Assessment of the Ability for Early Detection of Newly Hatched Larvae of *Hylotrupes bajulus* L. Using the Acoustic Emission Method in Scots Pine Wood

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The acoustic emission analysis method was used to determine the activity of very young *Hylotrupes bajulus* larvae in their long-term development. In the laboratory conditions the simulated scenario of a fresh, intense infestation inside the construction wood was evaluated. The sounds generated by the insects during their feeding on the wooden samples were processed by the measurement system, which was able to detect and count the larva-originated sound pulses and calculate related energy. So far, no one has examined possibilities of detecting infant larvae of *Hylotrupes bajulus* L. This work is a continuation of research on the influence of the insect mass on its AE-based detection. The experiments performed with multiple wood samples analyzed through the period of one year have shown dependency between the mass of the larva and the intensity of the sound generated by them. The moment of the earliest possible detection of infestation in the wooden structure was evaluated. In the appropriate conditions (large number of young larvae inside the wood and optimal temperature) the insects reach the mass of tens of mg, which makes them detectable using the AE method.

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INTRODUCTION

The old house borer (*Hylotrupes bajulus* L.) is a dangerous longhorn beetle (Coleoptera; Cerambycidae) pest that invades wooden constructions in Europe and other continents (Hickin 1963; Becker 1970). This species has been introduced almost everywhere, reaching a cosmopolitan distribution, even though it is very abundant in some countries within its native European range, such as Germany (Escherich 1938; Wichmand 1941; Becker 1949; Becker 1970) and Poland (Krajewski 1995). Because of significant threat to human economy, methodologies to control it, especially focusing on the non-chemical approaches, are of interest for researchers and practitioners (Reddy *et al*. 2005; Reddy 2007, 2011; Henin *et al*. 2014a,b). Although in some geographical regions the intensity of infestation is weaker due to the smaller usage of the wood in the construction industry (Dominik 2005), the global scale of the problem is significant. The old house borer is the most dangerous species for construction and building materials (Becker 1949; Hickin 1963; Dominik 1977; Dominik and Starzyk 2004). Behavioral aspects of its lifecycle were examined in the past, focusing on biology and ecology (considering environmental factors affecting the larvae habits). The main focus of the research was on the analysis of the food preferences (Wichmand 1941; Becker 1949; Becker 1963; Körting 1965; Haselberger and Fengel 1991a, b, c, d; Krajewski 1995; Nerg *et al*. 2004).

Detection of the old house borer larvae is a challenging task. Besides x-ray or computer tomography, the most popular approach is acoustic emission analysis (AEA) (Kerner *et al*. 1980; Plinke 1991; Schofield 2001; Krajewski *et al*. 2012; Creemers 2015; Bilski *et al*. 2017; Nowakowska *et al*. 2017; Krajewski *et al*. 2020). Experiments require relatively simple hardware (either microphones or accelerometers) and often exploit artificial intelligence (AI) methods to classify signals based on previously stored patterns of larva behavior.

The research is conducted usually on larvae with different levels of development, but always with relatively heavy body weight. This makes the detection relatively simple, but it allows for their identification only in later stages of the lifecycle, when the damage is already significant. Old house borer larvae live for many years, during which they feed in wood. Their reported activity periods range between 2 and 10 years (Becker 2000; Hickin 1963), 3 and 11 years (Kunike 1936), 3 and 6 years (the most common) (Hickin 1963), and extremely long periods of time such as 18 years (Dominik and Starzyk 2004) or even 32 years (Hickin 1963). For this reason, early-detecting its presence inside woody materials is of utmost importance. The old house borer larvae hatch from the eggs in the shape of a spindle having length of 1.2 to 2 mm (Schwarz 1935; Hickin 1963; Dominik and Starzyk 2004) (Fig. 1) and are light, with a mass of approximately 0.4 mg.

These small insects generate low sound energy during wood boring, which is difficult to detect, especially in a noisy environment. Another important issue is determining the relation between the larva activity and its mass, increasing with age. It is expected that for longer durations of dwelling inside the wood, the insects will become more active, making it possible to determine their presence based on the analysis of their sounds.

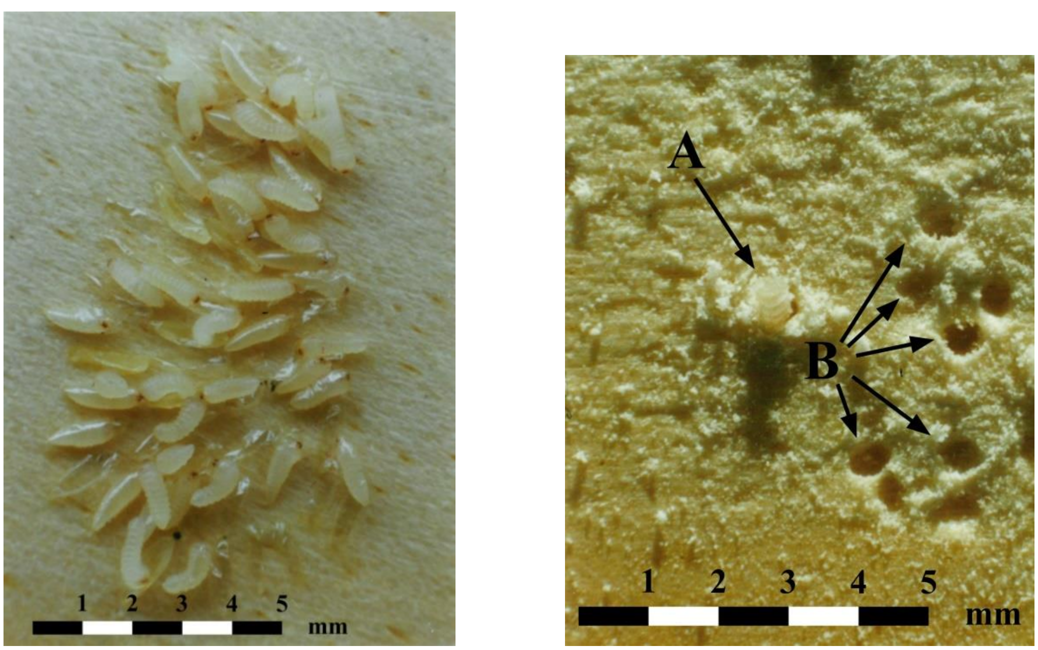

Fig. 1. Very young larvae of old house borer (left) and young larva penetrating the wood (A) and the holes left by other young larvae (B) – right

Due to the small initial weight and long duration of the wood boring by the larva until the adult phase, determining the earliest moment of possible detection is desired. The effective solution would lead to the better protection of wooden structures from the infestation. This paper presents the approach for the long-term analysis of the old house borer larvae activity based on the combination of AEA and AI-based methods. The individuals were analyzed in the period of the single year, during which repeated recordings were made. In the laboratory a large number of larvae were inserted into small wood samples, which emulates the typical, real-world infestation of the actual wooden constructions. A previously constructed measurement system was used to record sounds generated by the larvae when moving through and feeding on the wood. As experiments were conducted in a noisy environment, a denoising procedure and the module for discerning the insect-originated sounds from any other were introduced. The larva activity was evaluated by the calculation of the energy of the sound generated by them. This publication is a continuation of an earlier works (Krajewski *et. al*. 2022), where older and heavier *Hylotrupes bajulus* larvae were detected. This work, however, was aimed at determining the earliest possible stage of infestation development using the AE method, which was not done before.

The activity of the insect larva depends on its age and weight. As the latter increase with time, it should be easier to detect the infestation. As mentioned earlier, the important aspect is the threshold mass and activity detectable by the modern sensors. Previously the dependency between the larva activity and the surrounding temperature was shown to conform to the theoretical estimations (Krajewski *et al*. 2020). Now, it is important to evaluate the influence of the insect maturity on the generated sounds.

EXPERIMENTAL SETUP

The conducted experiments used the old house borer (*Hylotrupes bajulus* L.). The house old borer was reared at the entomological laboratory in Department of Wood Science and Wood Preservation of Institute of Wood Sciences and Furniture, Warsaw University of Life Sciences – SGGW. The larvae were newly hatched from eggs laid by five female adults near the end of July 2018.

The eggs were moved to the holes created using a spindle in specimens of Scots pine sapwood (*Pinus sylvestris* L.), measuring 15 x 20 x 50 mm. A total of 17 wood specimens (initially each with five larvae inside) were used. After biting into the wood, the recordings of larvae sounds were made using the AEA method. The larvae through their first month of life were bred in the incubator (to make the process as comfortable as possible), initially in the temperature of 24 °C and relative air humidity of 75%, and next in the temperature of 28 °C and relative humidity of 75%. The breeding was conducted in the darkness. The light is irrelevant to the larvae and pupae's life cycle. This is the widely used breeding standard, see the EN 22, EN 46, EN 47 norms, for instance. The light remains, however, crucial for the imagines while copulating and breeding.

Recordings of larvae sounds using the AEA method were made in four time instants: immediately after their entering into the wood (further referred to as start), at the end of June-beginning of July 2018, in October of 2018, and finally in May of 2019. The whole experiment was conducted at room temperature, outside the incubator. The times of the year when the measurements were taken differed significantly in the environmental conditions, so it was important to verify if the outside temperature also influences activity of insects (which could be crucial during evaluating the constructions' state outdoors). During the recording, similar wood samples with larvae were combined into clusters using a rubber band. Before the recording, each wood sample was positioned on a plastic foam pad. The acoustic sensor was installed inside the wooden block of the dimensions 25 x 50 mm. The recordings were performed for 60 min.

The applied measurement system was described previously (Krajewski *et al*. 2012; Bilski *et al*. 2017; Nowakowska *et al*. 2017; Krajewski *et al*. 2020). Acoustic emission signals were recorded using equipment consisting of a piezoelectric sensor (CCLD model 4507-B-005, Bruel & Kjaer), an external sound card (E-MU Tracker Pre, Creative), and a Lenovo Ideapad laptop with Windows 7 operating system and Adobe Audition software. A piezoelectric sound sensor was attached to the radial section of wooden elements with GE Bayer Silicones grease. The sensor was connected to the sound card through the analog-to-digital converter. The sound card was connected directly to the laptop via the USB 2.0 interface. The applied sampling frequency was 44.1kHz, with a 16-bit resolution. The recorded samples were stored in the uncompressed .wav files.

The second part of the system was software written in the Matlab 2018 environment, run on a separate computer. It was responsible for opening the wav files, performing the signal processing to extract sound pulses and their features, making the classification of sounds labeled as larva-originated or other, using the Support Vector Machines (SVM) algorithm, and calculating the overall number of pulses and energy related with the larva activity. The scheme of the measurement and energy evaluation procedure using the described system is shown in Fig. 2. The system identifies the sounds related to the larva bites based on the analysis of the pulse dynamics, mainly in the time domain, such as pulse power, duration, dynamic range, *etc*. The configurations of the classifier and the preprocessing operations are described in the authors' previous works (Bilski *et al.* 2017; Krajewski *et al.* 2020).

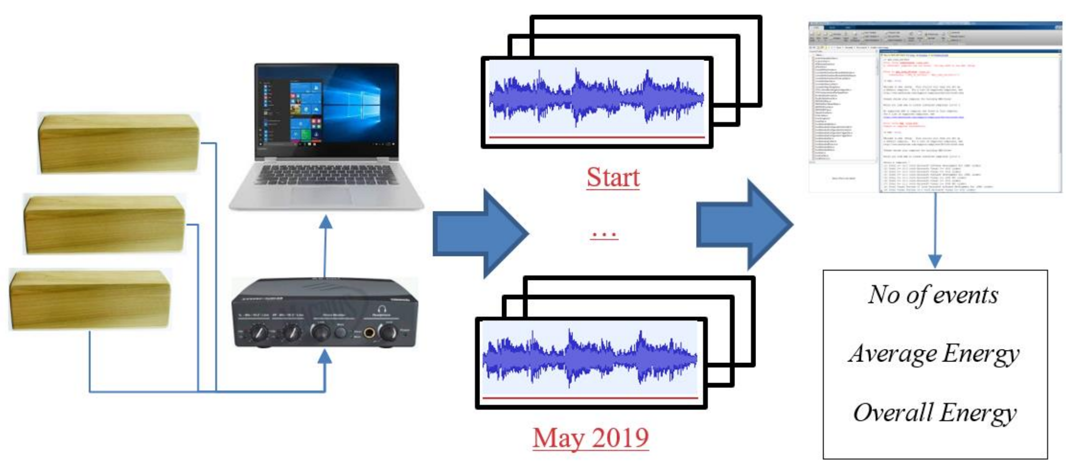

Fig. 2. Measurement and data processing procedure

Two criteria of larva activity were used in the experiment. The first one is the number of sound pulses related with the larva biting the wood. They have the form of changes in the voltage delivered by the sensor, which is proportional to the sound pressure. Its accuracy depends on the ability to distinguish between the bite sound and all others. The second criterion is based on the first one and exploits the energy of drilling sounds by the larva. As presented in Krajewski *et al*. (2020), the applied measurement system does not record the absolute energy calculated in J, but voltage values related to the reference level – the latter should be first determined during the sensor calibration. The acquired samples' values range 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 -5V to +5V). The energy is 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 sample value) 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 to calculate the energy calculated from the reference point v_{ref}. The calculations for both criteria (*i.e*., number of bites and the sound energy) were averaged for all wood samples and for each measurement time instant.

RESULTS AND DISCUSSION

This section discusses the results obtained after the analysis performed on the recorded data by the AI-based system. It processes all sounds that might be caused by the larva biting into the wood and performs the binary classification to isolate only the sounds that are indeed related to the insect's activity. The typical pulses caused by the larvae are presented in Fig. 3. Here the acoustic waveforms for the larvae at the beginning and the end of the experiment are compared. Though the pulse duration and shape are similar, the amplitudes are significantly different, which shows not only the number of bites is important, but also their energy, which is confirmed by Figs. 3 and 4. It is also clear that the significant difference between the energies was recorded in the last period of the experiment, where the larvae must have gained weight and were much larger than during the initial periods. The frequency spectrum of the signals is characteristic for short pulses, *i.e.* it is baseband, up to 1 kHz (Fig. 4) and similar for all events.

The isolated waveforms have been counted and their energy summed up for each wood block in the particular season. This way it was possible to evaluate the insect activity based on the number of events and also their energy. In both cases the obtained values may depend on the number and size of the larvae, which slowly grow, so the important question is about when the events detected by the AI-based classifier are significant enough to consider the infestation. Below results for both criteria are presented.

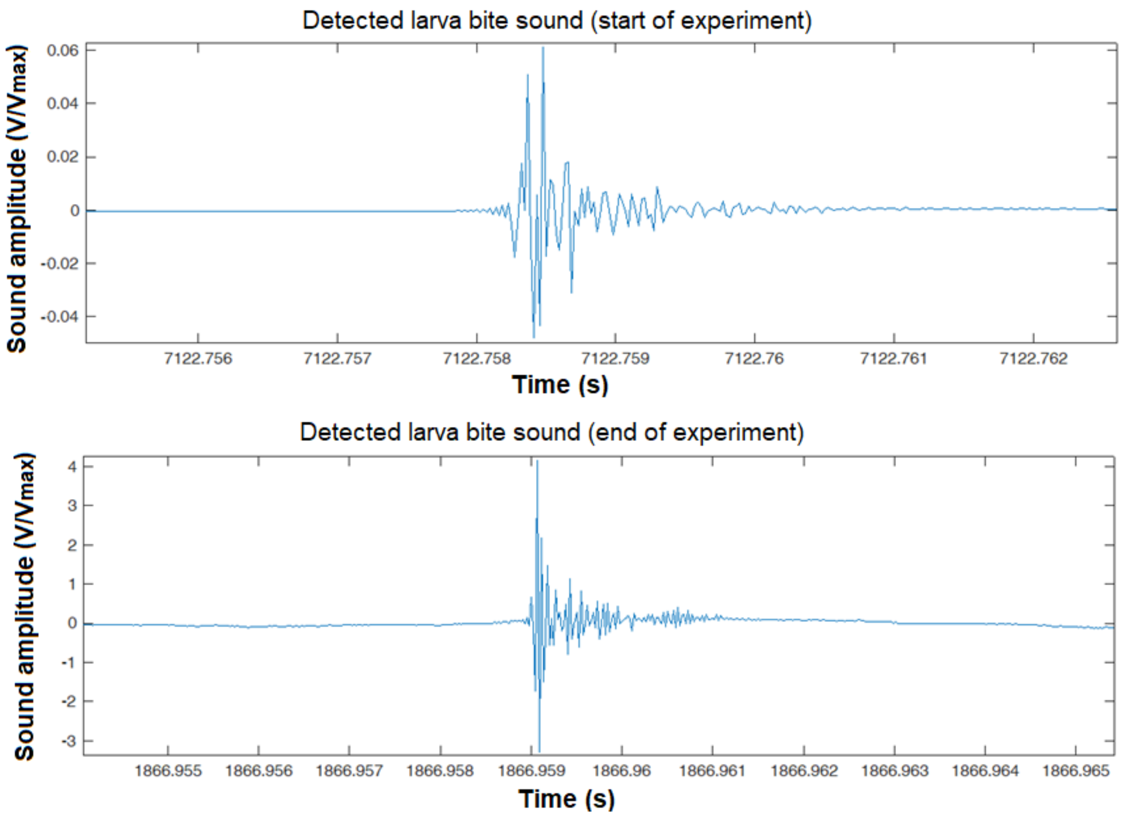

Fig. 3. Comparison between the bite sound pulse at the beginning (upper) and the end (lower) of the experiment. For the wood block No. 10.

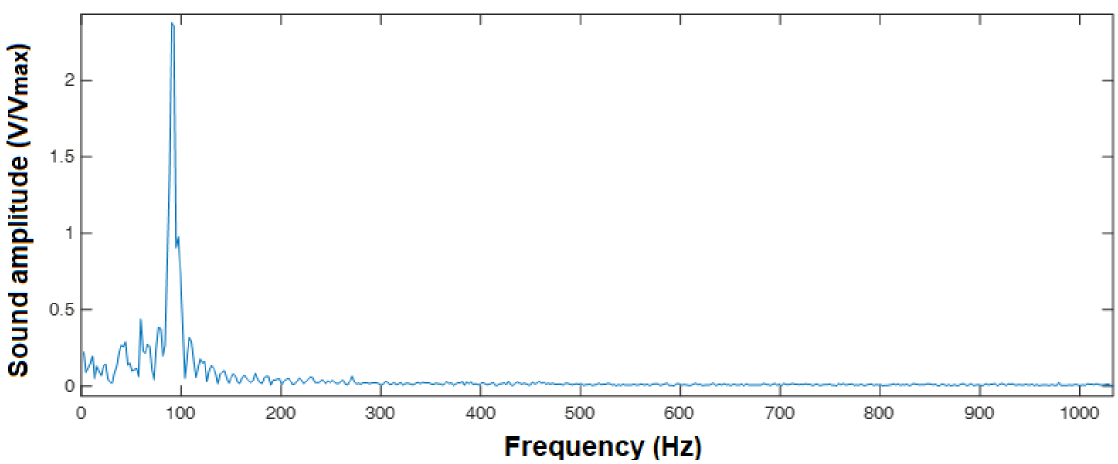

Fig. 4. The amplitude spectrum of the typical bite sound pulse

Average numbers of bites per wood sample (block No. 1) for four measurements in different time instants are presented in Fig. 5, with standard deviations in Table 1. The curve demonstrates the steady increase of recorded pulses with time. This shows that the growing larvae become easier to detect, though making more damage to the wooden structures, disregarding the tree species they are made of.

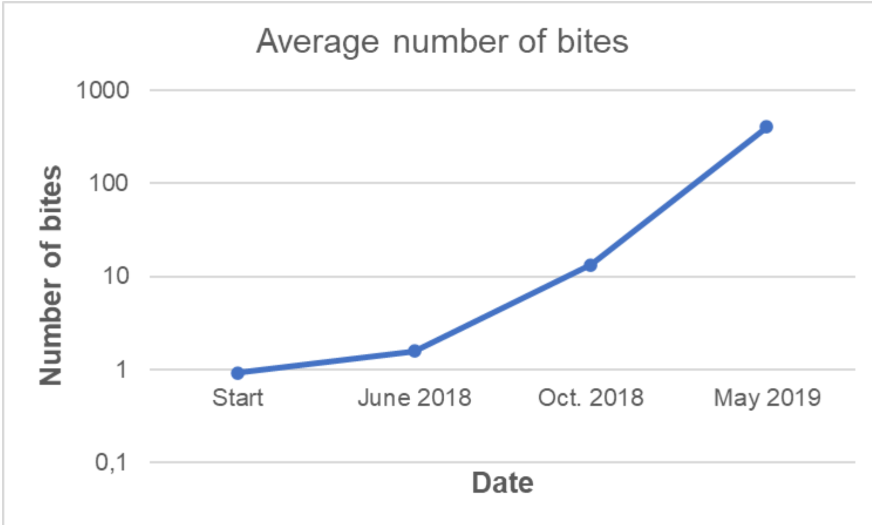

Fig. 5. Average numbers of bites in the analyzed wooden block No 1

Table 1. Standard Deviations for Average Number of Bites from Fig. 5

Start	June 2018	Oct 2018	May 2019
0.288675	1.157868	22.52988	372.7449

Statistical analysis was performed on the collected data to check the relations between the measurements taken during each season. The paired two sample for means test was selected for this purpose with the significance ratio equal to 0.05. The hypothesis verified assumes that there was no mean difference between the subsequent measurements (in the subsequent seasons). Results are shown in Table 2. The Pearson correlation coefficients show that data were not dependent, while the p-values for the first and the last pair of seasons show that the difference between averages was close to 0, while the difference between June and October was not small enough.

Table 2. Results of the T-Test for Paired Samples for Means (number of bites)

Seasons	Correlation	t-stats	P-value
Start-June 2018	0.1667	-1.9640	0.0406
June 2018-Oct 2018	-0.2978	-1.7323	0.0586
Oct 2018-May 2019	0.3847	-3.7711	0.0022

Similarly, the average sound energy evaluation results in the same wooden sample are presented in Fig. 6, with standard deviations in Table 3. The curve is similar, with higher values for earlier measurements. This result is caused by the amount of relatively high energy sound pulses generated by young larvae, though their number is small at that stage of development. The activity increase was observed between October 2018 and May 2019, which demonstrates that the larvae gain weight during this period and become louder.

Fig. 6. The average sound energy of wood boring in the wooden sample

Table 3. Standard Deviations for Average Sound Energy from Fig. 6

Start	June 2018	Oct 2018	May 2019
0,068067	0,071223	0,08339	32,93247

The statistical analysis was performed on the averaged energy the same way as for the number of bites. Results are in Table 3. Similarly to the number of bites, the calculated average energies are independent of each other based on the Pearson correlation criterion. This time, however, the hypothesis about the minimal difference between averages holds only for the most recent seasons, where the infestation is easier to detect.

After extracting the insect individuals from the wood, it was evident that many of them grew through the year, increasing their mass multiple times. However, some individuals remained small and light; they will be difficult to detect using AEA. Differences in the measurement results for various wooden samples are presented in Fig. 7. Here the average sound energy of wood boring for samples No. 4, 5, and 6 are visible. The main differences in both the number of bites and their energy emerge in the initial period of the measurement process, especially between “Start” and “June 2018’ time instants. This is due to their minimal activity, when even single additionally recorded sound makes the difference, see sample No. 6. In other cases, both measured parameters steadily increase, as can be seen in Fig. 8, where the energy for the other two wooden blocks, No. 7 and 8, containing only one larva inside each, is presented. Starting from the “October 2018” timestamp all measurements are similar, showing the abrupt significant change in the larvae activity. The detection of their presence is the most crucial in the initial time instants, before the infestation is intense and causes heavy damage to the wooden structures. Assessing the presence of insects depends on the accuracy of the applied classifier, exploiting the SVM module, as shown previously (Bilski *et al*. 2017).

The larvae mass measurements after terminating the experiment are presented in Table 4. The most significant examples of the largest larvae are indicated in bold font. It is reasonable to expect that they were responsible for the majority of sound recorded by the sensors. In most cases, during the first months of infestation, behaviour of larvae in all wooden samples was similar. Later, discrepancies started to emerge, mainly due to the differentiation in the particular groups of insects (due to dying, cannibalism, etc.). For instance, wooden samples No. 5 and 10 should be easily distinguishable based on the acoustic analysis, as they contain clearly different larvae groups. The signal analysis confirms that, but only during the last measurements, taken in May of 2019. Previous recordings indicate that larvae activity in both samples is similar, which might also suggest when the differentiation occurred.

Note that the number of individuals in particular samples is different (though in all cases 5 larvae were present initially), as some individuals did not survive in their dwelling locations (probably being eaten by their compatriots, which is typical in the real-world situation, as the larva is also a good protein source). Notably, there was a large difference in size between insects in the same sample (for instance, wooden block No. 1 and No. 15), even though all were bred and examined in identical conditions. The reason for these discrepancies might be individual preferences, such as stamina or strength or the cannibalism. This, however, is also a possible and typical phenomenon during the actual infestation.

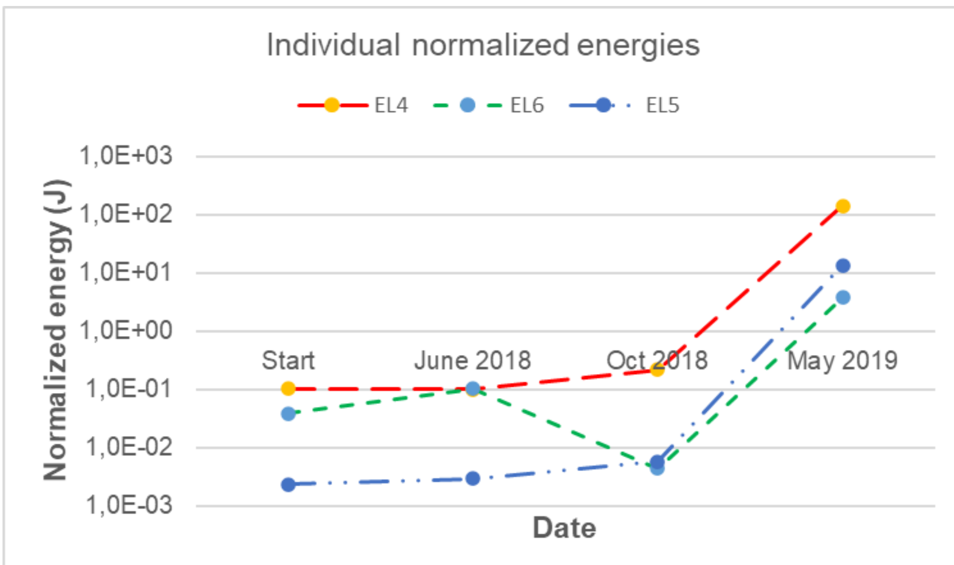

Fig. 7. The levels of sound energy of wood boring in the wood sample No. 4, 5, and 6

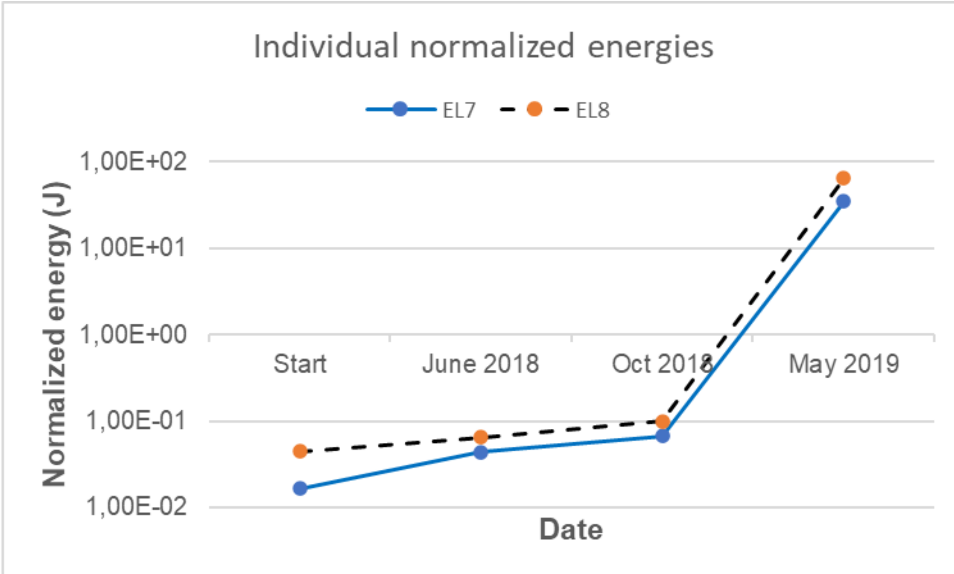

Fig. 8. The levels of sound energy of wood boring in the wood sample No. 7 and 8

Table 4. Number and Weight of Larvae in Wood Samples at the End of the Experiment

No of Wooden Sample	Number of Larvae Found	Weights of Larvae at the End of the Experiment (g)
1	2	0.007; **0.039**
2	3	0.007; 0,006; 0.007
3	2	0.023; **0.067**
4	2	0,005; 0.012
5	2	0.015; **0.054**
6	2	0.005; 0.006
7	1	**0.041**
8	1	**0.061**
9	1	0.014
10	1	0.003
11	1	0.010
12	1	0,081
13	3	0.004; 0.004; 0.019
14	4	0.004; 0.007; 0.006; 0.016
15	3	0.005; 0.015; **0.081**
16	1	0.003

In the research conducted by other authors, the AEA method was used to detect the presence of termites. The sound-based approach is considered useful and practically applicable due to its relatively high accuracy and low cost. There are many examples of its application for the detection of termites in buildings (Lemaster *et al*. 1997; Fujii *et al*. 1999; Mankin *et al*. 2002; Dunegan 2005; Dunegan 2009; Mankin and Moore 2010). Termites are small insects, but, as was verified, the mass of the single individual of *Reticulitermes lucifugus* var. *santonensis* de Feyteaud psudergate is approximately 0.0025 g. Compared to the newly hatched old house borer larvae, which weighs 0.0004 g, it is six times larger. As shown in Figs. 3 through 5, the sound energy of wood boring depends on the insect weight, and the detection is more challenging than for the termites. The ability of recording such sounds also relies on the distance between the individual in the wood and the sensor. As the actual location of larva in the wooden construction is initially unknown, this requires additional attention to increase the detection probability. The calculations indicated that the sound energy of wood boring is indeed small (see Fig. 7), especially for the individuals of the old house borer larvae newly hatched from eggs. Larvae struggling against the stress are trying to get to safety by biting inside the wooden structure as fast as possible. Based on the sound energy of wood boring recordings made by AEA, it was established that after a couple of the following days the insects become less active, which would not be possible to discover without the acoustic signal analysis. With time the larvae become more confident and start the process of wood boring, which leads to the increased number of bites' impulses and revealing their presence through the growing recorded sound energy.

The results show that only after a single year the detected sound energy is high enough to make the detection of the infestation possible, even in the conditions of the environmental noise. Young larvae are large and therefore loud enough to be identified by the system, which combines the AEA with the AI-based classifier. The graphical representation of the sound recording for the feeding larvae clearly shows the bite-related pulses in the laptop screen, even after a single year of wood dwelling. The development of the old house borer larvae may be very long, lasting for many years before the pupa and adult stages are achieved (Kunike 1936; Becker 1949; Hickin 1963; Dominik and Starzyk 2004). The remaining question refers to the cause of the intense mass increase for some larvae and relative fast increase of the sound energy of wood boring in the specific moment (Fig. 7).

The growth of the larvae depends on the existence of proteins in the wood (Becker 1963; Becker 1963; Körting 1965). The average-sized old house borer develops for the incoming years and in the most extreme cases, for 32 years (Hickin 1963). It is possible for the larvae to increase their protein intake through cannibalism (Becker 1949; Dominik and Starzyk 2004), which was probably the case in the presented experiments (Table 4). In every wood sample at least one larvae was missing. In some cases the larvae might have died of natural causes, which is the most probable for wood samples No. 2, 4, 6, 9, 10, 11, and 16, also potentially for blocks No. 13, 14. In other situations, cannibalism is more reasonable, which would also explain the significant growth in mass of the selected individual. The larvae of the weight of 0.040 g (Hickin 1963) or 0.050 g (Becker 1949; Dominik and Starzyk 2004) may already transform into the pupae stage. Such rapid growth of the insects was possible because of the convenient breeding temperature.

Predicting the inevitable deaths of some of the larvae due to the natural causes (and inevitable variability in obtained results for subsequent blocks of wood), five young individuals were inserted into each wooden sample. Increasing their number increases the chance of the recording the sound pulses using the AEA, even if some of them were to die of natural causes. In nature there is a large density of the population of the newly hatched larvae. The females of the old house borer are able to lay up to 500 eggs, even two hundreds in a single location (Becker 1949; Hickin 1963; Dominik and Starzyk 2004). The extreme value of 250 eggs has been reported (Schwarz 1935). With such a large density of the hatched larvae in the single location, cannibalism is highly probable, and in result the high growth of the mass increase in the wooden building constructions, which makes the infestation easily detectable using the AEA method.

One of the possible future research directions include the attempt to detect the infestation and its intensity, as well as the location of the larvae. This requires conducting experiments with much larger pieces of wood, where the direction of the sound propagation could be observed. In addition, modifications of the measurement system, including introduction of additional accelerometers, will be needed.

CONCLUSIONS

1. The presented experiments show that in most cases it is not possible to successfully record the very young *Hylotrupes bajulus* larvae in the same season they are hatched from the eggs (in our case Summer or early Autumn). This is independent of the applied hardware and the analyzed constructions, as well as the results from the small mass of larvae and related minimal Energy of the acoustic signal emitted during biting the wooden fibers.
2. However, detecting young larvae using the acoustic emission analysis (AEA) method in some cases became possible less than one year after their hatching and biting into the wood in the specifically friendly conditions (such as large density of larva inside the wood, which causes cannibalism, or optimal temperature for their development).

REFERENCES CITED

Becker, G. (1949). "Ergebnisse der Hausbock-Forschung," *Anzeiger für Schädlingskunde* 7(22), 97-102.

Becker, G. (1949). "Beiträge zur Ökologie der Hausbockkäfer-Larven," *Zeitschrift für angewandte Entomologie* 31, 135-174.

Becker, G. (1963). "Der Einfluss des Eiweis-Gehalts von Holz auf das Hausbocklarven-Wachstum," *Zeitschrift für angewandte Entomologie* 51, 368 – 390.

Becker, G. (1963). "Holzbestandteile und Hausbocklarven-Entwicklund," *Holz als Roh- und Werkstoff* 8(21).

Becker, H. (1970). "Über die Verbreitung des Hausbockkäfers Hylotrupes bajulus (L.) Serville (Col., Cerambycidae)," *Zeischrift für angewandte Entomologie* 67, 99- 102.

Becker, H. (2000). "Asian longhorn beetles," *Agricultural Research*, June, 18-21.

Bilski, P., Bobiński, P., Krajewski, A., and Witomski, P. (2017). "Detection of woodworms' larvae based on the acoustic signal analysis and the artificial intelligence algorithm," *Archives of Acoustics* 42(1), 61–70.

Creemers, J. G. M. (2015). "Use of acoustic emission (AE) to detect activity of common European dry-woodboring insects: Practical considerations," *Non-Destructive Testing in Civil Engineering (NDT-CE)*, Berlin, Germany.

Dominik, J. (1977). "Results of experiments on a possible damage of *Calocedrus decurrens* Torr. and *Taxodium distichum* Rich. wood by *Hylotrupes bajulus* L.," *Sylwan* 10, 25-26.

Dominik, J. (2005). "Observations on the declining reproduction base of the house longhorn beetle (*Hylotrupes bajulus* L.) (Cerambycidae, Col.) as a pest of wooden buildings in the north-eastern region Łódzkie Province," *Sylwan* 5, 62-64.

Dominik, J., and Starzyk, J. R. (2004). *Owady uszkadzające drewno (Wood destroying insects)*, P WR i L, Warszawa.

Dunegan, H. L. (2009). "Detection of movement of termites in wood by acoustic emission techniques," *Materials Science*. DOI: 10.1121/1.2125187

Escherich, K. (1938). "*Bemerkungen zur Hausbockstatistik," Anzeiger für Schädlingskunde* 10(14), 113-116.

Fujii, Y., Yanase, Y., Yoshimura, T., Imamura, Y., Okumura, S., and Kozaki, M. (1999). "Detection of acoustic emission (AE) generated by termite attack in wooden house," in: *30th Annual Meeting*, Rosenheim, Germany.

Haselberger, H., and Fengel, D. (1991a). "Versuche zur Wirksamkeit von Ligninabbauproducten und löslichen Laubholz-Bestandteilen gegen Hausbockbefall von Bauholz. Entwicklung von Hausbocklarven in jungen Fichtenholz," *Holz als Roh- und Werkstoff* 3(49), 115-120.

Haselberger, H., and Fengel, D. (1991b). "Versuche zur Wirksamkeit von Ligninabbauproducten und löslichen Laubholz-Bestandteilen gegen Hausbockbefall von Bauholz. Entwicklung von Hausbocklarven in verschieden behandeten Buchenholz und Kieferholz," *Holz als Roh- und Werkstoff* 4(49), 141-146.

Haselberger, H., and Fengel, D. (1991c). "Versuche zur Wirksamkeit von Ligninabbauproducten und löslichen Laubholz-Bestandteilen gegen Hausbockbefall von Bauholz. Entwicklung von Hausbocklarven in verschieden Buchenholz-Extrakten behandelten Kieferholz," *Holz als Roh- und Werkstoff* 6(49), 229-234.

Haselberger, H., and Fengel, D. (1991d). "Versuche zur Wirksamkeit von Ligninabbauproducten und löslichen Laubholz-Bestandteilen gegen Hausbockbefall von Bauholz. ZurHemmwirkung von Fraktionen der Buchenholzextrakte auf Larvenentwicklung in Kiefernholz," *Holz als Roh- und Werkstoff* 10(49), 333-339.

Henin, J.-M., Leyman, M., Bauduin, A., Jourez, B., and Hébert, J. (2014a). "Phytosanitary treatment of European pallets by microwave: Developing a program to ensure compliance with ISPM 15 and monitoring its efficacy on the house longhorn beetle (Hylotrupes bajulus L.)," *Eur. J. Wood. Prod*. DOI: 10.1007/s00107-014-0826-4.

Henin, J.-M., Charron, S., Luypaert, P. J., Benoit, J., and Hébert, J. (2014b). "Strategy to control the effectiveness of microwave treatment of wood in the framework of the implementation of ISPM 15," *Forest Products Journal* 58(12), 75-81.

Hickin, N. E. (1963). *The Insect Factor in Wood Decay*, Hutchinson, London.

Kerner, G., Thiele, H., and Unger, W. (1980). "Gesicherte und zerstörungsfreie Ortung der Larven holzzestörender Insekten im Holz," *Holztechnologie* 21, 131-137.

Körting, A. (1965). "Über das Verhalten von Hausbockkäfer-Larven in verschiedenen Splintholzzonen," *Anzeiger für Schädlingskunde vereinigt mit Schädlingsbekämpfung* 1(38), 1-4.

Krajewski, A. (1995). "Die Erschätzung des Vorkommens der Holzinsekten in Polen," *Acta Scansenologica* 7, 138-154.

Krajewski A., Bilski P., Witomski P., Bobiński P., and Guz J. (2020). "The progress in the research of AE detection method of old house borer larvae (Hylotrupes bajulus L.) in wooden structures," *Construction & Building Materials* 256,) 119387.

Krajewski, A., Jakieła, S., and Witomski, P. (2022). "Detection of old house borer larvae in wooden structures by acoustic emission method – Influence of larval size and sensor location," *BioResources* 17(2), 3435-3444. DOI: 10.15376/biores.17.2.3435-3444

Krajewski, A., Witomski, P., Bobiński, P., Wójcik, A., and Nowakowska, M. (2012). "An attempt to detect fully-grown house longhorn beetle larvae in coniferous wood based on electroacoustic signals," *Drewno. Prace naukowe. Doniesienia. Komunikaty* 55(108), 5-15.

Kunike, G. (1936). "Holzschädlinge und ihre Bekämpfung," *Anzeiger für Schädlingskunde* 8(12), 89-95.

Lemaster, R. I., Beall, F. C., and Lewis, V. R. (1997). "Detection of termites with Acoustic Emission," *Forest Product Journal* 47 (2), 75-79.

Mankin, R. W., Osbrink, W. L., Oi, F. M., and Anderson, J. B. (2002). "Acoustic detection of termite infestations in urban trees," *Journal of Economic Entomology* 95(5), 981-988.

Mankin, R. W., and Moore A. (2010). "Acoustic detection of *Oryctes rhinoceros* (Coleoptera: Scarabaeidae: Dynastinae) and Nasutitermes luzonicus (Isoptera: Termitidae) in palm trees in urban Guam," *Journal of Economic Entomology* 103, 1135-1143.

Nerg, A-M., Heijari, J., Noldt, U., Viitanen, H., Vuorinen, M., Kainulainen, P., and Holopainen, J. K. (2004). "Significance of wood terpenoids in the resistance of Scots pine provenances against the old house borer, *Hylotrupes bajulus*, and brown-rot fungus, *Coniophora putean*," *Journal of Chemical Ecology* 30(1), 125-141.

Nowakowska, M., Krajewski, A., Witomski, P., and Bobiński, P. (2017). "Thermic limitation of AE detection method of old house borer larvae (Hylotrupes bajulus L.) in wooden structures," *Construction & Building Materials* 136, 446-449.

Plinke, B. (1991). "Akustische Erkennung von Insektenbefall in Fachwerk," *Holz als Roh- und Wetrkstoff* 49(10), 404.

Reddy, G. V. P. (2007). "Improved semiochemical-based trapping method for old-house borer, Hylotrupes bajulus (Coleoptera: Cerambycidae)," *Environmental Entomology* 36, 281-286.

Reddy, G. V. P. (2011). "Development of semiochemical-based strategies for old-house borer, Hylotrupes bajulus (Coleoptera: Cerambycidae)," *Journal of Entomological and Acarochemical Research* 43(2), 111-115.

Reddy, G. V. P., Fettköther, R., Nold, U., and Dettner, K. (2005). "Capture of female Hylotrupes bajulus as influenced by trap type and pheromone blend," *Journal of Chemical Ecology* 31, 2169-2177.

Schofield, J. (2001). *Real-time Acoustic Identification of Invasive Wood-boring Beetles*, Submitted for the degree of Doctor of Philosophy, University of York, Department of Electronics, Toronto.

Schwarz, L. (1935). "Einige beobachtungen über Hausbock," *Anzeiger für Schädlingskunde* 12(11), 133-136.

Wichmand, H. (1941). "Wie lange dauert ein Hausbockbefall?," *Anzeiger für Schädlingskunde* 15(2), 21-24.

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