

Real Time & Long Term Acoustic Emission Monitoring: A New Way to Use Acoustic Emission - Application to Hydroelectric Penstocks and Paper Machine

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Abstract. For decades now, acoustic emission (AE) testing has been used in several fields of the industry, mainly for the control of pressure vessels (storage tanks, reactors ...), civil engineering structures, such as bridges. The specificity of acoustic emission technology is to be a global non-destructive method, able to detect and localize in real time active phenomenon, such as cracks, corrosion, leaks or impacts...

In order to fully exploit the unique capabilities of this technique, we have implemented AE on new fields that need real time and long term monitoring. Two original cases are presented:

The first one deals with strategic structure in the field of hydroelectric energy, i.e. the penstocks, that deliver water from a dam to hydraulic turbines. The challenge was to ensure the safety of this installation, built in the 50s, while continuing to produce electrical energy. Engineers have adapted existing technologies of acoustic emission to catch very specific degradation phenomena that could lead to the full rupture if not identified on time.

The second case deals with the monitoring of rotating mechanical parts, such as bearing or gearbox. We have implemented AE on a large Paper Machine, in the Frame of a European Project 'SUPREME'. We have been able to correlate AE and many other physical parameters such as vibrations ... and found interesting correlations and complementarities. The real time and continuous monitoring of five mechanical elements during six months, has allowed us to better understand the constraints linked to such complex environment and to draw conclusions on monitoring strategies.

1. AE Monitoring of Penstocks

1.1. Introduction

The hydroelectric complex of Tignes-Malgovert is an essential part of French electricity production system, able to inject nearly 400 MW to the national grid in a few minutes. Built between 1946 and 1953, it is characterized by a waterfall of about 800 m, fed through two penstocks, and 4 groups, each equipped with two Pelton turbines. Penstocks are partly banded with forged high strength steel hoops. For this purpose, during manufacturing, each pipe was banded with equally spaced hoops and placed in a hydrotesting machine. Then the



shell was expanded over its elastic limit, such that it pinched against the hoops. Therefore, hoops were prestressed against the pipe.

However, after almost 60 years of operation, hoops can be affected by stress corrosion cracking, which can result in ruptures of hoops, causing a decrease in the safety factor of the shell. In this context, EDF has decided to set up a monitoring system to be able to detect any hoop rupture and alert the operator in real time.



Picture 1: General view of the double hooped penstock

Acoustic emission has proved to be potentially interesting, because of its real time detection ability. However, it was necessary to adapt this technique to the case studied. Thus, all aspects of this problem were evaluated: Characteristics of the phenomenon to be detected, the acoustic characteristics of the structure, assessment of background noise caused by the operation of the plant, climatic conditions... From this, acoustic emission technology was adapted, requiring specific choice of instrumentation, software adaptations, and the creation of an interface with the system of supervision of the plant.

1.2. Feasibility Study

The study that has defined the conditions for application of acoustic emission in this particular case addressed the following points:

- Analysis of propagation conditions,
- Measurement of hoop's fracture characteristics,
- Measurement of background noise, related to the operation of the plant.

1.2.1. Characteristics of penstocks

The two penstocks have a diameter of 2.1 m. They are parallel to each other, installed in a slope up to 66%. In many places, the pipes are anchored in concrete foundations. Each line must be monitored for about 200 m, in its lower part, near the hydroelectric plant.

1.2.2. AE Measurements

The feasibility tests were performed with several types of sensors. For each type, listening range was measured with the aid of an artificial source of high energy, in relation to the phenomenon that should be detected.

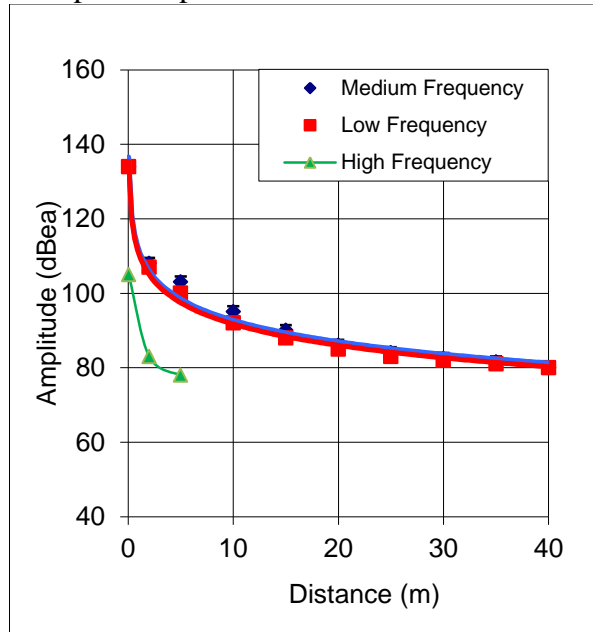
For these tests, more than 25 sensors with resonant frequencies ranging from 30 to 200 kHz were placed on the penstocks. The effect of the thickness of plates forming the

penstocks (they do not have the same thickness depending on the section) was measured, as well as the impact of anchors in concrete.

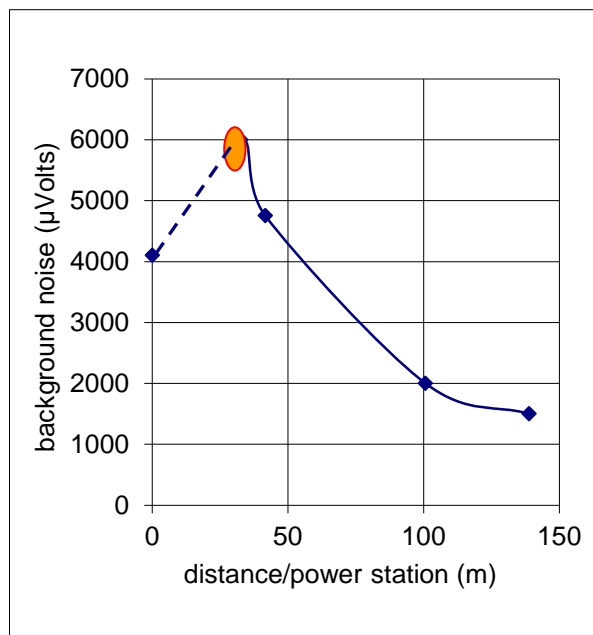
For each configuration, the propagation velocity of the acoustic waves was also measured.

1.2.3. Measurement of Background Noise

An essential parameter for defining the monitoring system is the level of background noise, which in this case is mainly due to the fluid flow as well as the turbines and associated mechanical components such as valves. Measurements were made in all possible configurations, from the stop of the plant to the situation with 4 turbines in operation.



Graph 1: AE Attenuation curves vs. Frequency



Graph 2: Background noise vs Distance from the power plant

These measurements showed (graph 2) for example that the level of noise depends on the distance from the turbines, and also on the presence of elements such as fluid distribution spherical parts.

Thus, from the outcome of these attenuation and background noise measures, we were able to define a mesh for a complete coverage of the penstocks sections to be monitored.

1.2.4. Qualification tests

The acoustic emission is a listening technique that can detect very thin phenomena, for example microcracking, fiber breaks in composite materials, ... In our case, the sought phenomena are much noisier because it consists in the rupture of a steel prestressed ring with an initial section of several cm².

Therefore, it has been necessary to evaluate the characteristics of this phenomenon in terms of energy released, to better adapt the dynamic range of the monitoring system, very different from that commonly used in the usual field of acoustic emission.



Picture 2: Rupture test of a forged hoop–Hydraulic System

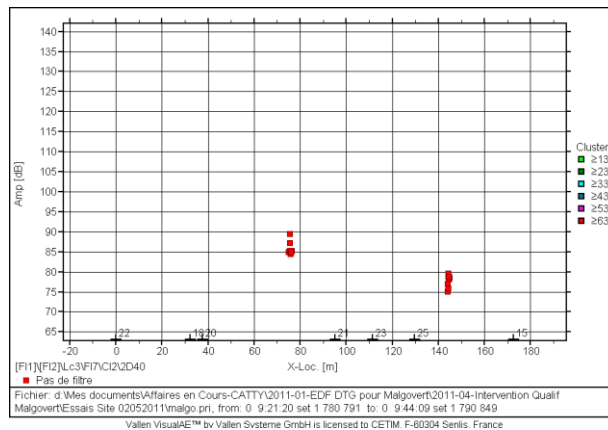
Rupture tests were carried out on three rings. To be as representative as possible of a rupture that may occur in service, the three rings being tested were previously notched with a grinder, gussets were welded on the ring in order to install a cylinder jack (see Picture 2). Thus, it allowed performing ruptures without noise. So that the propagation of acoustic waves should be representative of a normal operation situation, the lower sections of the penstocks were partially filled with water during the tests. The acoustic signal emitted by each of these three breaks was then measured by the instrumentation in place.

Prior to rupture tests, the artificial acoustic emission sources have been generated at the ring positions to be broken in order to assess the ability of the localization system; For this, a linear mesh was used (Graph 3).

All provoked ruptures were localized with an accuracy of the order of 2 m, for distances between sensors up to 60 m.



Picture 3: Rupture test of a forged hoop– Fracture Surface



Graph 3: Pre-localisation of failures by artificial source, linear location algorithm

1.2.5. Definition of the monitoring system

From all the data obtained, we were able to establish an optimal mesh of sensors, able to detect hoop failures, taking into account background noise, attenuation values and energy levels of the acoustic sources.

Thus, 20 sensors were installed on the two sections of penstock, monitoring the most critical 400 meters with respect to risk of frets rupture.

1.3. Implementation of the AE System

The installation was performed during autumn 2011.

1.3.1. Instrumentation of the Penstocks

The implementation of such a system must take into account environmental constraints: important moisture and temperature variations, possible disruptions due to falling objects, the intervention of maintenance team...

Each sensor has been protected by a plastic box, also integrating the first amplification and filtering stage.

Coaxial cables were pulled from each sensor to the acquisition system, located in the building of the hydroelectric plant. Almost 3,000 meters of cables were installed.



Picture 4: Cable path, and 2 boxes including sensor and pre-amplifier



Picture 5: A connexion box



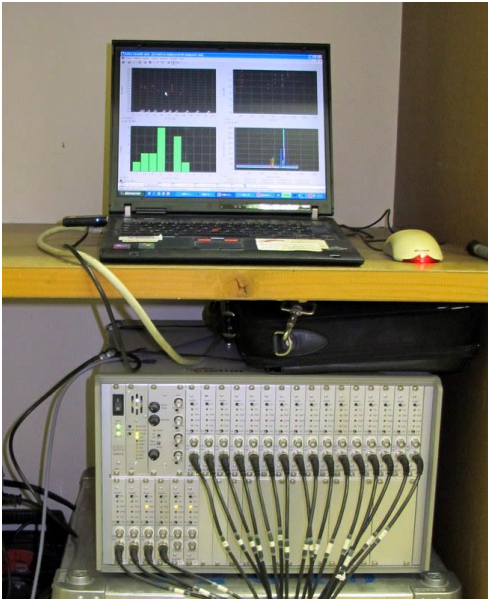
Picture 6: Sensor's Box

Due to the important slope of some sections of the penstocks, a part of the installation required a rope access, to work safely.

1.3.2. Acquisition and Warning system

An acquisition system 'VALLEN Amsy-5' was set up in the building of the plant. To assess the impact of weather conditions on the observed data, a multi-parameter weather station was installed, allowing the measurement of temperature, precipitation rate, wind.... This monitoring system fully ensures its function as it generates alarms in real time, and prevents the on-call personnel so that it can trigger appropriate actions. Therefore, the

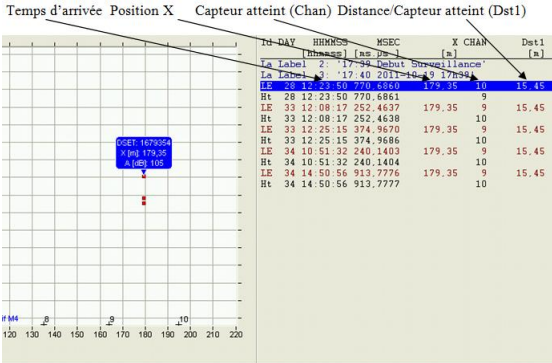
system has been configured to generate multiple alarm levels, either by abnormal acoustic activity or by a malfunction of the monitoring system. The VALLEN system was thus physically connected to the supervision system of the plant via controlled relay. Many settings of the acquisition system, both hardware and software were needed: Bandwidths adaptation, alarms setting, integration of time markers... Besides the fact that this application is very specific due to the monitored phenomena, it also stands conventional applications of acoustic emission monitoring by the fact that it required to be in-service over several years, while keeping its 'real time' performance. On the other hand, the recorded data must be viewed retrospectively, by identifying each AE event in time, and physically on the penstocks.



Picture 7: Valen Acquisition System

The system was also designed for a remote control at any time via a secured Internet connection. This feature allows an AE specialist to provide decision support in case of alarm or other abnormal event reported by the technicians of the plant.

An instruction manual written for technicians enabled them to have a high degree of autonomy to manage the system.



Graph 4: Monitoring Screen, showing an AE event, and its characteristics

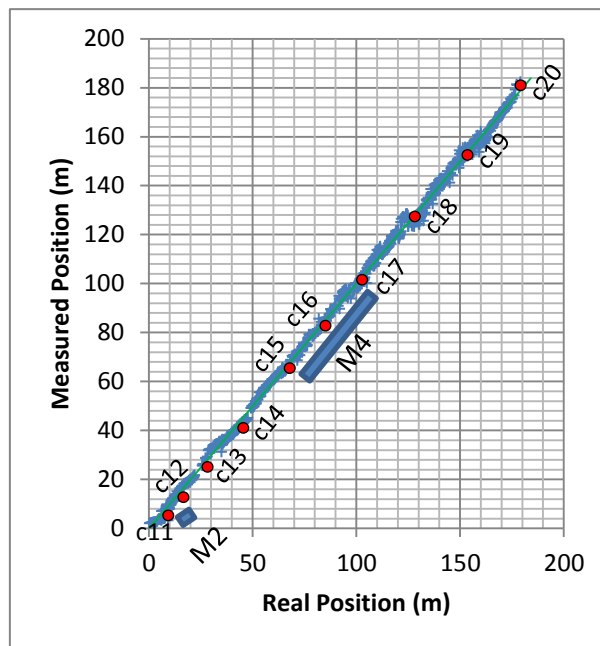
A sensor’s periodic verification procedure has also been implemented, applied locally by the staff, in order to detect any degradation of system performance.

1.3.3. Evaluation of the localisation accuracy

In order to qualify the system for operation, we quantified its ability to locate any AE source that can occur on penstocks sections under monitoring. For this, we generated acoustic emission sources on each ring, and then compared its true position to its position estimated – calculated- from acoustic signals detected.

Thus, more than 1,000 sources were generated and analyzed (graph 5). The average absolute deviation to the theoretical position is about 1.30 m; Approximately 90% of the measurements shows a difference of less than 2.5 m.

This system qualification enables to refine the intervention procedure in case of AE signal detection potentially representative of a ring's rupture: The controls are then focused on a narrow range.



Graph 5: Correlation between true position of the sources and calculated positions from AE signals.

1.4. Balance after 2 years of commissioning

1.4.1. Commissioning

In operation since November 2011, the system has been used during more than 2 years. In fact, it has been stopped when the 2 critical penstocks sections have been replaced. At the beginning, to allow on-site technicians to understand the system and react to any event, operating instructions supplemented by a training session has been provided.

A specific procedure linked to the acoustic emission monitoring system has been written and implemented by the power station staff, defining actions to be taken for each case that can be encountered: alarm or alert, periodic checking of sensors...

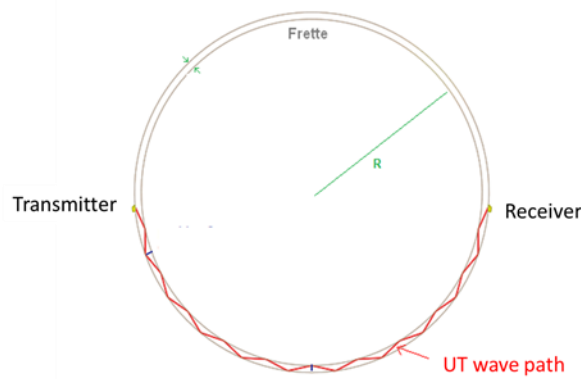
The first weeks of monitoring helped to refine the threshold values defined from background noise levels measured.

1.4.2. The actions taken in case of Alarm

Since its commissioning, the system recorded many localized events, including some that generated alarms (i.e. with high energy levels).

As such events must be considered as potential ring failures, technicians immediately investigated to confirm or not the indication detected. To this end, a first visual inspection focused on the area localized by AE is achieved. When the acoustic event is localized on rings which are partially embedded in the concrete, integrity must be checked by ultrasonic testing (UT) for every rings located in the emission zone. This control is achieved with an oblique UT device using separated transmitter and receiver: the measurement consists in transmitting a signal from one side of the hoop and recovering the transmitted signal at the opposite side, having undergone by successive bounces. The reception of the ultrasonic signal is interpreted as an absence of failure.

The added value of such a real time AE control system able to locate the potential break with an accuracy of a few meters then takes its full meaning: Corrective actions can be very fast and focused. This remains a major improvement in terms of safety, even if the on-call personnel is forced to intervene 7/7, sometimes under difficult weather conditions. Early detection of any rupture prevents prolonged operation with a broken hoop.



Picture 8: UT NDE of a hoop

1.4.3. *FeedBack after 2 years*

The monitoring system has continuously recorded all AE events collected by the 20 sensors installed on the penstocks during 27 months.

The analysis of all localized events made has highlighted that some sections are more emissive than others. The AE activity is evenly distributed in time. However, some events related to the operation of the plant seem to cause more acoustic activity, particularly in periods of high temperature variations.

This feedback has been capitalized both by the end-user and the designers.

1.4.4. *Missed detection and False alarm*

Like any monitoring system, usability issues may come from either missed detection or false alarm. This system being a prototype in this field, the operator has not given up control practices that had been in place for many years. Thus, a control by impact method was still carried out periodically. No broken hoop having been detected by this method, we can conclude that the rate of missed detections is zero over the analyzed period.

If we consider that false alarms exist as soon as a characteristic AE signal is not confirmed by a broken hoop detected by ultrasonic testing, less than 10 cases were recorded on 27 months.

The alarm criteria being based on an exceedance of an energy level of the signal, it is not excluded that other phenomena, such as rock falls, or sudden friction phenomena can provoke alarms. Now, the system cannot discriminate these 'false' sources, and safety

requirements supersede any filtering technique that could potentially cause missed detections.

1.5. Conclusions on the AE Penstocks monitoring

Acoustic emission is a nondestructive evaluation method which has the advantage to highlight dynamic phenomena, and to monitor large structures. The case of application described in part 1 perfectly uses these opportunities.

Due to the nature of the monitored phenomena, the structure and its environment, qualification tests were needed, leading to the definition of specific characteristics of the system: sensor characteristics and meshing, bandwidth, system location... After implementation of instrumentation, data acquisition system was connected to the plant to prevent, via alarms in case of suspected hazard or malfunction.

Running 7/7, capable of preventing in real-time the on-call personnel, this system, after more than two years of service, has increased the level of safety of the plant, and permitted to produce energy until the replacement of the critical parts.

2. SUPREME Project : AE monitoring of Rotating Parts

2.1. Introduction

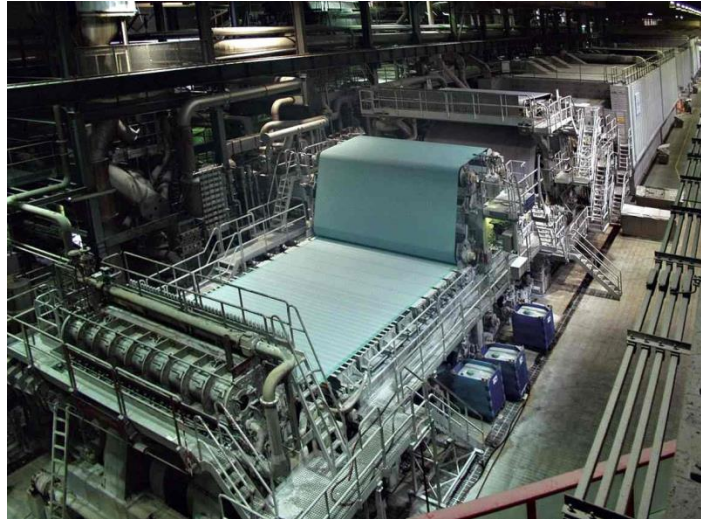
When analysing the literature dealing with AE applied to the detection of defects in bearings or gearboxes, it seems that AE technique has a great potential, demonstrated by the large number of works, publications, commercial systems that exist. Most of the papers dealing with this subject are based on laboratory tests, and then, measurements are not always influenced or contaminated by an industrial environment. Then, the challenge concerning AE for this European project (SUPREME, SUstainable PREdictive Maintenance for manufacturing Equipment) is to confront it with a real industrial case, make this technology more robust against varying environmental conditions, and to adapt the hardware, and data analysis to this specific industrial case.

The goal of the 'SUPREME' project is to improve the efficiency of the machine by optimising the planned shut-downs, detecting the failures of mechanical parts, detecting production problems such as paper breaks; An improvement of 20% of machinery failures, paper breaks and production problems should increase the total efficiency of the machine by around 1,5%. Energy costs could also be improved by some 2 to 5% mainly by the process stability.

The first step of this project is to have 'real time' information about the equipment: vibrations, acoustic emission, motor current, torque, etc. In this article, we will focus our report on AE instrumentation.

2.2. Instrumentation of the Machine

AE (Acoustic Emission) technique has been applied to the Paper Machine located in the CONDAT Plant (France). In a first step, this instrumentation has been defined. Then CETIM has instrumented 5 elements selected by the SUPREME Team: The 2 suction roll bearings, the 2 press P2 bearings and the Gearbox of the press P2. These elements are considered as critical by the plant. This work has been done during August 2013, and completed in September 2013. Since this date, the AE Acquisition system is recording data coming from 12 AE sensors.

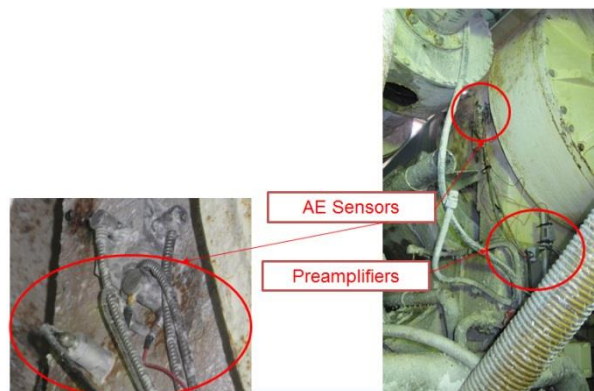


Picture 9: General View of the Paper Machine, CONDAT

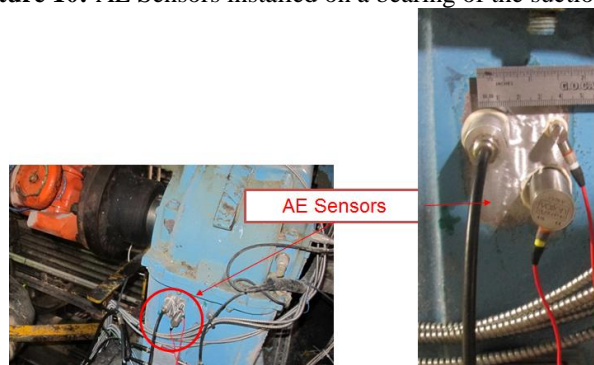
The environment of the paper machine is very aggressive for the material we have installed:

- Temperature: up to 80°C
- Instrumentation is exposed to steam, Caustic Soda (during cleaning operations), Phosphoric Acid...
- Mechanical action: due to maintenance operations, lubrication, liner change, breakage of the paper sheet...

To be robust against this harsh environment, we have, for example, installed specific Multi-coaxial RG174 cables, able to resist to temperature and acid.



Picture 10: AE Sensors installed on a bearing of the suction roll



Picture 11: AE Sensors installed on a gearbox



Picture 12: Vallen Acquisition System + Inverter + PC

The first step of this study being exploratory, our objective is to cover a large frequency band, from 50 KHz to 1000 KHz.

Then, the choice of sensors has been the following:

- Sensor CETIM K200 (resonant near 200 KHz),
- Sensor VALLEN AE105A (wide band between 400 KHz and 1000 KHz),
- Sensor VALLEN VS 75V (resonant near 75 KHz).

The three types of sensors (piezoelectric sensors) are attached to the mechanical parts by a specific glue (cement X60). The surface is prepared before the installation (cleaning and sanding).

2.3. Analysis of AE Data

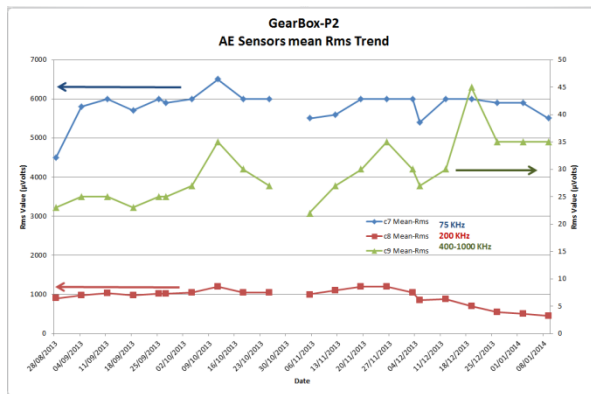
AE data recorded during the first 5 months represent a very large amount of data.

The Rms value of each channel and parametric data coming from the paper machine (speed, load,) are recorded every second.

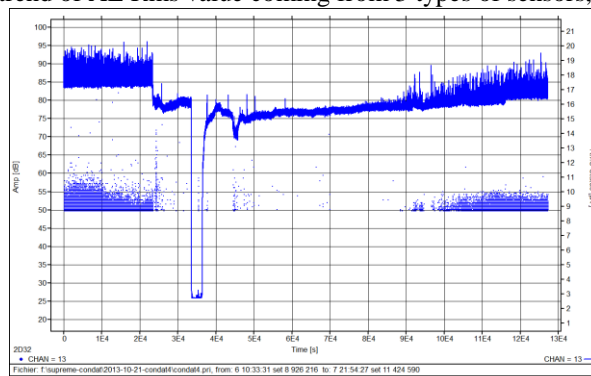
When a signal crosses the threshold, its characteristics (AE Features) are recorded. We have tried to put threshold values high enough not to have too many signals, but low enough to catch some signals that could correspond to events coming from the bearings or the gearbox. Moreover, we have activated the floating threshold function which automatically adapts the threshold of each channel to the Rms level (when the Rms level increases, the threshold automatically increases). It can be very useful to avoid the saturation of a channel.

Periodically, during few seconds, each signal that is higher than the threshold is fully recorded, at 2 MHz sampling rate. It allows us to analyse the frequency spectrum of the signal. The total amount of data is about 10 GB for the period of 5 months.

Our analysis has been done step by step, from global trends to detailed analysis.



Graph 6: General trend of AE Rms value coming from 3 types of sensors, Gearbox.(5 months)

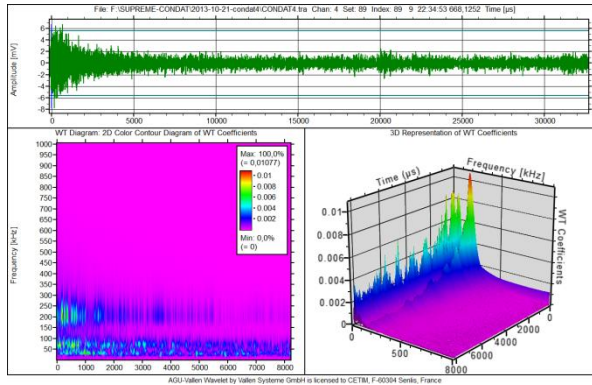


Graph 7: AE Sensor RMS Trend and AE Hits between the 2nd and the 3rd of October 2013

The analysis of AE data and the conclusions we can extract from depend on the time scale. If we globally observe AE data on a period of 5 months, we will not be able to find very thin evolutions. Then, we could conclude to very stable values ... At the contrary, if we only analyse a “short” period, for example one day, we could conclude sometimes, to very instable AE activity (see graph 7).

Most of the studies performed in the field of AE are not based on very long term periods of monitoring, in real production conditions. In the frame of this project, we have decided to record data during a long period, in order to detect long term evolutions, and understand the general behaviour of the machine, but also to take into account the short term variations, that could lead to false diagnosis, or not. Developing a pertinent diagnosis system necessitates this double approach, ie taking into account the time scale, and all the events that can occur on the machine.

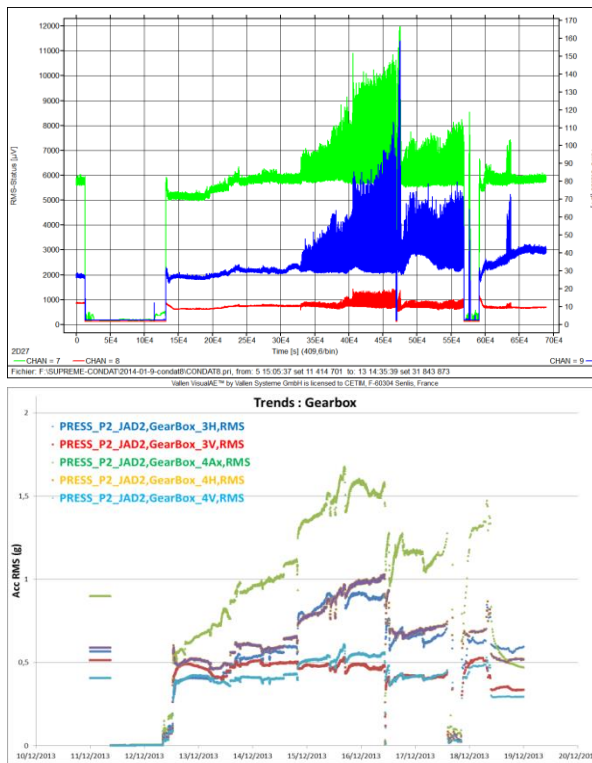
In this first step of the project, we have decided to catch as much as information as possible. Then, some AE hits have been fully recorded. The graph 8 shows a typical AE signal coming from a 200 KHz sensor, and its Wavelet analysis.



Graph 8: AE Waveform – Wavelet analysis

At the moment, it is difficult to say if this type of processing, demanding important needs in term of recording and calculation could improve the diagnosis.

2.4. Correlation between AE Data and vibration analysis



Graph 9 & 10: AE Rms trend and Vibration Rms trend (1 week)

The paper machine has been equipped with different type of sensors, such as vibration sensors, AE sensors, current measurement, torque measurement ... Our objective being to understand the behavior of the machine, and predict any drift of the process, or degradation of a component. Then, we have to cross the information coming from all these sensors. Graph 9 and 10 illustrate a correlation between AE and vibration, on a gearbox.

Sometimes, techniques can bring the same information (a good way to confirm a diagnosis), but we also have to find and exploit complementarity between them.

2.5. Conclusions

SUPREME is an ambitious technical project, involving many technologies, including AE, vibrations ...

The industrial context is complex: A paper machine is composed of hundred interconnected mechanical elements. Some critical elements have been chosen to be particularly instrumented: bearings and gearboxes.

After more than 5 months of data collection, and analysis, we are able to make conclusions on AE ability, and propose a more dedicated protocol to use AE in this context. Then, we should have some tracks to determine the best choices in term of AE Sensor, AE preamplifier, and AE parameter that are the most relevant of the health state of the monitored parts. We also have been able to correlate AE and many other physical parameters such as vibrations ... and found interesting correlations and complementarities that need now to be exploited by specific tools.

The real time and continuous monitoring of five mechanical elements during six months, has allowed us to better understand the constraints linked to such complex environment and to draw conclusions on monitoring strategies.

3. Acknowledgements

We thank all project partners of these two projects - EDF (Electricité de France), European Commission and all the partners of the SUPREME Project for their commitment to developing innovative solutions, as well as their technical and financial support.

4. References

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