ACOUSTIC EMISSION CONDITION MONITORING OF WIND TURBINE ROTOR BLADES: LABORATORY CERTIFICATION TESTING TO LARGE SCALE IN-SERVICE DEPLOYMENT

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Abstract

Wind turbines experience long term fluctuating variable amplitude fatigue loads with occasional large amplitude stochastic peak loads. The fatigue loads are usually characterised by a mean load with a fixed amplitude oscillation superimposed; the stochastic peak loads by modelled peak loads, such as the fifty year gust.

A methodology for wind turbine blade monitoring using acoustic emission (AE) detection of damage processes in the structure has been developed by the AEGIS consortium, supported by the European Commission. The methodology has been developed separately for the peak load events and the more usual operational fatigue loading. It can be applied as an enhancement to the conventional blade certification test and has the potential to be adapted to large-scale field application of the techniques on operational wind turbines.

Wind turbine blade certification tests are carried out to validate design and production. AE monitoring during all stages of a test can both locate and characterise damage processes in blades, starting with non-audible signals occurring due to damage propagation at relatively low loads. Characteristic results are presented of AE activity during peak loading events and fatigue blade tests to failure in the laboratory.

The transfer of the techniques to operating wind turbines is speculative, but the results presented indicate the kind of results which could be obtained from monitoring in-service machines. In particular, a dedicated pattern recognition software has been developed which could identify differences from turbine to turbine and help target preventative maintenance. Validation of the software from laboratory tests on blades is presented. Finally, the requirements for successful deployment of AE condition monitoring in the field are discussed.

Key words

Condition monitoring; wind turbine blades; composite materials; acoustic emission

1. INTRODUCTION

The increasing diameter and hence unit capital investment of wind turbine rotors and the location of future turbines offshore, where maintenance access will be difficult, increases the potential financial losses accruing from unscheduled outages. There is a growing requirement to monitor the condition of individual blades and so give early warning of developing problems. This paper describes the development of acoustic emission (AE) test techniques during the four year AEGIS project, primarily directed towards laboratory blade testing, but also applicable to field monitoring of blades.

AE arises when transient elastic waves are generated by a rapid release of energy inside a material. The AE method relies on the detection of these transient stress waves, usually by means of piezoelectric transducers (sensors), and their subsequent interpretation in terms of damage occurring in the material or structure. Such transient stress waves can be generated for various reasons, including, in composites, crack growth, friction, flow noise, matrix crazing, delamination, and fibre breakage.

The most important aspect of AE, compared to other NDT techniques, is that the material itself generates the signals. The main implication of this is that, when testing a structure, the conditions must be reached that will give rise to those mechanisms (crack propagation, fibre breakage, corrosion, partial discharge etc.) that will produce AE and hence allow any faults to be detected. Another significant aspect is that, with a relatively small number of sensors, the complete structure can be monitored non-intrusively.

Static and fatigue tests are routinely conducted as part of the certification process for wind turbine blades. These tests are designed to ensure that all parts of the blade can withstand extreme load cases as defined in the wind turbine design and testing standards [1,2]. It is usual practice to conduct one or more static tests up to an extreme load value, which typically may represent the 1 in 50 years gust, and then to use the same blade for an accelerated 20 years fatigue lifetime test. It is common for there to be sudden, audible acoustic emission during the static phase of the test, but without proper equipment it is impossible to locate the source. It is clearly important to discover the location and severity of any damage which occurs during the static test in order to be able to improve blade design and also to monitor such areas during the ensuing fatigue test.

In acoustic emission (AE) monitoring, surface mounted piezoelectric sensors detect and locate the origin of sound waves within a structure. The system is very sensitive and can detect much weaker signals than those normally audible to test engineers, mainly in the non-audible frequency domain (20-1200 kHz). The signals can be characterised in terms of features such as Amplitude and Energy and inferences made about the kinds of damage process taking place in the blade. AE monitoring can determine the location and sometimes the kind of damage which is taking place; it can also be used to determine damage criticality for a given load, but conventionally this has required the application of long-sustained loads at this particular level.

The conventional approach to AE testing (see, for example, the procedure applied to FRP fan blades [3]) involves loading a structure to slightly above the highest service load and holding that load for around 10 minutes - the so-called "load-hold" test. For a typical, undamaged fibre composite structure, emission will occur the very first time it is loaded above a given level, but it will not then re-emit significantly on subsequent loading to that level. Sustained emission during a load-hold is indicative of damage. Unfortunately, wind turbine blades can be subjected to very high, but short duration loads (e.g. the 50 year gust), which cannot be (and does not, necessarily, need to be) sustained for the length of time required for a regular AE load-hold test. A novel methodology had to be developed, therefore, to include AE monitoring during standard blade certification tests. This methodology has been used and verified during a series of tests on small, glass/polyester blades and the development of the methodology and some results from the tests have been previously reported in [4, 5].

This paper describes the finally developed procedures and discusses how they can be applied both to laboratory blade certification testing and field monitoring of wind turbines.

2. INSTRUMENTATION

A modern AE system comprises a set of AE sensors which are mounted on the structure, pre-amplifiers to amplify the signal and protect it from noise, cables to carry the signal to the data acquisition-analysis system, and the AE system itself. The sensors are typically piezoelectric crystals, characterised by the natural frequency of the crystal, which determines the response of the sensor. Sensors ratings are usually quoted in terms of the frequency of their maximum sensitivity. Modern AE acquisition systems usually include A/D converters and feature extraction circuitry so that they can receive and analyse a very large number of signals (of order thousands) per second, enabling all sources to be captured and investigated. The analysis is performed based on derived signal characteristics, such as Amplitude, Duration, Frequency, Counts, etc. In addition modern systems have graphical representation of data so that a wide range of plots can be viewed in real time and hence assist the operator in determining the source, its nature, and its possible influence on the test in progress.

Because of the very large variation in signal strength, from microvolts to volts, a logarithmic scale is used for the signal amplitude (i.e. Amplitude is expressed in dB). The voltage or dB level above which signals are detected is called the threshold and this is probably the most important parameter in AE testing as it sets the sensitivity of the test. For the tests reported here, the threshold was typically set in the range from 35 to 45 dB.

Measurements were taken using MISTRAS and SPARTAN AE systems manufactured by Physical Acoustics Corporation and piezoelectric sensors of the type PAC-R6 with resonant frequency of 60KHz and PAC-R15 with resonant frequency of 150KHz. Wideband sensors had been used for preliminary material investigations, but field sensitivity calls for the use of resonant transducers.

Attenuation characteristics were measured on plates of sample material and an ideal sensor spacing of 0.5 to 1.0 m adopted for the blade tests. Sensors were typically arranged down the quarter-chord line on the main spar, with additional sensors towards the trailing edge in the maximum chord area.

A series of 10 small (4.5 m) hand lay-up, glass/polyester blades and two commercial scale (17 m) resin-infused, glass/epoxy blades were tested to failure in order to develop and validate the procedures presented here. Representative results from those tests are reported alongside the test procedures.

3. AEGIS PRS PATTERN RECOGNITION SOFTWARE

Any set of AE data from a loaded structure is characterised according to signal features such as Amplitude, Counts, Energy, Duration, etc.

Aegis PR is a Pattern Recognition Software suite developed within the AEGIS project [6] to analyse and classify AE data from wind turbine blade tests. It is capable of performing Unsupervised (UPR) and Supervised (SPR) Pattern Recognition as well as classical AE data analysis. The Aegis PR software algorithms mathematically segregate the AE data based on their AE features and, ultimately, provide a grade for the structural integrity of discrete wind turbine blade sections according to user-selectable criteria based on the level of AE activity and/or the presence of trends in particular “families” of AE data. The Aegis PR software uses mathematical clustering algorithms in order to divide each set of AE hits into families called “clusters”, based on the similarity of their features.

Mathematically speaking, each AE hit is treated as a multi-dimensional vector, its dimension being the number of its AE features, and its coordinates being the actual AE features’ values. Therefore, AE hit similarity actually implies “close distance” of the corresponding vectors. The clustering algorithms that are used to create classes of AE data actually identify families of vectors which fall close to one another within the same data set. This classification process is known as Unsupervised Pattern Recognition (UPR).

UPR is a purely mathematical function. It is up to the user to select suitable parameters in the analysis and in the clustering algorithms so as to come up with a classification that has a physical importance. In view of the above, the Aegis PR software has been specially designed to be very flexible, in the sense that the user is offered lots of options that can adjust the classification results (e.g. selection of the AE features that will form the vector, vector normalization, definition of number of classes, etc.). Upon experimentation, the user can select (and store) the options and parameters that have led to the optimum classification of the AE data.

Once the user has achieved a satisfactory UPR-classification for a specific data set (e.g. data set A), the Aegis PR software can be trained to classify any new data set (e.g. data set B) based on the classification results of data set A. This procedure is known as Supervised Pattern Recognition (SPR) and is performed by Supervised Classification Algorithms (Supervised Classifiers). In SPR, the vectors (AE hits) of the new data set B are individually classified one by one, based on their AE features, to one of the predetermined classes allocated by the UPR classification of data set A. In other words, each hit of data set B will be classified in accordance with the similarity of its features with the features of one of the classes of data set A.

Any hit with features which are greater than some maximum distance from the class “centre” can then be detected as a “novel” signal.

4. AEGIS STATIC BLADE TEST PROCEDURE

A static AE testing procedure has been developed [7], taking into account both the current blade certification test requirements and the optimum AE evaluation loading, based on past experience and similar composite structure testing procedures. The loading envelope for this test (Figure 1) comprises two basic parts:

(i) a mandatory certification loading to maximum test load (MTL), which is typically a 10 second "spike" loading taken to be representative of the 50 years maximum gust, during which the blade is continuously monitored for AE, and,

(ii) an AE examination loading (AEL), which is a trapezium-shaped load envelope including a 10 minute load-hold period, performed before and after any certification loading as a means to evaluate the damage imposed on the blade by the certification load, or performed at any time during the life of the blade as a means to evaluate its condition and its capability to withstand a particular load level for long term operation.

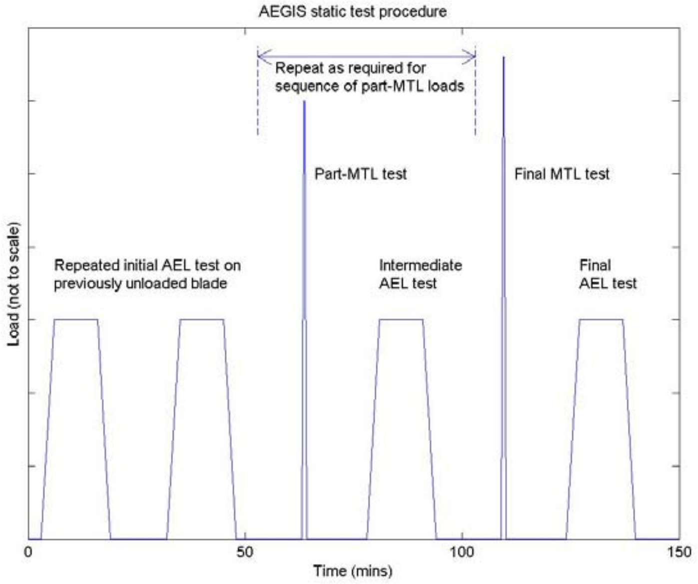


Figure 1 : AEGIS static test load profile proposed for blade certification testing.

It is highly desirable to perform *and repeat* the AEL test before any other loading is applied to the blade, since a high level of emission can always be expected when a structure is first loaded to a given level. The test laboratory may choose to apply "spike" loads at lower fractions of the MTL and these should be carried out exactly as if they were full MTL certification tests with AEL tests performed before and after.

A critical choice for the blade designer and test engineer is the appropriate level of the AEL, which is likely to be site-specific, depending on the local wind regime that the blade must withstand. It is suggested that the AEL should correspond to the maximum design load of the normal operating load cases without fault situations (i.e. Design Load Case 1.2 as described in [1]), but, in any case, should not exceed 65% of the MTL. In any case, the final load should always be agreed with the blade designer.

For a field test, where it is essential not to impose any damage on an otherwise sound blade as a consequence of the AE loading, it may be appropriate to apply the load-holds at progressively increasing load values, performing an intermediate evaluation prior to increasing the load value, in order to be able to stop the test following any significant indications of load criticality. The Aegis PR software has been calibrated to automatically analyse AE data and evaluate the blade's condition for a particular load level, having as input AE data from 10-minute load-holds. This eases the on-site analysis and enables fast and effective evaluation for a decision on whether to continue with the test or not.

Appropriate levels of AEL are discussed further in [8].

The AEL test, coupled with the AEGIS PR pattern recognition software, has been demonstrated to give a very good indication of damage criticality [6, 8]. In particular, all virgin blades with no known damage were passed unequivocally, a blade with an internal flaw, to which an inappropriately high initial AEL was applied, was graded 'E' or highly damaged, even though the test engineers were apparently unaware of the damage, and the blade subsequently failed after a very low number of fatigue cycles, and damaging MTL peak loads were immediately identified by the ensuing comparatively low magnitude AEL tests.

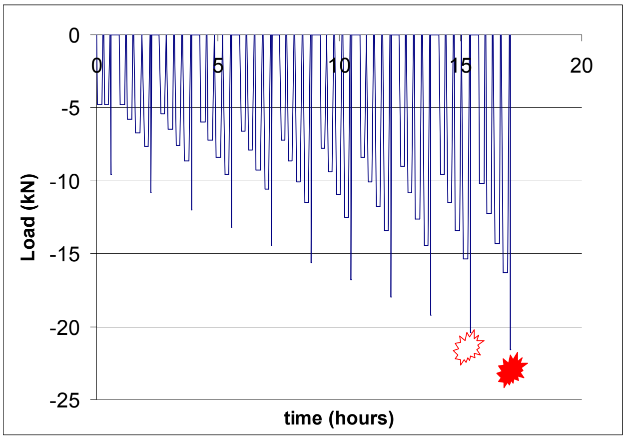
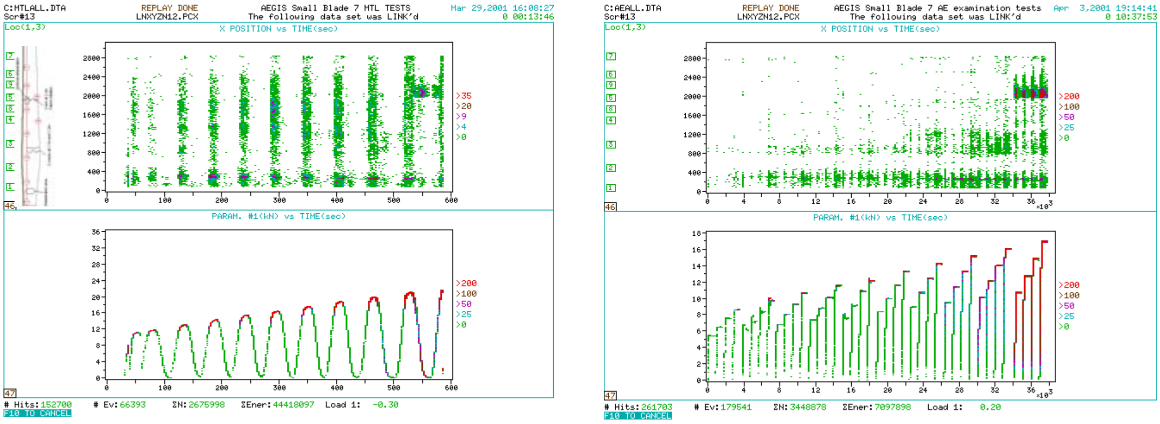


Figure 2 : AEGIS static blade test 7s – schematic representation of loading envelope for estimation of appropriate AEL magnitudes



(a) (b)

Figure 3 : AEGIS static blade test 7s – showing concatenated data from the linked MTL tests (left) and AEL tests (right), including linear location history (top) and loading envelope (bottom)

A typical load sequence from one of these evaluation tests is shown in Figure 2 with the corresponding response in Figure 3. The data from the test was divided into two separate sets for analysis: firstly, the AE data from the sequence of simulated MTL loadings and, secondly, the AE data from the intermediate sequences of AEL "proof" tests.

The history graph of linear location during the simulated MTL sequence (Figure 3a) shows:

- delamination at the root area was well detected from the very early stages of loading, *prior to any visual indication*,

- significant emission occurred from the area between 1.1m and 1.2 m during the simulated MTL test at 18.0 kN, whereas the two cracks which finally developed in this region were only visible after the test at 20.75 kN,

- the final fracture at 2.2 m, initiated during the simulated MTL test to 20.75 kN, was accurately located (close scrutiny of the graph reveals that the crack started propagating at the very peak of the load) and damage continued to occur even during unloading.

Analysis of the sequence of concatenated AEL tests (Figure 3b) is consistent with the MTL data and it can be concluded that:

- damage areas at the root and at 1.1 - 1.2 m were located at very early stages,

- the final failure area was extremely emissive during the last set of AEL tests, following the simulated MTL test at 20.75 kN, providing a very clear warning of the impending failure (which occurred during the subsequent simulated MTL test to 22.8 kN)

Applying the Aegis PR software grading trained on the data from blade 7s produced the progressive gradings shown in Figure 4. The figure shows the loading applied to the blade (bottom of figure) and the timing of the two major crack initiation events (i.e. the time when the cracks were first visible on the blade surface) during the MT11 load. The blade receives largely satisfactory grades at the AE11d loading prior to the MTL11 load (except at the root, which is known to be over-graded and therefore requires separate treatment). However, after the critical MTL11 load, sensor 5, where the main structural spar finally broke, was given the most critical “E” grading with an AEL at only 50% of the previous MTL magnitude (AE21a = 10.8 kN).

It should also be noted that, in this case, at least, the AEL sequence gives better discrimination than the MTL sequence of the critical blade sections at 1.1 m and 2.2 m. This is largely due to the very high load magnitudes in the MTL tests, commonly observed at extreme loading rates in composites, which caused temporarily continuous emission above threshold in the signals detected by the AE system.

5. AEGIS FATIGUE BLADE TEST PROCEDURE

The fatigue test, which typically follows a static blade certification test, provides an ideal opportunity to evaluate the AE arising from gradual damage growth. Since the AE sensors are very sensitive and glass composite wind turbine blades are inherently “noisy” structures (glass/epoxy was found to be less “noisy” than glass/polyester in that substantially less AE activity was detected at moderate loads), it is necessary to reduce the AE hits data by raising threshold levels and/or limiting data collection to regular sampling during the test.

Initially it was decided to sample the fatigue cycles at discrete intervals and to test the integrity of the blade using the static AE examination loading (AEL) test at more widely spaced intervals. The fatigue cycles were sampled during 10 slower, low strain rate cycles, periodically applied (every 10,000 cycles) to measure the blade stiffness, which it was postulated should be more severe than the faster cycles since the peak loads were actually held for longer (albeit at a lower strain rate). Unfortunately, some major visible cracks were not convincingly detected and located when applying these sampling conditions and the procedure was amended for the final tests to include AE Hits data collection during the top 10% of each normal fast load cycle.

The fatigue test procedure [9, 10] commences with a repeated AEL test, as used in the static tests, followed by the fatigue loading, interspersed with occasional static tests. Time-driven data (i.e. parametrics such as load and displacement, average AE signal level, and absolute energy) is recorded continuously on the AE monitoring system and AE Hits data collection is switched on as required according to an externally controlled enable/disable switch.

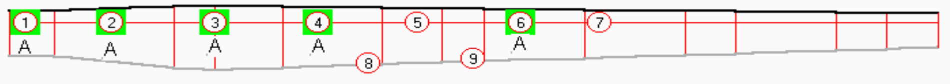
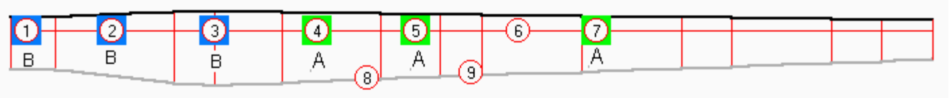
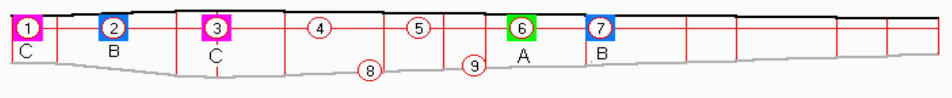
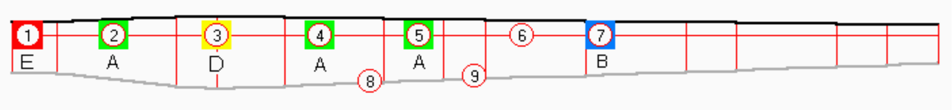
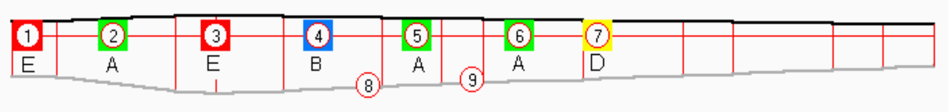
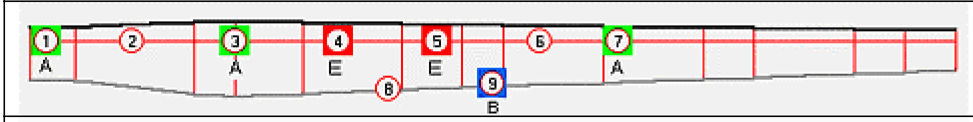
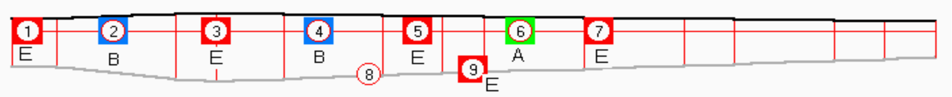
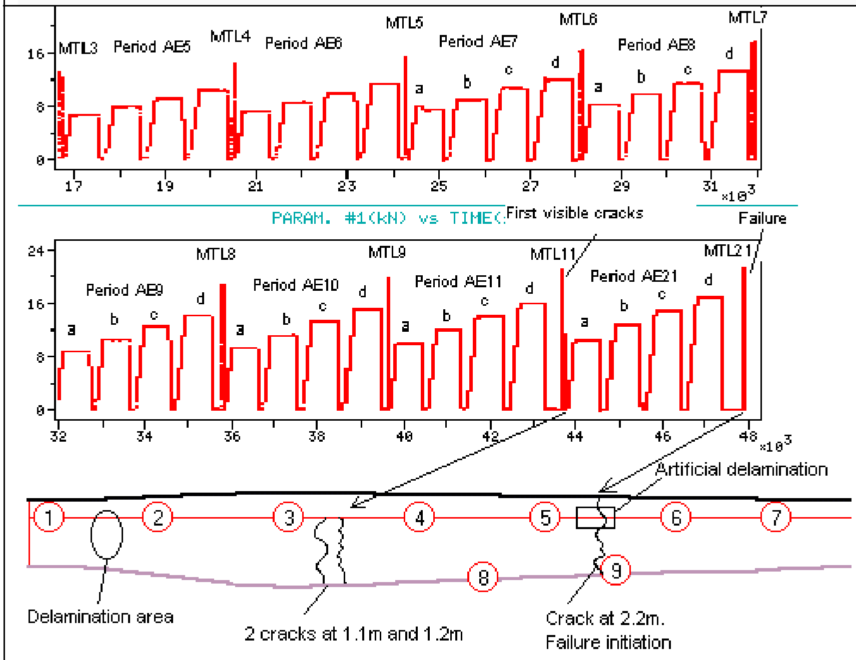
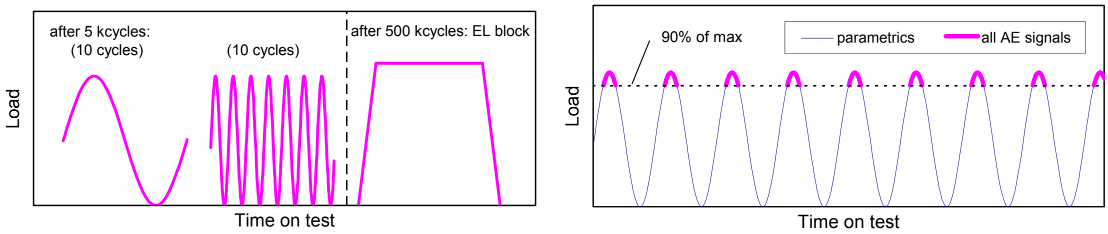
GRADED BLADE # 7 A B C D E	*Period and Load hold level KN*
	*AE7d* *12.48 KN*
	*AE8d* *13.44 KN*
	*AE9d* *14.4 KN*
	*AE10d* *15.36 KN*
	*AE11d* *16.32 KN*
	*AE21a* *10.8 KN*
	*AE21d* *17.28 KN*
	*Loading Envelope and damage occurrence information of Blade 7*

Figure 4 : Aegis PR software grading for small blade 7s



(a) (b)

Figure 5 : AEGIS blade fatigue test loading regimes - schematic showing periods when Hits data recording initiated: slow and fast cycles (a) and peak monitoring (b)

In all, therefore, the fatigue test consisted of four load stages (see Figure 5):

I : initial (low level) static AEL test to operating load (AE hits recorded),

II : static AEL test to 10% above peak fatigue load at start and after every 500000 cycles (AE hits recorded),

III : fast cycles at 2 Hz sinusoidal fatigue load (R-ratio = 0.1) to the peak fatigue load (for small blades, parametrics only - no AE hits data recorded; for commercial blade, AE hits data recorded for the peak 10% of each load cycle − see Figure 5b),

IV : after every 10000 cycles, load application rate reduced to give ten slower cycles at 0.2 Hz (load-strain characteristic and AE hits data recorded).

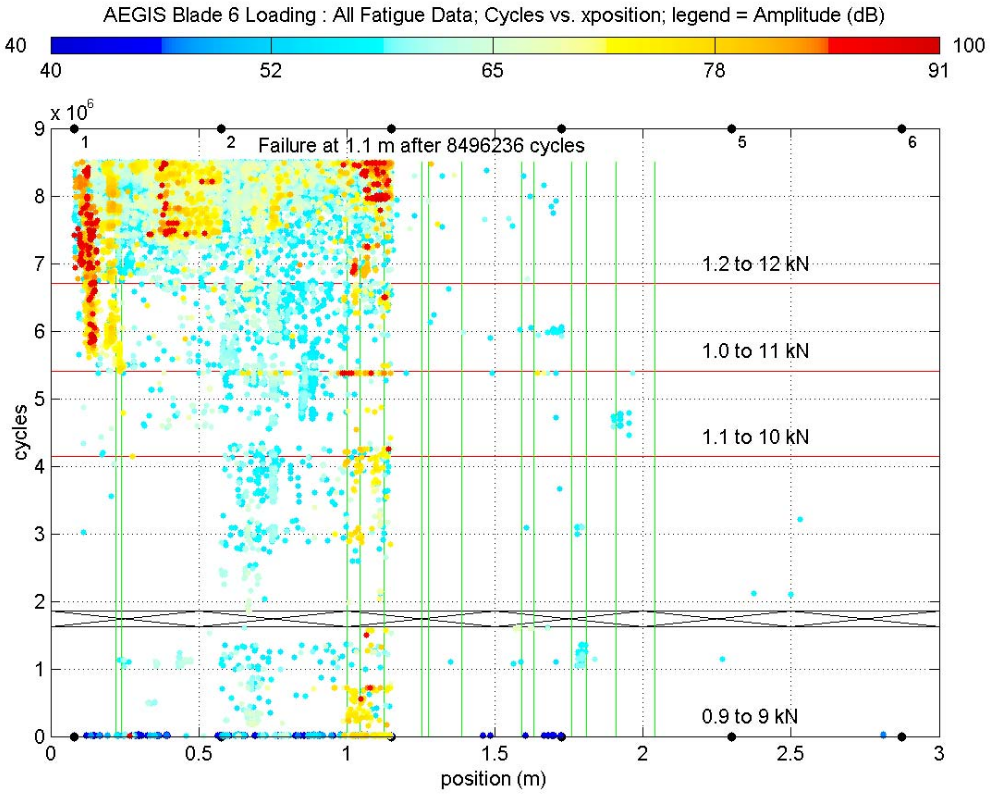


Figure 6 : Amplitude history of linearly located events for blade 6f

Representative results for a test on one of the small blades are presented in Figure 6, where a cluster of high Amplitude events can be seen at the 1.1 m failure point. Other clusters of high Amplitude events occur at 0.1-0.2 m in the root and at 0.4 m. The nominal locations of other visible cracks are also indicated (vertical lines). These cracks appeared in the sandwich part of the blade at various stages of the test. As noted above, many of these were not well located by high Amplitude (or high Energy) events. This phenomenon was investigated but never fully explained. It may, in part, have been due to the complex internal structure of the blade affecting the signal transmission. However, it may also have been that the AE data associated with these cracks actually originated during the (unlogged) fast cycles and, for this reason, the AE fatigue procedure was modified in later tests to include Hits logging during the peak 10% of each load cycle.

During the test, significant AE activity was measured in the root area of the blade. This activity corresponded with visual observations of delamination damage. However, post mortem inspection of the blade root section revealed that the damage was limited to a small number of outer layers and that the structural integrity of the root section was not significantly impaired. This indicates the need for some further work on classifying AE data related to the stress distribution in the blade as well as abrupt material and / or geometry changes (e.g. metal / FRP interfaces, moving parts, etc.).

6. IN-SERVICE TESTING

An array of six sensors was attached to the outside surface of blade on an operational wind turbine at the CCLRC Rutherford Appleton Laboratory Test Site.

The static test methodology was applied to the blade using a rope and pulley method. It was possible to load the blade and collect meaningful AE data. However, unless the loading mechanism was to be designed into the wind turbine with a number of discrete loading points, it would be impossible to fully test all regions of a blade.

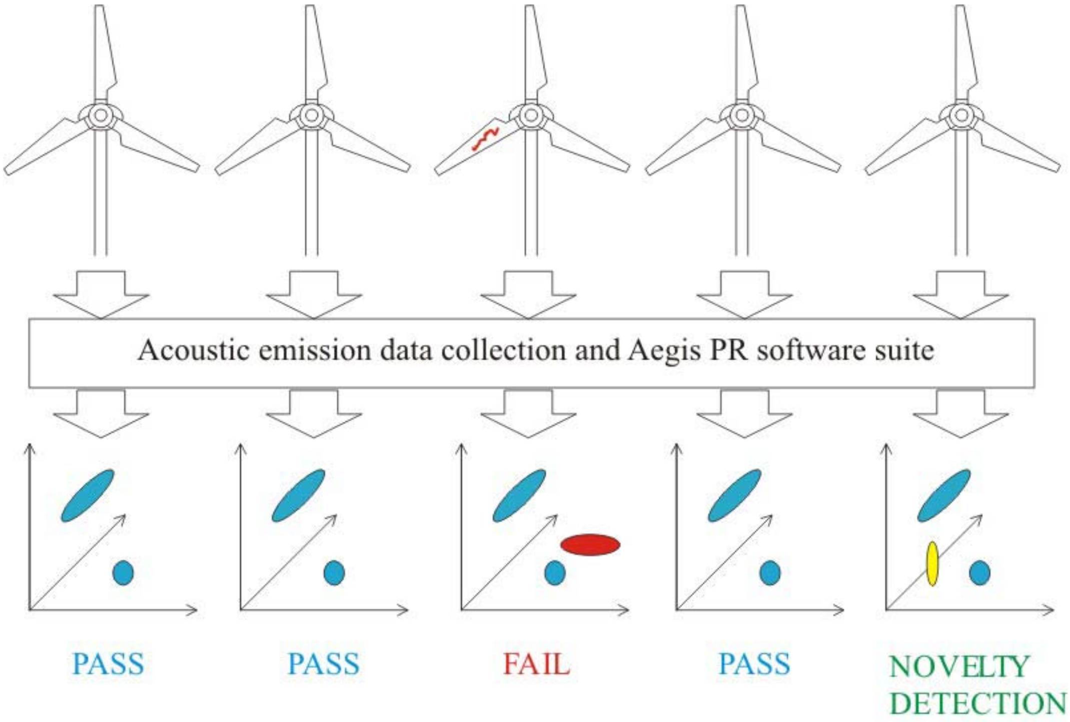


Figure 7 : Application of Aegis PR software to identify AE patterns with known damage implications or novel parameter patterns for future investigation and learning

A more promising approach would be to collect data from operating turbines under specific loading regimes, particularly when they are experiencing high loads due either to operating in high wind speeds or because of machine action such as braking or pitch actuation. The AEGIS project has pioneered the use of radio transmitted AE signal data collection and has successfully collected data from a single turbine operating in moderate wind speeds [11]. Results indicate the feasibility of collecting AE signals from the rotating frame and indicate an acceptable level of noise in low to moderate wind speeds. Further work is required to verify whether or not the noise level increases appreciably with wind speed and whether such signals can be filtered out.

AE monitoring could, in principle, be applied across a whole wind farm. A diagrammatic representation of an expanded system suitable for such an application is shown in Figure 7. It is assumed that each blade on each turbine is separately instrumented (ideally with an array of interior sensors installed during manufacture). The data is collected independently for each blade and graded using the Aegis PR software. For illustrative purposes, the figure shows a 3-dimensional representation of the n-dimensional AE parameter space for signals from each blade. The Aegis PR software has detected normal expected AE data clusters on all turbines, but a cluster typical of damage has been identified on turbine 3 and a novel data pattern has been identified on turbine 5. Recommended action might be to shut down turbine 3 pending inspection and to closely monitor developments on turbine 5. As with laboratory testing, it is expected that the usefulness of the system would increase with time and increasing number of blades monitored, since it would be possible to learn critical patterns, even where these were not know *a priori*. In other words, if the novel data pattern on turbine 5 later led to significant damage levels this could subsequently be used to identify possibly critical conditions on other blades and the initiation of preventative maintenance.

7. CONCLUSIONS

The initial laboratory application of AE monitoring must be within the context of the existing blade certification procedures [1,2]. Since these procedures effectively prescribe the mechanical load profile which can be applied to a blade, it follows that the type of load application and analysis procedures used by AE specialists to determine the criticality of defects in other structures (see, for example, [3]) cannot be directly applied to blade tests at present. Accordingly, a fresh approach has been successfully developed which attempts to integrate the AE testing methodology within the existing blade certification procedure.

The static and fatigue test methodologies have been applied during a series of ten small blade tests and two larger, commercial scale blade tests.

A successful damage classification software (Aegis PR) has also been developed to classify AE data from a static test, fatigue test, or any other extreme load event on a wind turbine blade. A critical damage cluster has been identified which occurred across a number of blade tests and originated only in blades with developing damage. The software should be applied during future blade tests in order to further validate the results on other blade types and geometries.

The Aegis PR software could form the nucleus of a wind farm AE monitoring system with the potential to learn new damage cluster signatures.

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