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The Use of Resonators in Ancient Greek Theatres

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Summary

The ancient theatre of Lyttus in Crete (Candia) was described by the traveller Onorio Belli (1580) as been constructed according to the rules described by Vitruvius, presented in the V book of "Architectura". As Onorio Belli informs us, the theatre contained three rows of 13 acoustic vases in each, known also as "echea". According to Vitruvius, "echea", which are actually Helmholtz resonators, were placed in ancient Greek and Roman theatres in order to improve their acoustic performance. A computer simulation model of Lyttus' theatre was designed in order to study the effect of the resonators, as acoustic elements on the most important acoustic indices and also to compare its acoustic behaviour to Epidaurus theatre. Based on a plan of the theatre sketched by Onorio Belli, a CAD model with 39 acoustic vases was designed. A computer simulation program showed that the resonators do not amplify the sound but they have a strong effect on the Centre Time and LEF indices.

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1. Introduction

The ancient Greek and Roman theatres are among the most important monuments of cultural heritage in the Mediterranean countries. Most of them were constructed with highly reflecting materials, such as stone and marble. Beyond the purely architectural aspects, it is like that some items were possibly used to modify their acoustics, such as the actors' masks and the sounding vessels. Regarding the vessels, the Roman architect-engineer Marcus Vitruvius Pollio, who lived around 50 B.C., described the construction technology of his age in his work titled "Ten Books on Architecture" [1].

Vitruvius addressed the vessels, using the Greek word "echea" ($\eta\chi\varepsilon\iota\alpha$), which in Greek means sounders.

Vitruvius in Chapter V of the book V mentions that "...but when the theatres are build of solid materials like masonry, stone, or marble, which cannot be resonant, then the principles of the echea must be applied…". Some acousticians, Knudsen for example [2], believed that Vitruvius' vessels, which actually are Helmholtz resonators, acted as sound absorbers. Others believed that they were used for voice reinforcement [3]. Vitruvius described the room resonant properties and installation of these vessels, although it is not clear whether these were used for sound amplification or sound quality improvement [2, 3, 4, 5, 6]. Another aspect is that the vases were used in order to generate an artificial reverberation in the theatres. To resolve this issue, a study of Lyttus' theatre is performed here, given that there is evidence [7] that this theatre employed such vessels.

Lyttus, was one of the most important cities of ancient Crete, and was located at the eastern side of Knossos. Polybius depicts it as the oldest Doric town of the island. It is one of the seven Cretan cities mentioned in the Homeric epics, the Iliad and Odyssey since Lyttus participated in the Trojan war. The largest theatre in Crete was the theatre of Lyttus. The ruins were visible until 1583, when the Venetian traveller Onorio Belli was captured there. As time was passing by, the theatre was covered by dust and today the exact location is unknown. The theatre of Lyttus is most likely the theatre that Vitruvius describes in his writings. Onorio Belli, travelling the Aegean, listed the species of the plants as well as the Roman and Greek theatres of Crete. In his manuscript "History of Candia" describes in detail the construction of the theatre of Lyttus [7].

According to the description of Onorio Belli "*…there were three rows of bronze vases (echea) in this theatre, almost all the cells for which are still visible…*" [7]. The plan of the theatre, recorded by Onorio Belli, shows the three rows with 13 vases in each [7]. This description agrees well to the one by Vitruvius'. In his Book V Chapter V, he describes the positions of the vases in detail: "*…The arrangement of these vessels, with reference to the situations in which they should be placed, may be described as following: If the theatre is of no great size, mark out a horizontal range halfway up and construct thirteen arched niches with twelve equal spaces between them, so that… But if the theatre be rather large, let its height be divided into four parts, so that three horizontal ranges of niches*

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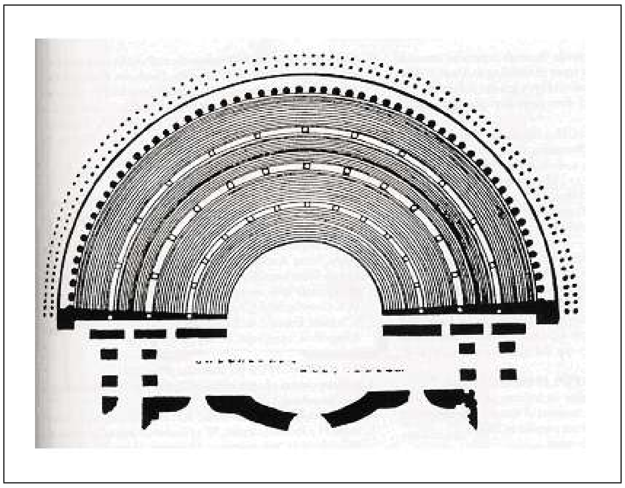

Figure 1. Plan of the theatre of Lyttus, according to Onorio Belli [7]. In the plan there are visible four sections of the theatre with thirteen vases in each.

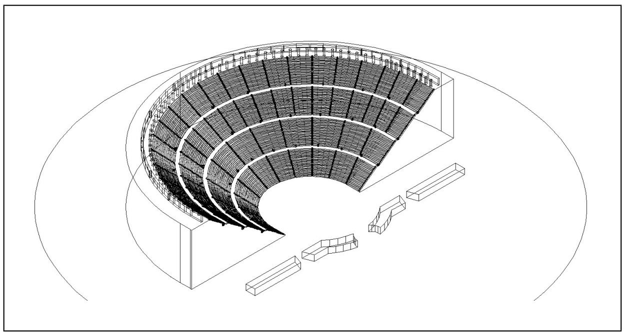

Figure 2. CAD model of the theatre of Lyttus.

may be marked out and constructed: one for the enharmonic, another for the chromatic, and the third for the diatonic system..." [1].

In Figure 1, a plan of Lyttus' theatre is presented according to the writings of Onorio Belli. This figure was used here in order to implement a 3-dimensional CAD model, as shown in Figure 2. Although it seems that the theatre of Lyttus was a Roman one, in absence of any information regarding the construction details of the back wall of the stage (as for example its height), it was not simulated.

2. Model of the theatre and resonators

Considering the available space at the points where the cavities-resonators were located, according to Belli's plan, and in absence of any other information, it was assumed, for the cavities and resonators, the following geometrical dimensions:

Cavity opening: 450 × 300 mm, cavity depth: 885 mm, resonator open area diameter 170 mm, resonator neck length: 20 mm, resonator diameter 215 mm. These dimensions suggest for the resonator, a resonant frequency of approximately 273 Hz. The accurate value of the resonant frequency was obtained using the FEM method.

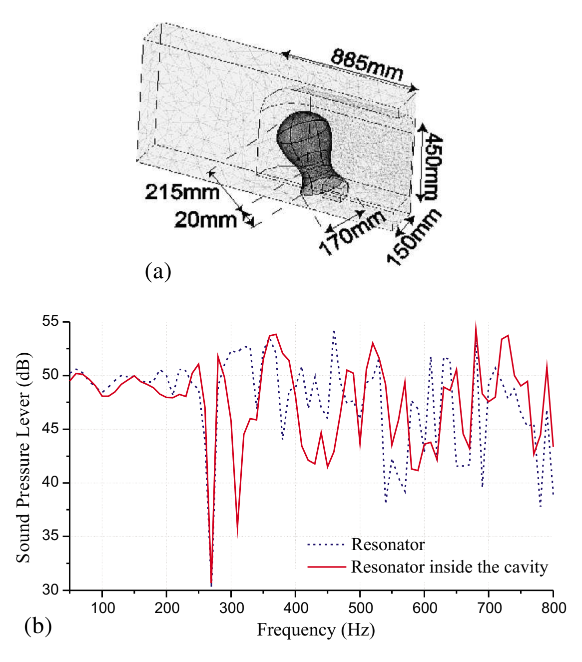

Figure 3. (a) FEM structure of the cavity - resonator coupled system. (b) Frequency response of the system (solid line), compared with the frequency response of the resonator alone (doted line).

The combined performance of the resonator–cavity system was studied using the FEM method [8] and Figure 3a shows the mesh of this FEM model. In this image, the cavity is not fully projected but cut in the middle, in order for the vessel to be visible. Figure 3b shows the frequency response of the cavity–resonator coupling system under a broadband noise excitation (20–800 Hz), in a receiver point located on the axis of the resonator, 1 meter away from the opening of the cavity. Observing the frequency response of the cavity–resonator system (red solid line line), there is evidence two main of resonant frequencies, one at 270 Hz and another at 310 Hz. Taking into account the equation (A1), with vessel (resonator) and cavity geometry, as shown in Figure 3a, it is concluded that the lower frequency (270 Hz) corresponds to the resonant frequency of the resonator and the second one (310 Hz) to the cavity. So the main effect of the cavity–resonator system appears in the 250 Hz octave band, with the quality factor of the resonator being $Q_A = 0.76$. Clearly from the gray line corresponding to the response of the resonator alone, one can see that the resonator attenuates mainly its resonance frequency, although some minor effects in other frequencies can be observed as well.

For the computer simulation of the theatre, a commercial software used, based on the ray tracing method [9]. This software has a limitation, regarding the number of surfaces that can handle (5000 surfaces) [9]. To overcome this difficulty as well as incorporate the Helmholtz resonators' effect on this software, it has been here assumed that each resonator behaves like a piston source, placed on a baffle [10]. The area of each baffle was designed to have the same absorption area as the absorption cross section of the resonator element, given by the equation (A2) in the appendix.

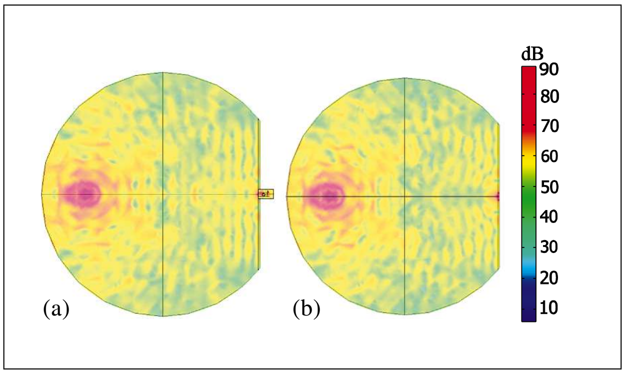

Figure 4. Output of the FEM models at the resonant frequency (270 Hz) of the resonator. (a) Calculated isosurface plot of the cavity–resonator coupled system. (b) Calculated isosurface plot of the equivalent source.

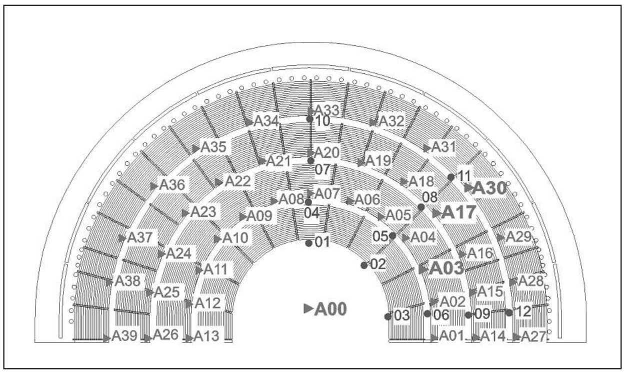

Figure 5. Plan of the theatre projecting the vases (▷) and the receivers' positions (●).

To confirm this hypothesis, the performance of a resonator, placed on an infinite flat surface made of stone, and a source with the baffle, placed on the same surface, were compared, using the FEM [8]. Figure 4 shows the results of this simulation in the form of isosurface plots. As one can see from this figure, the performance of the two models is quite similar.

The intensity of the re-emitted sound of each resonator was determined by the equation (A4) where I is the intensity of the incident sound emitted from the simulated source located in the stage (A00 in Figure 5), employing the above software [8].

The CAD drawing of Lyttus theatre was transferred, to the above acoustic simulation software, reaching the limiting number of surfaces that the software can handle efficiently. We assumed that the theatre was made from stone, a common material for the greater area, where the theatre was located. The absorption coefficient used in simulation for the 250 Hz octave band was 0.05. The absorption coefficients for the other frequencies were from 0.05 (for the low frequency region) to 0.2 for the higher frequencies.

An Omni-directional sound source (point A00 in Figure 5) was placed in the centre of the orchestra, emitting a pink noise broad band spectrum at a level of 94 dB for the 250 Hz octave band. 12 Receivers were placed at positions spread around the whole theatre koilon as shown in Figure 5 (noted by the corresponding numbers).

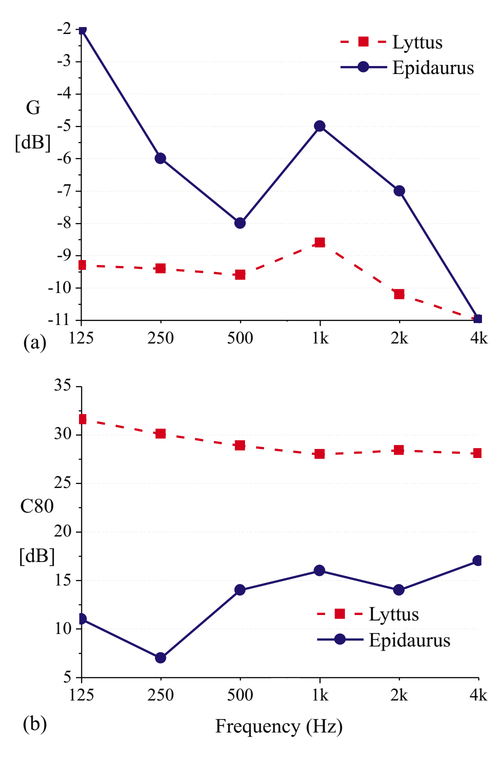

Figure 6. Comparison of the simulated results for the theatre of Lyttus with measurements of the theatre of Epidaurus performed by Psaras *et al.* [11]. (a) strength G vs frequency (b) clarity C80 vs frequency.

To study the effect of the resonators, 39 resonators (represented by their equivalent system of source- absorbing area as was previously described) were also employed at positions marked with Axx, where xx corresponds to the resonator number. Note that for this simulation the limit of the number of surfaces that the software can handle was reached. Furthermore, each resonator was studied in isolation with respect to the distance from it, in order to avoid any potential problems due to arbitrary superposition of narrow band correlated resonant sources.

Two models were simulated. The first corresponded to the theatre without resonators and the second one with the resonators placed in the positions, shown in Figure 5.

3. Results and discussion

3.1. Comparing Lyttus' without resonators to Epidaurus' theatre acoustics

Initially, the acoustic performance of the simulated Lyttus theatre was assessed by a comparison to the measured results given by Psaras *et al.* [11] for the theatre of Epidaurus.

From this comparison the theatre of Lyttus' acoustic behaviour is quite similar to the acoustics of the theatre of Epidaurus. From Figure 6a, the calculated source strength

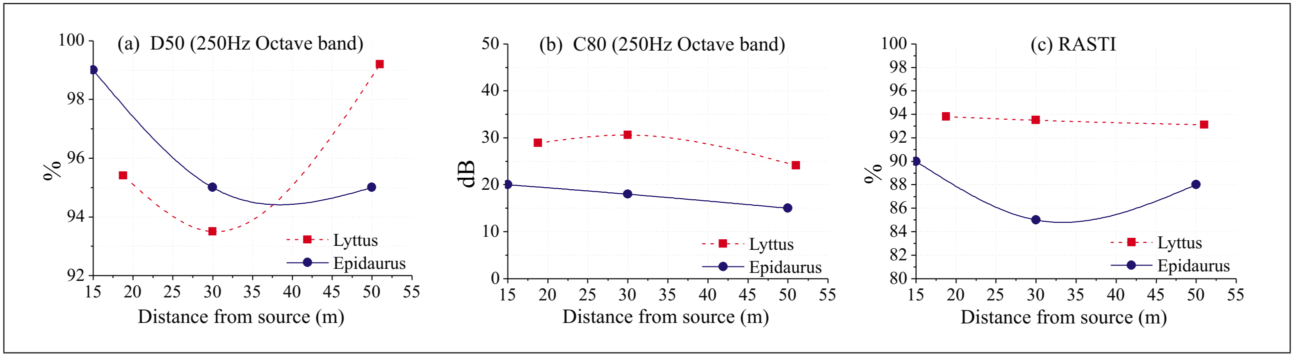

Figure 7. Comparison of simulated results of the theatre of Lyttus with the corresponding of the theatre of Epidaurus performed by Vassilantonopoulos *et al.* for (a) D50, (b) C80 and (c) RASTI. The D50 and C80 values correspond to the 250 Hz octave band.

G and clarity C80 of the measurements of Psaras *et al.* of the theatre of Epidaurus [12] and the theatre of Lyttus (simulated model without resonators) are presented. It is clear from Figure 6a that the calculated strength (G) of the theatre of Lyttus is lower than for the theatre of Epidaurus, although this difference varies with frequency range. At 125 Hz octave band, this difference is 7 dB but for the 4 kHz octave band, this is 0 dB. The values of C80, for all frequency bands, are greater for the theatre of Lyttus (Figure 6b).

Figure 7 shows the simulation results for the theatre of Lyttus (without resonators) compared to the simulation results of the theatre of Epidaurus as was performed by Vassilantonopoulos *et al.* [12], for different receiver positions. As one can see in Figure 7b and 7c, the Clarity (C80) and the RASTI parameters have lower values for Epidaurus' theatre for the different positions. This fact allows us to assume that the late relative energy in the impulse response, is greater in the theatre of Epidaurus and rather is an indication of a longer "reverberation". The D50 parameter, as can be seen in Figure 7a, is only lower for Lyttus for long distances from the source. Hence, it is assumed that for these distances, the tail of the impulse response is shorter than the corresponding one of the theatre of Epidaurus.

3.2. The effect of resonators on the theatre acoustics

To study the effect of resonators on the acoustical performance of the theatre of Lyttus, two simulations of the theatre were performed: one with the presence of resonators, and the other without them. The theatre was assumed to be empty of audience in both cases.

Figures 8 to 10 show the effect of the source (located in A00, see Figure 5) at various points, as a function of the distance from the main source (solid line), as well as the effect of the closest resonator (dashed line), for the 250 Hz octave band.

As can be observed in Figure 8, the main effect of the resonators is on the Centre Time parameter, which describes the centre of gravity of the squared impulse response. The Centre Time (T_s) is usually used to describe the balance between early and late sound. This is an indication of the ïreverberation time" of the open space theatres. In this figure, the Centre Time being calculated at various points of the theatre, as a function of the delay time, from the source A00 (main source at the stage), from a single resonator (source), placed at low (A03), middle (A17) and upper (A30) seat positions. For all positions the centre time is greater near the resonators and is decreasing when moving away from them. Note that without the presence of the resonators, the centre time remains almost constant (solid line). Thus, the resonators appear to increase the Centre Time for positions close to them in the theatre, and this increase is stronger for their near field area.

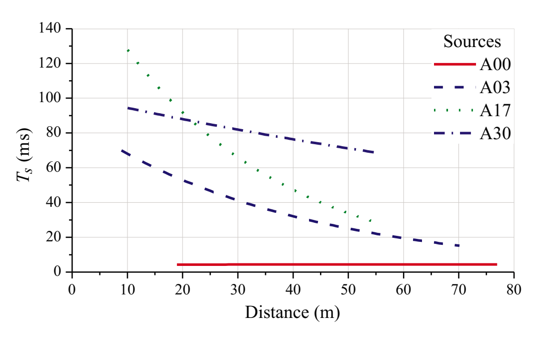

Figure 8. Centre Time (T_s) regression lines for the 250 Hz octave band as function of distance from the main or secondary source. The source A00 corresponds to the main sources placed at the centre of the stage and A03, A17 and A30, correspond to the secondary sources as shown in Figure 5.

In this figure, it is observed that, the Centre Time, corresponding to the emission from the resonators, is particularly high. Taking into account that the resonator appears to have a near field effect, it is reasonable to assume that this is a consequence of the presence of resonators.

The overall effect of resonators on the sound amplification was found to be minimal. Figure 9 compares the sound pressure level from the main source A00 with that of source A03 for the 250 Hz octave band. As one can see from this figure the produced sound level from the resonators is significantly lower (by approx. 30dB) than the one from the main source to be audible.

However, some effects were observed for the LEF index. The LEF index, which describes the early component of the lateral sound energy, compared with the direct sound

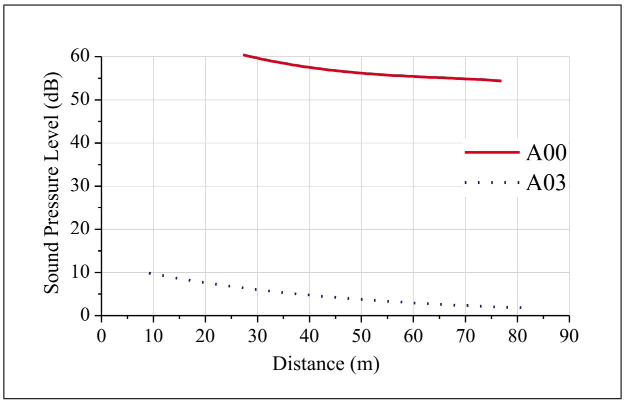

Figure 9. Comparison of the produced sound pressure level from main source (source A00 solid line) and from the secondary one (resonator A03, dotted line).

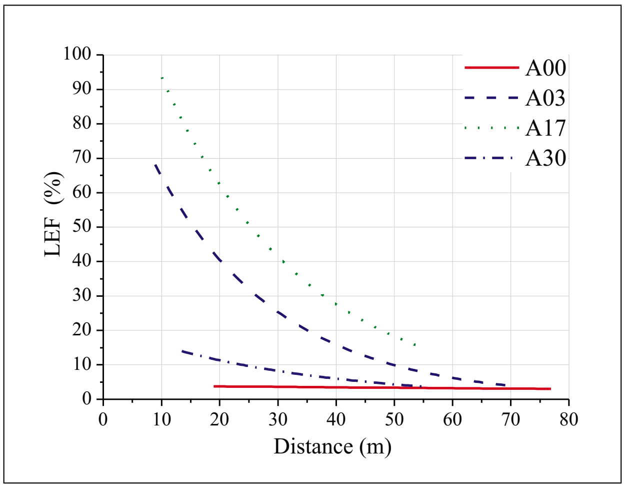

Figure 10. Effect of main source A00 and of resonators A03, A17 and A30 as function of distance from the receiver for the LEF (250 Hz octave band) index.

as well as all the early reflections [13], has high values for close distances around the resonators, but this effect is gradually decreasing for increasing distance.

4. Conclusion

The theatre of Lyttus was the largest theatre of Crete (Candia) and probably one of the largest theatres in ancient Greece. The construction of the theatre, according to Venetian traveller Onorio Belli, fits exactly the description of Vitruvius regarding the use of "sounding vessels". A computer simulation program of the theatre without the resonators showed that the acoustic quality indexes is comparable to that of the theatre of Epidaurus.

From these simulations, it appears that the effect of the resonators both on the Centre Time and on the LEF of the response is significant. For this it can be deduced that probably the cavity - resonator modules were used to provide a form of artificial reverberation for positions close to them in the ancient theatres. Their effect on other indexes was found to be rather poor, compared with the effect of the main source on the stage. This subtle acoustic effect could be the reason for their abandonment in subsequent theatres.

Appendix: A simplified theory of resonators

Helmholtz resonators are lumped acoustic elements. Their resonance frequency (f) is given by several accurate formulae, the simplest one is given by [14]:

$$f = \frac{c}{2\pi}\sqrt{\frac{S}{LV}} \quad \text{or} \quad \omega = c\sqrt{\frac{S}{LV}}, \tag{A1}$$

where c (m/s) is the speed of sound, S (m^2) the cross section area of the neck, L (m) is the effective length of the neck (including the end corrections), $L = L' + 1.7a$, L' (m) is the real length, a (m) is the radius of the resonator opening, V (m^3) the volume of the cavity and ω is their angular frequency. Their attenuation power is dictated by the absorption cross section. The absorption cross section is defined as the ratio between sound energy being attenuated per second by the resonator and the intensity of the incident sound wave at the position of the absorbent object [14, 15, 16, 17]. The maximum value of absorption cross section at the resonant frequency ($\sigma_{\text{abs,max}}$) in the matched case, where the internal resistance equals to the radiation one, is given by

$$\sigma_{\text{abs,max}} = \frac{P_{\text{abs,max}}}{I} = \frac{\lambda_0^2}{2\pi}, \tag{A2}$$

where λ_0 is the wavelength corresponding to the resonance frequency, $P_{\text{abs,max}}$ is the maximum absorbing power [8, 9, 12] and I is the intensity of the incident sound wave.

The frequency dependence of the absorption power ($P(\omega)$) is given by

$$P(\omega) = P_{\text{abs}}\frac{1}{1 + Q_A^2\left(\omega/\omega_0 - \omega_0/\omega\right)^2},$$
$$Q_A^2 = \frac{\pi}{V}\left(\frac{\lambda_0}{2\pi}\right)^3, \tag{A3}$$

where Q_A is the quality factor of the resonator and ω_0 is its resonant angular frequency. Helmholtz resonators are not only sound absorbers. According to Heckl [14], a Helmholtz resonator has a surprising large scattering cross section, when the exciting frequency and the resonant frequency coincide. The intensity of the radiated sound I_s (in the matched case) at a distance r is given by [10]

$$T_s = \left(\frac{\lambda_0}{2\pi r}\right)^2 I, \tag{A4}$$

where r is the distance from the resonator where the intensity (I_s) is calculated.

The sound inside the resonator's cavity reverberates. The reverberation time (T) of the resonator is given by

$$T = \frac{13.8 Q_A}{\omega_0}. \tag{A5}$$

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