Guiding inspections and maintenance with condition monitoring

Words: Obdulia Ley, PhD., Subject Matter Expert, Acoustic Emission, Sensoria™

On a wind farm, knowing the moment that new damage on a blade occurs or when existing blade damage is showing signs of worsening and degradation, helps prioritize repair and maintenance activities, improve fleet reliability, and manage complex schedules to meet production demands.

Condition monitoring (CM) is the process of monitoring a parameter in machinery, to identify a significant change indicative of a developing fault. CM relies on real-time sensor measurements, with outputs used to optimize maintenance operations and save effort and resources.

Sensoria™ uses acoustic sensors installed in the root area of the blade to continuously collect acoustic signals that are linked to damage onset, damage presence, and damage evolution/worsening. The acoustic signatures collected by the sensors are linked to the way that a blade responds to loading due to weather, turbine operation, and the presence of defects. Knowledge of the occurrence of new damage on a blade, or information about changes in the acoustic response of a blade with known critical defects, helps a blade or fleet engineer to prioritize inspections and maintenance operations.

Interpretation of acoustic data from a blade using the Sensoria™ blade monitor, takes into account several factors. Fiberglass composite structures produce a wide variety of acoustic signatures with various frequency and energy responses and the acoustic response and behavior of the blades in a given wind turbine is different if one of the blades has existing defects, experiences damage progression, or foreign object impact.

The higher the stresses experienced by the blade during operation, the higher the acoustic activity experienced by the blade, which is in turn related to the blade's response to the structural loads of operation. Delamination, unwanted vibration, and cracking events are associated with different frequency acoustic responses. Finally, damage progression is linked to the increase in acoustic energy release over time, so trending the level and number of acoustic signatures is a tool to identify damage evolution.

These considerations are the basis for signal interpretation in the Acoustic Emission (AE) technology, which is the basis of Sensoria.

The acoustic data collected by the sensors 24/7/365 and a database of acoustic signatures of different blade damage, calculate two proprietary parameters that are linked to the probability of the existence of blade defects and/or damage that are actively growing and the probability of some of the acoustic signatures from the blade to be the result of crack onset and propagation.

These quantities are called Probability of Defect Activity (PDA) and Crack-Like Activity (CLA), respectively. Both PDA and CLA are referred to as Structural Health (SH) quantities, as they are related to the blade's ability to respond to operational stresses.

SH quantities allow trending blade activity and comparison of all blades in a farm among themselves. More importantly, grading all the blades on a wind farm based on their acoustic response provides a tool to rank the presence of abnormal responses and the likelihood of crack growth. Identifying those blades that consistently rank higher than their neighbors provides a methodology to isolate and identify blades that require further inspection and/or maintenance.

Structural Health (SH) quantities and blade ranking

The SH quantities CLA and PDA are defined to assess the general response of each blade to the operational loads. SH quantities are calculated on a seven-day /weekly basis using different features and trends of the acoustic data collected by the sensor on each blade. The seven-day period allows the collection of acoustic information from the blades through all RPM values and various wind speeds; which, in turn, provides a statistically representative sample of the acoustical noise/signals during various loading/operational conditions.

The logistic and analysis value of PDA and CLA is the historical trending and the identification of the time/date or seasons where a type of acoustic signature dominates in a blade. This tracking is important, as such response is linked to a high probability of worsening of existing

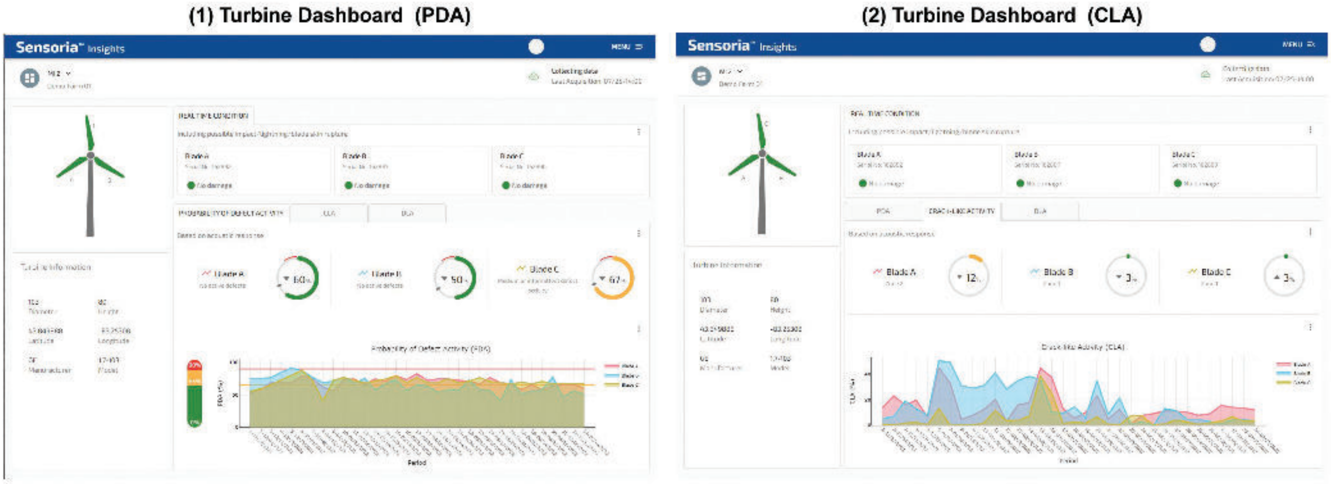

Figure 1: Example of Sensoria's Data Driven Web Application (DDWA) turbine dashboard showing PDA and CLA for a selected turbine. After logging in, the user can toggle through the different SH quantities presented. The progress rings show the current quantity value per blade

blade damages or the formation of new ones. PDA and CLA trends are shown in Sensoria's Data Driven Web Application (DDWA), when accessing the turbine dashboard as shown in Figure 1.

The SH quantities were developed by tracking 14 turbines with various defects during operation for an average time of 12 months and by comparing the evolution and worsening of damages from scheduled visual inspections with the acoustic signature changes and observed trends in between the blade inspection periods.

PDA was defined using several (AE) features of the sound waves collected by the sensors, correlation plots between such acoustic features and segmentation of data sets from blades with similar types of damages. PDA is used to identify when the acoustic signature of a blade goes outside the normal response of a healthy blade. This parameter increases in value in the event of changes in the noise characteristics due to the presence of damage. PDA is sensitive to any type of damage that affects the normal response. The PDA ranges between 30 and 100 and can oscillate significantly over time depending on activity or show a slowly-increasing trend.

The CLA is a number from 0 to 100 defined as the percentage of the acoustic activity collected by the Sensoria™ sensors (per blade) that satisfies characteristics associated with crack growth during the time period under consideration. CLA will be high when existing cracks in the blade are active or when a new crack is formed. Given the single sensor instrumentation, if there are multiple cracks on the blade, the response of multiple cracks present on the structure will be combined. When tracking crack growth with acoustic activity, it is known that activity tends to be present and then stops when the crack arrests or becomes stable. Following crack growth, cycles tend to show increased levels of energy release and activity, so tracking the evolution over time of CLA helps identify the growth cycles of the cracks.

The SH quantities (PDA and CLA) trends can indicate whether there are active cracks or other damages on the blade. If PDA or CLA are seen to increase in magnitude over time or if they present a drastic change at a given period, then the blade should be flagged for inspection. In addition, the need for inspection should increase if the blade is known to have a critical damage, such as a root crack, or other damage known or likely associated with blade failure.

PDA and CLA values, calculated per period and per blade, are classified into three main regions depending on severity and level of the acoustic response: green or normal, yellow or increased level, and red or highly active. When a blade consistently shows high levels of one or more of the SH quantities, it should be considered for inspection and/or closer observation and data analysis. Sensoria™ DDWA offers the ability to observe the CLA and PDA trend per turbine and blade, as well as the ability to observe monthly the average response of each blade on the farm, and offers a tool to rank all blades on the farm through the use of the 'Structural Health' and the 'Maintenance Planning' tabs.

In Sensoria™'s 'Maintenance Planning' tab, the blades are automatically ranked using both CLA and PDA values from highest, or worst, to lowest, with no active damage. The blades are labeled using a 3-color scale: Prioritize inspection in red, Medium inspection priority in yellow and Low inspection priority in green. A diagram of the process is shown in Figure 2, where the region boundaries are linked to the different levels of PDA and CLA defined.

The inspection priority ranking shown by Sensoria™ DDWA can be performed by considering the average quantities in the

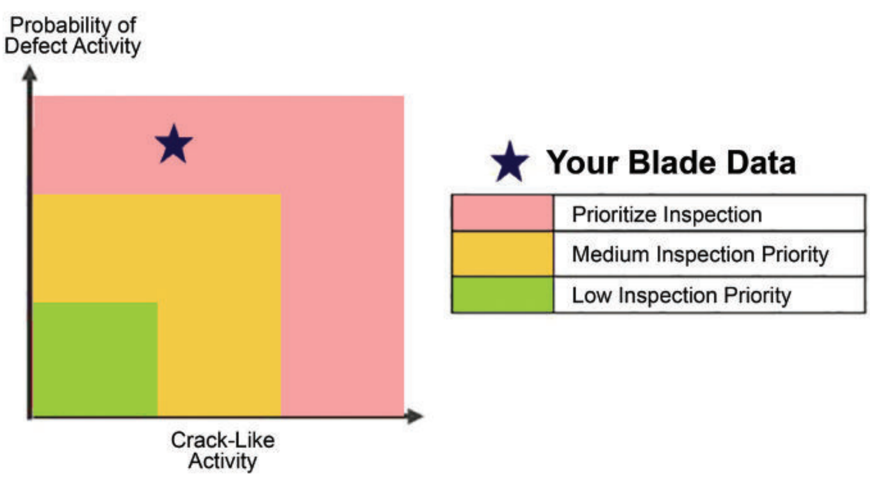

Figure 2: Use of period values of CLA and PDA to identify the ranking and type of follow up needed for a given blade. SH quantities for each blade during a user-defined time period are considered. All blades on the farm or selected blades are compared and ranked based on their CLA and PDA values

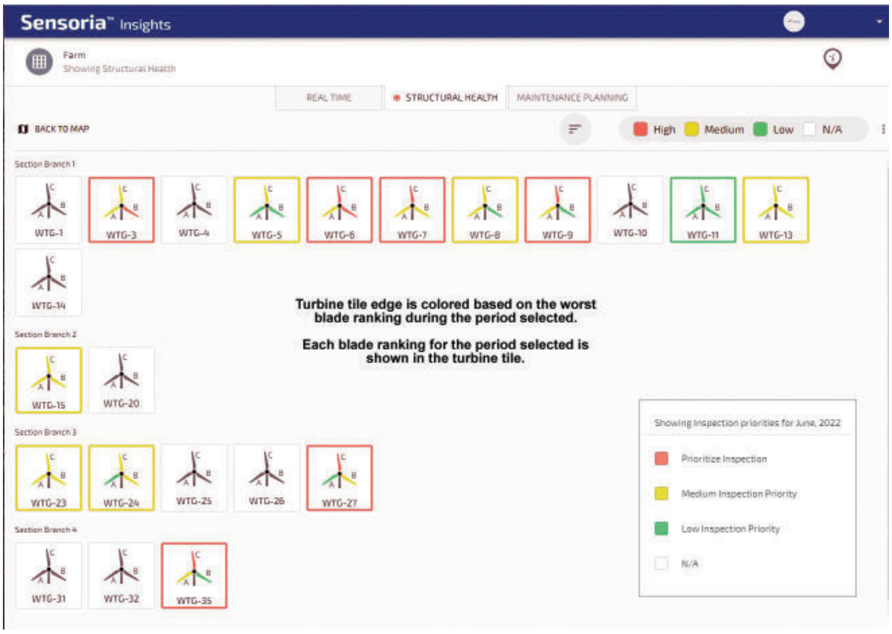

Figure 3: Example of Sensoria's Data Driven Web Application (DDWA) showing the monthly average ranking of the turbines instrumented in a farm. The ranking is performed based on CLA and PDA values, and the classification is based in a model similar to the region plot shown in Figure 2

selected user-defined time period or by considering the variability of CLA and PDA during the selected period. Independently of the ranking methodology used, it is recommended to generate and compare the blade ranking at different time intervals such as monthly, quarterly, or annually. Comparing the blades' ranking by selecting different time periods will showcase those blades that rank consistently higher. This is important, as damage is not always active and producing acoustic signatures, as discussed in the following example.

To rank all the blades in a farm, the user selects the time period. The DDWA will perform the averages and statistical analysis of all the trend CLA and PDA data from the blades/turbines in the farm and provide a list of blades ranked by CLA and PDA, given the boundary definition of green, yellow and red mentioned before.

The ranked list is directly displayed on the DDWA as part of the 'Maintenance Planning' tab, or it can be downloaded as a Microsoft Excel file. The user can also see a graphical representation by accessing the "Structural Health" tab of the DDWA as shown in Figure 3. In this graphic display, the turbine tile boundary will be colored based on categorizing the worst blade in the turbine. The turbine tile also shows the categorization of all blades in the turbine, colored using the scale shown in Figure 2.

When there is insufficient data to perform the analysis, that is the system is not being powered, the turbine tile is shown in gray. The graphic representation of the blades and turbines that require follow-up in figure 3 is based on the severity and level of the acoustic response. It can be used to identify the worst turbines, such as WGT-06 with two blades in red) and the ones that do not require immediate attention, such as turbine WTG-11.

Figure 4 shows a summary of the factors affecting damage onset and evolution, and the use of Sensoria™ to track damages and improve farm management operations. In summary, when using the acoustic ranking, one should consider that not all damages produce an acoustic signature all the time, so the response can vary over time. When a blade has active damage producing acoustic signatures, it will rank higher and will be assigned a higher priority. Finally, when a blade consistently appears in the high inspection priority level over several months, the probability of observing damage that has appeared or worsened is high.

Tracking SH quantities of three turbines for six months

This section shows an example of a small-scale pilot project to monitor three GE 2.0 turbines for six months, from November 2021 to June 2022. At the time of instrumentation, one turbine was considered 'healthy' (TT10) with severity 1 and 2 damages, and two of the turbines (TT11 and TT12) had damages with severity 5 and 3; the damages were associated with Root cracks and Trailing Edge (TE) cracks; the summary of damages is shown in Table 1.

Figure 5 shows an example of three different ranking tables generated using the PDA and CLA calculations for the three turbines instrumented at the farm (TT10 TT11, TT12). The ranked tables presented in

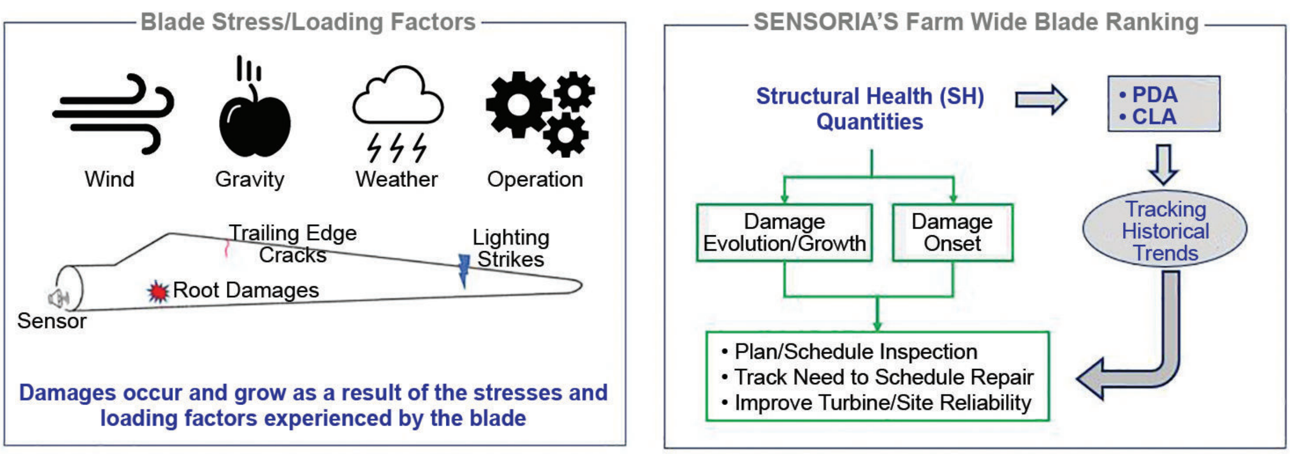

Figure 4: Summary of factors affecting damage growth and evolution wind turbine blades (left hand side), and diagram showing how Sensoria™ offers proprietary SH quantities (PDA and CLA) to track and rank acoustic activity of blades linked to presence of damages

Blade	Existing Damage from Inspection	Blade	Existing Damage from Inspection
TT11-A	Root crack (Severity 5), TE cracks (Severity 3) at 16.3 and 20m, P&S sides.	**TT12-A**	TE crack (Severity 3) @ 17.3m
TT11-B	TE P&S side cracks (Severity 3) @ 17m	**TT12-B**	Transverse root crack (Severity 4) @ 10m. TE crack (Severity 3) @17m, LE crack (Severity 4) @ 11m
TT11-C	TE cracks (Severity 3-4) @ 17.3 to 22.3m (P and S sides), chord crack (Severity 3) @32m.	**TT12-C**	Transverse root crack (Severity 5) @ 10m. LE crack (Severity 4) @ 14.8m, chord crack (Severity 4) @ 52.4m

Table 1: Summary of damages in Turbines TT11 and TT12

Figure 5 show different monitoring periods: (a) the latest month of monitoring, (b) the last three months of monitoring, and (c) the last six months of monitoring. Comparing these ranked lists (generated using CLA and PDA) it is seen that, consistently and independently of the time interval selected, the same blades are classified as red or in need of inspection.

When comparing the blades classified in red with the existing blade damages shown in Table 1, it is seen that the blades that were ranked higher for inspection are known to have existing cracks. The unexpected result was to see Blade C in turbine TT10 ranked high within the priority list. Follow-up inspection of this blade revealed a Severity 3 trailing edge (TE) crack, as seen in Figure 6, which also shows the CLA historical trend of Turbine TT10 since instrumentation.

Examples of Ranked Data using CLA and PDA

(a) Last Month

Turbine Name	Blade Name	Avg PDA	Avg CLA	Avg DLA
TT10	C	70.73	15.41	12.04
TT11	A	73.1	14.28	9.78
TT11	C	78.25	14.81	9.71
TT12	B	74.74	12.73	22.07
TT12	C	82.01	13.6	18.1
TT11	B	57.7	5.1	33.17
TT12	A	51.32	5.5	36.31
TT10	A	69.84	3.96	15.38
TT10	B	57.04	3.34	28.66

(b) Last 3 months

Turbine Name	Blade Name	Avg PDA	Avg CLA	Avg DLA
TT12	B	78.87	19.84	3.11
TT12	C	70.09	15.54	7.75
TT10	C	70.27	14.28	2.99
TT11	C	78.24	11.8	1.79
TT11	A	70.85	9.62	6.85
TT10	A	71.61	8.28	4.49
TT11	B	66.85	6.76	10.32
TT12	A	57.59	6.62	10.02
TT10	B	68.83	4.12	11.21

(c) Last 6 months

Turbine Name	Blade Name	Avg PDA	Avg CLA	Avg DLA
TT12	B	77.67	19.23	8.27
TT12	C	73.28	17.91	11.26
TT10	C	70.95	15.1	8.55
TT11	C	77.41	13.06	5.13
TT11	A	72.21	11.81	7.26
TT12	A	57.2	7.16	15.75
TT10	A	70.52	7.11	8.24
TT11	B	62.65	5.95	16.47
TT10	B	64.34	3.35	17.84

Figure 5: Example of three ranked lists for blades instrumented with Sensoria. Each list was generated using a different time interval (one month, three months and six months). The different time intervals considered produce a ranked list consistently showing the same group of blades presenting crack activity and need for follow-up inspection (by being colored red). The blades can change position in the list because not all damages are active all the time

The acoustic ranking shows the blades with active damage and it correlates with the presence of damage on the blades at the time of installation. More importantly, PDA and CLA trends per blade can identify the presence of the TE cracks in what was considered the healthy turbine.

Figure 6: CLA historical trend of Turbine TT10 since system installation. The CLA trend shows increased activity of blade C, where a Trailing Edge (TE) crack in pressure and suction sides (around 32m from the root) was observed after inspection

Summary and conclusions

Sensoria™ offers condition monitoring by defining two proprietary quantities associated with abnormal acoustic signatures on the dataset (PDA) and the level of acoustic signatures with crack-like characteristics (CLA). These quantities are used to compare and rank the blades on a wind farm based on the trends and correlations of the quantities.

CM with Sensoria™ helps to track wind turbine blades with known damages and increases confidence regarding the need to perform maintenance. Sensoria™ also provides information between inspection cycles regarding new or developing damages on the blades. The economic advantage of CM with Sensoria™ is to identify and separate blades needing immediate attention from those that do not require inspection and/or maintenance.

Finally, addressing and/or planning repairs on damages detected by Sensoria™ before they worsen helps reduce the cost of repairs and downtime.

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