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A STUDY ON ARISTOXENUS ACOUSTIC URNS

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Abstract
In chapters 4 and 5 of Vitruvius's 5th book titled "De Architectura", he analytically describes the practice of enhancing and enlivening the acoustics of Greek and Roman stone theaters using bronze resonating urns. These urns were based on the theories of the ancient Greek musician and philosopher Aristoxenus, whose theories are summarized and expanded upon in the same two chapters.
In spite of the above mentioned reliable archaeological source, and the fact that in at least several ancient Roman and Greek theaters special niches have been found that seem to match exactly with the niches described by Vitruvius for the placement of the bronze urns, no such urns have ever been found or excavated up to date.
On the same note, many scientists (acousticians) of our age, having examined Aristoxenus theory as described by Vitruvius and experimented with various urns and the Helmholtz effect that these produce, have come to the conclusion that the effect described, while being measurable, is barely audible at a small distance and definitely inadequate to produce the results described by Vitruvius.
All the above, has led many scientists to believe that the above mentioned chapters may not be exactly true in their descriptions, have many omissions and maybe mistakes or are just describing something that was only in Vitruvius mind.
In this paper the whole matter known in the circles of archaeoacoustics as "the Vitruvian secret" is reexamined, from both a theoretical and a practical (experimental) perspective, using modern tools offered us by acoustic science, and by highlighting certain details about the matter we are led to the conclusion that not only was Vitruvius absolutely correct in his assertions, but once the correct understanding of the phenomenon exists, it is "easily" repeatable in an experimental setting in both diffuse and open spaces.

Keywords: *Helmholtz resonator, ancient theatre, acoustic innovation, acoustic urns, Vitruvius, Aristoxenus.*

1. Introduction.

This work is concerned with the obvious question referring to the acoustic urns as they are described by Vitruvius in chapters 4 and 5 of his 5th book titled “De Architectura”, in which he explains and expands upon the theories of the ancient Greek musician and philosopher Aristoxenus.

The question that arises in a modern researcher who looks at all the information on the subject that has been accumulated by both modern and ancient sources could be simply stated as such: is Vitruvius exact in his descriptions (which means that there is a way to recreate the phenomenon in a modern setting) or is he very imaginative and poetic in his descriptions and not based in reality?

If one looks at the ancient sources besides Vitruvius such as Aristotle [1] and Hippasus [2] and also at the archaeological evidence such as niches found in ruins of ancient theatres matching the positions described by Vitruvius [3], one seems obliged to believe his description as being very exact and real. But the lack of any such object ever having being found and the scepticism of many modern scientists as to the practical implementation of such a scheme as described by him, may lead one to believe just the opposite.

2. Unravelling the enigma.

Taking the hypothesis that the archaeological evidence, as found both in other authors of antiquity and as evidence found in modern ruins of ancient theatres, was a proof of something like Vitruvius’s acoustic urns having existed in ancient times, and since his description was so realistic, it seemed a good idea to try and recreate the phenomenon as he described it, figuring from his descriptions what type of object to use, as we all know that such an object has yet to be found and may never be found.

Before beginning to experiment on our own, a thorough bibliographic search was done in order to update us on the advances and experiments other researchers have done on the same subject and a wealth of information was obtained which can be summarized in two categories: a) research on ancient sources and archaeological evidence and b) experiments by fellow acousticians with various types of Helmholtz resonators (pots, bottles, urns...).

The first category of research is definitely positive about the existence of something like what Vitruvius describes as having existed, but doesn’t know what these objects would look like or has any details on them other than Vitruvius’s own description [4][5][6][7], while in the second category we find experiments with various objects which all show an inability of the objects tested to produce such a phenomenon as the one described by Vitruvius and to give a definite answer and a solution to the dilemma as to the preciseness of his descriptions [8][9][10][11].

3. The first experiments.

After a brief set of measurements on various clay pots which confirmed the findings of the second category of researchers, a second reading of Vitruvius as well as a practical understanding of the effect that was taking place (through our own measurements) gave us the unique understanding that the reason our experiments, as well as the one’s of others, were not producing the expected results, was that only half of the phenomenon of what Vitruvius describes was being recreated.

In our practical understanding of the Helmholtz effect taking place inside any object with such a quality [12], the best example of which is a sphere with a hole in it, a transformation of energy is taking place around the resonant frequency of the sphere which is clearly shown in the following figure.

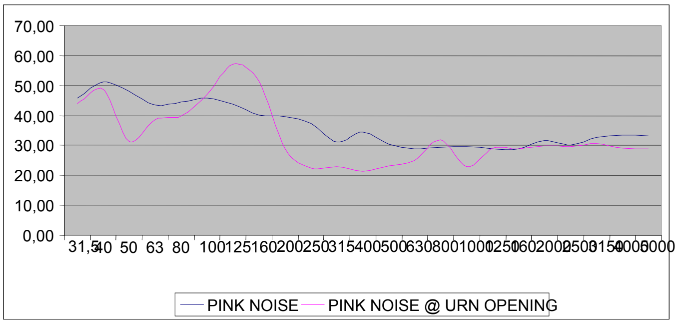

Figure 1. Measurement of a 1.5mm thick glass sphere of 30cm diameter with an 8cm opening, in the laboratory

This phenomenon is the same in any Helmholtz resonator irrespective of the material of the object since it is the result of the geometry that produces this effect, which, coupled to the space surrounding it with the efficiency offered by the neck of the object, results in a measurable but generally weak effect on the acoustics of the space, with a predominately absorbing effect at the specific frequency.

Still, the reason for this absorption and its frequency characteristic seems to be the tremendous amount of vibration transferred to the object (Helmholtz resonator) from the air at the resonant frequency. It can be gleamed from the graph above and it can be felt if the resonator is freestanding and light enough to afford movement to be felt. And if it is excited in a useful manner must be added, as the effect of various "noises" (pink, white, etc) as excitation signals is not the preferred method in this case, as we found out from our own measurements.

4. Making sense of the measurements (Rereading Vitruvius).

A careful examination of what is written by Vitruvius reveals that the objects of interest were in almost all cases made of metal (some cases of clay pots are mentioned, which might be in reality an inaccuracy on his part or a lack of further understanding on our part), and most importantly in his own words, "capable of producing sound of the desired notes when touched"![13].

Now, such an object would perform very differently than a heavy clay pot which is unable to resonate itself, as all the vibration absorbed by its hull is converted to heat, if it was also made into a shape which would give it the geometric characteristic of the Helmholtz resonator, such as a sphere with the appropriate diameter.

The resulting object would then transform inside it the energy from the surrounding space in a manner similar to that shown in the above figure, but in this case, the vibration transferred to the hull would be reemitted in the surrounding spaces amplified many times, according to the capability of the object to resonate at the specific frequency and the fine tuning of the two resonances, the one of the material and the geometric one, defined by the shape and size of the object.

5. A new experiment.

According to the above hypothesis, a new test object was experimented with, a

30cm diameter glass sphere with an 8cm opening and a thickness of 1.5mm. Using the geometric resonant frequency of the object as excitation signal (138 Hz) it was shown that even thought the glass was as a material not resonant in the same frequency as its shape defined, there was a very audible effect which varied greatly with the positioning of the object in the space, coupled to the ability of the object to resonate freely.

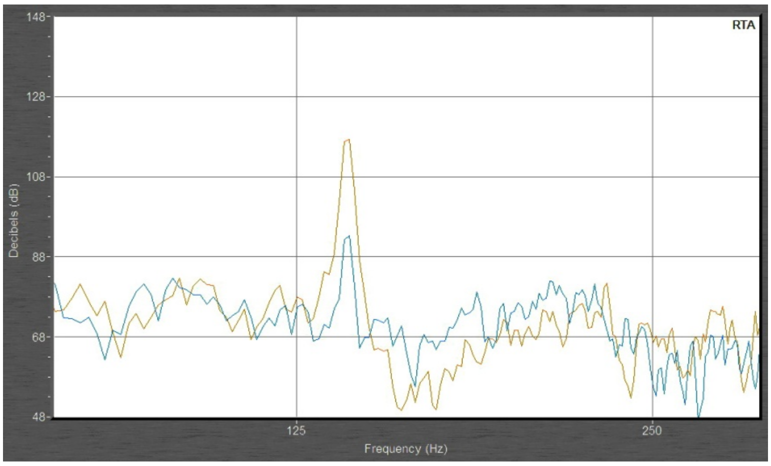

Figure 2. Measurement of the effect of the glass sphere. Mic. at two meters from the source and two meters from the sphere (yellow line with the sphere, blue only source)

A second test subject was afforded by our meagre research budget which was a copper 40cm diameter sphere with a 15.1cm opening and a thickness of 1.2mm, as shown in the following figure. The geometric resonance of this sphere is 116 Hz while the resonant frequency of the material was found to be 124 Hz.

Figure 3. Photograph of the new test subject, a copper sphere of 40cm diameter with a 15.1cm opening and a thickness of 1.2mm

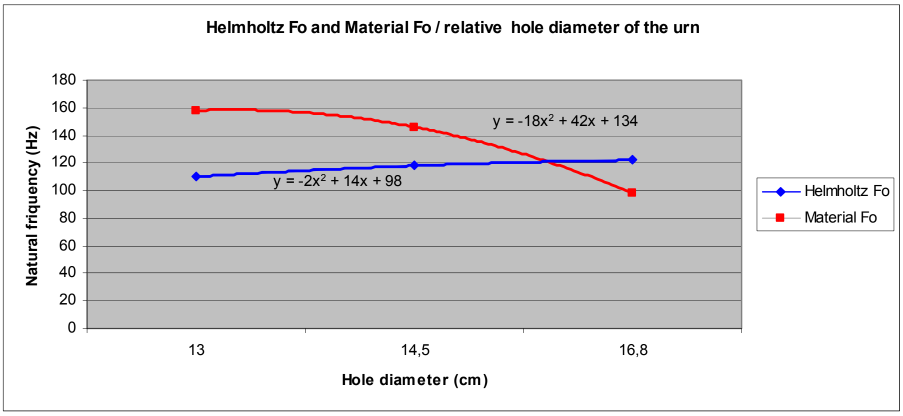

Figure 4. Graph of the calculation of the two resonances in the copper sphere

As the detailed and varied measurements of this object revealed, even though its geometric resonant frequency is audible when it is excited (following the description of Vitruvius), it has a very weak ability to act as a resonating urn and in very few positions, most probably due to the material and the construction method, but despite its unworthy retransmitting characteristics for which it was intended, it proved to have such an exceptional absorption characteristic in a semi open space setting, that an absorption map is presented in the following figure.

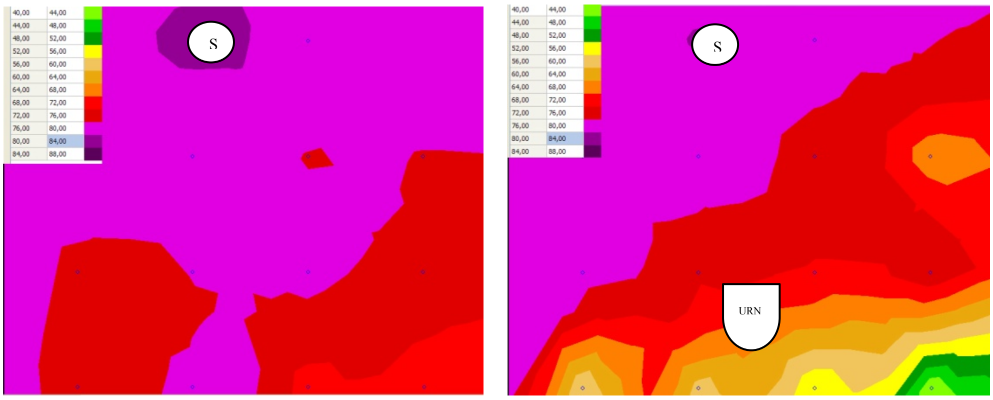

Figure 5. Absorption map of copper sphere in semi open field at its resonant frequency of 116 Hz. Left-source only, Right-source+sphere.

This effect, which is the predominant one measured for the majority of positions of the test object in a semi open space setting, is most probably the result of the mismatch of the resonances of the Helmholtz resonator (geometric) and the material resonance of our object. Also, the “softness” of the material and its inability to resonate uniformly (as one unity) as a mechanical structure in the basic “mode”, because of structural defects and non uniform thickness, played a definite role in its poor performance as a sounding vessel. But this absorption characteristic still shows that a simple Helmholtz resonator such as this, which can vibrate freely, can have real, measurable characteristics, which audibly affect the surrounding space. The other finding from the latest experiments was the realization that the function the object performs, whether it absorbs or even amplifies the source, is exclusively dependant on the positioning of the object in relation to both the source and both vertical and horizontal reflecting surfaces.

This is of course only logical as an average acoustician can deduce, since every space has its "modes" and of course semi open spaces such as theatres are no exception. The fact that Vitruvius refers to the diagram of Aristoxenus which was incorporated in his books, but has since been lost, seems only more proof that he is very exact in his descriptions. A reconstruction of the exact positioning of the urns according to the descriptions of Vitruvius as well as the notes that each urn was tuned to is shown below in the following figure [14].

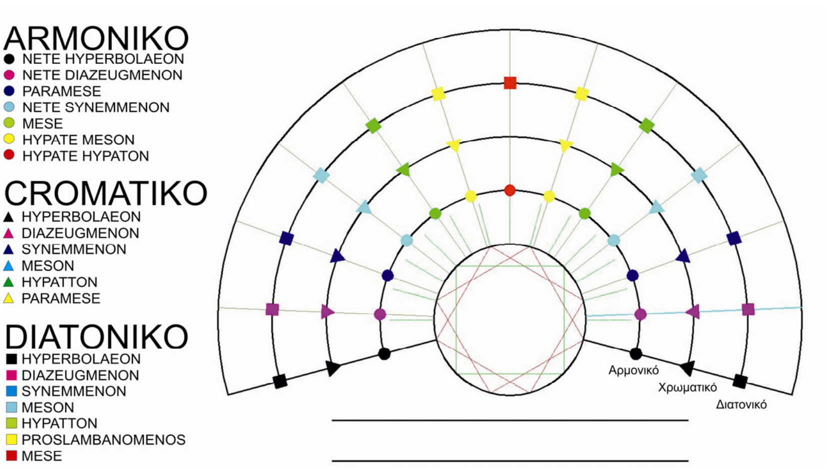

Figure 6. An array of acoustic urns designed for large theatres (deduced from the writings of Vitruvius)

6. A mathematical model for the double resonance hypothesis.

In order to investigate the phenomenon of the two resonances, a computer simulation was created using COMSOL Multiphysics 3.5 [15] a Finite Elements Method (F.E.M.) software. The model consisted of a 30cm diameter sphere with an 8 cm hole and a thickness of 2mm (the material used for the simulation shown below was aluminum), an omnidirectional source at 20 cm from the source and a receiver at 2 m from the object.

This system was enclosed in a bigger sphere with total absorption on the surface elements, simulating an open space. The interior of the big sphere was set as being air at 20^{o} C. The excitation signal of the source was discrete sine waves from 120 up to 190 Hz in 1 Hz steps. The time frame of observation was found to be very important, since the phenomenon does not show itself before some time has passed and the resonator starts transmitting (i.e. there is a "delay" in the operation of the two resonances).

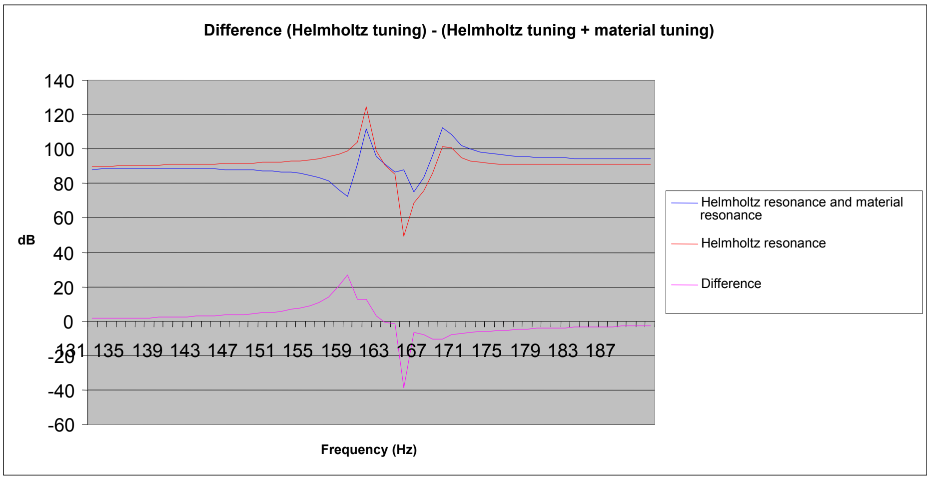

Figure 7. Helmholtz and material tuning (resonances)

Further similar models were investigated using glass and other materials as the material of the resonating sphere which showed similar and even more striking performances. The general conclusion that can be drawn from these models is that the material resonance of the object can have an amplifying effect of up to 18 dB at a 2 m distance, if the two aforementioned "resonances" coincide.

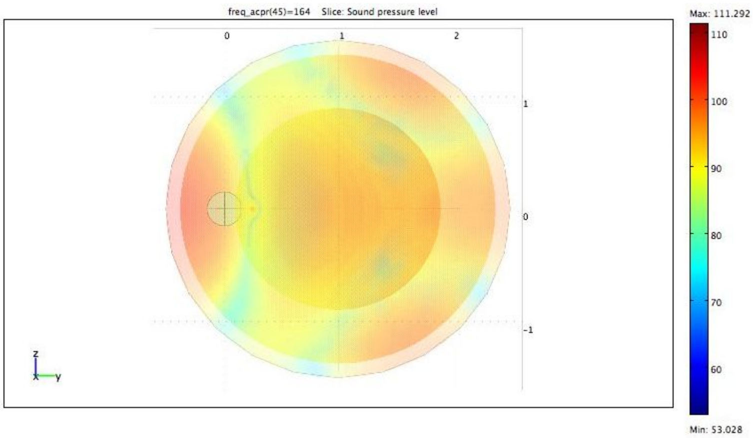

Figure 8. Simulation of the effect of the resonant vase in the environment of the model.

7. Conclusions.

As the results of the mathematical model reveal, it is very probable that a real life prototype can be constructed with these characteristics that could have an "amplification" effect on certain frequencies of up to 18 dB and maybe more, when placed in the correct position in the theatre.

Similar results were also seen with both the glass sphere and the copper sphere experiments, both of which are of such material that the second resonance effect was in effect but not entirely in tune, in which very audible results were obtained in certain settings. The reconstruction of a "working" acoustic urn by tuning the two resonances so the effect becomes profound and clearly audible is the next logical step in our investigation.

Still, since these objects are quite frequency specific and have to be designed such that they are in tune with each other and so transmit sound from one to the another, according to Vitruvius description, all on some ancient musical “genus”, the one which will be used for the performance at hand, there is still much to be done before one can clarify all the details involved. Some of these details such as the fine tuning of the urns in situ for each performance were clarified in our previous work [16].

Another detail that came up in our recent measurements is that it seems that the most probable position of the urns on the ground is at precise distances from the side and bottom reflectors, i.e. back tier and ground respectively, at fraction wavelength distances from their resonant frequency, as in these positions the effect seems to be maximized.

As often happens with real research, even though the first question we investigated seems to have being answered, many more questions have arisen such as: “Was the ancient theatrical mask some type of “microphone” designed to excite this primitive but truly working speaker – artificial reverberation system?”, “Were even bigger “tuned” urns being used in very low frequencies (inaudible but powerful) to further strengthen the amplification effect in positions designed to absorb the noise and transform it in amplification strength?” “Were different urns used in different positions only for their absorption characteristic in order to further improve the sound of the whole theater?”

To answer these and other questions more research is obviously needed, but the key thing to remember is that this ancient “sound system” was incepted by its ancient builders as a complicated system of tuned bronze urns located at precise positions that worked, together with the audience, orchestra and actors as a whole, a unity, with the sum much greater than its parts. It is our wish to one day hear with our own ears the sound of a fully equipped ancient theater with Vitruvian resonating urns enlivening and enriching the sound of a play, and to have given a helping hand in reaching this goal with this research we will truly have had our wish fulfilled.

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