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THE RATTLES FROM TELL EL-FARCHA
ACOUSTIC RESEARCH WITH THE USE OF NUMERICAL SOUND RECONSTRUCTION

Abstract: Vessel rattles were one of the first sound-producing tools made from clay. Throughout history, they were developed in many ancient cultures, convergently in many places around the world. To obtain a complete picture of the sounds produced by clay rattles, the short-time Fourier transform analysis is used. On top of that, to determine the full spectrum of their acoustical possibilities, numerical reconstruction of sound is done. The results provide us an opportunity to explore the soundscape of the past.

Keywords: ancient Egyptian rattles; archaeological clay rattles; music in ancient Egypt; ancient Egyptian instruments; acoustics; acoustic analysis; numerical sound reconstruction

Ancient Egyptian Clay Rattles

Clay rattles are one of the simplest and most common sounding tools. Even today, clay is a material willingly used to make sounding objects and simple musical instruments all over the world. It is plastic and easy to form. During firing, the clay acquires hardness and strength. Ceramics are insensitive to changes in temperature and humidity. In other words, clay has good dimensional stability. It is characterized by stiffness that enables making a sound. Under appropriate conditions, when a ceramic object is, for example, struck, it produces a sonorous sound with a metallic timbre. Depending on the size and shape of the object, it could be different pitches.

Sounding tools made of clay are common in almost every society, regardless of time or geography. The simplicity of the form and the almost unlimited availability of this material meant that their development was convergent in many ancient cultures that are distant from each other. The most popular are forms in which rattling objects are enclosed inside a vessel and strike against its walls and against each other (MIMO Consortium, 5). The examples are known, among others, from the early archaeological layers of Mesopotamia (Sachs 1989, 55), from Israel (Braun 2009, 19-20), Mesoamerica (Joyce 1999, 30), central Europe (Malinowski 1993, 19), as well as Greece, Rome (Jiménez Pasalados, García and Fernández 2014, 50), and of course ancient Egypt (Pl. 1: 1).

Rhythm was of big importance in ancient Egyptian music. A large amount of evidence comes from iconography, scenes where next to musicians playing melodic instruments (flute, oboe, harp or lute), other characters use various techniques of clapping hands, shaking the sistrum or beating the drums, as well as using clappers and finally rattles (Köpp-Junk 2018, 273-274). Moreover, many of the preserved instruments also belong to idiophones.

Ceramic vessel rattles were used since the earliest times in Egypt. All clay rattles that have survived to our times represent the handleless types. They take various shapes, both geometrized, with a relatively simple shape of the body whose longitudinal or transverse section is close to a geometric figure (Malinowski 1993, 5), as well as figural: zoomorphic, ornithomorphic and anthropomorphic. H. Hickmann also distinguished forms suited for hanging, with a hole in the upper part (Hickmann 1954, 116-117).

Throughout the history of civilization, various groups of instruments and sounding tools have varied in popularity that was rising or dropping over time (Tatoń 2013, 57-118). Some were native to ancient Egypt, such as the naos sistrum (Pawlicki 1974, 12) or arched harp (Manniche 1991, 25), others, such as lyre (Sachs 1989, 84) or angular harp (Manniche 1991, 37), clearly appeared due to foreign influences. Over time, evolutionary changes were taking place in their construction. This is also the case with ceramic rattles. They were present throughout all history of ancient Egypt, from the Predynastic to the Late Period (Pl. 1: 2), and across the whole country. Various types and shapes were popular in particular periods.

The oldest clay rattles in Egypt date from the Predynastic Period. At that time, Egypt's cultural development proceeded independently in Lower and Upper Egypt (Ciałowicz 1999, 46). The discoveries of ceramic rattles come from both of these areas and include geometrical handleless forms, for example two egg-shaped rattles from Merimde (Hickmann 1954, 117) and seven pear-shaped rattles with hanging holes from Mahasna (Ayrton and Loat 1911, 16).

Early dynastic rattles, apart from geometrical ones, e.g., from Hierakonpolis (Petrie Museum, UC15008), sometimes had a more complicated shape, close to the zoomorphic (Hickmann 1954, 117). The collection of rattles from Tell el-Farcha also comes from this period (Ciałowicz 2008, 204). Clay rattles disappear in the archaeological material starting from the Third Dynasty (Köpp-Junk 2021, 74). The Cairo Museum has a rattle discovered on the Giza Plateau, however, its dating is uncertain (Hickmann 1954, 17). This bird-rattle (CG 69716) is a geometrical one. The anatomical details are only suggested with painted black lines.

We come across well-dated rattles again in the Middle Kingdom. Trends in the development of zoomorphic shapes are clearly visible. They are marked by connecting a geometric body with an animal's head, as in the case of the rattle from the collection of the Petri Museum in London (UC30028) dating from the Twelfth Dynasty or another rattle dated more widely to the times of the Middle–early New Kingdom belonging to the Metropolitan Museum of Art in New York (32.8.9). The first glazed rattles also appeared at this time, for example, the hedgehog rattle in the Brooklyn Museum in New York (59.186) or a similar object from the Petrie Museum (UC45081).

In the New Kingdom, both geometric forms, represented, for example, by glazed ball rattles from the Petrie Museum (UC45072) or the Brooklyn Museum (36.125), and unglazed forms, referring to the predynastic for example bottle-shaped rattle from Shekh'Abd el-Qurnah (Hickmann 1954, 119), or a rattle from the Petrie Museum collection (UC59266), were popular. Finally, zoomorphic forms were frequent, with an excellent example of a cow rattle from the Metropolitan Museum of Art (10.176.89), perfectly reflecting anatomical details, as well as a tilapia-shaped rattle from the Brooklyn Museum (48.111) made with great attention to detail.

Greek and Roman influences in ancient Egypt did not diminish the presence of clay vessel rattles. We have examples that prove the popularity of all their shapes: two rattles from the Petrie Museum (UC71557 and UC65087) as well as the gourd rattle from the collection of British Museum in London (EA23323). Figurine rattles are represented by two hedgehogs: from the British Museum (EA74326) and the Ashmolean Museum in Oxford (AN1886.511; Thomas 2015, 31); pig-rattle (86.381); squatting naked pregnant woman-rattle with legs raised on each side, from the British Museum (E.86.1914); and a bird-rattle from the Petrie Museum (UC34972).

Despite their long existence, ancient Egyptian ceramic rattles were never associated with music at any time. They never appear in a musical context, neither in iconography nor in inscriptions or other sources (Köpp--Junk 2021, 76). The few scenes with vessel rattles are of a sacrificial or ritual nature and concern the wicker handle basket rattles (Hickmann 1954, 120). The primary function of any rattle is to make sounds. They were created in very purposeful form, sometimes complex and requiring fine craftsmanship skills to produce sound. Hence, it is justified to focus research on this aspect. The sound perspective approach requires acoustic research.

Spectral Analysis

Research was carried out on the replica of the rattle from[1] Ägyptisches Museum und Papyrussammlung in Berlin, catalog number: ÄMB 17548 (Pl. 1: 3, Ćwiek 2005, 46, Fig. 59), which is on deposit at the Archaeological Museum in Poznań. The original one was discovered at Shekh' Abd el-Qurnah and dated to the Eighteenth Dynasty. It is bottle-shaped with a rounded bottom and a spout. Acoustically, it represents an egg-shaped type (Tatoń 2020, 12). It has an analogy in the form of a prehistoric rattle from Sahel el-Baghlieh, also from the collection of Ägyptisches Museum und Papyrussammlung in Berlin (Sachs 1921, 27-28). It is made of red clay with decorative white circles painted on the body. In addition, the rounded bottom and the spout were painted white. Inside, there are a few tiny pellets that rattle when shaken. There are no holes in the body. The condition of the rattle is very good, however, due to the risk for this unique object, the study was conducted with a modern replica. It makes a bright metallic sound which was recorded and analyzed using the Short-Time Fourier Transform.

The sound was recorded in non-laboratory conditions at the Archaeological Museum in Poznań. The rattle was shaken in different ways: movements made in different directions, a series of quick shakes, and slower single shakes. The recording was made with a sampling rate of 96 kHz.

The obtained time-frequency, spectra were presented in a graphical form of the spectrogram (Pl. 2: 1). Usually, it takes the form of a two-dimensional

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[1] 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.

image, in which the horizontal axis represents time, the vertical axis – the frequency, and the amplitude of a specific frequency at a given moment – the intensity of each point, indicated by a color change in the graph. In this way, time dependencies between the frequencies become visible. This makes it possible to observe changes in the tonal structure of the signal. The amplitude can also be presented as a height value, which will make the graph three-dimensional (Pl. 2: 2), but in this form, it is more difficult to analyze and usually less readable.

The Fourier Transform decomposes the signal into sinusoidal components, thus allowing for precise determination of such features as the number of overtones, their pitch, and relative loudness (Szabatin 2007, 225). The enhancements of the component tones in certain ranges, shown as clearly lighter lines, are called formants. The frequency within a formant where it is maximized is called main (Drobner 1973, 38).

The sound spectrum of the rattle is heterogeneous, which is characteristic of idiophones of this type. It is a combination of noise with a continuous spectrum and an inharmonic multitone spectrum where the formants lines appear (Drobner 1973, 54).

The most important tone produced by a musical instrument is its fundamental tone. Most often it has the lowest frequency value of all the tones produced by the instrument. It appears first and disappears last. The fundamental tone specifies the pitch of the sound. The lowest formant on the spectrogram of the replica from Shekh'Abd el-Qurnah is ranging about 6400Hz, which corresponds to the sound G8. Overtones, affecting the timbre of the rattle sound, appear in 9600, 11700 and 12100Hz. Depending on the way the rattle is held and the movements that are made, another overtones appear: about 15000 and 20000 Hz and higher. It is over the human hearing range. When the rattle is held by the spout – the amplitude and envelope of the overtones change as well (Pl. 2: 3). New formant line appears about 8000 Hz (B8).

The rattle produces noise ranging up over 25kHz. Changing the recording parameters by increasing the frequency response of the microphone would probably reveal the higher frequencies in the ultrasonic range.

Numerical Sound Reconstruction

In the first stage of work on digital sound reconstruction, the method was verified on the basis of the recorded acoustic signal of the replica of the rattle from the Ägyptisches Museum und Papyrussammlung in Berlin. For this purpose, the available photographic documentation was used to develop a solid model of this rattle. The basic difficulties with building the model were related to the lack of information on the optical system of the camera and its position in relation to the rattle, which could introduce distortions related to projecting the image of the object onto the plane of the semiconductor transducer. The second very important problem was the lack of information on the wall thickness and shape of the rattle's interior, which introduced uncertainty to the obtained results.

The interior of the rattle was created by scaling the outer surface with minor modifications to the shaft. As a result, an almost constant wall thickness of the rattle is achieved. The thickness value was determined by conducting a computer experiment. The wall thickness was changed in the computer model and the value of the first natural frequency was tested. As a result of this preliminary study, it was found that an interior with dimensions reduced by 5% with respect to the dimensions of the outer surface, giving a wall thickness of about 2-2.5mm, corresponds to the proper value of the first natural frequency. The main dimensions of the resulting model are shown in Pl. 3: 1.

Based on the recordings, the target natural frequencies were determined. The obtained amplitude-frequency spectrum is shown in Pl. 3: 2. Pl. 3: 3 shows a photograph of the modeled rattle, the corresponding solid model, which shows the wall thicknesses, the assumed shape of the inner surface, and the superimposed finite element mesh. After arriving at the geometric model, a finite element mesh was superimposed on the tested object, the values of material coefficients were determined, and a modal analysis was carried out, which allowed to determine the natural frequency and the mode of natural vibrations (Suder-Dębska, Gołaś and Filipek 2018, 179-184).

The material density was 1819.9kg/m^3, the Young's modulus was 10128MPa, and the Poisson's ratio was 0.25. The adopted values of density, Poisson's ratio and Young's modulus were taken from the study on the rattle from the Zbrojewsko in Poland, grave 1248. After adopting the density, the mass of the resulting model was 60.5g.

Isoparametric elements with parabolic shape functions were used in the construction of the mesh. As no kinematic boundary conditions were imposed, the natural frequencies between 10Hz and 30kHz were taken into account.

The results of the modal analysis in the form of the determined frequency values are shown in Pl. 4: 1. The figure shows the frequencies in the form of horizontal lines in a pattern similar to a spectrogram (Alm and Walker 2002, 458). It is important to remember that not all natural frequencies produce an acoustic signal of the same intensity. Only those forms of vibrations that are perpendicular to the surface give strong stripes in the spectrograms of recordings. In contrast, forms where the vibrations are mainly torsional give almost no acoustic effects.

For this reason, it may be advisable to perform a coupled analysis to determine the effectiveness of sound radiation into the air surrounding the rattle. Unfortunately, such an analysis requires much higher computational resources and is subjected to considerable uncertainty in higher frequencies.

Since no coupled analysis has been performed, it is not possible to determine the value of the acoustic pressure amplitudes for individual frequencies, therefore the horizontal lines do not indicate the intensity of the sound, but only indicate the form of natural vibrations that is excited at a given frequency.

The free vibration forms of the analyzed rattle replica are very interesting. A few selected forms are presented in Pl. 4: 2. In order to be able to observe changes in the shape of the rattle, displacements of individual points were significantly enlarged.

The first five pictures relate to the first modes of natural vibrations corresponding to relatively low frequencies – below 10kHz. The last three correspond to the ultrasonic frequencies of 21, 23 and 27kHz, respectively. One can judge the length of the standing waves excited in the rattle material. The length of these waves translates into the frequency of a given mode of natural vibrations. Besides, the shorter the wave, the more difficult it is to excite it and the faster it fades away. For this reason, the highest frequencies tend to be the quietest.

Taking into account the purpose of the analysis, it can be concluded that the numerical analysis allows to determine the characteristic frequencies for vibrating objects, such as rattles. Even with a limited knowledge about the shape of the rattles, it is possible to obtain quite good frequency compliance with the recorded signal of the physical object. Thus, they can be used to reconstruct the sound of damaged rattles or objects known only from photographic documentation.

Spectral Analysis of the Tell el-Farcha Rattles Based on Numerical Sound Reconstruction

All the rattles from Tell el-Farcha are geometrized. Five of them are egg-shaped (Pl. 5: 1-5), one is spherical. They are stylistically similar, although they differ in the precision of the decoration. Their shape and ornaments may be identified as buds of water-lily (*Nymphaea caerulea*, Pommerening, Marinova and Hendrickx 2010, 22). Since they are not available for recording of their sound, the analysis will be based on a numerical experiment.

General Methodology

Of the six rattles found at Tell el-Farcha, two representative rattles were selected for the acoustic analysis: an egg-shaped rattle, previously described as rattle 4, and a spherical-shaped rattle.

Since the only available information on the details of the construction of the rattles came from the drawing and photo documentation, it was necessary to use reverse engineering techniques to build their geometric models.

The open-source software FreeCAD was used to this purpose. Based on the photos and drawings, shapes of objects were drawn in two perpendicular planes, and then 3D surfaces that were visually similar in shape to the images of analyzed rattles were created.

With one exception, the most problematic was determining the shape of the inside of the rattle because only with a spherical rattle, this information is available (Tatoń 2013, 67-68) while the discovered fragments of the further rattles suggest a different shape of the interior (Pl. 5: 6). In the case of the second rattle, the influence of the interior shape on the frequency distribution of natural vibrations was tested. The changes in frequencies resulting from the size of the rattle are also presented.

The natural frequencies were determined with the use of the open-source software Code_Aster, used to carry out analyses with the finite element method. The process of applying the mesh and the boundary conditions was carried out using the Salome open-source software.

The material coefficients were adopted similarly to the replica of the rattle from the Ägyptisches Museum und Papyrussammlung in Berlin, corresponding to the rattle dated to the Bronze Age from the Zbrojewsko Poland, grave 1248.

Analysis of Rattle 4

Based on the photographic and drawing documentation, an external surface was created that corresponded to the shape and dimensions of the real object, as shown in Pl. 5: 7.

As part of the research, the reconstructed outer surface of an Egyptian rattle marked for the purposes of this work as 4 was used.

The research consisted in changing the shape of the inner surface of the rattle. The shape of the internal surface was assumed as

- identical to the outer one and scaled to 90% of its size
- a sphere with a radius of 25mm, which makes the wall thickness approx. 3mm,
- a biconical shape with a maximum diameter of 50mm and a height of 60mm, which makes the wall thickness at its narrowest point approximately 3mm.

Besides, two additional tests were carried out, which allowed us to see the changes in the frequency distribution of natural vibrations with the changes in the wall thickness and the size of the rattle.

Change of the Wall Thickness

As part of the work, the influence of wall thickness on the spectrum of natural frequencies was tested. Since it was assumed that the inner surface will be simply the reduced outer surface, changes in wall thickness were obtained by changing the scaling factor for the dimensions of the inner surface of the rattle. The basic version had a thickness of 5% of the linear dimensions of the rattle. The scaling factor for it was 0.9. For the version with thinned walls, it was 0.92, i.e., the wall thickness was approx. 4% of the linear dimension. On the other hand, the model with thickened walls was scaled by the factor 0.88, which gives the model with walls of 6% of the linear dimension. Discretization was performed with parabolic isoparametric elements.

The results are presented graphically in Pl. 5: 8. There are visible shifts of the frequency groups when the wall thickness is changed. Unfortunately, it is not easy to find a simple function that drives the changes in the position of these groups as the wall thickness changes.

Change of the Size of the Rattle

Another study, carried out for the analyzed rattle number 4 from Tell el-Farcha, was to reduce the dimensions so that its height was 7.8cm.

The wall thickness was 5% of the linear dimension, which in this case is about 2mm. The obtained results are shown in Pl. 6: 1.

There is a visible shift of all frequencies towards the higher parts of the spectrum while preserving groups of close related frequencies.

Changes in the Shape of the Inner Surface

Three different shapes of the rattle's interior were adopted for the tests. These variants are shown in Pl. 6: 2. As can be seen, in the first case, the shape of the interior corresponds to the outer shape.

In the second case, the shape of the interior is a sphere with a diameter selected so that the wall thickness is similar to the first case. In the last case, the interior has a two-conical shape. The conducted analysis allowed to determine the values of the natural frequency of the rattle. The obtained results are shown in Pl. 6: 3.

Spherical Rattle

The other analyzed rattle was spherical. It shows some deviation from the spherical shape of the outer surface. The differences are approximately 1mm along the radius averaging 26.5mm. The inner surface appears to be spherical with a radius of 23.2mm, although the center of this sphere does not coincide with the center of the outer sphere. More accurate measurements using the least-squares method indicate an offset of approximately 0.72mm. It was assumed that such small differences should not be taken into account and the built geometric model consisted of two spheres delineating the outer and inner surfaces. In order to reflect the differences in the wall thickness, the eccentricity of the spheres was maintained. The results of the analysis are presented in Pl. 7: 1.

A Few Observations about the Accuracy of the Analysis

The results presented provide an additional insight into the way rattles produce sound. Nevertheless, these results are not free from uncertainty. Sources of possible errors appear at each stage of the analysis. Therefore, it is important to have as complete information about the tested object as possible.

The first and main source of errors is the mapping of the rattle surface. Since only single photos are available, what can only be defined is the position of several points and possibly the shape of the outline. In addition, the available photos have inherent distortions related to, among other things, perspective.

While small deviations in shape do not have to lead to significant errors in the results, changes in the radii of curvatures may significantly affect the stiffness of the walls.

The introduction of a partition mesh into finite elements also introduces errors, although they do not have to be as significant as those resulting from the shape mapping.

The most important source of errors will be the shape of the inside of the rattle. Even if it is known in general, as in the case of a spherical rattle, there is still uncertainty about the location of vital points, e.g., the center of the sphere.

Since it is relatively easy to determine the volume of the resulting models, then, given the density of the rattle's material, its mass can be determined. Therefore, it should be suggested that the documentation of this type of artifacts should also include information about the mass of finds after the maintenance process.

Tell el-Farcha Rattles Spectral Analysis

The numerical sound reconstruction is based on the natural vibration forms and does not include the noise produced by the tools. Noise is part of the spectrum of every vessel rattle. To see a complete spectrum of the rattles from Tell el-Farcha, all formants obtained as a result of the reconstruction should be imposed on the noise spectrum.

Looking at the fundamental tones, it can be said that the egg-shaped rattles are quite high-tuned. They are in the range of about 6000Hz (F#8). Depending on the actual inner shape, it can be located much higher, even around 9000Hz (C#9). The pitch of the base tone will also depend on the size of the rattle – a smaller rattle makes a higher tone.

A small difference in wall thickness will affect the number of component tones without significantly changing the fundamental tone.

All egg-shaped rattles will have overtones widely spaced within the audible range. Moreover, all of them will have ultrasonic formants which, as shown by comparative studies, is characteristic of egg-shaped forms (Gruszczyńska-Ziółkowska 2018, 121; Tatoń 2020, 18).

A spherical rattle will produce a sound much higher than an egg-shaped rattle. Its fundamental tone is around 1200Hz. The spectrum is completely different. Apart from the noise, it consists of only a few inharmonic components. They are spread throughout the spectrum, but only a few fall in the audible range. We can hear the sound of this rattle only partially.

A similar phenomenon occurs in the case of spectra of other spherical rattles (Pl. 7: 2).

Based on the findings of damaged examples at Tell el-Farcha, it can be assumed that the tested rattles contain little clay balls, making sound when shaken. Due to the building material used, as well as the frequency range of the overtones, this sound should have a metallic timber. The higher frequency of fundamental tone will increase this impression.

Conclusions

Despite being ones of the eldest sounding tools in Egypt, clay vessel rattles were not related to music. Their social function went beyond the accompaniment of singing or dancing. They often took the form of magical or protective objects: the hedgehog (Bartnik 2019, 130; Sherbiny and Bassir 2014, 186), tilapia (Kroeter 2009, 48) or the figurine of a naked, pregnant woman (Beer 2015, 340). The rattles of Tell el-Farcha are linked to the form of the water-lily, one of the greatest symbols of Egypt (Pommerening, Marinova and Hendrickx 2010, 22). All of this speaks for a more symbolic or ritual function of ceramic rattles. Of course, this function was performed not only by the form and shape but also, and perhaps even above all, by their timber: a characteristic sound, between noise and inharmonic tones. This sound, as it seems, has a perceptible pitch, but one that eludes our perception. It was an important component of the world of sounds of that time, long-lasting in the soundscape of ancient Egypt. Finally, it went silent thousands of years ago and can be known today thanks to numerical experiments (Le Conte *et al.* 2012, 162).

The method applied gave satisfactory results; it is possible to present the frequency structure by numerical experiments. The basic conclusion drawn at the stage of model preparation concerns the method of documenting archaeological finds. Drawings show the object in side view, as well as the front and bottom view. There is no reliable information about the shape of the solid in the plane passing through its axis and perpendicular to the side view. For this reason, the presented reconstruction is an approximation resulting from the assumption that in the second plane the rattle looks similar to the first. Therefore, this reconstruction cannot be considered a complete shape reconstruction. However, it can be assumed that it is as good as the reconstructions of objects that have survived in a fragmentary form and are supplemented with foreign material.

Another approximation is the use of material coefficients obtained on the basis of the Bronze Age rattle from the Zbrojewsko site from the grave 1248. Without additional research, it cannot be stated to what extent the calculations correspond to the behavior of the real object.

The conducted research shows the theoretically possible acoustic signal frequencies. Not all of them have to be present in the acoustic signal because the sound of the rattle is affected by the way it is held, which introduces an additional strong damping of vibrations at certain frequencies. Moreover, no research on the efficiency of sound radiation has been conducted for individual modes of natural vibrations, which also significantly influences the acoustic signal.

It should be kept in mind that a strong acoustic signal is only produced by those forms of natural vibrations in which the surface of the rattle vibrates perpendicularly to its surface. In those forms whose vibrations resemble the twisting of a rattle, the acoustic signal is very weak.

It should also be concluded that modern imaging technologies, such as X-ray tomography or x-rays, will allow the development of much better models of archaeological finds.

Today’s researchers often turn to experimental archeology. In one of such studies, led by E. Swift, replicas of Late Period Egyptian musical instruments in the Petrie Museum collection were created with the use of 3D scanning and printing technology (Swift *et al.* 2021, 5-14). These replicas also include three ceramic rattles. A similar approach, i.e., building replicas and recreating the sound of ancient instruments, was implemented by The European Music Archeology Project (EMAP). Furthermore, there is also the sound of a ceramic rattle to be considered. The acoustic analysis of the sound of rattles is a great complement to such studies. At the same time, the numerical sound reconstruction method, although it still requires fine tuning, is the next step in this direction.

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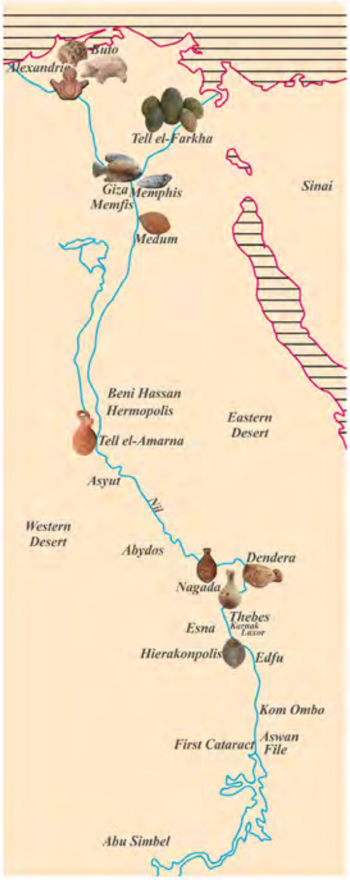

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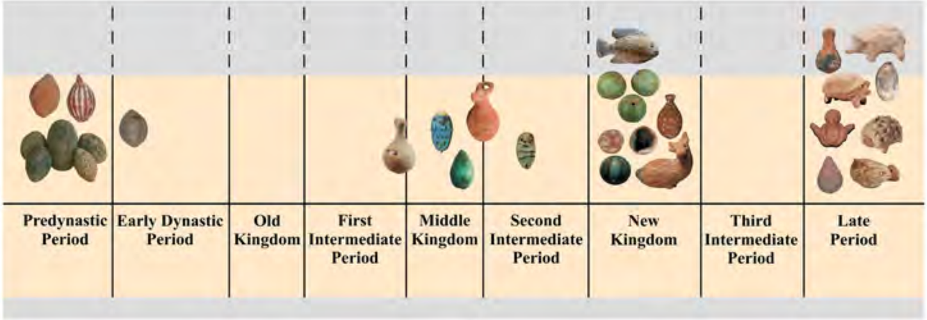

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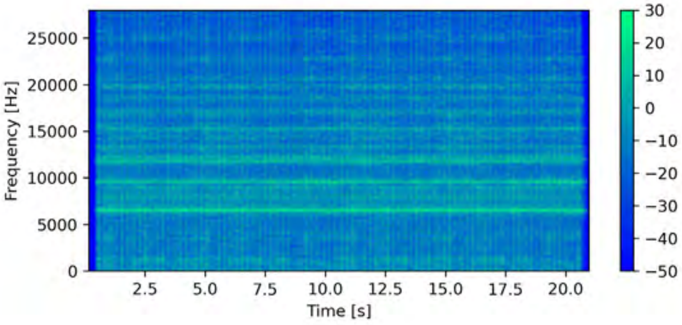
Pl. 1: 1 – Map of the discoveries of vessel clay rattles in ancient Egypt. Drawing by K. Tatoń Pl. 1: 2 – Chronology of the vessel clay rattles in ancient Egypt. Drawing by K. Tatoń Pl. 1: 3 – Rattle 17548 (up) and its copy (bottom), Ägyptisches Museum und Papyrussammlung in Berlin. Photos by M. Kuraszkiewicz (up), K. Tatoń (bottom).



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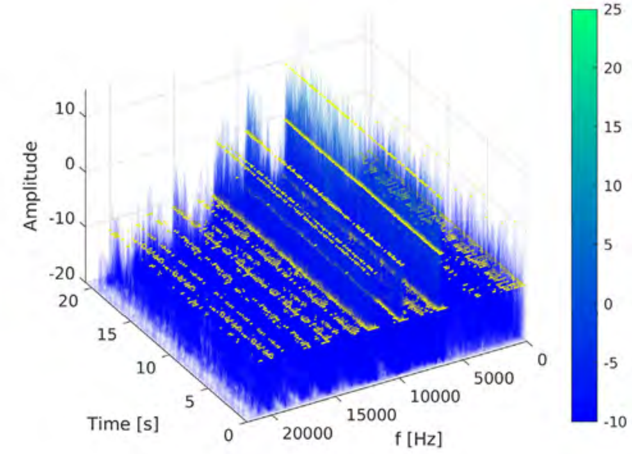

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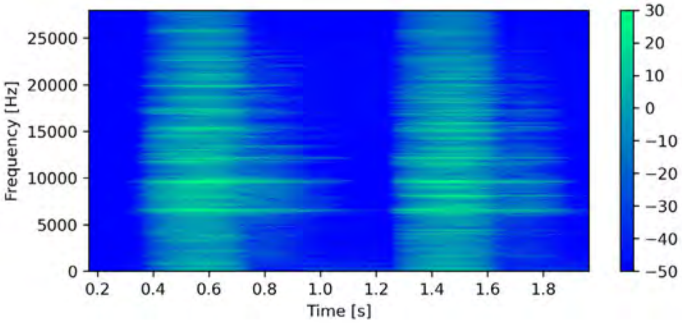

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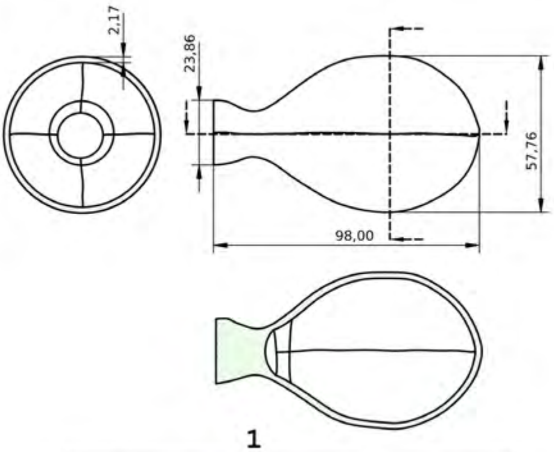
Pl. 2: 1 – Spectrogram of the replica of the rattle 17548, Ägyptisches Museum und Papyrussammlung in Berlin. Drawing by I. Czajka

Pl. 2: 2 – Spectrogram 3D of the replica of the rattle 17548, Ägyptisches Museum und Papyrussammlung in Berlin. Drawing by I. Czajka

Pl. 2: 3 – Different frequency amplification of the replica of the rattle 17548, Ägyptisches Museum und Papyrussammlung in Berlin. Drawing by I. Czajka



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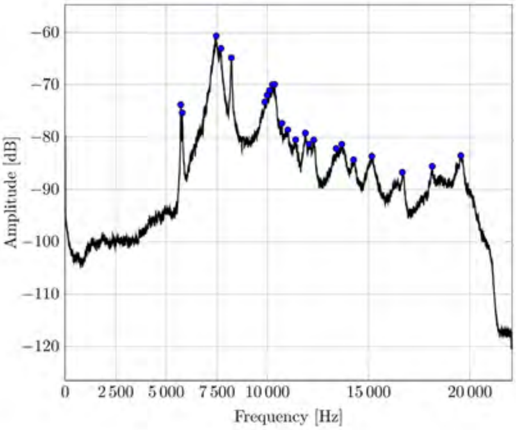

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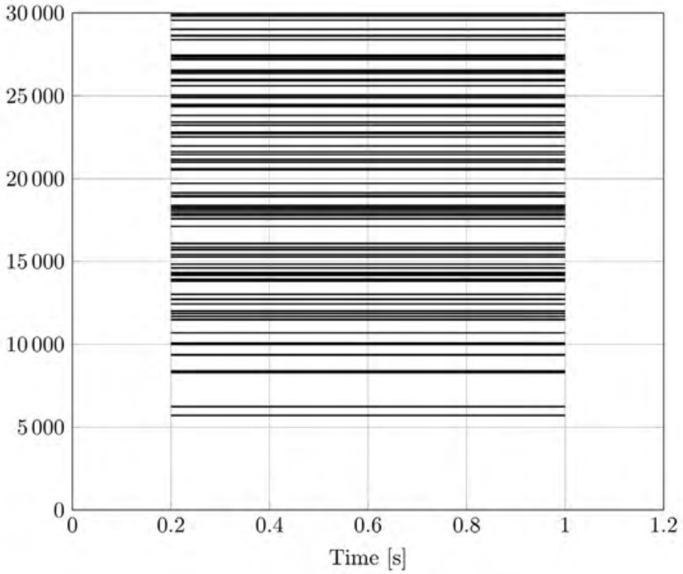
Pl. 3: 1 – Main dimensions of solid model of the rattle. Drawing by I. Czajka
Pl. 3: 2 – Spectrum of the recorded rattle’s sound. Drawing by I. Czajka
Pl. 3: 3 – Analysed object, solid model and computational mesh. Drawind by I. Czajka



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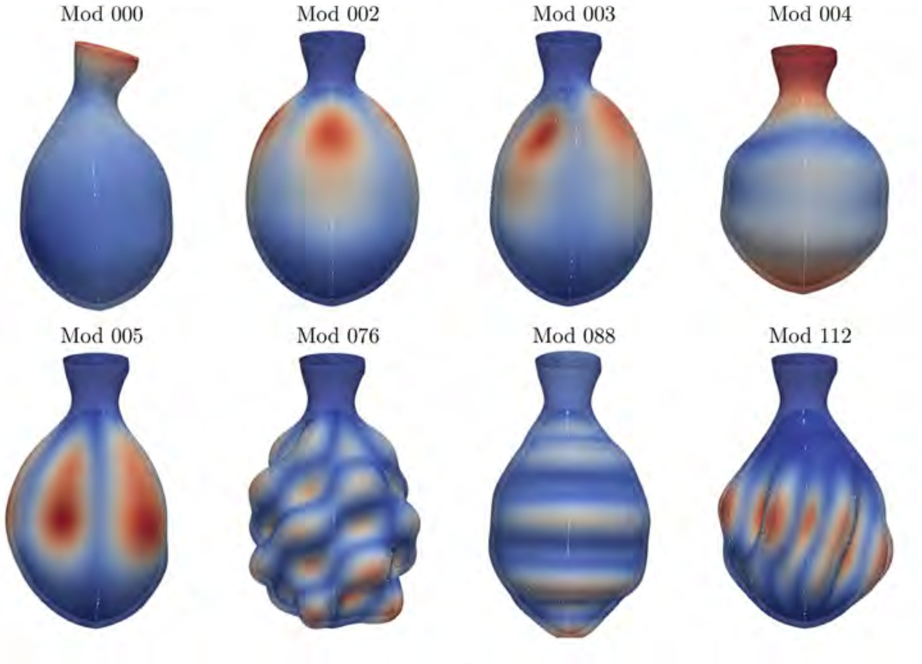

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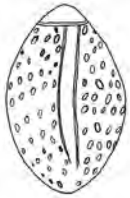
Pl. 4: 1 – Natural frequencies of the modelled clay rattle. Drawing by I. Czajka
Pl. 4: 2 – Forms of natural vibrations of the modelled clay rattle. Drawing by I. Czajka



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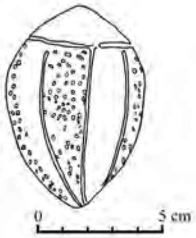

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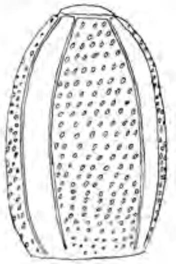

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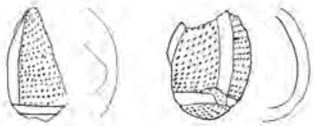

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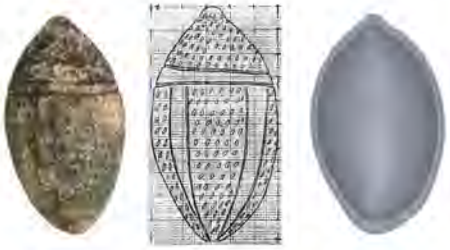

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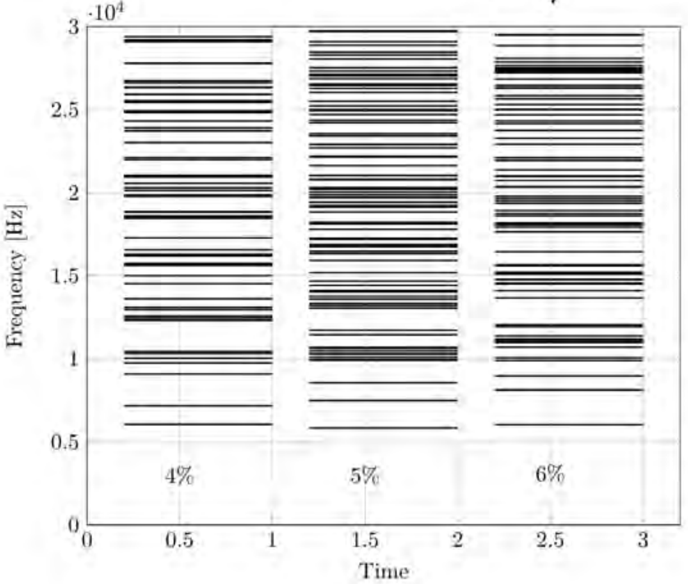

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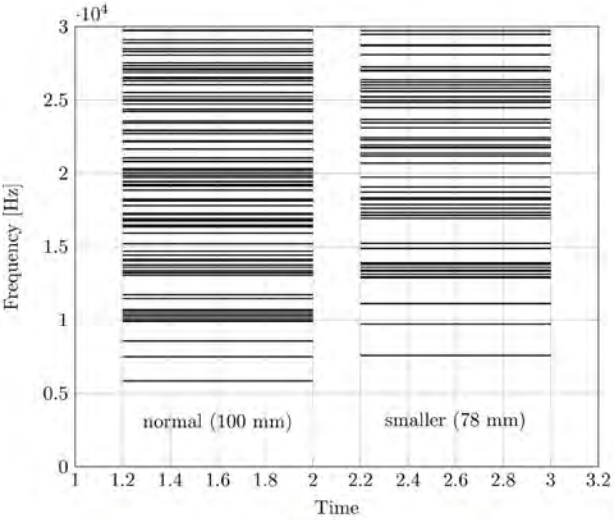
Pl. 5: 1-5 – The rattles from Tell el-Farkha. Drawing by A. Longa

Pl. 5: 6 – The fragments of rattles from Tell el-Farkha, different inner shape. Drawing by K. Tatoń

Pl. 5: 7 – Analyzed clay rattle from Tell el-Farkha, sketch and solid model. Drawing by I. Czajka, Photo by R. Słaboński, rattle drawing - archives of the expedition, A. Longa

Pl. 5: 8 – Eigenfrequency change as a function of wall thickness of the rattle. Drawing by I. Czajka



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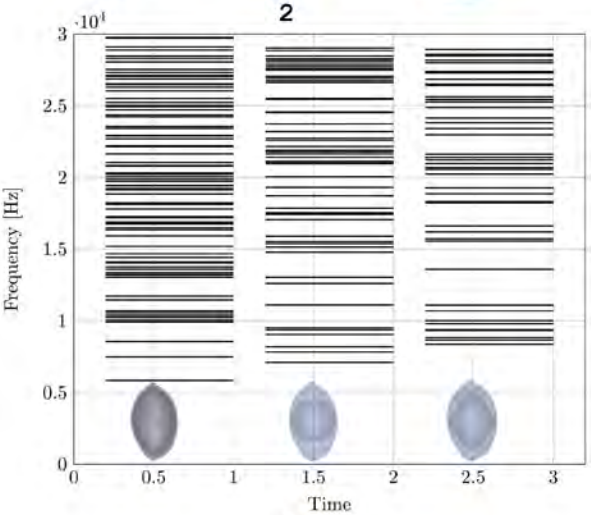

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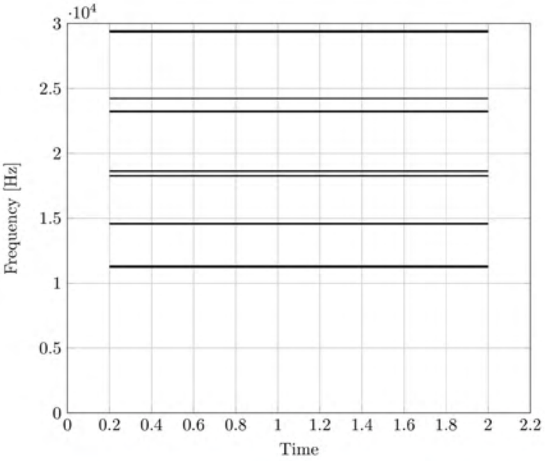
Pl. 6: 1 – The influence of the rattle size on natural frequency distribution. Drawing by I. Czajka

Pl. 6: 2 – Analyzed variants of a shape of the rattle's interior. Drawing by I. Czajka

Pl. 6: 3 – Natural frequency distribution for different variants of the inside rattle's shape. Drawing by I. Czajka



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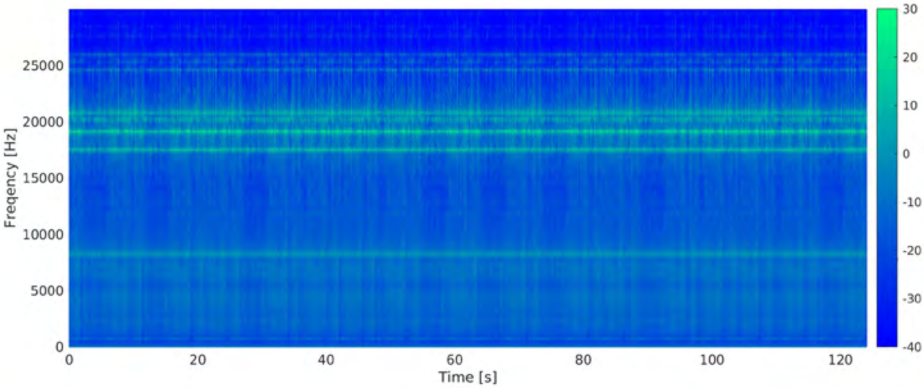

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Pl. 7: 1 – Spherical rattle natural frequencies. Drawing by I. Czajka
Pl. 7: 2 – Spectrogram of a copy of spherical rattle. Drawing by I. Czajka