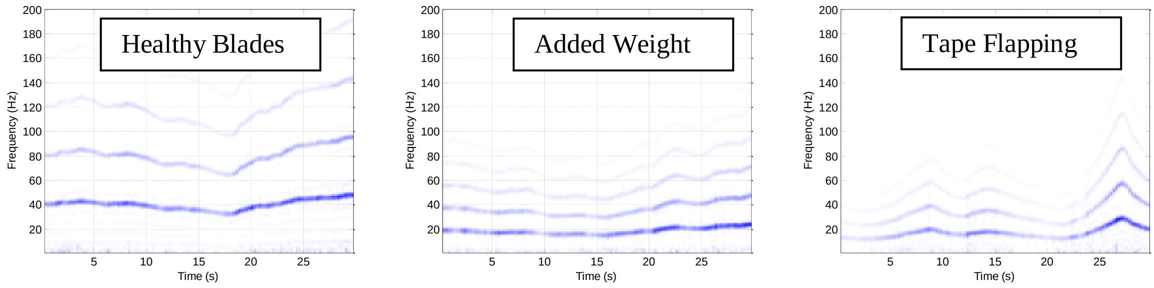

Figure 6. Spectrogram for 5 blade Micro Wind Turbine. The variation of speed can be clearly seen as a frequency modulation over the duration of the measurement.

To run an analysis on fault data, tacho data was measured on site and verified against data extracted directly from the signal. The blade pass frequency was then extracted and plotted in Figure 7.

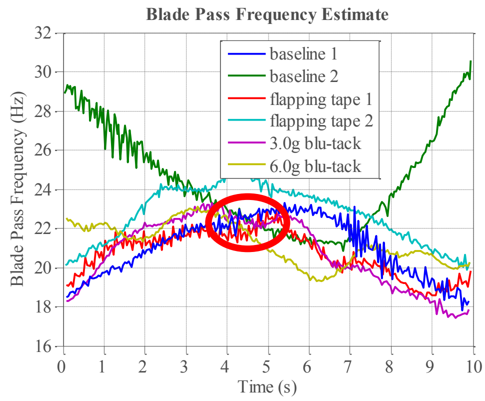

Figure 7. Estimation of the blade passing frequency for 5 blade micro wind turbine over the duration of the measurement.

The period between 4 and 5 seconds provides the most consistent and similar speed for all cases investigated on this turbine - the 3g added weight falls well outside the group and as such this scenario has not been included in the analysis. 'Baseline 2' was also not used for the analysis.

Figure 8 shows the amplitude for each IMF in each scenario. As in section 2.1, this display of data shows clear differences between the scenarios. It is however difficult to determine a reliable feature or indeed to presume some physical principle associated with the fault.

Individual spectra were calculated for all IMFs of orders between 4 and 9 and plotted in Figure 9.

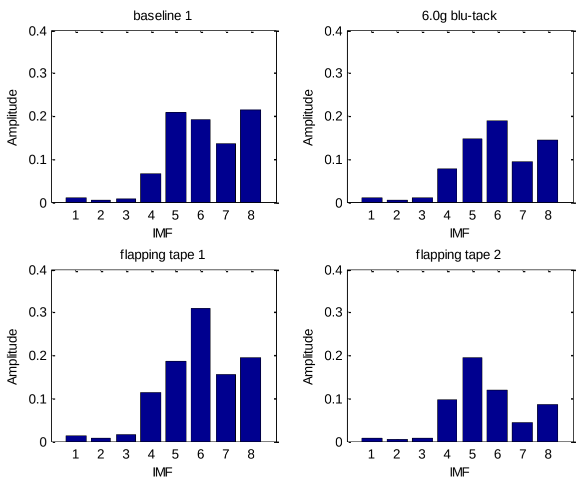

Figure 8. Intrinsic Mode Function amplitude (rms) for all 'faulty' systems using a 5 blade micro wind turbine.

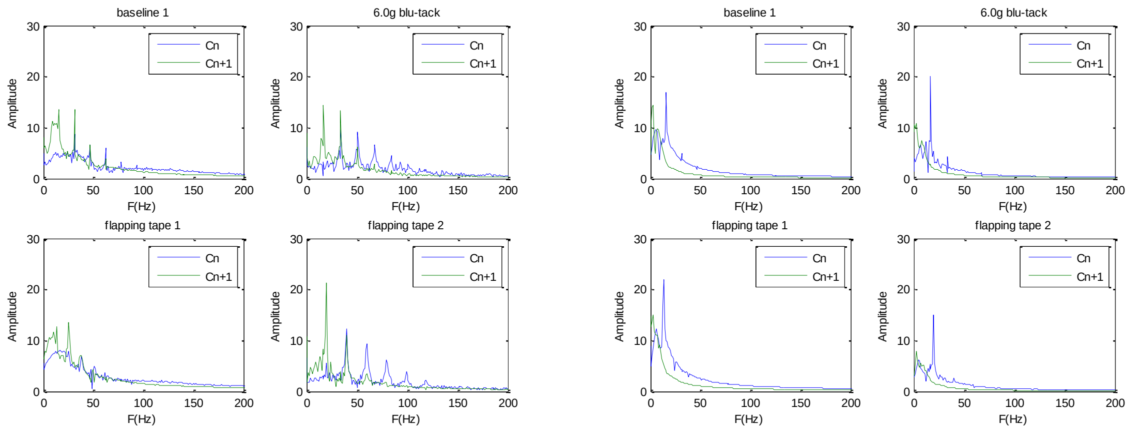

Figure 9. Magnitude Spectra for IMFs 4 and 5 (left) and 6 and 7 (right) for all systems.

The spectra plots show a clear introduction of harmonic content when in the presence of faults. This is particular evident in the plots showing IMFs 4 and 5 (left plots). Analogous to the results observed for the fixed BPF system described in 2.1, the lowest components segregated in IMFs 4 and 5 correspond to RF and BPF of the micro wind turbine.

3. Concluding Remarks

- The EMD method may provide important features for the detection of incipient faults on blades, particularly in systems of fixed rotational frequency.
- Analysis of non-periodic data obtained from varying speed micro turbines poses a different challenge for which the use of an empirical decomposition method alone may not be appropriate.
- Analysis of non-constant rotational frequency is still possible if applied locally to data rather than globally. A section of identical speeds for all faults being compared is required.
- A more comprehensive mapping of the feature space is required to ensure accurate characterization and classification of faults.

These are now subject of further research.

REFERENCES

1. *Wind Energy- The Facts, A guide to the tecnology, economics and future of wind power,* European Wind Energy Association (EWEA), Earthscan, London, 2009
2. Von Hunerbein, S, King, A, Hargreaves, JA, Moorhouse, AT and Plack, C 2010, *Perception of noise from large wind turbines (EFP-06 Project)* , Technical Report, University of Salford, Salford, UK.
3. Hubbard, H.H., Shepperd, K.P., "Aeroacoustics of large wind turbines", *Journal of the Acoustical Society of America* **89** (6), June (1991).
4. N. E. Huang, Z. Shen etc, “The Empirical Mode Decomposition and the Hilbert Spectrum for Nonlinear and Non-stationary Time Series Analysis”. *Proc. R. Soc.Lond. A*. pp. 903-995, 1998.
5. A. O. Boudraa, J. C. Cexus and Z. Saidi, “EMD-Based Signal Noise Reduction”, *International Journal of Signal Processing*, Vol 1, No. 1, 2005.
6. Q. Gao, C. Duan, H. Fan and Q. Meng, “Rotating Machine Fault Diagnosis Using Empirical Mode Decomposition”, *Mechanical Systems and Signal Processin*g, Vol 22, pp. 1072-1081, 2008.
7. Q. Du, S. Yang, “Application of the EMD Method in the Vibration Analysis of Ball Bearings”, *Mechanical Systems and Signal Processin*g, Vol 21, pp. 2634-2644, 2007.
8. Guan, Luyang, Shao, Yimin, Gu, Fengshou, Fazenda, Bruno and Ball, Andrew,"Gearbox Fault Diagnosis under Different Operating Conditions Based on Time Synchronous Average and Ensemble Empirical Mode Decomposition", Proceedings of the ICROS-SICE International Joint Conference 2009, Fukuoka, Japan, IEEE Xplore
9. Z. Wu, N. E. Huang, “Ensemble Empirical Mode Decomposition: A Noise Assisted Data Analysis Method”, *Advances in Adaptive Data Analysis*, Vol 1, No. 1, 2008.
10. Guan, L., Shao, Y., Gu, F., Fazenda, B. and Ball, A.,"Gearbox Fault Diagnosis under Different Operating Conditions Based on Time Synchronous Average and Ensemble Empirical Mode Decomposition", Proc. of the ICROS-SICE International Joint Conference 2009, Fukuoka, Japan, IEEE Xplore