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The Rattle from Szadek: Acoustic Research with the Use of Numerical Sound Reconstruction

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Abstract

Ceramic sound tools using clay as a raw material have been produced since the very beginning of human history. This was also the case for the cultures that inhabited the area comprised by present-day Poland. So far, over 1,200 ceramic rattles or their fragments have been discovered in this area. They are the subject of interdisciplinary research, using various methods from archaeology, musicology, acoustics, and even mechanical engineering. The state of preservation of the artefacts is often unsatisfactory, and thus important information about their original behavior has been lost. Traditional reconstructions of ceramic rattles restored their appearance only, without reconstructing the basic function of sound production. In order for the sound to be reliably reconstructed, the shape of the rattle, the material from which it was originally made, as well as the entire technological process must be precisely recreated. This is an extremely difficult task, especially in the case of poorly preserved objects. In these cases, reverse engineering methods using numerical modeling are often of use, because they allow the determination of the frequency structure of the rattle sound spectrum. Using reverse engineering techniques, it is possible to build a model that will allow us to recreate at least some of the sound characteristics of the reconstructed ceramic rattles.

Keywords

Archaeomusicology – Archaeoacoustics – Acoustic analysis – Clay rattles – Experimental sound reconstruction – Reverse engineering – Sound synthesis

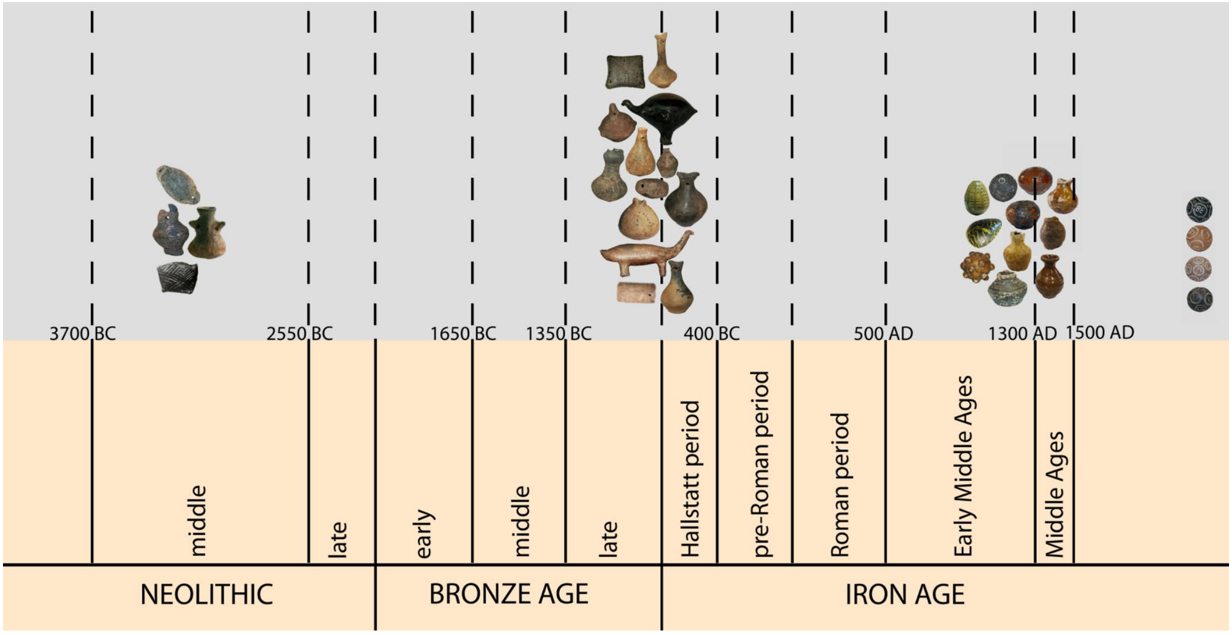

Figure 1: Chronology of the occurrence of rattles in Poland. Elaboration by K. Tatoń.

1 Chronology

Ceramic rattles from the area of present-day Poland constitute a large collection of over a thousand identified archaeological objects, which makes them quite a numerous group of findings from this territory. The first specimens, of different shapes, appeared in the Neolithic, when clay became a widespread raw material for the production of objects for everyday use. Although the clay rattles have enjoyed varying degrees of popularity throughout history (Figure 1), they were present in this area until the beginning of the 20th century. The youngest rattles, which were spherical in form, were plowed out of the ground around 1918.[1] It was the last case of the occurrence of ceramic rattles in Poland. They are not present in today's folk instruments. The tradition of using the sound of these ceramic objects developed unevenly over the centuries. Its heyday came at the turn of the Late Bronze Age and the Early Iron Age and was associated with the Urnfield cultures, traditionally known as the Lusatian culture[2] or, as the authors of the latest research describe it, the Lusatian cultures.

Many of the preserved rattles are equipped with various types of holes. Some pierce the inner chamber, others are placed in protruding parts, e.g. in the cones or the shaft, thought by previous researchers to be handles. Some of the holes are interpreted as being used for threading the rattle onto a strap and suspending it. As for the holes that penetrate the inner chamber, some researchers think they were necessitated by technological reasons. In their opinion, without a hole in the corpus, during firing, the temperature and pressure difference would burst the rattle from the inside.

1 Seweryn 1960: 41.
2 Tatoń 2021: 68.

The hole was meant to ensure unrestrained air circulation during the firing of the rattle, and thus to prevent it from being destroyed.[3] However, this idea requires further investigation. Research conducted on clay rattles from the Numantine Museum of Soria, including replicas produced using a reconstruction of the original Hallstatt kiln, confirmed the possibility of firing rattles without holes.[4] In addition, it is contradicted by the excellently preserved Lusatian rattles from present-day Poland, which are devoid of any holes.

According to the Hornbostel-Sachs system revised by the MIMO consortium, all of them are classified as indirectly struck, shaken idiophones (112.1), vessel rattles (112.13), in which the rattling objects are enclosed in a ceramic vessel.[5] In archaeological typology there are several classification systems in use, because as research progressed, multiple systems were developed, however the most comprehensive is the systematics established by Jerzy Tomasz Nowiński. The general division is based on morphological features, such as the shape of the belly, and distinguishes between two classes: geometrized – characterized by a simple form and a belly with a cross-sectional or longitudinal cross-section similar to a geometrical figure, and figural – ornithomorphic, zoomorphic[6] and anthropomorphic.[7]

1.1 Lusatian rattles[8]

All Lusatian rattles differ in appearance (Figure 2). Although they are quite easily distinguishable from other rattles, each has an individual form, size, and shape. The smallest of them are no more than 3 cm in diameter, while the largest ones reach 12 cm or more. One individualizing feature is the composition of the ceramic mass and the firing method. They result in a different color of the surface of each rattle, as well as discolorations and darker spots resulting from uneven access to oxygen during firing.

They are all handmade, but have been formed in different ways: from a single piece of clay; or from several assembled parts, using coil pots or a mixed technique. The majority are devoid of any decoration. On those that do have ornamentation, it can take many different forms, from simple punctures and engravings to relief patterns. Rattles painted with red paint are the rarest and come from the youngest phases of the Lusatian culture (HaC).[9]

Sometimes, they are of the unsophisticated form, simply made, seemingly carelessly, as if in haste. Sometimes the quality of the firing was so poor that after being left in the ground for centuries, the walls delaminated and fell apart. At other times they are refined in every detail,

3 Kontny et al. 2021: 97.
4 Jiménez et al. 2014: 58–63.
5 MIMO Consortium 2011: 5.
6 Nowiński 2003: 16.
7 Tatoń 2021: 73.
8 Research done within the program of the Minister of Science and Higher Education 'National Program for the Development of Humanities' in 2014–2020, Project no. 11H 13 0382 82 Archaeological musical instruments in Polish museum collections, carried out at the Institute of Musicology of the University of Warsaw.
9 Gediga 1991: 80.

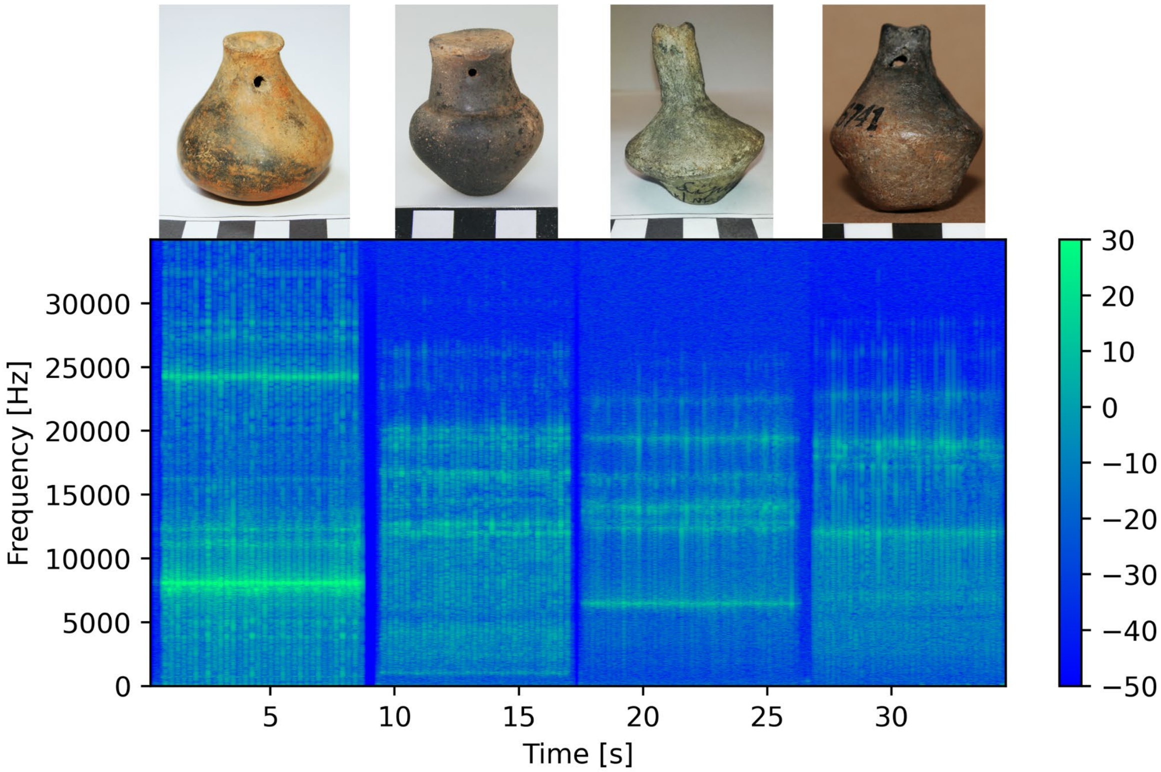

Figure 2: Spectrograms of sample Lusatian rattles: Zbrojewsko grave 1289 (courtesy of the Institute of Archaeology of the Jagiellonian University in Krakow); Dunino cat. no. W25/2015 (Museum of Copper in Legnica); Lipie cat. no. MAK/3267 rattle 1 (Archaeological Museum in Krakow); Laski cat. no. 6741 (Archaeological Museum in Poznań). Recording, photos graphic and elaboration by K. Tatoń.

elaborately decorated, and they are examples of very well fired ceramics. Although some of them are similar in form – at times very similar – they are all unique.

Also, the sounds of rattles each have a unique timbre, and are all differently tuned. Of course, the analysis of the rattle sounds cannot be made solely on the basis of auditory assessment. Spectrograms reveal time dependencies between the frequencies, which makes it possible to observe changes in the tonal structure of the signal, in other words, the features that cannot be detected by hearing alone. Acoustic analysis reveals the noise ranges, as well as the presence of amplified sound components and formant areas.

The tradition of using ceramic rattles did not cover the entire territory of Lusatian culture. They occurred only in certain areas and certain periods. They were absent in its oldest phases, emerged in the Late Bronze Age and were in use until the Early Iron Age. They first occurred in Dolny Śląsk, and then gradually expanded to Wielkopolska, Śląsk, part of Małopolska, the western part of central Poland and part of Pomorze Zachodnie.[10] The number of rattles discovered at individual sites varies. There are sites with several dozen, while on the other hand, in many locations only a few instruments or even a single one were discovered.

10 Malinowski 1993: 23.

The Lusatian rattles occurred mainly in cemeteries, often deposited in children's graves. They constitute grave equipment, but were used for other purposes as well. They are also discovered above graves, in their stone casings or paving or even outside the grave complexes. Next to complete, undamaged rattles, we find single fragments and rattles that were deliberately defragmented or with a hole drilled into them.[11] According to Tadeusz Malinowski, many of the so-called loose finds of rattles do not come from destroyed graves, but may be evidence of various funeral rites.[12] This suggests the use of ceramic rattles by the Lusatian people, among others, during funeral ceremonies, in the final phase of laying graves, and during some later rituals performed at the places where the deceased were buried. Justyna Baron highlights another aspect of rattles that indicates that the sound of breaking pottery during rites of passage, such as funerals, had a symbolic meaning. Producing noise, as opposed to grave silence, was crucial in most of these rituals.[13]

2 Sound of rattles

Current methods for the musicological study of the sound of ceramic rattles allow for the detection of hitherto unknown features. The mere presence of distinct, amplified components, with well-marked rise and echoing phases (Figure 2), may be surprising, especially in the light of earlier results from studies of ceramic idiophones found in Poland. In the only work on ceramic sound tools found in this area (from the end of the 20th century), ethnomusicologist Alojzy Kopoczek described the sound produced by rattles as noise. He stated that it was impossible to isolate component tones with similar vibration frequencies. In his opinion, the only measures of this sound were the duration and intensity of the noise.[14] Based on observations, and probably partly intuitively, he described the features that influenced the differentiation of the sound of rattles: the size of the body, the thickness of the walls and the type of ceramic mass. Without appropriate acoustic analysis tools, and relying solely on auditory assessment, Kopoczek described the nature of the sound of the ceramic rattles as a timbre with significant expressive and imitative properties that could accompany ecstatic dances, putting participants into a trance.[15] Archaeologist Tadeusz Malinowski, while examining Lusatian rattles, noticed that their sounds, although quiet, varied greatly in pitch.[16] Recently, Anna Gruszczyńska-Ziółkowska turned to ceramic rattles. She was the first researcher who recorded their sound and then made an in-depth acoustic analysis,[17] giving rise to the current extensive interdisciplinary research.

Today's sound analysis tools allow us to base our research on objective physical characteristics – excited frequencies, amplitude, and thorough spectrum observation. Unlike auditory sensations,

11 Baron 2005: 9.
12 Malinowski 1993: 29.
13 Baron 2005: 9.
14 Kopoczek 1989: 35.
15 Kopoczek 1989: 35.
16 Malinowski 1993: 26.
17 Gruszczyńska-Ziółkowska 2018: 121–2.

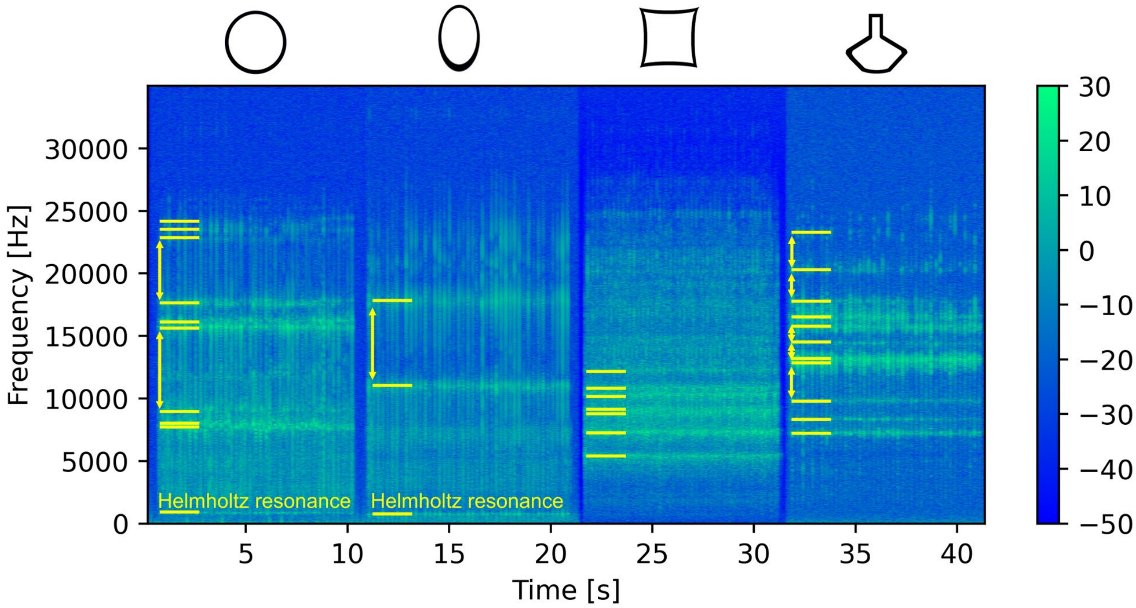

Figure 3: Four groups-types with the examples of rattle sound spectrograms; from left to right: Kalisz Zawodzie, the knobbed rattle (District Museum of the Kalisz Land in Kalisz), the easter-egg rattle from the Opole Ostrówek, cat. no. MSO/235/61 (Opole Silesia Museum in Opole), Dunino, cat. no. W/214/2015 (Museum of Copper in Legnica), Czarnków, cat. no. 1935:697 (Archaeological Museum in Poznań). Recording: Kalisz Zawodzie – P. Ziółkowski and K. Tatoń, the remaining ones – K. Tatoń. Graphic and elaboration by K. Tatoń.

visual representations of the time relationships between frequencies provide detailed insight into changes in the tonal structure of the signal. The use of frequency analysis, called Fourier after its creator Joseph Fourier (1768-1830), allows the signal to be decomposed into sinusoidal components, and then for the precise determination of such features as the number of component tones, their pitch, and relative loudness.[18]

The sound spectra of all the rattles examined, as well as the sound tools that produce them, are characterized by great diversity. Most well-preserved rattles produce a sound, the spectrum of which contains an element of noise, but above all it contains amplified frequency bands clearly separated from the background. The sound spectra of some rattles include only broad bands of noise. Each rattle has its own individual range of excited frequencies; they all are differently tuned. The spectra differ in the width of the amplified frequency bands, the number of these bands, and their distribution. Most of them are inharmonic components. However, the acoustic analysis of the full structure of the sound allows us to observe some analogies within several group-types of sound. Analogies often apply to similarly shaped rattles, but this may not always be the case. The similarities sometimes reveal different shapes and a different provenance in the spectra of sounds of rattles. They relate to the excited frequency range, the formant area, the number of essential components, and their distribution in the spectrum. The order of this distribution forms a kind of

[18] Szabatin 2007: 225.

pattern. This made it possible to initially distinguish four 'types' of sounds that do not necessarily coincide with the rattle categories resulting from archaeological systematics (Figure 3).

The first clearly distinguishable group is that of spherical rattles. The spectra of their sounds contain only a few amplified components, most often arranged in groups of two or three, loosely distributed, which are also in the ultrasonic frequency range. Sometimes, as can be seen in Figure 3, there is a component in the spectrum at an unusually low level of several hundred Hz. This is the Helmholtz resonance, not related to the shape of the tool, but rather to the presence of a hole of an appropriate diameter in its body, passing into the internal chamber.[19]

The most coherent and best-studied group of sounds so far is the egg-shaped type. It is possible to establish the features that are characteristic for this type:

- a flattened noise envelope with a fairly high intensity level of up to approximately 10 kHz, and reduction in the noise level in favour of the appearance of peaks of amplified sound components in the higher register.
- a small number of narrow bands of amplified sound components (from two to four in the analysed range of up to 27 kHz).
- loose distribution of these single bands in the sound spectrum.
- a generally high tuning, namely, the dominant band of amplified components is usually above 9 kHz, which makes the egg-shaped the highest-tuned ceramic rattles from Polish sites.[20]

It should be added that in the egg-shaped type of sound all these features occur simultaneously. As can be seen from the above, when we consider the sound of egg-shaped rattles, we must bear in mind that it borders on the edge of the human auditory range. There are three factors that limit how these sounds are perceived: the pitch, the volume, and the individual's sensitivity and hearing range. Gruszczyńska-Ziółkowska points out that the sound range of the egg rattle available to the human ear is its least attractive part – a flat noise envelope with a relatively high intensity level. In fact, it is only in the very high frequency range that it 'resounds'. The boundary between these two zones is usually distinct, and in the spectrum it takes two forms: a peak of the amplified component or, on the contrary, a deep gap preceding the hills that form further away.[21] The composition of the sound produced by egg-shaped rattles demonstrates dual inclinations. Despite the small number of important component frequencies, it is not always easy to indicate those that could be indisputably considered the strongest, constituting the formant area. It is often easier to identify two such oscillating and competing dominants, which humans can only partially perceive.[22]

The next group of rattles, the sounds of which have similar spectra, is the least coherent and most difficult to describe by indicating the external features of the artifacts. This category includes, but is not limited to pillow-shaped. The features of the sounds produced by this group are

19 Gruszczyńska-Ziółkowska and Tatoń 2021: 117–18.
20 Gruszczyńska-Ziółkowska and Tatoń 2021: 116.
21 Gruszczyńska-Ziółkowska and Tatoń 2021: 119.
22 Gruszczyńska-Ziółkowska and Tatoń 2021: 123.

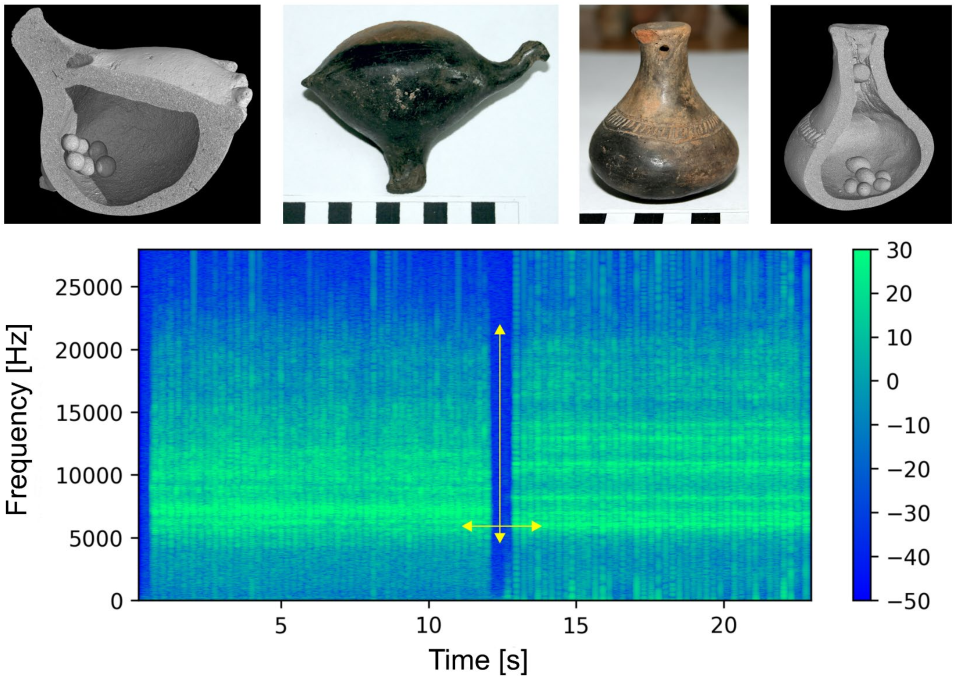

Figure 4: Comparison of similar spectrograms of rattle sounds: Lusatian rattles from the Brzezie site, on the left, cat. no. 1922, on the right, cat. no. 3287 (District Museum of the Kalisz Land in Kalisz). Recording by P. Ziółkowski and K. Tatoń; tomographic imaging by NANOTOM S device at the AGH Laboratory of Micro and Nano Tomography in Kraków. Photos, graphic and elaboration by K. Tatoń.[23]

shown in the sound spectrograms of rattles with other shapes, for instance a lens-like shape. The common features of these sounds can be described as follows: a large number of amplified important components and closely spaced bands, most often in the 5–10 kHz range. Sometimes the enhanced bands are located so close to each other that they seem to form one wide band with a significantly increased amplitude.

The last distinctive group of rattles, the sound spectrum of which can be described as characteristic, is the biconical. This is the largest group of rattles, with a wide variety of forms. In addition to corpus forms composed of two cones, there are also rattles equipped with the so-called handle, i.e. in the form of cones pulled directly from the body. Sometimes there is a wide, short cylinder, hollow inside, which enlarges the internal chamber, or a slightly longer, full cylinder, that sometimes ends with cones or a disc, etc. The spectra in this group contain quite a large number of essential components that are closely distributed in several groups across the spectrum, including very high registers and ultrasounds.

In order to find the reason for the similarity of the sound spectra of rattles with completely different external shapes, a zoomorphic rattle from the Brzezie site, dated to the 5th period of the Bronze Age, and a pear-shaped rattle from the same site, but dated to the Hallstatt period, were subjected to computer X-ray tomographic examination. The results were surprising (Figure 4). The tomogram illustrates how the inside form of the zoomorphic rattle's body differs from the outward

[23] Tatoń 2021: 90, Fig. 23.

form, which is figurative. The chamber has a slightly conical, geometric shape. Likewise, the pyriform rattle tomogram reveals that one of the clay balls inside has been lodged in the neck. It does not contribute to sound production, but rather modifies the chamber's shape in such a way that it resembles the inside of a zoomorphic rattle.

At the current stage of research, we can say that the phenomenon of a type of sound may be closely related to the internal shape of the rattle chamber, which is not always in keeping with its external form. The sound itself is, of course, the product of many morphological factors, but the internal shape of the belly-corpus seems to be of decisive importance. It should be emphasized that the above conclusions are preliminary and require confirmation in the course of further research.

Figure 5: The rattle from Szadek, grave 32, cat. no. 3597 (District Museum of the Kalisz Land in Kalisz). Photo by K. Tatoń.

3 Acoustic analysis of the rattle from Szadek

3.1 Szadek

The site in Szadek, Kalisz District, is a Lusatian cemetery located in South Wielkopolska Lowland upon the middle and lower Prosna River, ranking among the most remarkable Hallstatt burial sites in Wielkopolska. Based on the results of excavations and information about accidental discoveries, the area of the site has been tentatively estimated to be roughly 1.9 ha in extent. The investigations estimate that 750 graves could have been deposited in the destroyed area of the site, while an unexcavated part of the cemetery may potentially still hide nearly 2800 burials. So far only one rattle was discovered in the cemetery (Figure 5), in grave No. 32, which is the rather well-equipped burial site of a child – *infans II*. Apart from the rattle, the following items were found: a cremation urn, a pot covered by a plate, two cups inserted one in the other, a vase, a miniature vase, a mug, an iron ring, and a fragment of a bronze coil.[24]

[24] Szczurek and Pudełko 2015: 12–113.

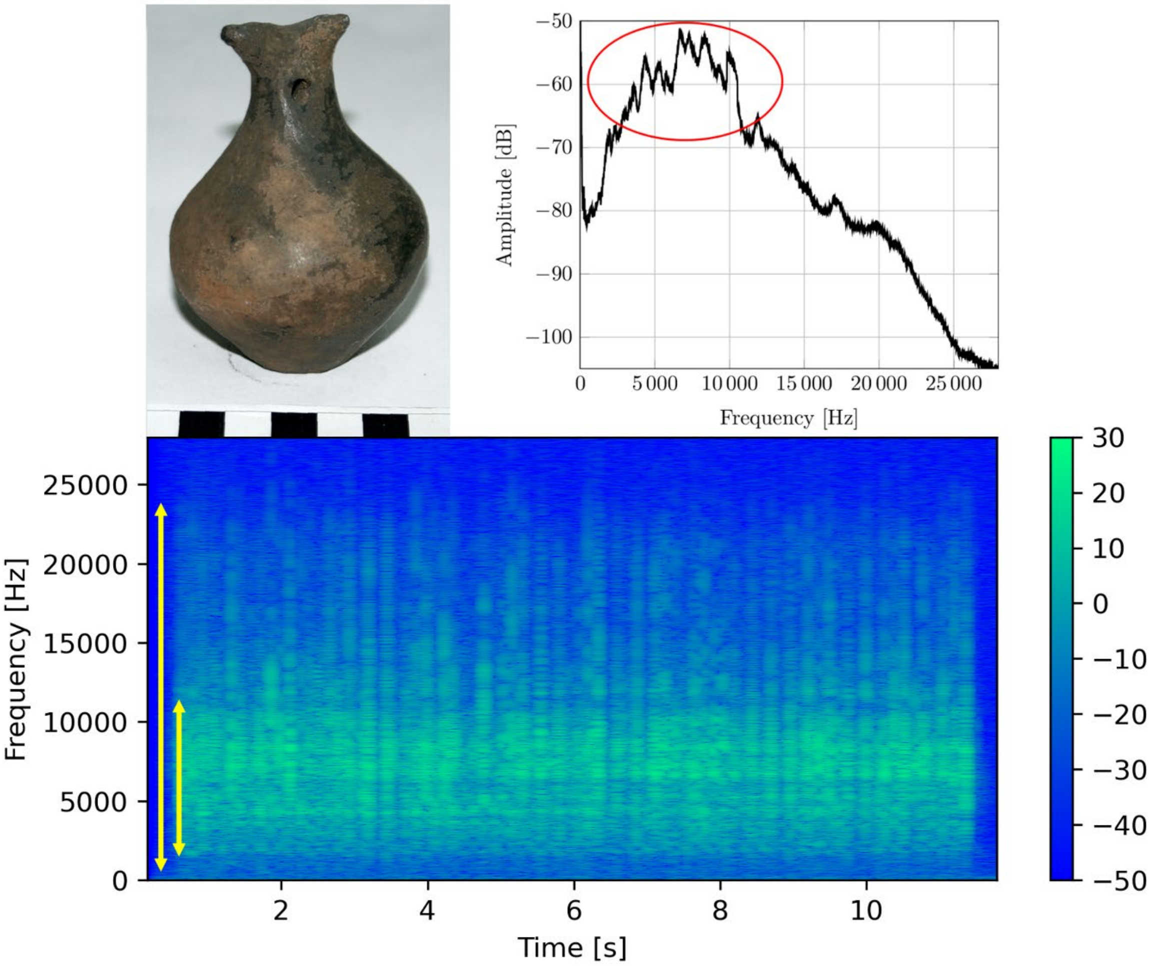

Figure 6: The rattle from Szadek. Top: sound spectrum; bottom: sonogram with marked two, differently amplified areas of noise, without distinct bands of amplified frequencies. Recording, photo, graphic and elaboration by K. Tatoń.

According to archaeological typology, the rattle from Szadek represents geometrized type – it is biconical, with a rounded body, a horn-shaped handle, and pierced with a hole.[25] The rattle's outer surface is smooth, fired a dark brown-black. The clay body was tempered with fine-grained crushed rock.[26] It seemed to be quite well preserved, but the sound spectrogram shows the opposite (Figure 6).

The rattle sound was recorded in non-laboratory conditions at the District Museum of the Kalisz Land. The recording was made with a sampling rate of 96 kHz and 32-bit float. The spectrogram shows an almost balanced spectrum, which is atypical for ceramic rattles. There are no clearly visible narrow enhanced bands, only one wide range, up to 10 kHz. The formant area is almost invisible (approx. 8 kHz). The remaining excited frequencies are noise. This type of

[25] Tatoń 2021: 73–4.
[26] Szczurek and Pudełko 2015: 44.

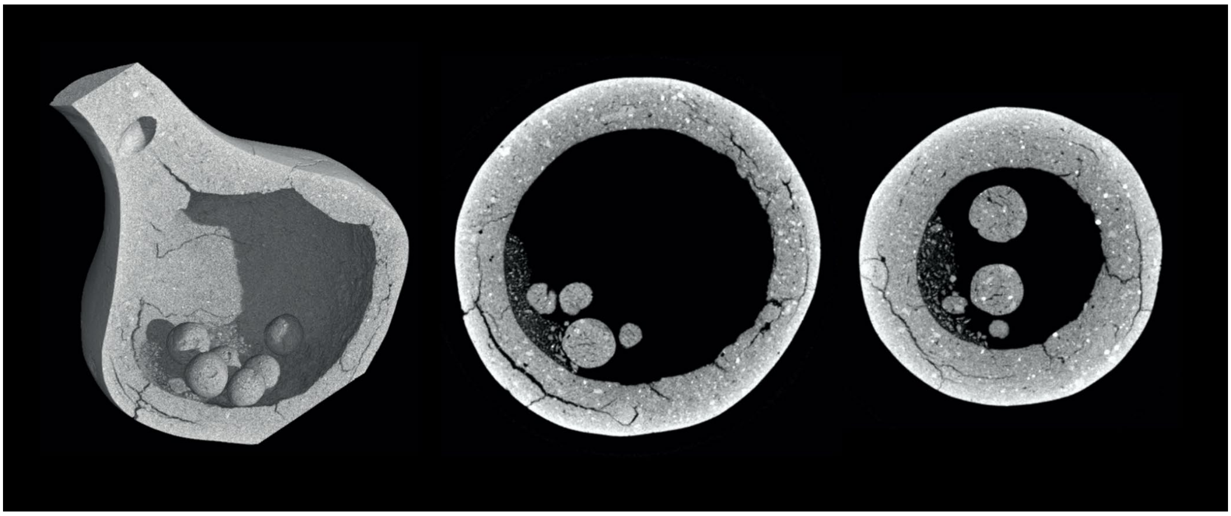

Figure 7: Rattle from Szadek. Tomographic imaging by NANOTOM S device by the AGH Laboratory of Micro and Nano Tomography in Kraków.

spectrum is characteristic for damaged rattles. The X-ray tomographic test[27] revealed features not visible at first glance. The condition of the rattle is not as good as its outer surface looks (Figure 7). There are numerous cracks in its walls. Also inside, apart from the ceramic balls, there is a lot of small debris. These damages significantly affect the acoustic properties of the rattle.

3.2 Analogies

Since it is known that the Szadek rattle's present sound is not its original, it is worth taking a closer look at objects of this type from nearby Lusatian sites. Rattles of a similar shape, biconical with a horn-shaped upper part, were abundant at the cemeteries of the Górnośląsko-Małopolska group of Lusatian culture.

The spectrogram of the rattle from Kępno (Figure 8) shows the spectrum typical for such idiophones, characteristic of multifarious sounds. Against the background of the wide noise band up to 24 kHz range, narrower enhanced areas (7–17 kHz) are clearly visible. The highest amplitude is achieved by the amplified components of about 8 kHz (H8–C9 sound) and it is the decisive spectral component with regard to tuning: the formant area. The other significant components are distributed closely in several groups across the spectrum. All the lines in the spectrum create a certain order: bundles of several amplified bands distributed quite densely throughout all the spectrum.

Another object, analogous to Szadek, is the biconical rattle from Nadziejewo (Figure 9). The main formant area can be seen in the range of 9–11 kHz with a maximum amplification of 10.5 kHz (E9 sound). In addition, there are other well-marked important components, grouped into several bands, distributed over the entire spectrum: 6–7 kHz, 14–15 kHz and 17.5–19 kHz.

A comparison of the spectra of the rattles from Kępno and Nadziejewo shows many similarities in shaping the sound (Figure 10). They not only look alike but also, when set in motion, they produce a congruent sound. In the lower frequency range, up to approx. 6 kHz, while the spectrum

27 Tomographic imaging: NANOTOM S device at the AGH Laboratory of Micro and Nano Tomography in Kraków.

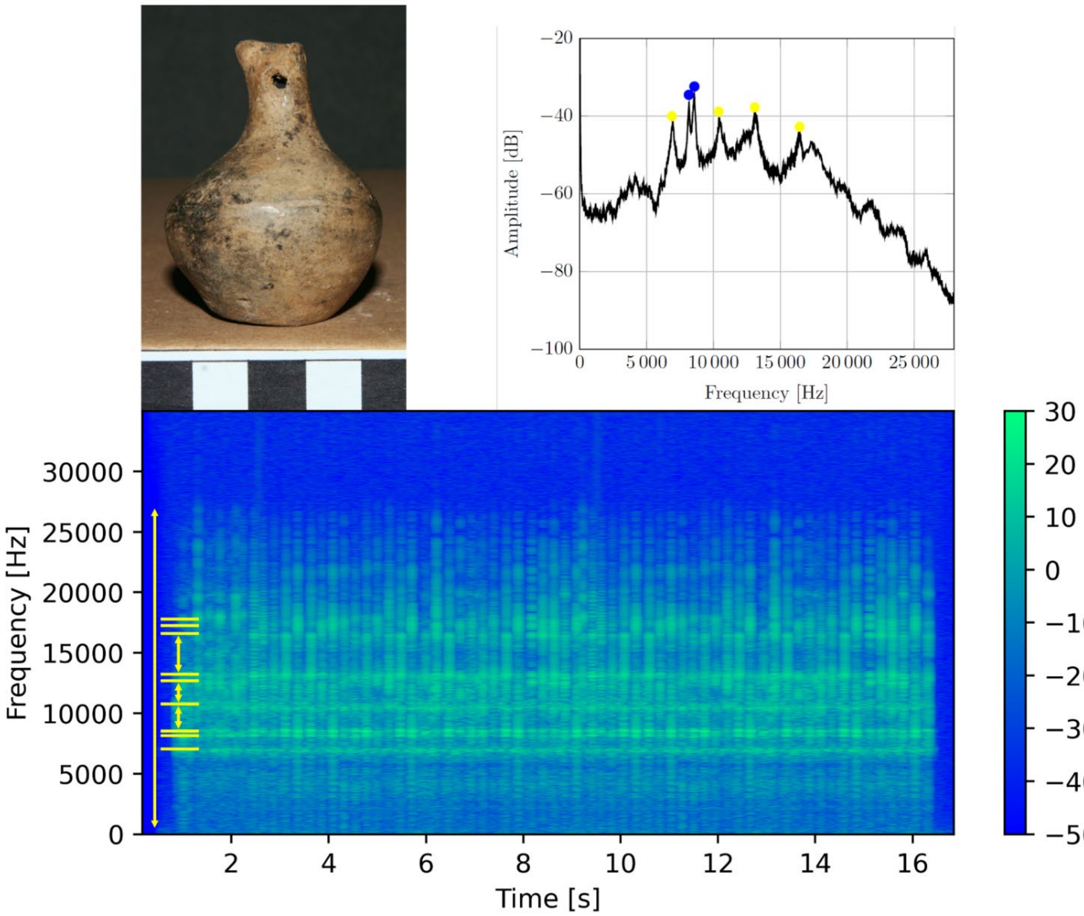

Figure 8: Kępno cat. no. 1942:1731 (Archaeological Museum in Poznań). Top: sound spectrum. Peaks of amplified components are marked with yellow dots, formant with blue ones; bottom: sonogram with marked distinct, amplified components. Recording, photo, graphic and elaboration by K. Tatoń.

basically flattens, the noise remains slightly elevated. The spectrum also consists of a large number of band groups distributed over a wide range of 7–20 kHz. In the case of the rattle from Szadek, the sound spectrum is characterized only by a broad band of high-intensity noise. It is not easy to identify the peaks with the greatest amplitude. In addition, the noise range of the rattle from Szadek is limited to about 10 kHz, while in the spectra of the rattles from Kępno and Nadziejewo, the main formant area is located between 8 and 11 kHz, and the densely spaced remaining components are located up to the limit of audibility.

3.3 Ceramic models

In the absence of any current comparison material from Poland, studies on ceramic rattle copies – models made specifically for this use – provide fruitful conclusions. These kinds of experiments have already been conducted and have yielded satisfactory results. The models were manually constructed, so their compatibility with the originals is subject to considerable error. The first difficulty concerned the manual repetition of the form, the second one concerned the lack of knowledge about the rattling elements placed inside the rattles, and the next one resulted from

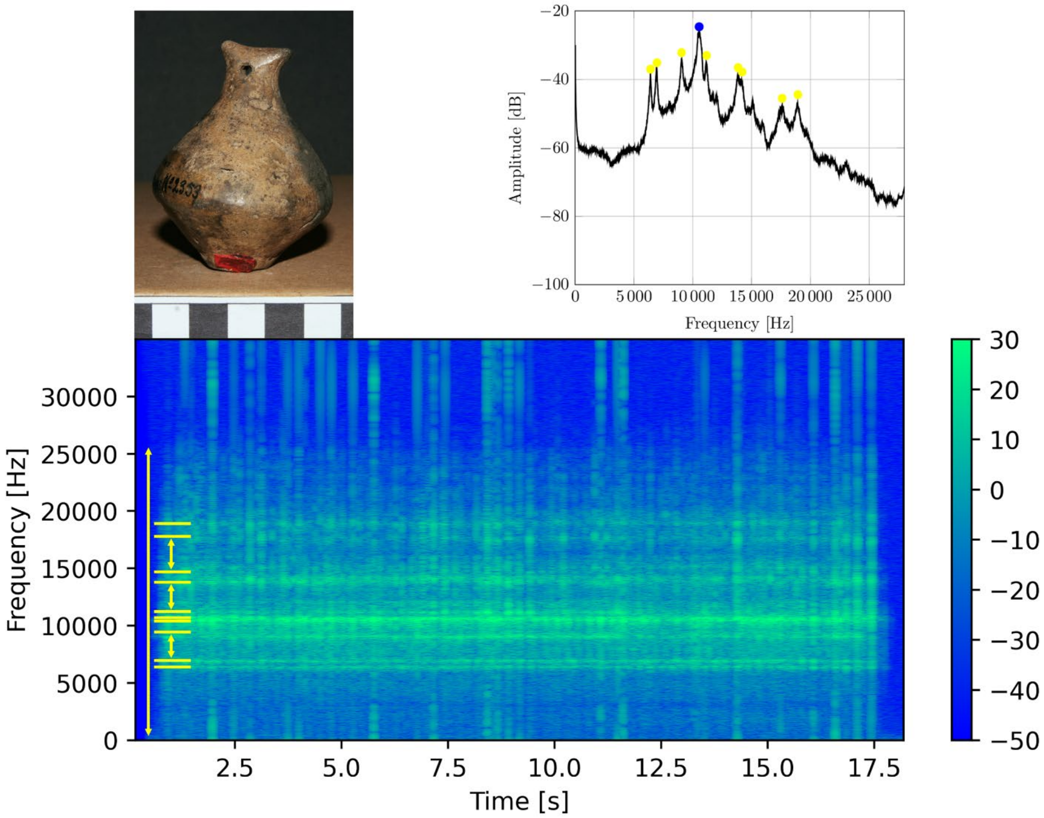

Figure 9: Nadziejewo cat. no. TPN 2353 (Archaeological Museum in Poznań). Top: sound spectrum. Peaks of amplified components are marked with yellow dots, formant with a blue one; bottom: sonogram with marked distinct, amplified components. Recording, photo, graphic and elaboration by K. Tatoń.

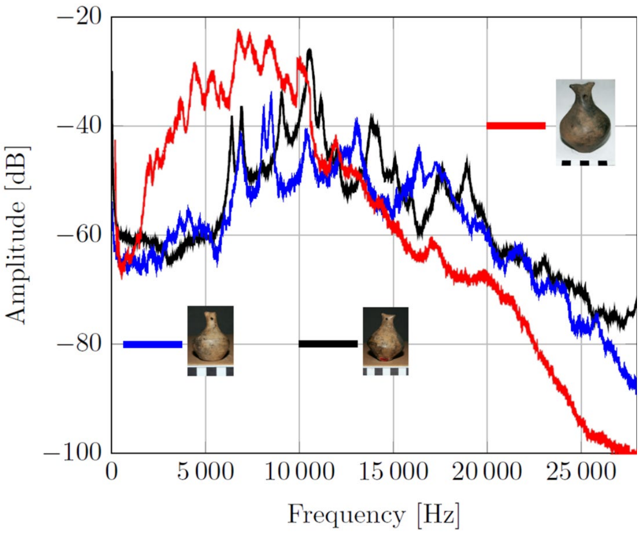

Figure 10: Comparison of the sound spectra of rattles from Szadek (District Museum of the Kalisz Land in Kalisz) – red line, Kępno cat. no. 1942:1731 – blue line, and Nadziejewo cat. no. TPN 2353 – black line (Archaeological Museum in Poznań). Elaboration by K. Tatoń.

the use of modern ceramic mass intended for firing in an electric kiln. Despite this, the sound spectra obtained by setting the models in motion are very similar to the sound spectra of their prototypes (Figure 11 and Figure 12).

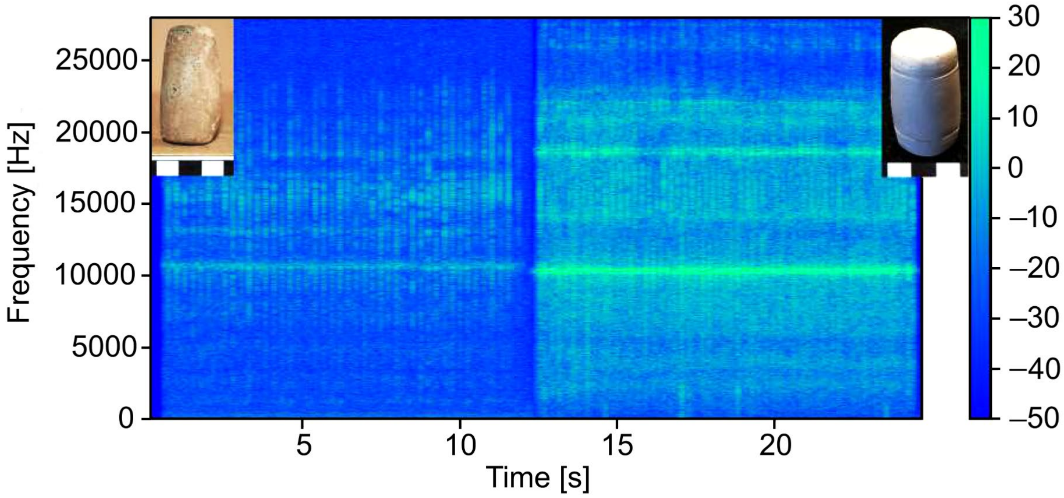

Figure 11: On the left: spectrogram of a rattle from Kowalewko, cat. no. 1991:30, Archaeological Museum in Poznań; on the right: spectrogram of a ceramic model of the rattle. Model, recording, photo and elaboration by K. Tatoń.[28]

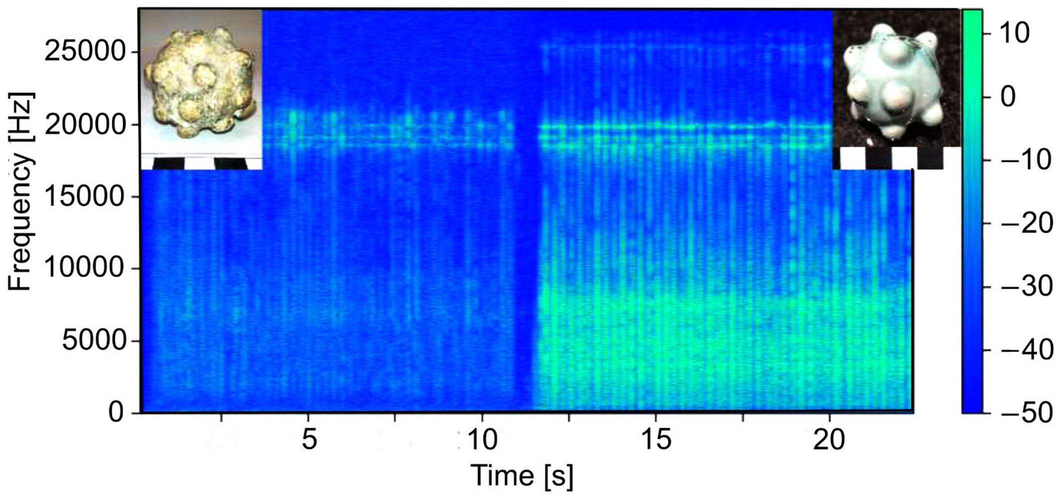

Figure 12: On the left: spectrogram of a knobby rattle from Krakow, cat. no. 47/9, Archaeological Museum in Krakow; on the right: spectrogram of a ceramic model of the rattle. Model, recording, photo and elaboration by K. Tatoń.[29]

Also, the character of the sound of the rattle from Szadek is confirmed with the use of the modern ceramic model (Figure 13). The sound spectrum of the model is similar to the spectra of rattles from Kępno and Nadziejewo. Of course, they are all differently tuned, but their spectra have many common features, including a large number of important components and their specific distribution across the entire spectrum.

It can be assumed that the original sound of the rattle from Szadek represented all the features of the sounds of analogous objects from Kępno and Nadziejewo, as well as the ceramic model. Therefore, its spectrum can be classified as typical for the group of biconical rattles (Figure 14). Due to a large number of high-frequency components, it probably had a bright, maybe even metallic, timbre.

[28] Tatoń 2023: 199, Fig. 6.
[29] Tatoń 2023: 200, Fig. 7.

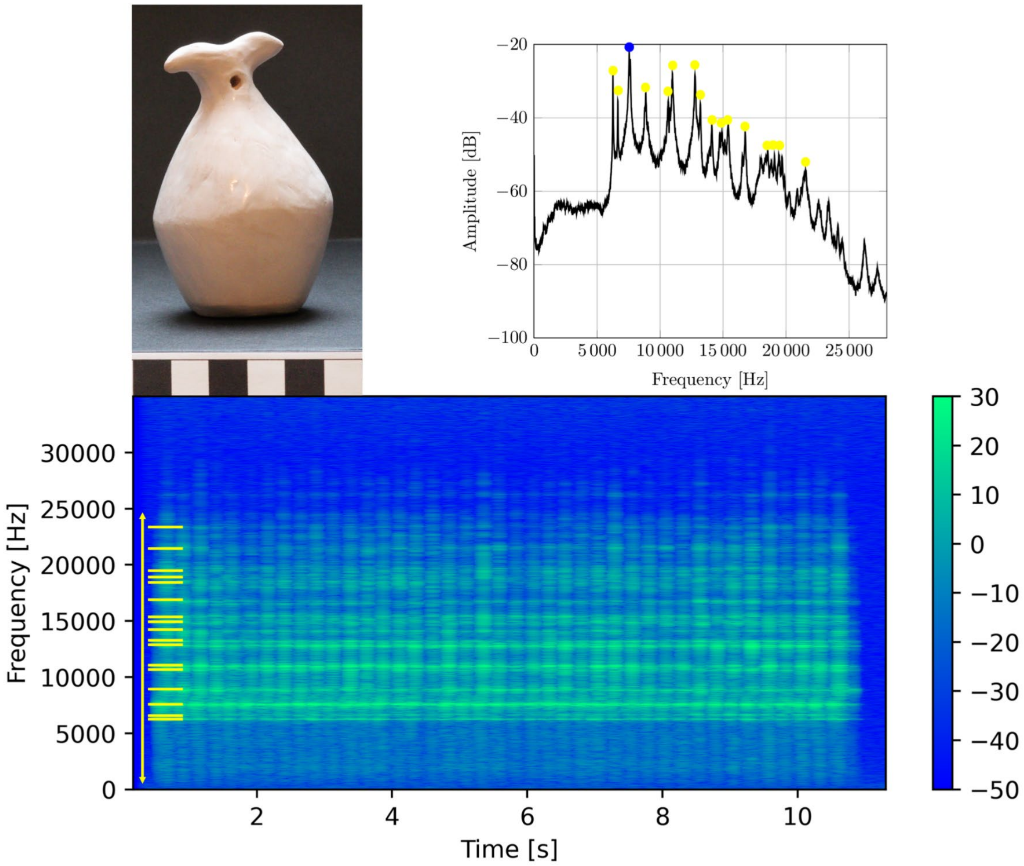

Figure 13: Ceramic model of the rattle from Szadek. Top: sound spectrum with peaks of amplified components marked with yellow dots, formant marked with blue one; bottom: sonogram with marked distinct, amplified components. Model, recording, photo and elaboration by K. Tatoń.

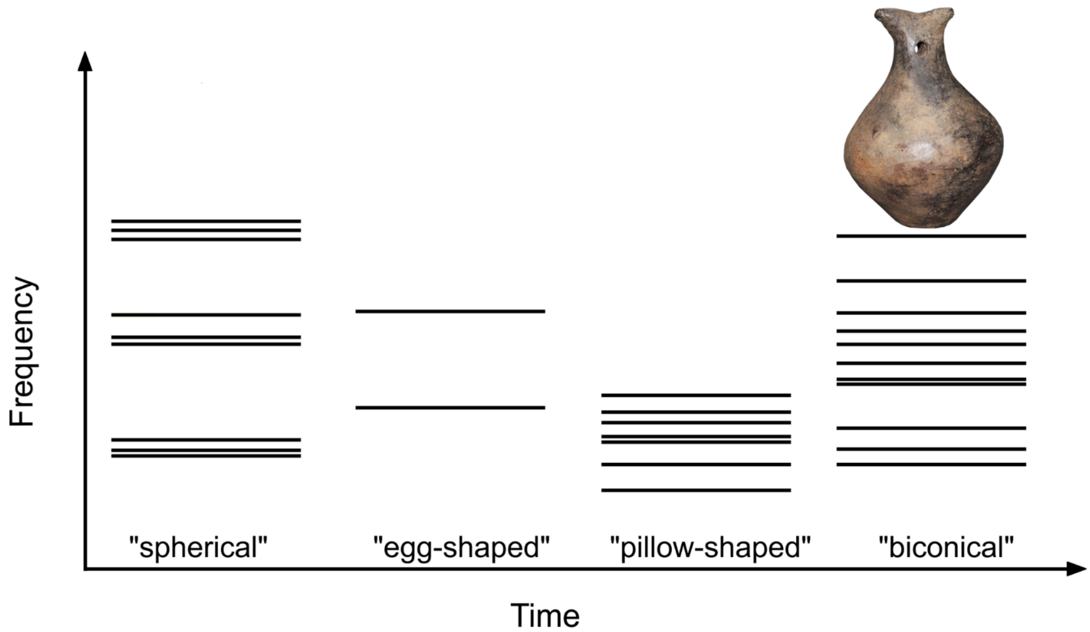

Figure 14: Four groups-types of sound and a “biconical” character of the rattle from Szadek. Elaboration by K. Tatoń.

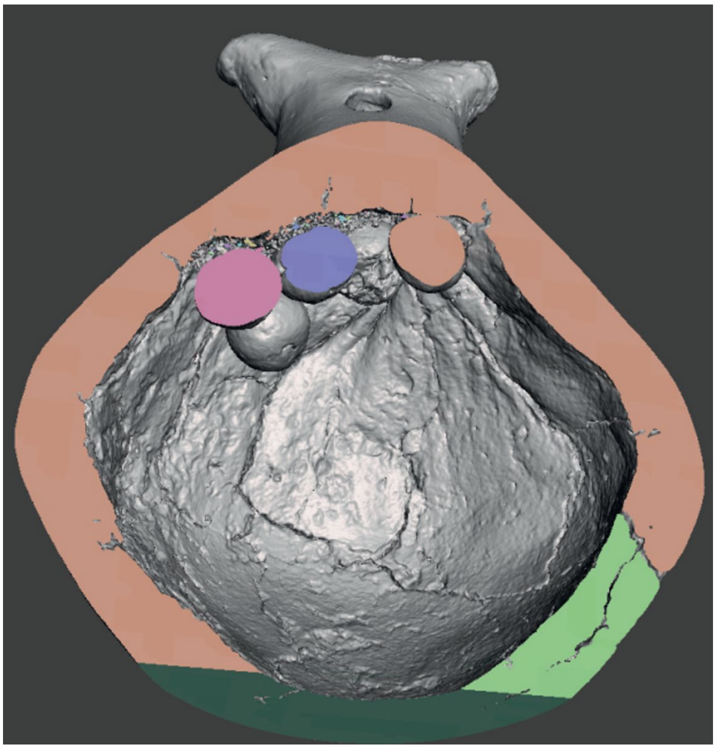

Figure 15: Rattle from Szadek. 3D tomographic imaging by NANOTOM S device at the AGH Laboratory of Micro and Nano Tomography in Kraków.

4 Numerical sound reconstruction

As has been shown earlier, the state of preservation of these artefacts is often unsatisfactory, and thus the original behavior of the discovered objects has been lost. One of the commonly practised methods is making a replica. In order for such a replica to fulfill its function, its creator must have very high manual qualifications. Moreover, such a copy requires recreating not only the shape but also the material and the technological process itself. Those factors are of equal importance because of the influence of technological processes on material parameters such as Young's modulus and density. Those parameters determine the value of sound speed in material (in this case ceramics) which determines values of *eigenfrequencies* (natural frequencies).[30]

The analyzed ceramic rattle from Szadek seemed undamaged, but after careful examination of the side surface, it turned out that it was cracked. A more detailed analysis showed that the crack was large enough to disqualify the acquired sound recordings. There was a need to describe the geometrical shape of the rattle with the real values of wall thicknesses, so X-ray tomography was performed to determine these values, as well as the state of preservation of this artefact (Figure 15).

[30] Each physical object is vibrating with a set of natural vibration shapes called also 'eigenmodes' or 'modes'. Those shapes are determined by object shape and dimensions (i.e. spring sinusoidal shapes with zero displacement at mounting points). Natural vibrations' shapes can be interpreted as standing waves, so the value of sound speed determines frequencies for each natural mode of vibrations (called 'eigenfrequencies') and therefore determines peaks of the sound spectrum of such objects.

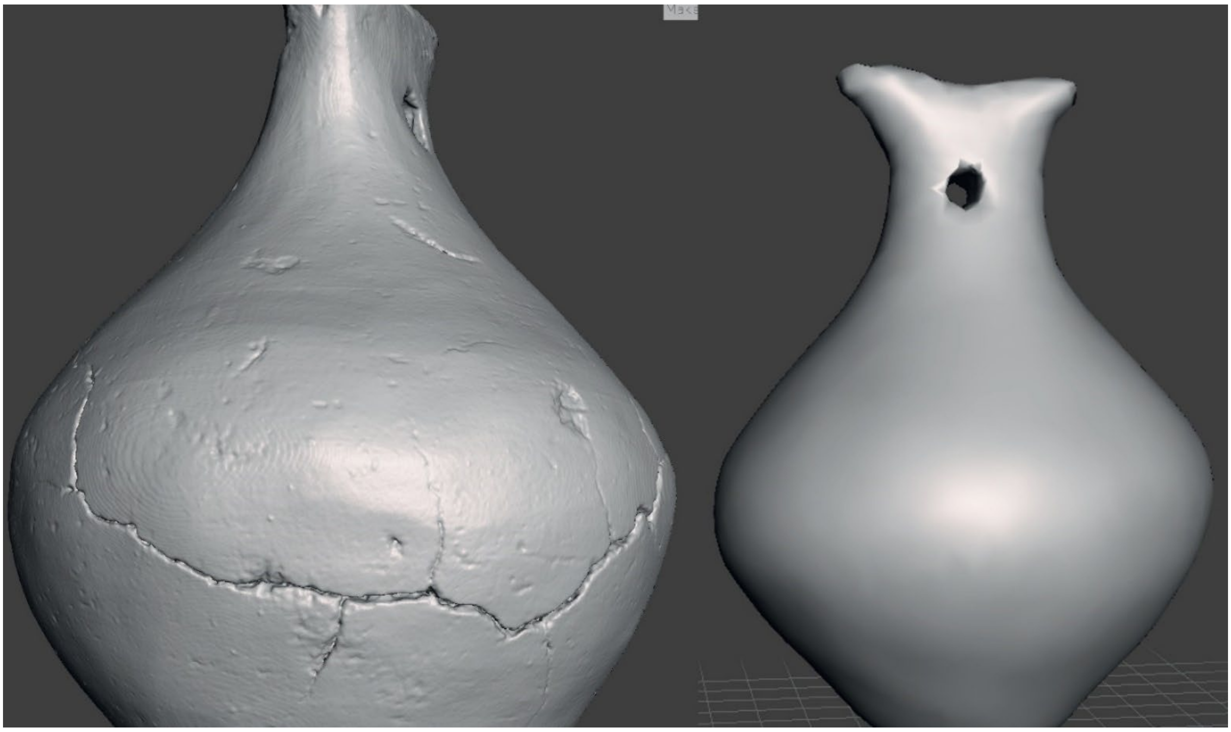

Figure 16: Scanned clay rattle surface before (with cracks) and after necessary corrections. Elaboration by I. Czajka.

The tomography was performed at the Laboratory of Micro and Nano Tomography of AGH University of Kraków. As a result of the tomography, 7,833,768,572 cubic cells with a size of 60 µm were obtained. Each of the cells contained information about the relative density of the material, which describes its ability to absorb X-rays. The obtained relative density values were in the range of 0 to 1. Based on the density value, it was possible to determine the boundaries of the body of the rattle. In this way, the initial grid describing the surface of the rattle with triangles was obtained. The average size of the triangle was about 0.1 mm, therefore this grid was very accurate, but consisted of more than 6.5 million faces and 3.3 million vertices. Since the material of the rattle is full of discontinuities (cracks), which were probably caused by post-deposit processes, it was necessary to make some adjustments. After these adjustments were introduced, the size of the mesh had 3571 vertices and 7138 triangular faces. Both the initial and corrected mesh can be compared visually in Figure 16.

After correcting the mesh, it was necessary to build a solid model, on which a computational mesh, mostly consisting of tetrahedral elements, was superimposed. After the meshing process, it was necessary to adopt coefficients describing the mechanical properties of the ceramic material of the rattle.

The values obtained from the analysis of the rattle from Zbrojewsko from the grave No. 1248 were adopted: Young's modulus 10.128 GPa, Poisson's ratio 0.25, density 1810.9 kg/m^3.[31] The numerical analysis consisted of solving the eigenproblem, called the modal analysis, which allows us to determine the set of natural frequencies and the shapes of natural vibrations corresponding to

31 Czajka 2021; Vojtko et al. 2011.

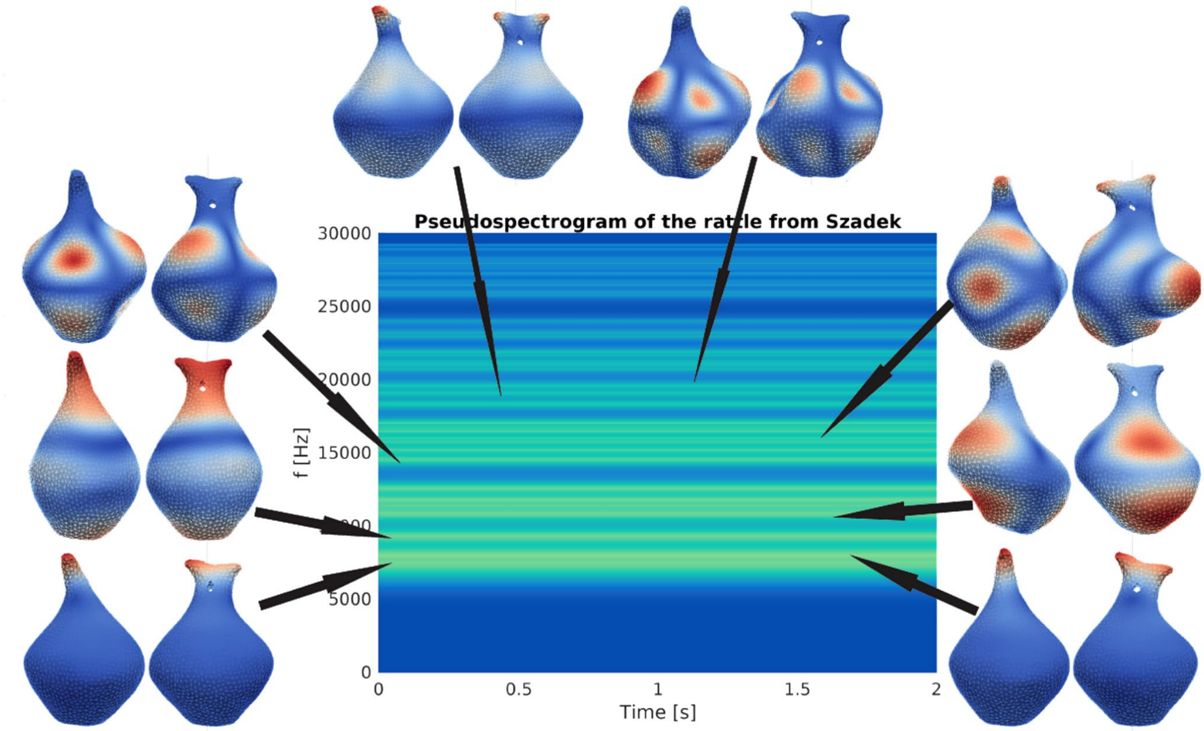

Figure 17: Sound pseudospectrogram of the rattle from Szadek. Elaboration by I. Czajka.

each of these frequencies.[32] Based on the determined frequencies of natural vibrations, the spectrum shown in Figure 17 was constructed, which allowed for the reconstruction of the rattle sound.[33]

The sound produced by the object comes from the vibrations of its surface, which compress air near the object's surface. *Eigenfrequencies* (natural frequencies) are related to the natural forms (shapes) of vibrations of an object (e.g. rattle). We can think of natural forms of vibrations as certain patterns of fundamental vibrations, and any movement of the surface of an object can be understood as an infinite sum of those fundamental vibrations with some amplitudes. Because each mechanical system can be thought of as a low-pass filter, we are able to sum up a finite amount of natural forms of vibrations to obtain any kind of vibrations. In reality, we can consider any vibration system to be a superposition of those natural forms of vibrations. As stated earlier the vibrations' shapes depend on the shape of the rattle. Therefore, we can consider the form of a set of natural vibrations to be a consequence of the internal void shape and wall thickness, or external shape and wall thickness, but we will be able to describe it in more detail after further investigation. Figure 17 shows eigenmodes for frequencies: 7,500 Hz, 8,010 Hz, 9,326 Hz, 10,871 Hz, 14,501 Hz, 15,997 Hz, 19,112 Hz, 19,655 Hz.

[32] Pluta 2019.
[33] Czyżewski 2001.

We achieved a very good qualitative agreement with the recorded spectrum. The numerical reconstruction of the sound confirmed the 'biconical' character of the rattle sound from Szadek. It can therefore be used to effectively reconstruct the sounds of defragmented artefacts. The main difficulty in carrying out such a reconstruction is the need to know the values of the parameters describing the mechanical properties of the material of the artefact, because these parameters, such as Young modulus, density and damping, depend not only on the chemical composition of the material, but also on admixtures, manufacturing technology, and process parameters. Straw or fibers, for example, can be used as admixtures. Process parameters are, for example, firing temperature, oxidising or reducing atmosphere, re-firing, and so on.

The second important piece of information researchers must have is the shape and dimensions of a rattle. The more precise the shape, the better the results that can be obtained. But, as we can see in Figure 17, the wavelength of the standing waves for each mode depends on the frequency. Higher frequencies have eigenmodes with shorter waves. And the wavelength determines the size of the shape imperfections, which affects modes. In other words, the natural shape of vibrations remains the same as long as the rattle shape modification is much smaller than wavelength. This feature allows for rattle model simplifications while still obtaining results with quite good agreement with the measurements.

5 Conclusion

The interdisciplinary study of ceramic rattles, exemplified by the rattle from Szadek, highlights the complex interplay between archaeology, acoustics, and material science in reconstructing the auditory characteristics of ancient artifacts. Despite the challenges posed by poor preservation, modern techniques such as reverse engineering and numerical sound reconstruction have proven invaluable in uncovering the acoustic properties of these artifacts. The diverse sound spectra of rattles, influenced by their internal structure rather than external morphology, underscore the importance of comprehensive acoustic analysis.

Our research has revealed that the rattle from Szadek, although visually well-preserved, exhibits significant internal damage that affects its sound production. This finding emphasizes the necessity of thorough non-invasive examinations, such as X-ray tomography, to accurately assess the condition and acoustic potential of archaeological finds. The reconstruction of the sound spectrum of the rattle was achieved through comparison with other similar objects and a hand-crafted reproduction imitating its original, undamaged shape.

The variability in the sound spectra of Lusatian rattles, from distinct amplified components to predominantly noise spectra, suggests a rich diversity in their use and cultural significance. The identification of sound types and their correlation with internal structures, rather than external forms, opens new avenues for understanding the functional and symbolic roles of these instruments in ancient societies.

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