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Original article

Acoustic emission to detect xylophagous insects in wooden musical instrument

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ABSTRACT

Acoustic emission monitoring was applied for the detection of xylophagous insects and more specifically *oligomerus* and relative species in wooden cultural heritage musical instruments kept in European museums where the temperature and hygrometry are controlled according to International Council of Museums (ICOM) rules. Using broadband high frequency sensors [75–1000 kHz] and a high level of amplification to compensate the acoustic attenuation in wood, it is possible to detect the presence of very small larvae (1–2 mm length) in a wooden object. Different coupling materials which respect conservation rules have been tested to fix the sensor to the artefact with an optimized signal to noise ratio. Such coupling materials must not damage the surface of the object and must enable a reversible operation. Since the acoustic signal (frequency and amplitude) depends on the distance between the sensor and the source, robust data processing based on an orthogonal linear transformation is then applied to the recorded signals to distinguish insect signals from ambient noise.

1. Research aim

Diagnosing the presence of xylophagous insects in cultural heritage artefacts is a concern for many curators in European museums or in private collections, especially when the climate is regulated (according to the ICOM rules, $T = 20 \pm 2\,^{\circ}C$ and $H\ (\%) = 55 \pm 5\%$). For well-equipped collections, once a risk appears, the objects are treated against pest infestation by non-destructive methods (passive or active anoxia with oxygen absorber bags or nitrogen income). This technique is expensive, requires a long treatment period and is sometimes unnecessary when non-infested objects are treated. Our research aims at developing an acoustic emission detection system – consisting not only in an acquisition system but also in effective data processing – sensitive enough to detect the low activity of the xylophagous larvae while respecting the reversibility principles and museum deontology.

2. Woodboring beetles and acoustic emission – state of the art

Woodboring beetles that damage wooden cultural heritage objects are primarily members of the Anobiid family. They are characterized by a capacity to digest dry wood (xylophagous) and their ability to dig galleries inside the wood [1]. The larval stage is the most damaging: during this stage they feed exclusively on wood, tunnelling into the substrate. An average life cycle takes one to several years, depending on temperature, humidity and the nutritional value of wood [2].

Detecting the activity of these larvae is difficult because tunnelling and development occur entirely below the wood surface. The close relationship between larvae and wood allows us to use the characteristic of wave transmission in wood to follow insect activity through acoustic emission.

Acoustic emission (AE) monitoring is an important non-destructive tool to track the evolution of damages in materials and has also been used in wood science [3]. Many studies deal with the relationship between the stress level in wood under flexural loading and AE energy due to the fracture process [4] using ultrasonic sensors with a nominative frequency of 200 kHz. Aicher et al. [5] have shown that using several ultrasonic sensors it was possible

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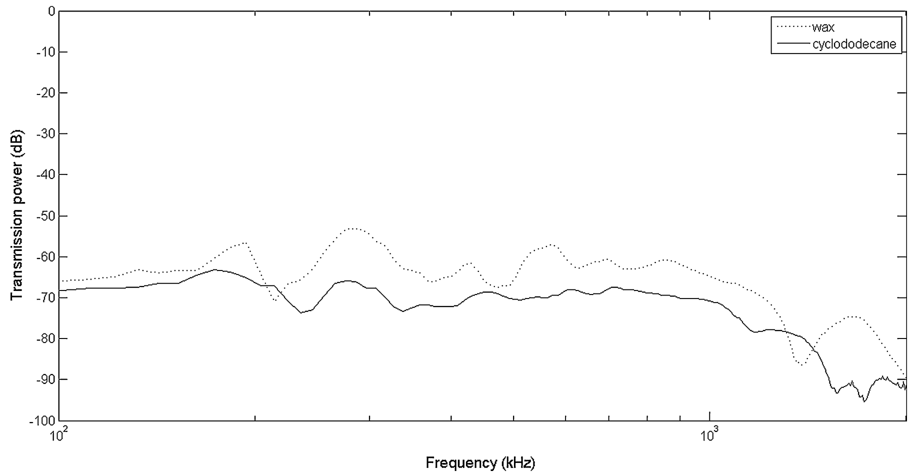

Fig. 1. Comparison of acoustic transmission coefficient using traditional wax and cyclododecane for ultrasonic waves.

to locate the damage before the rupture. The influence of external parameters has been also reported, especially the variation in ambient relative humidity [6–9]. Moreover, analysing the acoustic energy level has led to differentiating micro-fractures (low energy) from surface shrinking during drying [9]. AE has been used to monitor the natural degradation of wood due to termite activity [10–12] or fungal infestations [13].

However, in spite of its characteristics and popularity, AE has been very little used to monitor cultural heritage objects. One exception concerns the tracking of the stress induced by climate variations in wooden paintings [14,15]. The acoustic energy is correlated to the temperature change.

The coupling materials needed to fix the ultrasonic sensor on the cultural woodcraft have to be carefully chosen. Indeed, to obtain a high signal to noise ratio, the sensor has to be perfectly glued to the surface due to the high attenuation coefficient of the ultrasonic wave in wood.

Acoustic detection tests were conducted on *Anobium punctatum* and related species [16,17] using audio frequency range sensors (20 Hz–10 kHz) but the signal to noise ratio was too low to robustly detect insect activity.

In this paper, detection of woodboring beetles is presented using AE after proposing a material adapted to fix an ultrasonic sensor to a wooden musical instrument or to woodcrafts in general. For that, preliminary experiments were conducted in laboratory conditions using an infested piece of wood and a blank sample. In the following section, a first subsection is dedicated to the choice of a coupling material. The challenge for cultural heritage applications is to propose a material which is both acoustically effective and removable. We then present different labelled signals that were recorded and processed with a principal component analysis (PCA). We have both signals that are due to the insect activity (before and during the anoxia treatment) and signals that were recorded on the blank sample. These last signals correspond to noise signals: electronic noise and the noise from the anoxia treatment, which is due to the increase in temperature and humidity from the oxygen bags. Finally, the last section will detail the application of the device in a museum where the temperature and humidity content are quite stable according to the ICOM rules.

3. Materials and method

3.1. Coupling material

The limited use of AE to trace damages (natural or mechanical) in wooden heritage objects could be due to the material coupling. Indeed, in classical AE processes, very strong adhesives are used, such as cyanoacrylate. The advantage of these adhesives is that they provide a high transmission of the acoustic signal between the support and the sensor. However, these adhesives do not respect conservation deontology principles since they are not reversible. In some cases, specific wax could be used, but this solution is not suitable in the case of fragile paintings or varnished layers, where the wax removal could also remove the top layer. Since cyclododecane sublimates at room temperature with continued air exposure, it has been used for more than ten years in short-term applications, as an adhesive [18], a moulding material [19], barrier layer [20], or consolidant [21]. Sublimation negates the need for later removal of the adhesive, and temporary treatment with cyclododecane should not interfere with subsequent study, analysis, or treatment.

Cyclododecane has then been chosen as a coupling material to fix the ultrasonic sensors to wood artefacts. To validate the ultrasonic (US) transmission power of this material, two US panametrics (1 MHz and 2.25 MHz resonant frequency) sensors have been glued on each side of a 2 mm thick wooden plate, first with a traditional

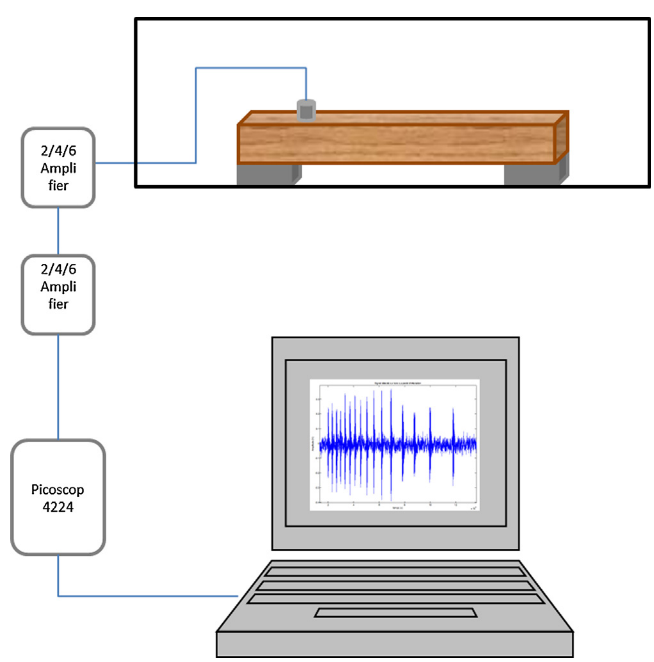

Fig. 2. Acoustic emission (AE) set up for tracking xylophagous activity.

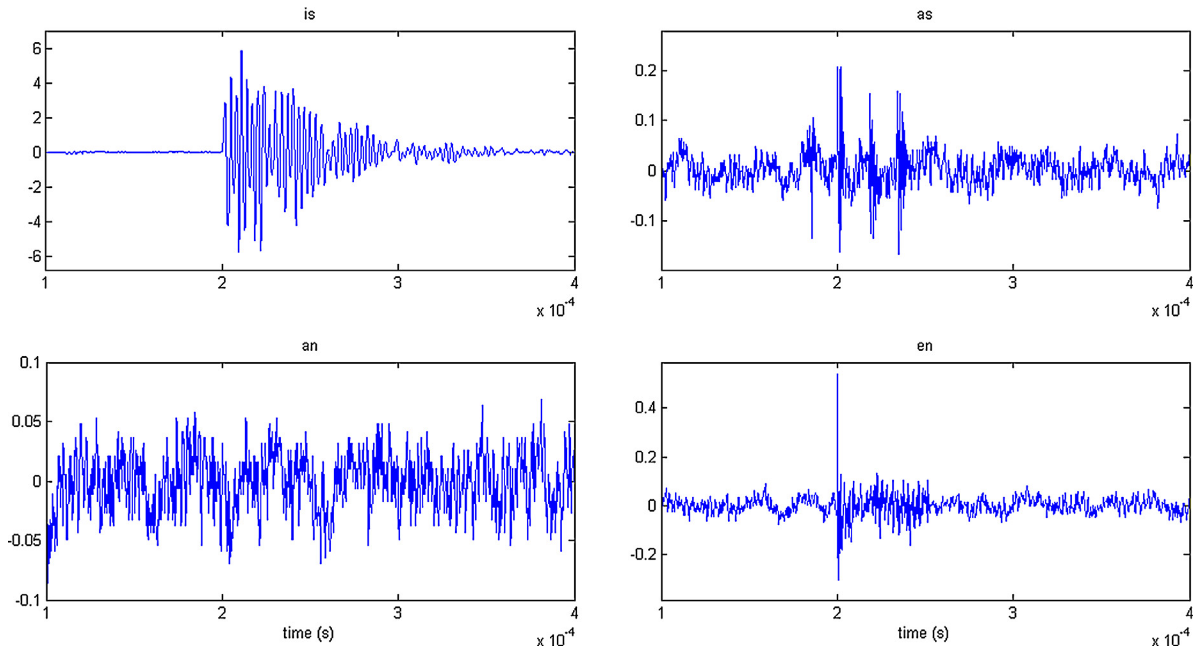

Fig. 3. Examples of the four types of signals recorded during the test phase: parasitic electronic and magnetic feedback signals (*en*), noise resulting from anoxia treatment (*an*), signals generated by insects (*is*) and signals acquired during the anoxia process (*as*).

wax, and then with the cyclododecane. A frequency modulated signal is emitted from 100 kHz to 2 MHz during 15 seconds. Fig. 1 represents the transmission power, defined as the logarithm of the ratio of the emitted power to the received power. Cyclododecane is slightly less effective than the dedicated wax (5 dB in average) but AE sensors require high amplification (more than 50 dB) so this difference is small enough to consider the cyclododecane as a good coupling material for our purpose.

3.2. Sensors and acquisition device

The AE waves were measured with a MISTRAS micro80 piezoelectric sensor in the [175–1000 kHz] frequency range. The signal is amplified twice (40 dB each) with two MISTRAS amplifiers 2/4/8. The signal was continuously acquired with a sampling rate of 1 MHz by means of a Picoscope 4224 card with 16 bit amplitude resolution. The signal is recorded when it reaches a trigger value. This trigger value depends on the object thickness and is determined manually by a tapping test.

3.3. Samples

Two kinds of samples were used for this experiment. The first one is a spruce beam (approximately 500 × 40 × 10 mm) which is definitively healthy, without any insect inside. The second sample is a furniture leg infested by *Oligomerus ptilinoides*. The first sample is equipped with the sensor and put in an airproof box to record the parasitic electronic or magnetic feedback signals (*en*). Then, oxygen absorber bags are added in the box to record signals resulting from anoxia treatment (*an*). The furniture leg is equipped with the sensor and put in the empty airproof box to record the signals generated by insects (*is*) (Fig. 2). After a few days, the oxygen bags are added to treat the wooden furniture and signals are recorded (*as*).

3.4. Signal processing

Four signal classes are available: electronic and magnetic noises (*en*), the anoxia noises (*an*), the signals emitted by insects (*is*) and the signals acquired during the anoxia process (*as*). Fig. 3 illustrates these four signal types.

The recorded signals are very short. Their frequency content is broadband. Their power spectrum density (PSD) is calculated using the Welch periodogram [22]. The aim is to develop an automatic classification without any visual selection to let the equipment and the software be self-sufficient in different museums. From the PSD, the frequency corresponding to the highest peak, the maximum power and the energy in different bandwidths are calculated for each signal and compose the 12 features of the patterns used as input parameters for a principal component analysis (PCA) [23]. The goal of the PCA here is to assess the relevance of the features extracted from the signals for separating the different classes.

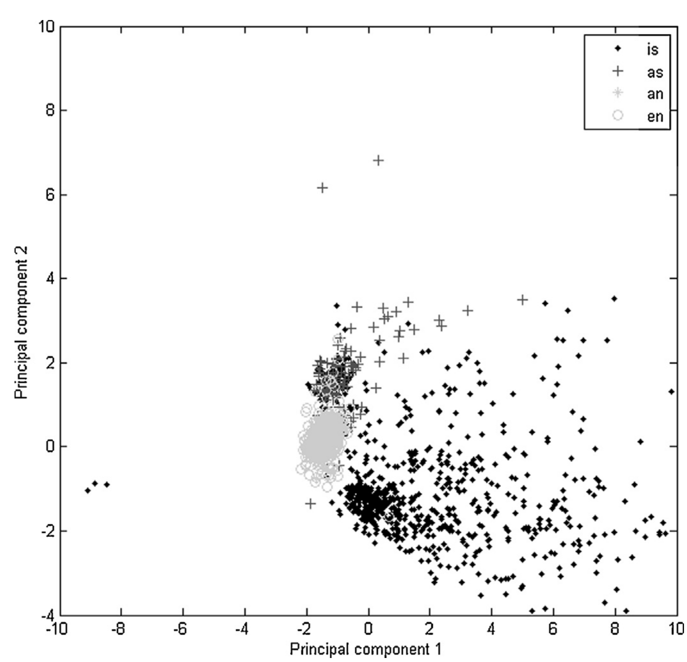

Fig. 4. Principal component analysis (PCA) results.

Fig. 5. African drum equipped with the acoustic emission (AE) set up.

4. Results

Fig. 4 is the projection of the patterns provided by the PCA when classifying all signals (809 *is*, 50 *an*, 980 *en*, 160 *as*). The two principal components shown in Fig. 4 retain 88% of the total variance associated with the original 12 variables, which means that one can trust the representation. Whereas the noise signals are clustered in the same area, representing the noise class, the patterns corresponding to insects are in another area. However, some dots labelled as insect signatures are in the noise area. It is supposed that some noise was acquired during the larvae recording phase and that these signals are not correctly labelled.

With adapted equipment and minimal data processing, it is possible to effectively detect woodboring activities. It can then be asked whether the above features are relevant when the signals are recorded without being labeled previously. In other words, are these features relevant enough to detect the woodboring activity in real conditions?

5. Application to museum storage monitoring

One of the most original aspects of the architecture of the Musée du Quai Branly is, without contest, the visible storage of the musical instruments collection: a 23 meters high glass tower crossing the building throughout its height. It is 6 levels high with a total floor space of about 620 square meters. The architectural gesture is magnificent, reminding that music is the most universal artistic form of expression.

However, it makes preventive conservation a challenge. With the exception of the fifth level, the floor is made of metal grating. The configuration of the tower and visible from many public areas (hall, permanent and temporary display galleries, auditorium, children workshops. . .) generate several issues in terms of environmental control and pest monitoring.

The choice of the instrument and of the registration period was made based on museum data on “hot spots” and “hot period” conducive to pest infestations. Therefore, a drum (n° 71.1993.0.9 X Em) with a vibrating membrane from Western Africa was picked for the following reasons:

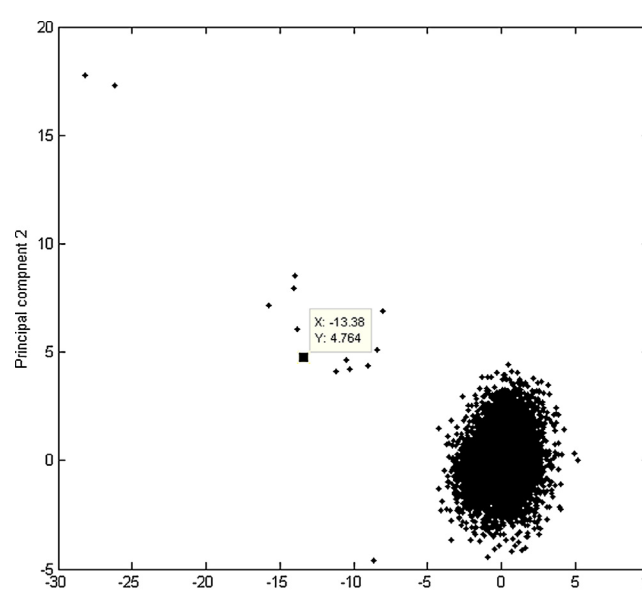

Fig. 6. Principal component analysis (PCA) results of in situ experiment.

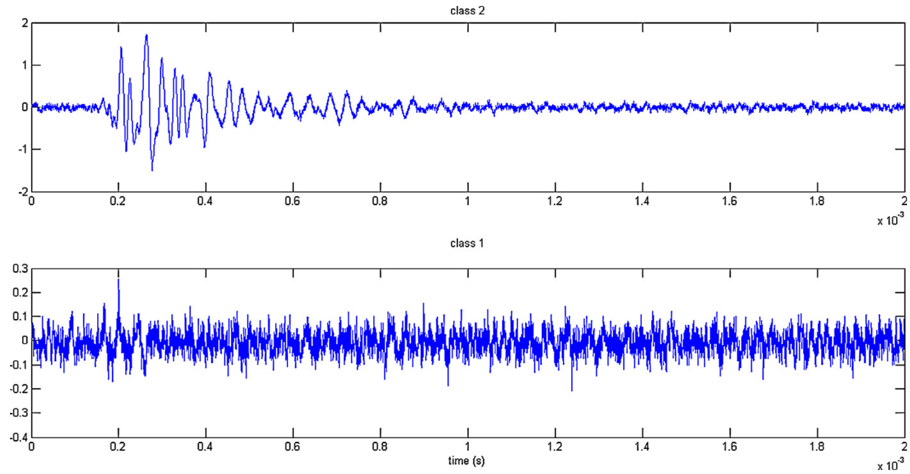

Fig. 7. Signals recorded on the drum.

- the drum integrated the collections of the Musée de l'Homme in 1993;
- the drum presented, at the time of the test, signs of infestation: woodpulp at the bottom, holes, and galleries (Fig. 5). These signs maybe old but this cannot be ascertained as the floor is made of metallic gratings that induces vibrations;
- the observation of the climatic data shows that level R R1 provides a favourable environment for infestation development in terms of temperature and hygrometry (average of 22 °C and between 55% and 59% HR);
- the accounts describing the object (movements, anoxia treatment, and presentation) in The Museum System (TMS) database show that in 2004 the drum already presented signs of advanced infestation and was treated via anoxia at that time.

The analysis of these historical records shows that the probability of woodboring infestation exists and makes this drum the ideal candidate to test AE monitoring. Consequently, the drum was equipped with the sensor fixed with wax. This coupling was chosen because there is no varnish or paint layer on the instrument (Fig. 5).

Furthermore, 160 signals were recorded during one week. The features were extracted and a PCA was applied to the set of 12 patterns defined previously. The results are presented in Fig. 6. Two classes were found. The first class (class 1) is the largest. It is centred around (0,0). The second class (class 2) is centred around (−11,6). Picking one of the dots included in each of these classes, it is possible to recognize the shape of the labelled test signals. Fig. 7 presents one signal of each class obtained after the PCA.

6. Conclusion

With the objective to detect definitively the small xylophagous insects in the wooden artefacts, AE has been used and seems well adapted to the problem. Indeed, the PCA analysis applied to the patterns composed of features extracted from frequency representations of AE signals, demonstrated the ability of these features to separate the patterns characterizing the sound radiated by insect activity from other classes such as electronic noise or sound from anoxic effects on wood.

In this context, using ultrasonic sensor to record low amplitude signals requires the use of an effective coupling material. Cyclododecane, subliming at room temperature with continued air exposure, has been found as a relevant substitution material when traditional wax cannot be used for conservation reasons. After a laboratory test phase, the set up was deployed in situ conditions since an African drum kept in The Musée du Quai Branly was equipped and the results conclude on the activity of the insects.

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