Detection of Old House Borer Larvae in Wooden Structures by Acoustic Emission Method – Influence of Larval Size and Sensor Location

Adam Krajewski,[a] Slawomir Jakiela,[b] and Piotr Witomski [a,]*

The detection of old house borer larvae (*Hylotrupes bajulus* L.) in Scots pine wood (*Pinus sylvestris* L.) was performed using the acoustic emission (AE) method. Laboratory experiments (as preliminary) as well as real tests in full-sized building elements were performed. The sound energy of larvae with a mass of 0.011 g to 0.065 g placed in small samples of wood was calculated. A remarkable relationship was found between the calculated sound energy and larva mass. The AE measurement of an old house borer larva in construction element with a cross-section of 11.0 cm × 5.5 cm and a length of 203 cm was also performed. A remarkable drop in calculated sound energy was observed with increasing distance of the sensor from the larval presence. Similar measurements were also conducted in wood with a cross-section of 1.5 cm × 1.5 cm and a length of 203 cm. There was a smaller decline in the calculated energy of sound than in previous studies. For this reason, the AE method should be used in detecting wood-boring insects in furniture.

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*Contact information: a: Department of Wood Science and Wood Preservation, Institute of Wood Sciences and Furniture, Warsaw University of Life Sciences, Nowoursynowska 159 St., 02-787 Warsaw, Poland; b: Department of Physics and Biophysics, Institute of Biology, Warsaw University of Life Sciences, Nowoursynowska 159 St., 02-787 Warsaw, Poland; *Corresponding author: piotr_witomski@sggw.edu.pl*

INTRODUCTION

The detection method using acoustic emission (AE) has been of interest for several decades for identifying and studying the biology of wood-destroying insects. The experimental results mainly report cases of old house borer infection (*H. bajulus* L.) (Kerner *et al.* 1980; Pallaske 1988; Plinke 1991; Krajewski *et al.* 2012; Brandstetter and Hubner 2014; Creemers 2015; Bilski *et al.* 2017; Nowakowska *et al.* 2017a). The insect species is prevalent all over the world (Becker 1949a,b, 1970), especially in Central and Northern Europe, where it is still the most dangerous species identified for wooden structures (Wichmand 1941; Becker 1949a,b; Krajewski 1995), despite the observed decrease in the number of infected buildings in some European regions (Dominik 2005). The possibility of recording acoustic effects of the presence of old house borer larvae in the wood has been proven (Kerner *et al.* 1980; Plinke 1991), and even the larval number in a thick wooden element has been estimated (Krajewski *et al.* 2012).

The larval activity is strongly influenced by temperature. Therefore, recording the presence of old house borer larvae in wood using the AE method in the range of temperatures that may prevail in buildings and their attics (Creemers 2015; Nowakowska *et al.* 2017b; Krajewski *et al.* 2020) are required. The key factor that affects the ability to record old house borer larvae in wood using the AE method, as well as other insects, is their size.

The acoustic effect recorded by the AE method is caused by the feeding of the larvae – the biting of wood with mandibles. Insects of different species of various sizes have been registered in the previous studies: Anobiidae (Esser *et al.* 1999; Creemers 2015), termites (Fujii *et al.* 1989; Mankin *et al.* 1996; Lemaster *et al.* 1997; Fujii *et al.* 1999; Mankin *et al.* 2002; Nocero 2003; Dunegan 2005; Mankin and Moore 2010), and Asian longhorned beetle (*Anaplophora glabripennis* Motschulsky). The old house borer larvae show a large span of size and mass. The larvae that hatched from eggs have a mass of less than 1.0 mg, while old, full-grown larvae can reach a mass of 300 mg and sometimes-even 500 mg. Their weight is closely correlated with body length (Nowakowska *et al.* 2017a).

The old house borer larvae hatched from eggs have a mass and size smaller than the pseudo-ergates termites, while the mature and full-grown house borer larvae have a mass at the level of the mature and full-grown larvae of Asian longhorned beetle. The feeding of sizeable old house borer larvae with a weight of 300 mg and over can be easily heard by humans, while the feeding of small young ones is unfortunately inaudible. Critical factors in the instrumental registration of the feeding of insects are the thickness of the infected wooden element and the distance between the larva and the sensor. Thus far, laboratory tests have been conducted only on relatively small samples of wood. As the distance between the sensor and the larvae increases, the sound is suppressed by the material (wood) and the amplitude of AE event is smaller. Moreover, tiny larvae emit weak signals that are difficult to detecting.

Methodological experiments were performed in this study to determine an appropriate parameter to assess the scale of the insect chewing of wood by measuring the energy of the AE events (Krajewski *et al.* 2020). This prompted the authors to put forward further research hypotheses: (i) What is the influence of larval size and mass on the possibility of their registration with the help of AE? (ii) How does the size of the wooden element (its length and cross-section) affect the likelihood of larvae registration? (iii) At what distances should sensors be placed on infected wooden structures?

This study is an attempt to transfer from the laboratory phase to the practical use of AE techniques for the detection of old house borer larvae feeding in full-sized building elements.

EXPERIMENTAL

Materials and Methods

In the present study, it was assumed that the activity of old house borer larvae (*Hylotrupes bajulus* L.), as a cold-blooded organism, depends mostly on temperature. The studies were conducted at a temperature of 24 °C to 26 °C. Acoustic emission signals were recorded using equipment consisting of a piezoelectric sensor (DeltaTron accelerometer model 4507-B-005; Brüel & Kjær Vibro A/S, Nærum, Denmark), an external sound card (E-MU Tracker Pre, Creative, Creative Labs (Ireland) Ltd., Dublin, Ireland), and a laptop (Lenovo Ideapad Y650, Lenovo (Singapore) Pte. Ltd., Singapore) with Windows 7 operating system and Adobe Audition software (Adobe Inc., San Jose, CA, USA).

A piezoelectric sensor was attached to the radial section of wooden elements with the use of GE Bayer Silicones Baysilocone-Paste (Carl Roth GmbH + Co. KG, Karlsruhe, Germany). The sensor worked *via* a converter with the sound card that was connected directly to the computer *via* USB 2.0. The applied sampling frequency was 44.1 kHz, with a 16-bit resolution. That experimental system, described in more detail in earlier publications (Krajewski *et al.* 2012, 2020; Bilski *et al.* 2017; Nowakowska *et al.* 2017b), was used for recording the acoustic events of larvae feeding in the wood. In this study, some improvements and modifications have been introduced in the field of numerical data processing. A specialized measurement application for data processing was implemented in the custom-written software in LabWindows. This software enabled:

- Reading the file containing the waveform as a result of the accelerometer vibration acquisition
- Detection of all events potentially related to larvae activity based on an analysis of the characteristic frequencies (wavelet analysis) related to the feeding larvae in the wood (earlier calibration was required)
- Calculation of acoustic emission energy of each correctly selected 1 minute periods
- Statistical analysis based on AE energies of individual 1 minute periods

Due to the relatively high sensitivity of the equipment and the long duration of sound recording (longer than 2 h), the recorded files, by the system, were quite large (over 1.0 GB). The software analyzed the frequencies of each event in comparison to frequencies of the feeding old house borer larvae. The recording was done on a single channel.

Scots pine wood samples (*Pinus sylvestris* L.) was used in all stages of the study. The material had a moisture content of approximately 8% to 9%. The density varied as follows: 0.443 to 0.483 to 0.512 g/cm^3 (first stage), 0.434 to 0.472 to 0.507 g/cm^3 (second stage), and 0.477 to 0.496 to 0.515 g/cm^3 (third stage).

In the first stage of research, the effect of larval body weight on the energy of acoustic emission emitted during feeding in relatively small wood samples was analyzed. The study was performed on 29 house borer larvae (*H. bajulus* L.), whose weight was between 0.011 g and 0.320 g. Scots pine sapwood samples of dimensions 2.5 × 3.0 × 5.0 cm^3 were used for this part of the study. In each sample, a single larva was placed in a drilled hole (depth *c.a.* 2.0 cm) in the middle of the cross-sectional area (2.5 × 3.0 cm^2) on the block face. The diameter of the drilled hole was adjusted to the larval body diameter. The samples with larvae were left at a temperature of 24 °C to 26 °C for 24 h; this enabled larvae adaptation to the new environment. Then, the individual registration of acoustic emission of larvae living in a sample was performed, using the AE method. The sensor was placed in the center of the 2.5 × 5.0 cm^2 area. The recording was conducted for 20 min.

In the second stage, seven structural elements made of Scots pine wood of dimensions 5.5 × 11.0 × 203.0 cm^3 were used. These elements contained sapwood and heartwood (less than 20%) and had a rough abrasive surface. The single larva was placed individually in a hole drilled (depth *c.a.* 3 cm; in the center of the cross section of dimension a 11 x 5.5 cm in the sapwood part of structural elements. After the adaptation period, the presence of larva was recorded with the use of the AE method. The AE sensor was placed on the axis of the longitudinal/transversal surface 5.5 × 203.0 cm at the following distances: 0, 50, 100, 150, and 200 cm from the larva. In some cases, the registration was also carried out at additional measurement points noted as shown Table 1. In the third stage of the study, for comparison with the second stage samples, AE was recorded in thin elements of 1.5 × 1.5 cm cross-section and 203 cm length. These elements had a smooth textured surface. The ten larvae were placed individually in the holes in the foreheads of these sapwoods in holes drilled to a depth of 3 cm in the center of the cross-section of a 1.5 x 1.5 cm. After the larvae adaptation, the sensor was placed on the axis of the surface of 1.5 × 203 cm at distances from the location of the larvae 0, 50, 100, 150, and 200 cm. Then, the presence of the larvae was registered using the AE method.

In accordance with the principle adopted in the earlier publication (Krajewski *et al.* 2020), the recording of the acoustic emission of each larva measured by the AE method was converted into numerical data in the described system and presented graphically. One criterion was used here – the amount of sound energy of drilling by the larva based on the measurement of changes in the voltage of the current. On their basis, the acoustic emission energy of sound for each lava was calculated independently.

The criterion for the larval activity evaluation uses the energy of each event calculated directly from the acquired voltage signal. The applied measurement system does not record the absolute energy (given in J), but voltage values related to the reference level (the latter should be first determined during the sensor calibration). The acquired values ranged between "-1" and "+1", as the ratio between the measured signal and the reference level, *i.e.*, the peak-to-peak-voltage (V_{ref}). Its value was assumed as 10 V (with the range from -5 V to +5 V). The energy was calculated as follows,

$$E(i) = v_{ref}^2 \cdot \frac{1}{f_s} \cdot \sum_{l=i}^{i+L} v_n(l)^2 \ \ [a.u. - auxiliary\ units] \tag{1}$$

where f_s is the hardware sampling rate (here 44.1 kHz), v_n is a normalized measured voltage (related to the referential level v_{ref}), calculated *as* $v_n = v / v_{ref}$ (with V being the measured voltage of sample), and the index l means that the i-th sound pulse (length L), classified as generated by the larva, passes through the samples in order

More details are provided in an earlier publication (Krajewski *et al.* 2020). The presentation of the results of the second and third stages of the research took into account the measurement of sound energy and the presence of the AE graphic notation, which allows the determination of the presence of the larva in the wood.

RESULTS AND DISCUSSION

The results of the dependence calculated sound energy of larvae carving wood in small samples of wood and larval mass in the first stage of the research are presented in the Fig. 1.

The obtained results show a clear dependence of sound energy of larvae wood-carving on the size of the larva. A high value of the coefficient of determination (R^2 = 0.974) supports this dependency (Excel 2016, Microsoft Corporation, Redmond, WA, USA). Therefore, in the second and third stages of the research, low-mass larvae were used, as it was expected that their presence in wooden construction elements would be difficult to register. The results of the second stage of the research, *i.e.*, the record of the larval presence in large wooden-structural elements (section 5.5 × 11.0 cm) by the AE method are presented in Table 1.

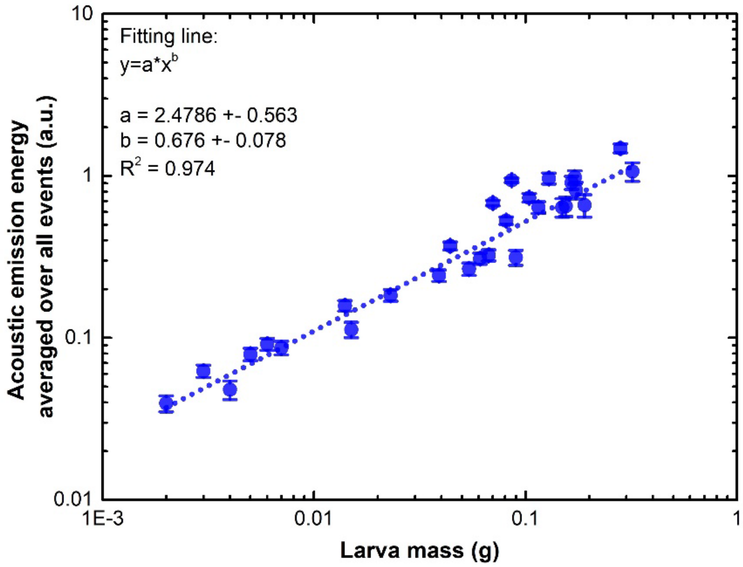

Fig. 1. Dependence of the calculated averaged sound energy of larvae carving wood on larval mass; the average standard deviation for each point is marked

Table 1. Results from Recording of the Larval Presence in Pine Construction Elements

		Distance of the Sensor from the Larva (cm)								
Larva No	Larva Mass (g)	12.5	25	37.5	50	75	100	112.5	125	150
1	0.064				+		+	-		-
2	0.028				+		+	+	+	-
3	0.041				+		+			+
4	0.037		+	+	+		+	-		-
5	0.067				+	-	-			-
6	0.023	+			+		+	-		-
7	0.038	+			+	+	+	+	-	-
"+" detected sounds of larva activity, "-"no sounds of larval activity detected										

Table 1 shows the distances between the larvae and the sensors. As can be seen, it is possible to detect larvae on the basis of AE registration in relatively thick elements. If the signal was not registered at the basic distance of 50 cm, it was divided into the next 25 and 12.5 cm halves. The cross-section of wooden building elements is often *circa* 5.5 11.0 cm. The presence of larvae was not recorded in the element at a 2 m sensor distance. As the distance increased, the graphic record became less visible. The larvae were at a depth of 10 cm. The results of the calculated average acoustic emission energy of larvae based on the measurements by the AE method in the second stage of the study are presented in Fig. 2.

It is noticeable that the increasing distance of the sensor from the larvae in the wood caused a large decrease in the energy recorded by the AE method. The results of the third stage study, *i.e.*, recording activity of the larva by the AE method for thin wooden slats are presented in Table 2.

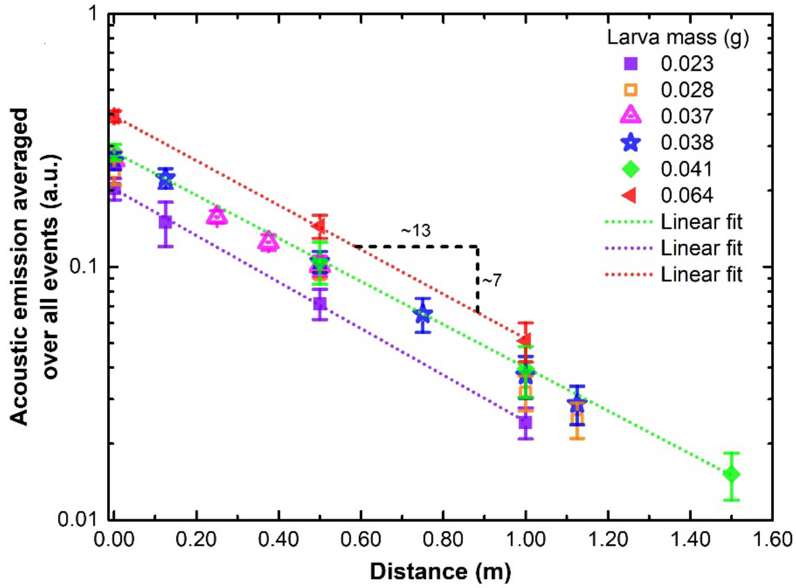

Fig. 2. Dependence between calculated acoustic energy of carving wood larvae and the sensor distance in the elements with dimension of 5.5 × 11.0 × 203 cm; the average standard deviation for each point is marked.

Table 2. Results from Recording the Larva in Thin Elements of Pine Wood with a Cross-section of 1.5 × 1.5 cm by the AE Method According to the Graphic Record on the Laptop Screen

		Distance of the Sensor From the Larva (cm)				
Larva No.	Larva Mass (g)	0	50	100	150	200
1	0.065	+	+	+	+	+
2	0.051	+	+	+	+	+
3	0.042	+	+	+	+	+
4	0.077	+	+	+	+	+
5	0.036	+	+	+	+	+
6	0.023	+	+	+	+	+
7	0.011	+	+	+	+	+
8	0.017	+	+	+	+	+
9	0.039	+	+	+	+	+
10	0.020	+	+	+	+	+
"+" - detected sounds of larva activity; "-" - no sounds of larval activity detected						

In all strips, the presence of larvae was clearly visible in the graphic record on the laptop screen even at a distance of 200 cm. Figure 3 shows the calculated average acoustic emission energy, at different distances of the sensor from the larva in thin wooden strips.

It should be emphasized that for wood hollowing larvae of thick wooden elements with a cross-section of 5.5 × 11.0 cm, an essential lower calculated acoustic emission energy of larvae was found compared to that calculated using the AE method in thin strips with a cross-section of 1.5 × 1.5 cm. The decline in calculated acoustic emission energy was also less intense here.

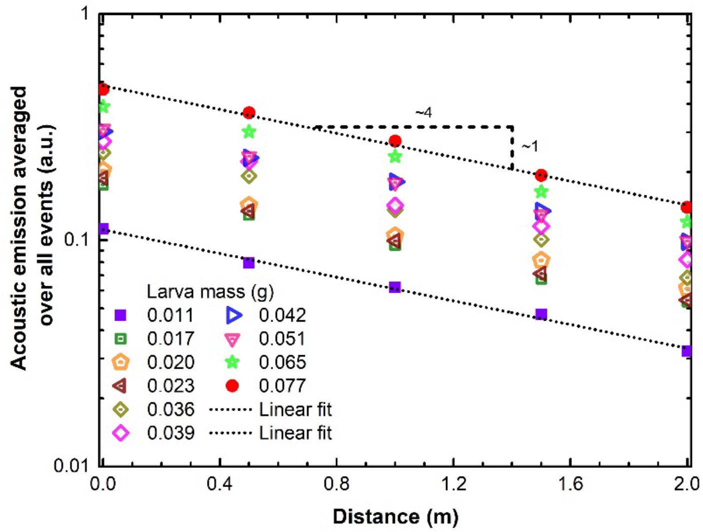

Fig. 3. Dependence between calculated acoustic energy of carving wood larvae and the sensor distance in the strips with dimensions of 1.5 × 1.5 × 203 cm; the average standard deviation was omitted to make the graph more readable. The obtained values of the average standard deviation are comparable with those presented in Fig. 2.

The AE method has long been popular in the field of testing wooden products and structures. Thus far, attempts have been made to use the AE method to detect the presence of insects in wood and to monitor wood cracking in furniture with changes in temperature and relative humidity (RH) (Jakieła *et al.* 2007, 2008). The presence of various insect species was also recorded: Old house borer larvae (Kerner *et al.* 1980; Pallaske 1988; Plinke 1991; Krajewski *et al.* 2012, 2020; Brandstetter and Hubner 2014, Creemers 2015; Bilski *et al.* 2017; Nowakowska *et al.* 2017), Asian longhorned beetle, larvae of Anobiidae (Esser *et al.* 1999; Creemers 2015), *Lyctus* sp. (Creemers 2015), termites (Lemaster *et al.* 1997; Fujii *et al.* 1989, 1999; Mankin *et al.* 1996, 2002; Nocero 2003; Dunegan 2005; Mankin and Moore 2010). The previous studies have been conducted on large larvae and small or relatively small wood samples. In the above studies, only small dimensions of wood samples were used in the AE tests and the same applies to other wood boring insects. The results of this study are the starting point of research on building structures.

Old house borer larvae can weigh up to 0.5 g (Hickin 1963) or, for female larvae, even close to 0.8 g (Becker 1949b). Wood boring by such large larvae produces crunchy sounds that can be perceived even "with the naked ear". On average, however, the larvae pupate reaching the mass of 0.15 g to 0.5 g. In contrast, larval mass reaching only 0.040 g (Hickin 1963) or 0.050 g (Becker 1949b) can pupate. They are mainly male larvae. This information, which is given in the literature, justifies the use of larvae having a mass of 0.011 g to 0.067 g in this study. It should be emphasized that the use of larvae of this body weight, unfortunately, does not make it possible to evaluate as soon as possible after hatching of the old house borer larvae from eggs. However, it is possible to register their presence in wood using the AE method. Freshly hatched larvae have a body weight of less than 0.0005 g. This aspect of the applicability of the AE method requires further research. The old house larvae can feed in wood an average of 3 to 6 years (Hickin 1963), an extreme of 2 years (Hickin 1963) or over 10 years (Becker 1949b), or even 32 years (Hickin 1963). Therefore, it is required to detect the settlement of wooden structures by old house borer larvae as early as possible.

The wood specimens used so far in the research have had different dimensions and shapes, for example: blocks 7 × 5 × 4 cm (old house borer), small stem *ca.* 40 × ø 6 cm, quartered stem 30 × ø 13 cm (*Anobium punctatum* De Geer), a branch *ca.* 40 × ø 4 cm, halfved stem *ca.* 20 × ø 7 cm, a piece of structural wood *ca.* 25 × 8 cm (*Xestobium rufovillosum* De Geer) and 35 × 10 cm, several halved stems 35 × 10 cm (*Lyctus sp.*) (Creemers 2015), pieces of structural wood 6 × 12 × 20 cm (Krajewski *et al.* 2012), pine wood samples 2.1 × 2.1 × 24.0 cm (old house borer) (Nowakowska *et al.* 2017), and pine wood samples 2.5 × 3.0 × 5.0 cm (old house borer) (Krajewski *et al.* 2020). For examining the influence of temperature on insect activity, which was recorded by the AE method, small dimensions of wood samples facilitated quick heating of the wood, resulting in a quick reaction of insects (Krajewski *et al.* 2012; Creemers 2015; Nowakowska *et al.* 2017). However, examining the ability to detect larvae feeding in small pieces of wood may lead to overly optimistic conclusions. These conclusions cannot be transferred to large-size timber structures.

The size of wooden elements that are used to detect larvae feeding affects the effectiveness of recording using the AE method, as shown by the presented research results. The wood is a fibrous and porous material. On the one hand, wood fibers torn by mandibulae of larvae allow for good acoustic response, but in contrast, the sound waves are absorbed by the wood of large components. For this reason, research was undertaken on large elements of wooden structures with dimensions of 5.5 × 11.0 × 203 cm. Additionally, the larvae were introduced 10.0 cm below the surface of the wood where the sensors were placed. Relatively difficult conditions for registering the presence of larvae were ensured in this way. The acoustic wave had to travel not only a relatively long distance along the wood grain, but also a 10.0 cm zone across the grain. The zone across the fibers has a much greater ability to dampen the voice wave also due to the repeatedly alternating arrangement of the earlywood (lower density) and latewood (higher density) layers. A separate issue is the influence of the wood species on the transmission of acoustic signals. The density of the wood and its anatomical structure and microstructure may be of importance here. This study was performed exclusively on Scots pine wood, the most widely used structural timber in modern buildings in Central and Eastern Europe.

The small cross-section of the slats used in the third stage of the research resulted in good larvae registration even at the distance of the sensor 200 cm from the place where the larva was introduced into the wood. It seems that due to the smaller construction elements in furniture, the AE method can be effectively used in the assessment of the risk of furniture and pieces of art by wood destroying insects. However, for wood with large cross-sections in building structures, the spacing of the sensors must not be too large. Unfortunately, this requires more effort when using the AE method, if the recording is done on a single-channel basis. Therefore, it is necessary to check the multi-channel recording system with the AE method when used in building structures.

CONCLUSIONS

1. The calculated acoustic emission energy of larvae with the acoustic emission (AE) method depends on the size of the insects expressed in body weight.
2. The acoustic emission energy increased as the 0.676 power of larva mass.

3. The ability to register the presence of an old house borer larva is dependent on the parameters of the structural elements: the transverse dimension and length.
4. There is a large decrease in energy of larvae recorded with the AE method, with the increasing distance of the sensor from the larva habitat. Based on the obtained results, for the detection of small larvae sensors should be placed at 1.0 m intervals.

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