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ACOUSTIC BEHAVIOR OF CERAMIC POTS USED IN MIDDLE AGE WORSHIP SPACES – A LABORATORY ANALYSIS

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Abstract:
This paper presents the results of laboratory measurements of ceramic acoustic pots similar to those used in the vaults and walls of some Middle Age churches in Switzerland and other countries. The resonance frequency of the pots was found to be from 237 Hz to 444 Hz. A good estimation of the resonance frequency is given by the formula of Alster (with a cylindrical modeling) or by the traditional formula for Helmholtz resonators, slightly adapted. The intensimetric and sound level measurements highlighted a weak-operating range for the pots (difference open/closed pot on a radius of 0.3 m) of the omnidirectional re-emitted wave by the pots at the natural frequency and at certain harmonics. The sound absorption measurements in reverberation chamber highlighted a small but very selective absorption. The acoustic pots present around their resonance frequency and certain harmonics, light phenomena of amplification, sound absorption and diffusion.

INTRODUCTION

At all times one can find strong defenders or detractors of the use of acoustic pots. The conclusions which one can draw from these varied opinions relate more to the role allotted to the pots than on their real effectiveness. In fact, neither their utility nor their inefficiency was formally shown until this century. It is probable that the use of the acoustic pots rested more on an empirical tradition than on a real knowledge of the laws of acoustics.

The acoustic pots are Helmholtz resonators of a particular type, whose form is generally not spherical and whose neck is generally not straight. The characterization of the physical properties of the acoustic pots thus passes to an application of the theory of the Helmholtz resonators to these particular examples. We will first expose the basic principles for the modeling of the pots used and then calculate and measure the resonance frequency, the sound absorption and the radiation proprieties.

A Helmholtz resonator is an oscillating circuit (presenting a resonance frequency which depends on the geometric characteristics of its neck and volume) that has the property to absorb part of the incident energy and to re-emit acoustic waves having particular characteristics in the temporal, spectral and spatial domains. In the presence of a resonator, one can assist to: an acoustic energy absorption involving a reduction in the reverberation at certain frequencies, an acoustic amplification at certain frequencies, a modification of the temporal structure of the sound at certain frequencies and an acoustic diffusion at the spatial level by the mechanism of reemission.

MODELING OF THE ACOUSTIC POTS

The length l of the neck is defined by the distance between the points A and B where A is the most external point of the pot and B the intersection of a straight line parallel with the axis of the pot passing by A and the interior surface of the pottery (Fig. 1a). The cross-sectional area S of the neck is the average of the larger area (calculated from OA) and the smallest (calculated from $O'C$). The volume of the neck V_N is

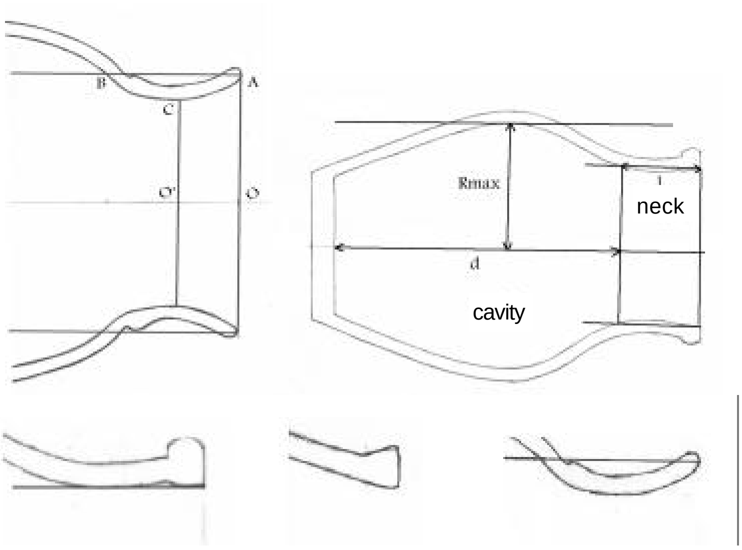

Figure 1 - a) top left: Description of the neck; b) bottom: Types of necks: straight, short and open (from left to right); c) top right: Characteristics of the volume cavity

defined by the product of the area by its length: $V_N = S*l$. The necks are distinguished according to their length and form: A neck is called *long* if $l \geq 1$ cm or *short* if $l < 1$ cm and it is called *open* if $OA\text{-}O'C \geq 0.5$ cm or *straight* if $OA\text{-}O'C < 0.5$ cm (Fig. 1b).

Naming *Rmax*, the interior maximum radius of the pot and *d*, the length of the volume cavity (overall length of the pot minus the length of the neck), a cavity will be called *spherical* if $Rmax \geq d/2$, *standard* if $d/2 > Rmax > d/2.5$, and *cylindrical* if $Rmax \leq d/2.5$. A *standard* cavity is by far the more common (Fig. 1c).

MEASUREMENTS IN LABORATORY

Eight pots (six made of unglazed terra-cotta and two varnished as seen in Fig. 2), of different sizes and shapes, but similar to those found in churches in Switzerland, were used to carry out measurements in laboratory. More detailed investigations were carried out on the pot type number 2 because its geometry is the most representative to the pots found on the walls of several churches [1].

Figure 2 - Pots used in laboratory measurements (left: pots 1 to 6 of unglazed terra-cotta, right: pots 7 and 8 varnished)

Resonance Frequency

To evaluate the resonance frequency, the response in frequency of the pot was measured in an anechoic room with the microphone placed inside the pot (and deducting the answer measured without the pot to disregard the microphone and the loudspeaker characteristics). These measurements were carried out for each pot to determine the resonance frequency (maximum peak) and the quality factor (width of the peak, for this and other details see [2]).

The *classical formula* [f_r *class* $= [c(A/l_e.V)^{1/2}]/(2\pi)$ with $le=l+lc$, where lc is the length for end correction], makes it possible to correctly predict the resonance frequency (Table 1). The mean difference between theory and practice is 7% (27 Hz) and remains within the margin of uncertainties (30 Hz). The systematic error, relatively high, must come from the undervaluation of the neck correction.

The *formula of Alster* [3] using a *cylindrical* modeling (*fr cyl*, Table 2) makes possible to predict the resonance frequency with an error lower than 3% and without a systematic error. This formula seems quite appropriate for the majority of pots. The *spherical* modeling (*fr sph*, Table 2) gives very good results if pot 7 is excluded. With this modeling, the Alster's formula gives an uncertainty higher than with the classical formula, because it is more sensitive to the geometrical parameters.

Similar measurements as previously described were carried out with the pot enclosed in a wooden board (Fig. 3) instead of a freestanding position. The resonance frequency of each pot was measured in both states (Table 3). With the enclosed pot, a decrease of the resonance frequency was found slightly lower than envisaged theoretically but within the limits predicted by the calculation (< 5%).

Table 1 - Measured and calculated resonance freq. (fr) by the classical formula.

Pot no.	Neck	Cavity	Measured resonance frequencies (Hz)	fr class (Hz)	±	Difference (Hz)	Difference (%)
1	straight	standard	325	354	27	29	9.1
2	straight	standard	297	309	24	12	4.1
3	short	standard	444	474	40	30	6.8
4	open	standard	369	380	29	11	2.9
5	open	standard	237	246	19	9	3.8
6	short	standard	393	425	34	32	8.0
7	short	cylindrical	435	538	43	103	23.8
8	open	standard	343	337	26	-6	-1.9
			Mean		30	27	7.1
			Standard deviation		8	33	7.6

Table 2 - Measured and calculated resonance frequencies (fr) by the Alster formula.

Pot no.	Neck	Cavity	fr meas. (Hz)	fr cyl (Hz)	±	Diff. (Hz)	Diff. (%)	fr sph (Hz)	±	Diff. (Hz)	Diff. (%)
1	straight	standard	325	337	44	12	3.7	338	57	13	3.9
2	straight	standard	297	302	42	5	1.8	295	48	-2	-0.6
3	short	standard	444	438	82	-6	-1.4	449	100	5	1.1
4	open	standard	369	364	54	-5	-1.4	362	63	-7	-1.9
5	open	standard	237	241	31	4	1.9	235	35	-2	-0.7
6	short	standard	393	401	67	8	2.0	404	82	11	2.8
7	short	cylindrical	435	422	72	-13	-2.9	526	115	91	20.9
8	open	standard	343	331	47	-12	-3.5	321	54	-22	-6.4
			Mean		55	-0.7	0.04		69	11	2.4
			Standard deviation		17	9.5	2.7		27	34	8.1

Sound Absorption

To measure the sound absorption proprieties of the pots, reverberant chamber measurements were done with thirty type 2 pots (Fig. 4). The results, according to various spatial pots configurations (Fig. 5) in the chamber, show that sound absorption increases, at low frequencies, when the pots are located at the corners of the room. This conclusion confirms the relevance of the tradition that often involves the laying out of the acoustic pots in the churches especially near the angles.

Figure 3 - (left) Measurements in anechoic room with an enclosed pot
Figure 4 - (right) Measurements in reverberant chamber with 30 scattered pots

Table 3 - Comparison of the resonance frequency (fr) for free and enclosed pots.

Pot no	Neck	Cavity	f_r free pots (Hz)	f_r enclosed pots (Hz)	Difference (%)	Difference theoretical (%)
1	straight	standard	325	316	2.8	3.0
2	straight	standard	297	291	2.0	3.2
3	short	standard	444	433	2.5	4.5
4	open	standard	369	359	2.7	3.3
5	open	standard	237	234	1.3	2.6
6	short	standard	393	384	2.3	4.7
7	short	cylindrical	435	424	2.5	5.0
8	open	standard	343	336	2.0	3.2

For a more precise sound absorption study around the resonance frequency, measurements were done in fine band (10 Hz) in the 1/3-octave bands centered in the 250 Hz and 315 Hz. Both the theoretical and the measured curve present a Gaussian distribution, but they are shifted in frequency and do not have the same amplitude (Fig. 6).

These remarks are mainly explained by the craftsmanship manufacture of the used pots that induces variations of their resonance frequency. The average of the resonance frequencies was calculated as 276 ± 11 Hz. The difference between the resonance frequencies of the pots used, also explains the more flattened shape of the measured curve. As the average resonance frequency of the pots is weaker than the calculated resonance frequency of the reference pot (309 Hz), the mean measured value of the sound absorption area of the type 2 pots (0.050 m^2) is slightly higher [2] than the theoretical value (0.043 m^2).

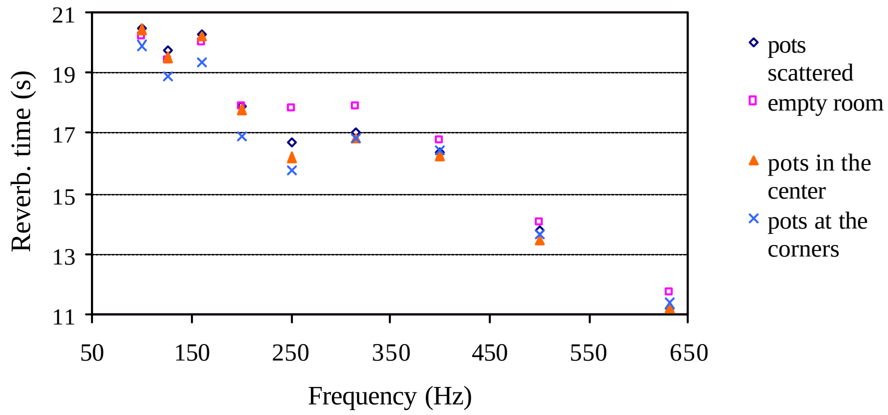

Figure 5 - Measure in reverberation chamber of 30 pots in various configurations

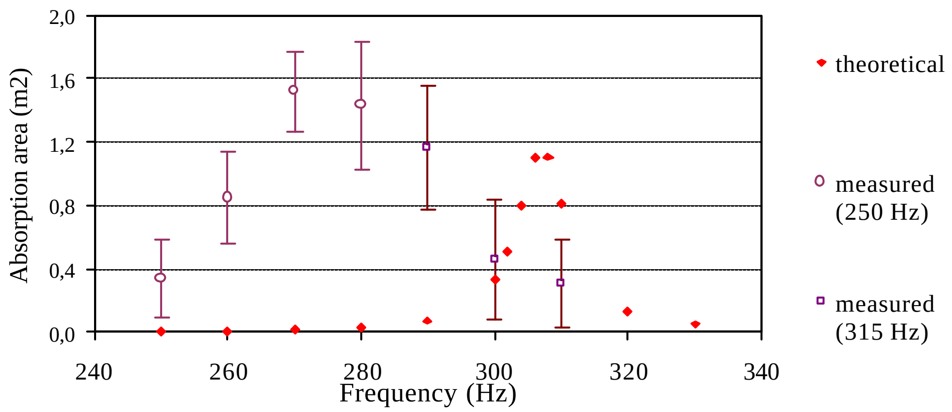

Figure 6 - Sound absorption of 30 pots (type 2) around the resonance frequency

Re-emitted Signal

To analyze the sound radiation of a pot, this was excited (in an anechoic room) by a short duration noise (pure tone or pink noise) and its response measured at the opening of the pot after the disappearance of the excitation signal. The following analysis relates to the temporal and spectral structure of the re-emitted signal and concerns to pot number 2.

When the excitation signal is a *pure tone* equal to the pot's resonance frequency (297 Hz), the re-emitted signal by the pot contains a strong component at the resonance frequency as well as a weaker contribution in the 1260 Hz that corresponds to the second mode of the pot.

When the frequency of the excitation signal is different from the resonance of the pot (for example 500 Hz), the temporal signal after the cut of the signal shows, in addition to a phase shift, a spectral change of the signal. The spectral analysis highlights, in addition to the emitted component (peak at 500 Hz), contributions at the eigentones of the pot located below (297 Hz for the fundamental mode) and above (1260 and 1870 Hz) of this frequency that decrease exponentially with time.

When the frequency of excitation becomes high (for example 1100 Hz) a weak component at the resonance frequency (297 Hz) and a more significant contribution to the second mode of the pot (1260 Hz) are observed.

With a *pink noise*, after the appearance of the signal and even more after the extinction of the excitation signal, one finds also the presence of the resonance frequency of the pot (297 Hz) as its odd harmonics (1260, 1870 and 2350 Hz).

Radiation

To determine the distance of effectiveness and the type of spatial radiation of the enclosed pots, sound intensity measurements were done in an anechoic room by evaluating the difference in radiated intensity between an open and a closed pot using a cork.

To establish the distance of effectiveness of pot type no. 2, measurements were undertaken at various distances along the normal axis of its opening (Fig. 7). When the excitation signal is at the resonance frequency, the intensity radiated by the open pot is larger at certain distances than when it is closed. The effectiveness of the pot quickly increases with the distance to reach a maximum at a distance of about 10-15 cm of the pot, then it decreases linearly to become zero at about 30 cm. At this distance, as at a very short distance to the pot (< 5 cm), the radiated intensity is the same as the reflected intensity (when the pot is closed). When the excitation signal is different from eigentones of the pot, this does not involve any variation of sound level and no difference is found between the radiated intensity by the open pot and that reflected when it is closed.

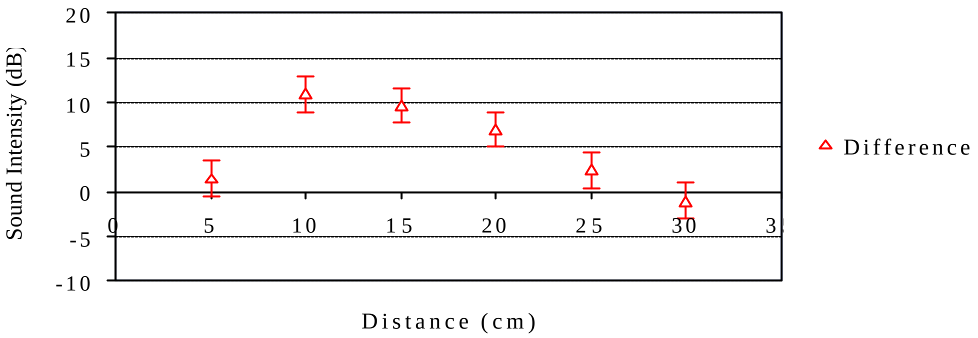

Figure 7 - Difference in radiation (with opening of pot's aperture) at the resonance frequency at perpendicular distances to the pot

To determine the spatial type of radiation, angular measurements were undertaken but preserving a constant distance of 20 cm to the pot's opening. When the excitation signal is at the pots' resonance frequency, the intensity radiated by the pot is the same in all directions. In accordance with the theoretical predictions [2], the pot behaves like an omnidirectional secondary source placed on a wall.

CONCLUSIONS

The measurements in laboratory enabled us to highlight the acoustic properties of the pots and to check various theoretical models:

- the measured resonances frequencies for the pots are rather well predicted by the various models used (traditional and Alster formula with spherical modeling; the cylindrical approach giving bad results for certain pots);
- the sound radiation of a pot, which appears at the beginning and at the cutting of the signal energy, is mainly composed by its resonance frequency and to a lesser extent, by the higher modes that decrease exponentially with time;
- the sound radiation of a pot at its resonance frequency is omnidirectional but presents a weak range of effectiveness (< 30 cm). For frequencies different from the resonance frequency, the pot does not increase the sound level. It does not seem very probable that an amplification effect can be heard in a church;
- the sound absorption of a pot is, in agreement with the theory, weak and very selective, but can be optimized to become significant at low frequencies (< 200 Hz). The very selective sound absorption as well as the omnidirectional radiation could cause a partial elimination of a normal mode of the room. This use requires however a "tuning" of the pot on the room and a judicious positioning.

On the basis of our investigation the use of correctly positioned and dimensioned resonators, can improve acoustics of certain churches by:

- decreasing the reverberation time in low frequency (effect of absorption);
- locally amplifying the sound level at certain frequencies (effect of amplification);
- decreasing the focusing effects (of a vault or cupola) by the omnidirectional re-emitted waves with a certain delay (effect of diffusion);
- decreasing the standing wave phenomena (effects of absorption and diffusion);
- regularizing the transients (phenomenon of diffusion).

ACKNOWLEDGEMENTS

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