

Article

Resonant Vessels in Russian Churches and Their Study in a Concert Hall

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Abstract: Resonant vessels in ancient and medieval buildings are the subject of some historical and acoustic research today. There have been a number of detailed surveys of European churches, where acoustic pots remain in the buildings. Despite the fact that in medieval Russia the use of built-in vessels was very common in the construction of churches, they have been hardly considered in recent publications. Therefore, the first goal of this paper is to give a brief overview of the Russian experience. Some of the most interesting examples of Russian churches are presented, and among them there may be a world record for the number of the vessels in a single room. The Church of St. Nicholas in Pskov has about 300 pots inserted into the walls, apse and pendentives. The second goal is to study the efficiency of acoustic vessels in an ordinary room. Acoustic measurements were carried out in the Rachmaninov Hall, which is part of the Moscow Conservatory. This chamber concert hall built over 100 years ago has 29 vessels. The first conclusion is that the vessels behave like resonators, their natural frequencies have been identified. The second conclusion is that we found no considerable changes of the acoustics due to the vessels.

Keywords: acoustic vessels; room acoustics; church; concert hall; Helmholtz resonator; acoustic measurements; archaeoacoustics

1. Introduction

Acoustic vessels in old buildings attract the attention of researchers from various fields of science. Historians investigate how knowledge was transmitted between peoples, architects study the development of construction science, for archaeologists the vessels offer unique evidence and, finally, acousticians are interested in the reasons and benefits of their use. In any case, every scientist working on the acoustic vessels mentions primarily Vitruvius's treatise [1], which contains precise recommendations on the arrangement of bronze vessels or large clay jars in theatres. A number of papers are devoted to the analysis of Vitruvius's ideas. Valière et al. [2] reviewed the acoustical experience of Vitruvius and its relation with pots inserted in the walls of the European churches. Arns and Crawford [3] described the use of resonant cavities in the history of architectural acoustics starting with Vitruvius. A large part of recent research was published in a special issue of the "Bulletin Monumental" [4].

Some studies provide detailed information about the acoustic vessels in ancient and medieval buildings in different countries. The most complete and detailed review has been made for France [3,4], where the acoustics pots were investigated in 25 churches. Some interesting dependencies were discovered, in particular, that the number of pots increased with the church volume and the mean resonance frequency decreased with church volume, remaining close to the frequency bands where reverberation times generally were longest. Serbian cases are also well described. Đorđević et al. [5] talk in detail about the acoustic vessels in sacred edifices of medieval Serbia. Fifteen churches were observed, the largest number of the vessels in one church is 20 and the average number is seven. Mijic and Sumarac-Pavlovic [6,7] reported on resonators found in 24 Serbian churches and chapels. The sebu (clay pot) technique was applied in some mosques in Turkey. Süleymaniye Mosque in

Istanbul has 256 pots open towards the interior space [8]. There is also information about the vessels in Switzerland [9], Greece [10], Albania [11] and other countries [3]. The built-in vessels were widespread throughout Russia, but most of the information on this topic is only available in Russian with the exception of Rappoport's book [12]. Perhaps for this reason they are almost not mentioned in the reviews. Therefore, one of the purposes of this paper is to give a brief overview of the use of acoustic vessels in Russia.

From an acoustic point of view the vessels are considered as resonators. The most popular physical model is a Helmholtz resonator, which is a cavity with a short neck. The theory of resonators is well developed at present and they have found application in many areas of practical acoustics [13–16]. It is well known that the Helmholtz resonator may be an effective absorber or scatterer of sound waves. At its resonant frequency absorption and scattering cross sections depend only on a wavelength. So, at low frequencies, one can expect that the resonators can change reverberation time and other acoustic parameters of the room. Another possible reason is reradiation of incidence sound waves, which can be subjectively perceived as a special sound effect. But it is always important to take into account that the resonators operate only in a narrow frequency band in the vicinity of their own frequencies, so it is impossible to assume a significant influence of the resonators in wide frequency bands typical for speech and music.

The results of acoustic studies of vessels are also regularly published. Mijic and Sumarac-Pavlovic [6,7] measured characteristics of resonators found in old Serbian churches. Along with the resonant frequencies, which were 56–131 Hz, the decay time of the oscillations similar to reverberation time was measured. The decay time was in the range 0.4–1.0 s and much shorter than ordinary reverberation time in churches. The authors concluded that the building of ceramic vessels into walls and domes of the churches was the result of orally transmitted tradition, without any real knowledge of their function.

Carvalho et al. [17] carried out laboratory measurements of the ceramic acoustic pots. Their resonance frequencies were found in the range from 237 to 444 Hz. The pots were tested as absorbers, but the sound absorption area was only about 0.05 m² at the resonance frequency. The change in the sound field in the vicinity of the pot was found only within a radius of 30 cm. The same authors studied the pots in two Swiss churches, but the effect of the pots was almost unobservable [9].

Zakinthinos and Skarlatos [10] did a specific experiment in an old Byzantine church. They placed 480 identical resonators on the floor and investigated their effect on most of the acoustic indexes used for evaluation of the acoustic quality of rooms. Even in the room with a volume of only 530 m³, such a large number of the resonators did not significantly affect the acoustic parameters. Only sound absorption was slightly increased, while a small improvement was also registered for local indexes. Further simulation [18] tried to study the effect of the resonators on the acoustic performance of the theatre of Lyttus. They discovered changes of the central time and the lateral sound energy near the resonators, but the changes were decreasing when moving away from them. The effect on other indexes was found to be rather poor.

Experiments of Bruel [19] with models made of vases described by Vitruvius and of sound vases placed in Danish churches did not prove that the vases caused the excellent acoustical quality of ancient theaters and the shortened reverberation time in Nordic churches. Bruel states that it remains a mystery why vases were installed under the seats of ancient Greek theaters and why, 1000 years later, Danes placed vases in their churches.

On the other hand, some researchers obtained more optimistic results. Karampatzakis et al. [20] found resonance properties of both a cooper and glass sphere and applied them for simulations of sound field near the sphere. They expected an amplification effect at certain frequencies in the real theatre if the resonators were to be placed at the correct positions.

As mentioned above, acoustic vessels were widely used in Russian churches. The main difference from European churches is the number of vessels. In European churches [3–7,9–11,21], the number of vessels only occasionally reach double digits, whereas in Russia there are often hundreds. Moreover, in Russia, there is at least one concert hall equipped with the acoustic vessels. In this paper we give a

brief overview of the use of the built-in vessels in the history of Russian architecture with some of the most interesting examples. In addition, the results of measuring the influence of the vessels on the acoustics of the chamber concert hall are presented.

2. Russian Churches

Undoubtedly the Russian tradition of building churches has its origins in Byzantium [12,22]. Master builders there included ceramic pipes and amphorae in the construction of churches. Circular openings representing exposed ends of pipes or the mouths of amphorae are often visible in the centers or in the lower corners of pendentives, which are triangular segments of a sphere connecting a circular dome and a square room. During construction, problems of excess weight appeared at the upper level of the building. Another problem was that large masses of masonry required an excessive period of time to dry, and improper drying could lead eventually to structural failure. Both problems were frequently met by filling the dead space with empty amphorae. However, these amphorae did not have a direct connection to the inner surface of the pendentive. In most Byzantine examples, the visible openings are simply the ends of ceramic tubes, which were most likely intended to facilitate during the construction process and to prevent a subsequent buildup of moisture in the dead space behind the pendentive. Thus, the pipes and amphorae were not given acoustic functions by the builders.

Byzantine masons created effective and efficient building methods that were best suited for the small buildings that characterize the architecture of the late Byzantium period. After the Christianization of Russia in 988, Byzantine construction experience was in high demand in Russia. Master builders were invited and assisted in the construction of the first churches in Russia. The builders imported the technology of using empty vessels. From the 11th century onward, masons in Kyivan Rus' (a protostate partially overlapping with the territory of modern day Ukraine, Belorussia and Western Russia) included ceramic pots in the vaulting, following the Byzantine example, but they added pots in wall surfaces as well. R. Ousterhout supposes that the empty vessels are resonators improving the acoustics of the churches. Nothing like this is found in Byzantine buildings, and the resonators must represent the development of building traditions specific to Russia [22].

In Russian architecture, such vessels are usually named “golosniki”, derived from the word “golos” meaning voice. Due to this name, it has repeatedly been claimed in the literature that the principal purpose of the vessels was to improve the acoustics of places of worship. But, in most cases, the vessels were not laid in the brickwork with their openings facing into the building, so they could not have affected the acoustics. It is evident that the vessels were mainly used to reduce to the weight of the vaults (Figure 1a). However, when the vessels were embedded in the stone or brick walls or vaults with their mouths facing into the church, architects and builders were sure of a positive effect on the acoustics.

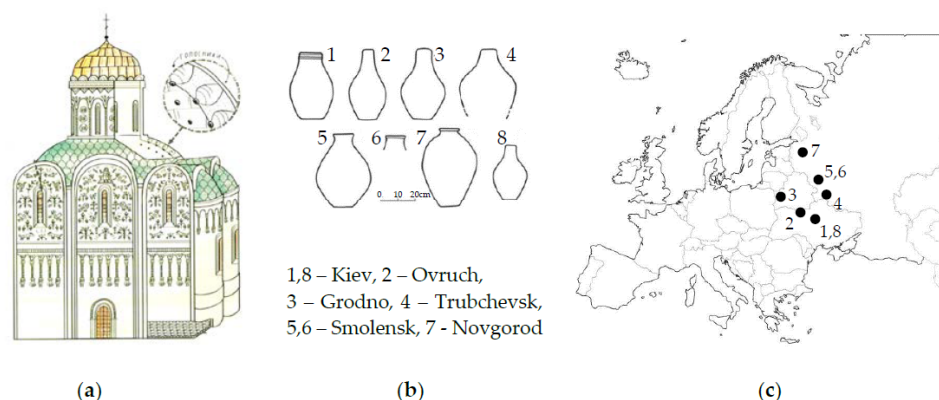


Figure 1. The acoustics vessels or “golosniki” in a Russian-style church (a), locally produced vessels (b) in the different construction centers of Russia till the beginning of 13th century (c).

Based on excavated shards, archeologists concluded that the vessels were used in the most ancient building in Kyiv, the Church of the Tithe. Later they were used in many monuments in Kyiv Rus'—they were found in the monuments of Pereslavl, Volynia, Chernigov, Polotsk, Smolensk and Novgorod built up till the beginning of the 13th century. Two types of vessel are known. The first one was the imported Greek amphorae, the second one was locally produced pots, most of which were specially manufactured for the construction industry. The second type of vessel differed both in shape and fabric (Figure 1b) in the different construction centers of Russia (Figure 1c). In most cases the ratio of amphorae to locally produced pots cannot be determined. Sometimes only one type of vessel has been found in a monument.

After the Mongol invasions, the use of acoustic vessels in the construction of churches expanded eastwards; one can find them in Moscow, Rostov, Nizhny Novgorod and other cities. It is interesting that they seem to hardly ever appear in Vladimir and Suzdal, which were also important cultural centers in medieval Russia.

There is quite a lot of information about acoustic vessels in Russian churches, but it is not well systematized. It is impossible to give a full and comprehensive overview of this issue in one article, so we will limit our consideration to a few of the most striking examples.

2.1. St. Basil's Cathedral

St Basil's Cathedral (the Cathedral of the Intercession of the Most Holy Theotokos on the Moat, Moscow, Russia), shown in Figure 2a, is the best-known unofficial symbol of Moscow and Russia. Due to an unusual architectural composition, multicolor domes, 16th–19th century wall paintings, it became the outstanding monument of world architecture and is on the UNESCO World Heritage List. The cathedral was constructed between 1555 and 1561. The original building contained eight churches arranged around a ninth connected with galleries and passageways (Figure 2b shows the plan of the second floor). Churches number ten and eleven, with their respective domes, were added in 1588 and 1672; they are not shown in Figure 2b.

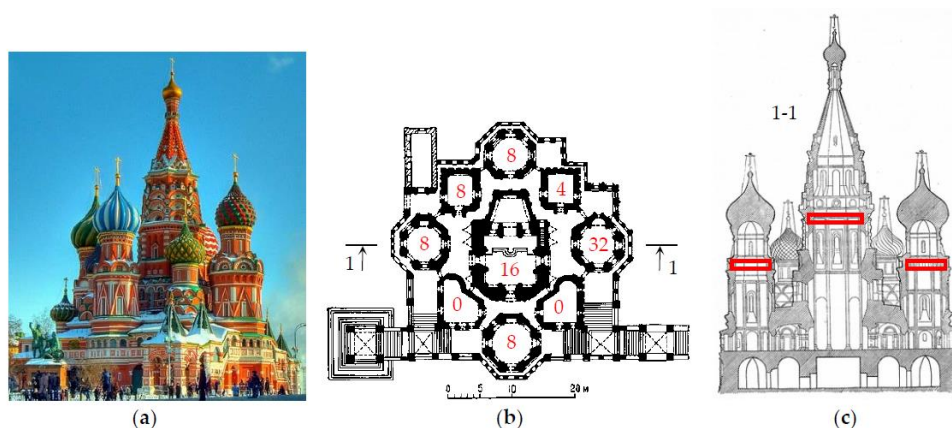


Figure 2. St Basil's Cathedral (a), the plan of its second floor (b) and the central section (c). The numbers on the plan indicate the number of the vessels in each church, the red rectangles on the section mark the displacement of the vessel in the central church.

Ceramic vessels were found in seven churches [23], but we cannot exclude the possibility that they could exist in the other churches as well. The vessels can be covered with layers of plaster applied to the ceilings and walls during the several repairs that have taken place over the long history of the cathedral. Red numbers in Figure 2b show the numbers of the vessels in each of the seven churches.

The central and the largest church, named the Church of the Intercession, has 16 vessels. All vessels are ceramic pitchers of the same ovoid form, which are embedded into the walls at the height of 21 m from the floor level, as the red rectangles on the section in Figure 2b mark. The pitchers' height and

maximal diameter are about 51–55 cm and 43 cm, so their volume is approximately 65 L. The diameter of the neck 13–15 cm. The same large pitchers are found in the other two churches. The smallest pitchers have the height of 27–32 cm and the maximal diameter of 29–31 cm. So the minimal volume is about 15 L.

The biggest number of the vessels is in the church of St. Nicholas Velikoretsky, but there is no information about their sizes and forms.

It is interesting that 136 vessels are located on the facades of two churches. Archeologists note [23] that the external placement of the ceramic vessels is a fairly rare and little studied phenomenon in ancient Russian architecture.

2.2. Churches in Pskov

Pskov is one of the most ancient cities of Russia. According to the archeological data the settlement that later became the city was founded at the latest in the sixth century. Pskov together with Novgorod, Kyiv and other cities, has been the origin of Russian national identity.

The Pskov school of architecture developed under the influence of the Byzantine and Novgorod traditions by the beginning of the 14th century and reached its peak in the 15th and 16th centuries. In the 16th century, Pskov architecture developed, but in the middle of the century the influence of regal Moscow architecture became more obvious. It was one of the most influential Russian schools of architecture, which fostered continuous exchange of ideas and characterized the development of architectural styles in Russia over five centuries. The group of 10 monuments located in the historic city of Pskov was included in the World Heritage List of UNESCO [24] in 2019.

Characteristics of the buildings produced by the Pskov school include cubic volumes, domes, porches and belfries, with the oldest elements dating back to the 12th century. It developed a number of distinctive techniques, which made Pskov churches unique and easily recognizable. Among them are three apses covered over the gables, elevated strengthened arches in the interior, rounded piers and a lot of built-in vessels. The latter feature is the subject of interest of this article.

Today, when visiting the many churches of Pskov, one can see a large number of vessels on the inner surface at an upper part of the church. They are located regularly and consistently in clearly visible places, which probably indicates not only their functionality, but also their aesthetic purpose. We will demonstrate this feature with two examples of churches.

The first example is the Church of Theophany, built in 1496 (Figure 3a). This church is canonical for Pskov architecture. It has a single cupola, three apses, two symmetrical side-altars with one apse and galleries joined by a shared narthex from the west, and, in the north-western corner, a five-span belfry on a powerful chamber. Many vessels can be seen in the main room marked by the red rectangle on the ground floor plan in Figure 3b. This plan and the plan of the second church considered below are made by the famous Russian historian of Pskov architecture Spegalsky and are available on the website dedicated to his work [25]. The vessels are put in the drum, pendentives, central apse and upper parts of the walls over windows (Figure 3c).

The total number of visible vessels is about 250. The volume of the church is about 1250 m³, what gives an average of one vessel for 5 m³. This value is much smaller than in the well-known European churches [3,4].

The second example is the Church Nikoly so Usokhi (St. Nicholas from the Dry Place) built in 1535 (Figure 4a). The church is located in the historic center of Pskov. The composition is made of a cubic, three-apse, single-dome church with a western narthex and a porch. From the north, a side-altar and a narthex are attached to it; a chapel is on the south-east. Above the side-altar, a two-span belfry stands on the northern wall of the cube. The vessels are seen in the church marked on the ground floor plan (Figure 4b). Figure 4 contains two inner views of the church; view A is of the altar wall and view B is of the side wall. We can see the mouths of the vessels in the pendentives, central apse and upper part of all walls. There are no the vessels in the drum, probably because of its windows. It is should be noted that, in view A (Figure 4c), the openings are arranged in an original pattern, which immediately catches the eye when entering the church.

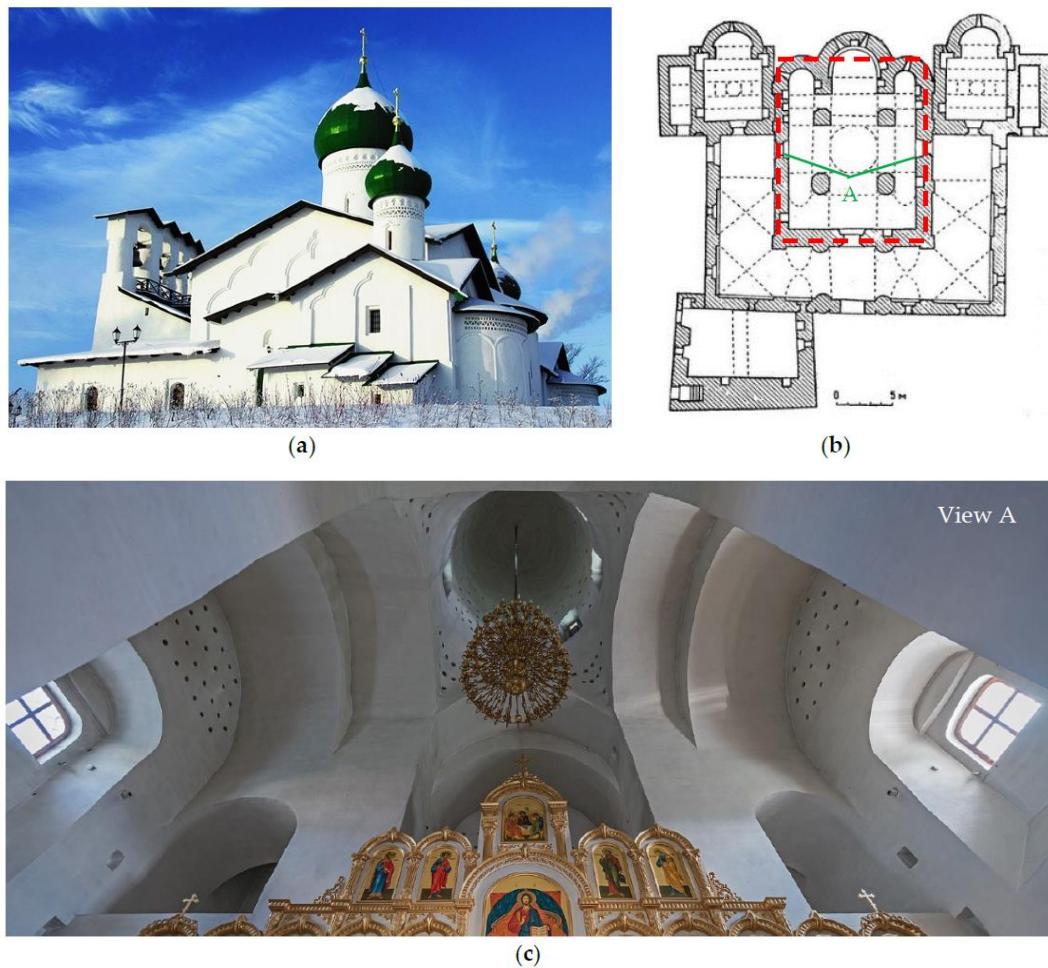


Figure 3. Church of Theophany (constructed in 1496) in Pskov with belfry: the southern facade (a), the plan of the ground floor (b), the vessels in a drum, pendentives and upper parts of walls (c). The red rectangular on the plan shows a main room of the church, green lines define the viewing angle of the photo inside the main room.

The total number of visible vessels is about 300. The volume of the church is about 1450 m^3 , what gives an average of one vessel for 5 m^3 , as in the Church of Theophany.

The number of vessels in the Pskov churches varies; the two considered examples have demonstrated a maximal number. In some churches, there are only 10–20 vessels in the pendentives or drum. We have no reliable information about their sizes, so we can only rely on historical descriptions of Pskov churches [26]. It is known that the vessels are clay pots placed horizontally in the walls. Several types of pots were used; the diameter of the mouth was from 10 to 26 cm. However, today, the mouths with a diameter of 10–15 cm can be seen in accessible churches. The diameter of the pot is about twice the diameter of the mouth, i.e., 20–30 cm. So the pots are relatively small, this is also confirmed by the proximity of their location (Figures 3c and 4c,d). The expected volumes of the pots vary from 5 to 15 L.

Let us pay attention to the proximity of the pots inserted into the walls and apses. The distance between them is smaller than a wavelength, because expected resonance frequencies are about 100–300 Hz and respective wavelengths are approximately 1–3 m. It means that the vessels interact acoustically with each other and, from the physical point of view, they should be considered as an array of resonators [27,28]. Sound absorption and scattering properties of the array may differ from those of a single resonator.

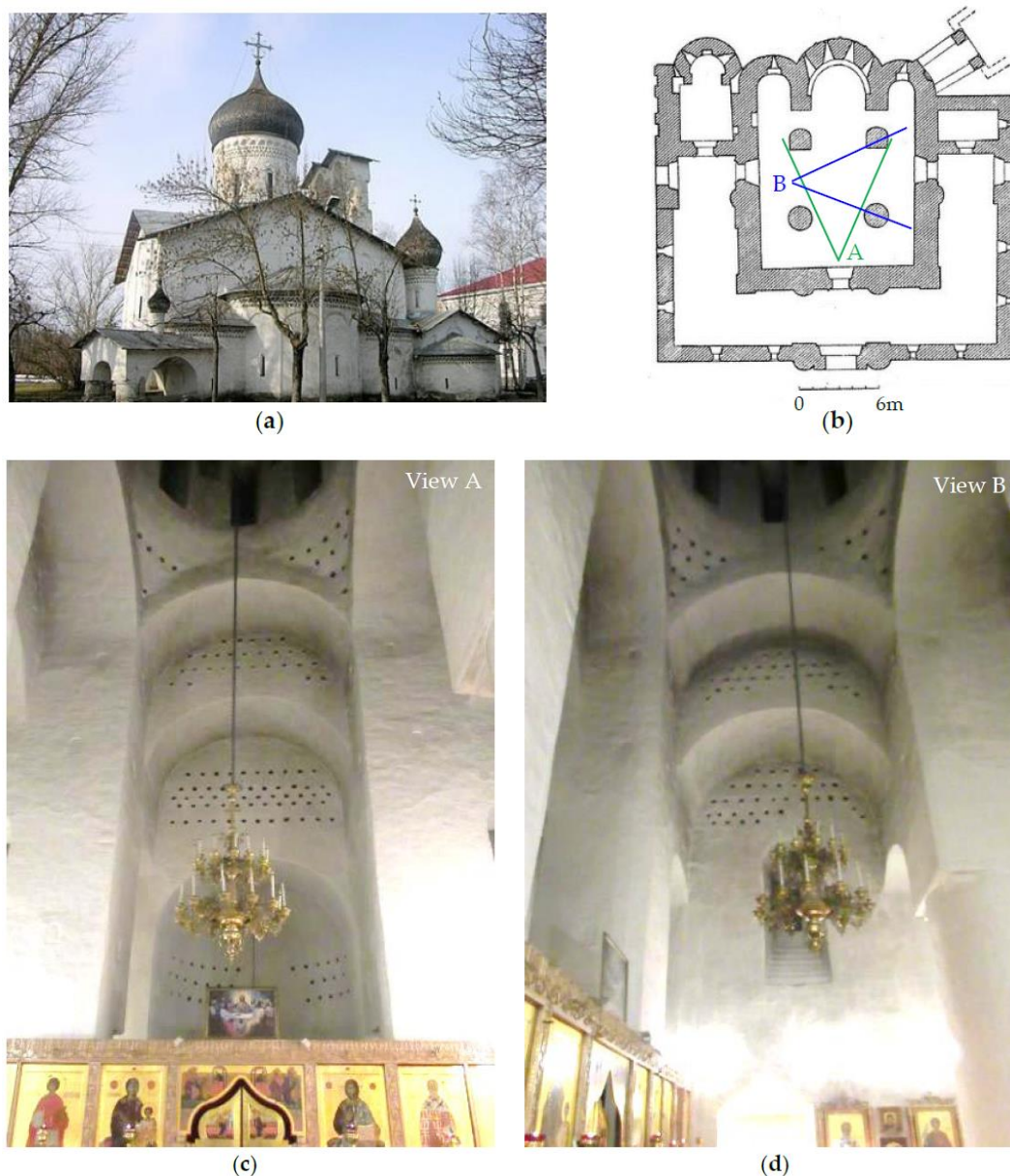


Figure 4. Church Nikoly so Usokhi (St. Nicholas from the Dry Place), constructed in 1535, in Pskov: the eastern facade (a), the plan of the ground floor (b), the vessels in the pendentives, an apse and upper parts of walls (c,d).

We can conclude that the Pskov churches, along with other advantages, are also acoustic monuments, although special studies of the acoustic effectiveness of the pots have not been made.

Even today acoustic pots are sometimes used in the construction of churches. It is necessary to mention the London Russian Orthodox Church Abroad's Cathedral of the Nativity of the Most Holy Mother of God and the Royal Martyrs, which was recently built in the Pskov style [29].

2.3. Kalozha Church

The Kalozha Church of Sts. Boris and Gleb is the oldest extant structure in Grodno, Belarus. It was built at the end of the 12th century on the high right bank of the River Nieman in the territory of the former Kalozha settlement. The materials used for construction were brick, stone, glaze and lime mortar. The church is a rectangular building of 13.5 m × 21.5 m with three semicircular altar apses at the eastern side. The walls have a thickness about 1.2 m. The exterior and interior are shown in Figure 5.

The location of the church was unfortunate because of the subsidence of the ground washed away by the Nieman. So it is always in danger of collapse. Despite all efforts to stop the ground sliding, the church was partially destroyed by a landslide in 1853, and, in 1889, the southern apse collapsed. Only the southern wall, a part of the western wall, three apses and two western under-cupola pillars are preserved now. In Figure 5c, these elements are shown on the plan, the dotted lines indicate the destroyed parts. Later, the missing walls and roof were replaced with wooden ones.

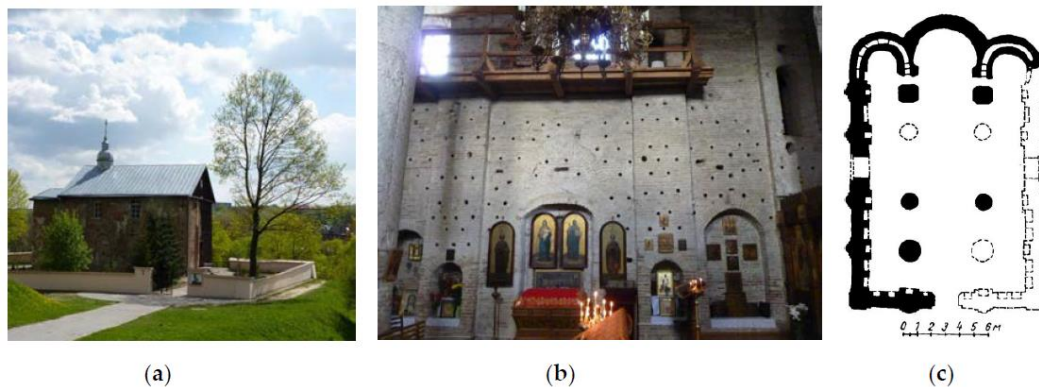


Figure 5. The Kalozha Church in Grodno (a), its interior (b) and its plan (c) with the destroyed walls marked by the dotted lines.

A lot of openings seen on the northern wall in Figure 5b are necks of the vessels embedded in the brick wall. They are placed more or less regularly, only in Figure 5b there are 115 items. However, there may be more of them, because some may be covered with icons. The visible area of the wall is about 50 m^2 , so an average surface density, which is the number of vessels per square meter is about 2.3. Inside the church, one can see the vessels on the other walls and apses. The total number that could be counted is 209. However, it should be taken into account that some openings could be closed by icons, furniture, wooded stairs and balcony. Considering that only 60% of the walls are preserved, we can assume that the total number of vessels in the walls was about 350. We have no information about whether there were vessels in the ceiling and dome, but, if there were, their total number would be even greater.

The considered churches in Pskov have more resonators than the Kalozha Church. However, if we take into account the number of vessels it had before the destruction, it may have had the largest number of acoustic vessels in the world. The internal volume of the church is about 2000 m^3 , so it could have had one vessel for 6 m^3 . The Pskov churches have the larger number of vessels per unit volume.

Russian archeologist and historian P. Rappoport supposed that numerous vessels were not used to improve the acoustics, since for this purpose a few vessels placed in the pendentives would have been sufficient [12]. This feature of the use of vessels he attributes to the architectural school of Grodno. A large number of vessels were found in the debris during excavations of another church in Grodno, where the vessels were similarly distributed in the walls. The regular positioning of the vessels, as well as the fact that the walls of the Grodno churches were not plastered on the inside, suggest that, in this case, they were used as one of the elements of the interior decoration.

Special research on the vessels in the Kalozha Church is not known, so we can rely on information from an old review [26]. All vessels have a similar shape, but they can be divided into two groups by size. The vessels of the first group have a height of 48 cm and a maximum diameter of 27 cm; their volume is about 25 L. The parameters for the vessels of the second group are 40 cm, 23 cm and 15 L respectively. A photo of two vessels are in Figure 6, where one vessel is completely undamaged, and the brickwork around the second one is partially destroyed. The relief outer surface of the vessel is visible, as well as the internal cavity.



Figure 6. The clay vessels in Kalozha Church.

3. Rachmaninov Concert Hall

Rachmaninov Hall belongs to the Tchaikovsky Moscow State Conservatory, founded in 1866 by Nikolay Rubinstein. There are three concert halls in the Moscow Conservatory, the most famous is the Great Hall [30]. It has high acoustic qualities comparable to the best concert halls in the world such as Grosser Musikvereinssaal in Vienna, Concertgebouw in Amsterdam, Boston Symphonic Hall [31]. Two other halls have been acoustically evaluated as well [32].

3.1. Short History and Description

The oldest concert hall of the Moscow Conservatory is Rachmaninov Hall. It was built in 1890 for Moscow Synodal School. In 1968, the hall was affiliated to the Moscow Conservatory and reopened in 1983 after a long renovation. In 1986, it was named in honor of one of the most famous Moscow Conservatory graduates, the outstanding Russian composer and pianist Sergey Rachmaninov, whose life was associated with the Synodal School as well. The hall is a stunning building due to its beautiful multiple windows and elegant decoration of the ceiling and walls. Many of chamber music and choir concerts are held there, almost every day, and classical and modern music are also performed occasionally here. In 2016, the latest renovation of the hall was finished.

The acoustic parameters of the hall have values close to those of European chamber halls [33]. The acoustic reputation of the hall is also quite high; sometimes its acoustics are called “flight”. Figure 7 shows photos of the hall taken more than 100 years ago and at the present time. Generally, its architectural appearance has been preserved, but several large-scale reconstructions have been carried out over its history. So the modern finish may differ from the original one, and, therefore, the acoustics may differ as well.

Figure 7c contains the drawings of the hall, which has a classic shoebox form and a capacity of 246 seats. The hall has a balcony around the perimeter, but today there are no fixed seats for the audience at the balcony. The volume of the hall is about 2500 m³; its length is 24 m. The many windows on the side walls make the hall light and easy to see.

An interesting feature of the Rachmaninov Hall is the presence of resonant vessels built into the walls. Their locations on the side walls are marked by the red points in Figure 7c; they are installed around the perimeter under the balconies and under the ceiling. Fourteen vessels are on each side wall, two vessels are on the front wall and one vessel is on the back wall. The total number of vessels is 29. It corresponds to 11.6 vessels per 1000 m³, which is ten times less in comparison with the Kalozha Church and Pskov churches.

We have some memoirs of graduates of the Synodal School, two of them concerning the vessels. A. Smirnov, who studied at the school between 1909 and 1917, remembered a legend that was told among the students: “Behind the holes in the pilasters there are pipes that ‘help singing’”. N. Belkin, who studied between 1899 and 1910, was sure that the good quality of the acoustics was provided, among other things, due to the clay pots embedded in the walls. Today, many singers and musicians believe that resonators help a good performance.

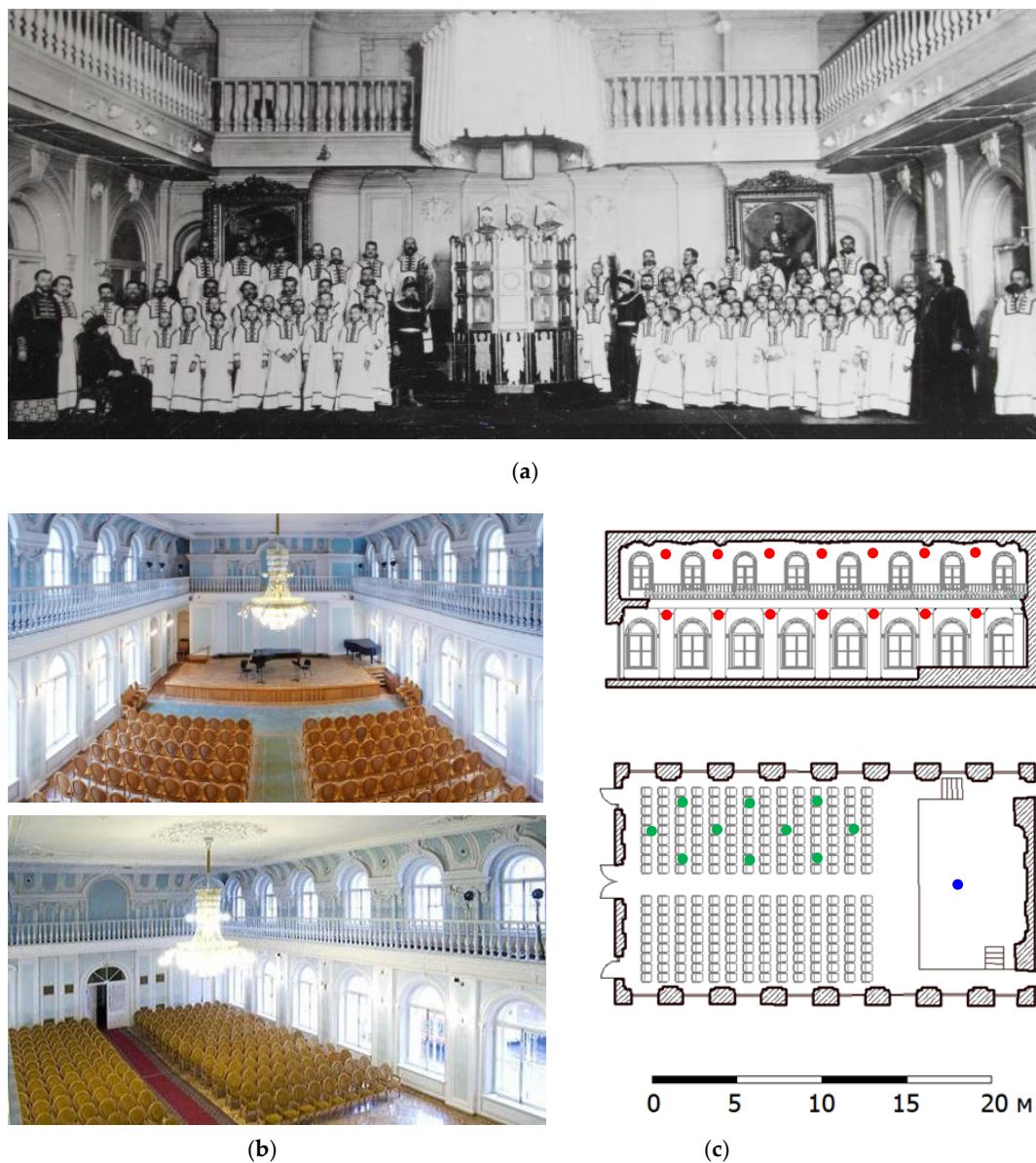


Figure 7. Rachmaninov Hall of the Moscow Conservatory before 1917 (a) and now (b); its section and plan (c). Red points on the section indicate the displacement of the resonant vessels in the side walls; the blue point on the plan is the position of the sound source; green points are the positions of the microphone.

Initially this hall was built for studies, rehearsals and concerts of young singers and choirs that performed church music. Perhaps for this reason, architects decided to apply their experience of building churches and use resonators. Anyway, now we have a unique concert hall equipped with resonators, which allows us to study their effectiveness.

3.2. Resonators

As we can see in Figure 7, the vessels are located at a low height, which makes it easy to measure their geometric dimensions. They have a spherical cavity and a neck which ends have slightly different sizes. The outer end of the neck expands and looks like a small horn (Figure 8a). This design seems to be related to aesthetic reasons rather than acoustic ones. Figure 8b introduces five geometrical parameters characterizing the resonator form. It was found that the resonator sizes are different. In order to characterize the variation of the received data, minimum, maximum and average values

of these parameters are given in Table 1, as well as their volumes V and resonance frequencies f_0 . The vessels in the Rachmaninov Hall are much smaller than the vessels in the churches considered above. The maximum volume is only about 4 L.

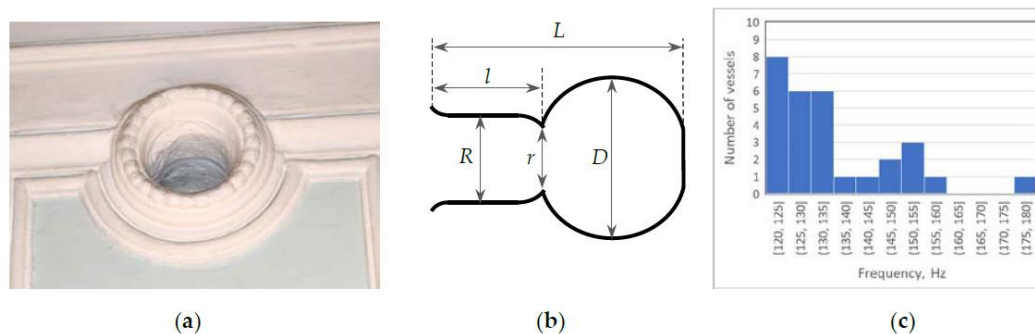


Figure 8. The resonator in the Rachmaninov Hall (a), its dimensions (b) and distribution of the resonance frequencies (c).

Table 1. Parameters of the resonant vessel in the Rachmaninov Hall.

Parameter	Min	Max	Average
R , mm	95	115	106
r , mm	75	95	85
D , mm	130	200	178
l , mm	198	300	252
L , mm	330	480	442
V , liters	1.8	4.2	3.1
f_0 , Hz	120	176	136

The most interesting parameter is the resonance frequency, which deviates like other parameters. The deviation of the resonant frequency is described by the histogram in Figure 8c. All frequencies are in the range 120–176 Hz, but most are in the band 120–135 Hz. It is difficult to understand whether this distribution was meaningful or an uncontrolled consequence of the variation in the size of the resonators. Probably the architects tried to make resonators of different sizes following the well-known ideas that resonators should be different but they did not adjust the resonant frequencies themselves.

First of all, it was interesting whether the vessels in the Rachmaninov Hall are really resonators. During routing evaluation of the hall acoustics [34] along with measurements of impulse responses in the audience area, the impulse response was measured in the vessel as well. An omnidirectional sound source stayed at the center of the stage at a height of 1.5 m, a microphone was placed inside the vessel located in the middle of the lower row of resonators shown in Figure 7c. In this state the standard measurement procedure was performed and resulted in the impulse response, which initial part presented in Figure 9. For comparison, Figure 9 also shows the impulse response measured at the nearest seat to the vessel. Both responses are normalized to the maximum absolute value of the amplitude.

We see that two responses are very different. The response in the hall is typical for a room, whereas the response in the vessel is similar to a sinusoidal signal. It means that the incident sound field excites oscillations at a single frequency, so the vessel responds to the excitation as a resonator. At the initial part (50–100 ms), the oscillation amplitude increases, then it gradually decreases with a decrease in the amplitude of the incident field.

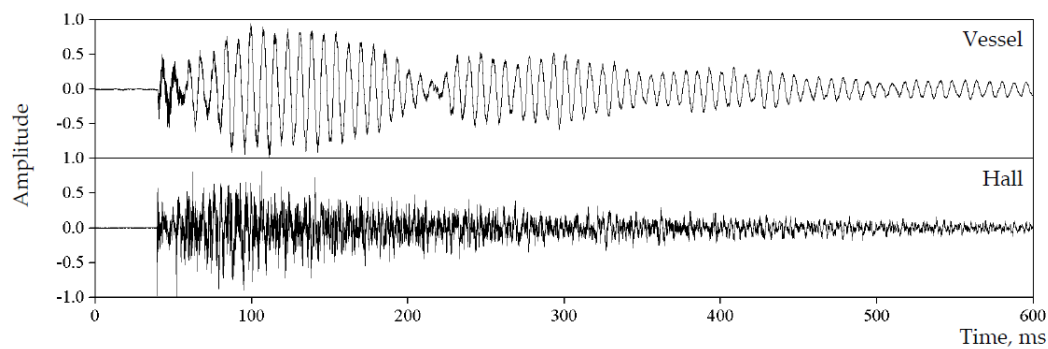


Figure 9. Impulse responses measured inside the vessel and at the seat nearest to the vessel.

3.3. Reverberation Time

Measurement of acoustic parameters was carried out in accordance with the standard [34]. The dodecahedron sound source was placed in the geometrical center of the stage, 10 positions for the microphone were evenly distributed in the audience area. They are shown on the plan of the hall in Figure 7c. In each receiver position, the impulse response was measured and analyzed. In order to estimate the influence of the resonators on the acoustic parameters of the hall, the impulse responses were measured under the same conditions with open and closed resonators. Figure 10a presents the reverberation time in third-octave bands averaged over 10 measurements. Two curves on the plot are close to each other, but it is possible to observe a slight difference. To estimate this difference let us introduce the relative change in reverberation time.

$$\delta = 100 \frac{|T_o - T_c|}{T_o}, \quad (1)$$

where T_o and T_c are the reverberation times with open and closed resonators respectively. The relative difference δ is shown in Figure 10b. At all frequencies except 160 Hz, its values do not exceed 2%, only at 160 Hz it reaches 3%.

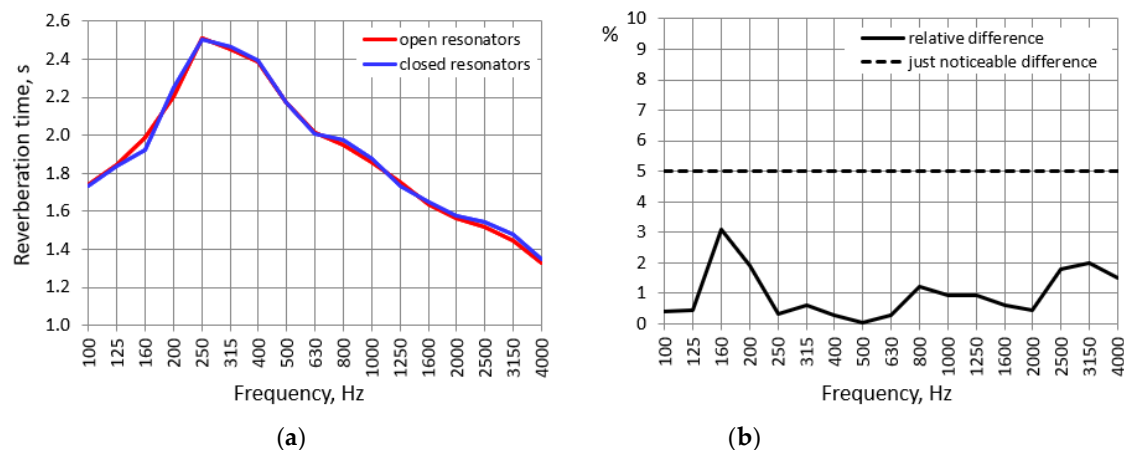


Figure 10. Reverberation time in the Rachmaninov Hall measured with open and closed resonators (a), the relative difference δ the reverberation time (b).

The sensitivity of listeners to small changes of acoustic parameters is described by a just noticeable difference or JND [34,35]. The JND of the reverberation time is 5%. In Figure 10b, the found relative difference is compared with the JND. We can observe the variation of the reverberation time is

significantly smaller than the JND. Moreover, the change comparable to the JND in the reverberation time in only one third-octave band is unlikely to be noticed by the listener.

At the same time, we cannot confidently associate the peak relative difference at 160 Hz with the influence of the resonators. The first reason is that the most vessels have resonance frequencies at the range 120–135 Hz and it would be expected the difference be at the third octave band of 125 Hz. However, at this frequency the relative difference is only 0.5%. The second is that the standard deviation of the reverberation time at 160 Hz defined by all measured values is about 5%. Therefore, the found difference may be related to the usual measurement uncertainty.

3.4. C_{80} and EDT

The reverberation time is not affected by the resonators. It means that the resonators neither absorb sound significantly nor make reverberation longer, but they reradiate sound energy, which is stored by them once the incident sound excites their oscillations. One can expect additional signals in the initial part of the impulse response. Figure 11 demonstrates the influence of the resonator on the response in the simplest case. The resonator is embedded into a rigid wall, and a source and a receiver are placed in points S and M respectively (Figure 11a). The impulse response P_M of this system is schematically shown in Figure 11b. The direct sound coming to the point M is the fastest and gives the peak 1 in the response. The reflected sound gives the delayed peak 2 with slightly smaller amplitude. The incident sound 3 excites oscillations of the resonator, which starts to radiate a spherical sound wave at its resonant frequency. As a result, a decaying sinusoid appears in the response. Certainly, there are many reflections in the room and many sinusoids with different delay times due to the resonators that may be observed in the point M .

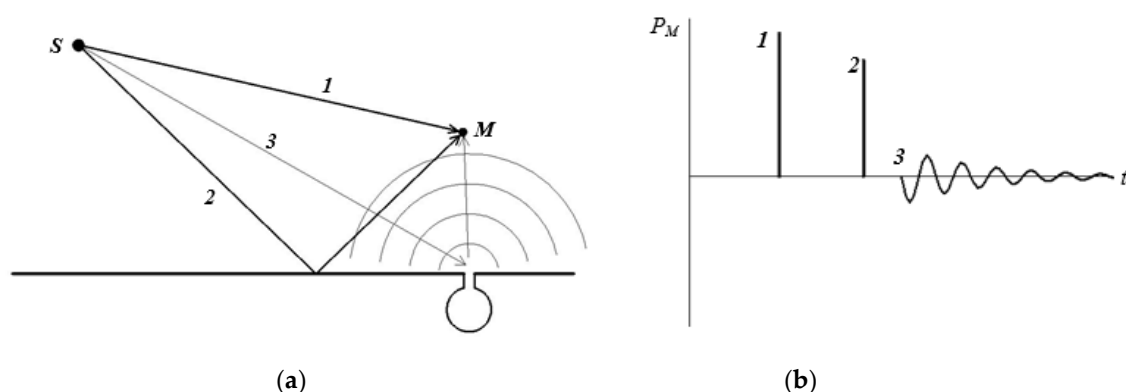


Figure 11. Effect of the resonator (a) on the impulse response (b).

To evaluate the influence of the resonator on the early part of the response, the parameters C_{80} and EDT are analyzed in third-octave bands [34]. Both parameters were measured with open and closed resonators in 10 points shown in Figure 7c. The largest deviation of the reverberation time was observed at 160 Hz, whereas most vessels have their resonant frequency at 125 Hz. At these frequencies, it is the most probable to find the changes of the parameters. At frequencies 500 and 1000 Hz, changes are not expected, so these frequencies are considered too to compare the ordinary variations due to measurement dispersion. Usually, the parameters C_{80} and EDT measured in octave bands of 500 and 1000 Hz are used to evaluate acoustics of concert halls [31], so these values are considered as well.

The standard JND of C_{80} is 1 dB [34], whereas, according to one study [36], the JND is about 1.3 dB if the reverberation time is about 2 s. The JND of EDT is 5% in accordance with [34], which corresponds to 0.1 s in the investigated hall. However, recent research [37] has demonstrated that the JND can be much higher than 5%, especially at low frequencies; the JND under different conditions varies from

19% till 53%. The JND values from [34,36,37] are given in Table 2 for comparison with the dispersion of the measured parameters.

Table 2 contains the values of C_{80} and EDT averaged over 10 measurements. We can see that the differences between average values for open and closed resonators do not exceed 0.3 dB of C_{80} and 0.09 s of EDT at all frequencies. So the found differences between the average values for both parameters are much smaller than the JND. At the same time, the parameters are local, which means that their values change from point to point. For this reason it is necessary to analyze changes at all points. If $P_{n,o}$ and $P_{n,c}$ are the values of the parameter C_{80} or EDT measured at the point with number n with open and closed resonators respectively, we can introduce the absolute difference of the measured parameter for each point $\delta P_n = |P_{n,o} - P_{n,c}|$. Then the average and maximal differences can be calculated as follows

$$\delta P_{av} = \frac{1}{10} \sum_n \delta P_n, \delta P_{max} = \max_n \delta P_n. \quad (2)$$

Table 2. Measured values of C_{80} and EDT and their variations.

Parameter	Frequency, Hz	Average Values		Abs. Differences		JND	
		Open	Close	δP_{av}	δP_{max}	[34]	[36,37]
C_{80} , dB	125 (1/3 oct.)	−0.32	−0.20	0.56	0.74	1.0	1.3
	160 (1/3 oct.)	0.48	0.34	0.68	0.92		
	500 (1/3 oct.)	−1.49	−1.76	0.69	1.05		
	1000 (1/3 oct.)	−0.69	−0.52	0.33	0.75		
	500 (1/1 oct.)	−1.88	−1.83	0.43	0.68		
	1000 (1/1 oct.)	−0.84	−0.68	0.24	0.42		
EDT, s	125 (1/3 oct.)	1.74	1.78	0.09	0.15	0.1	0.4
	160 (1/3 oct.)	1.78	1.87	0.10	0.15		
	500 (1/3 oct.)	2.19	2.18	0.09	0.17		
	1000 (1/3 oct.)	1.75	1.80	0.07	0.12		
	500 (1/1 oct.)	2.20	2.19	0.10	0.14		
	1000 (1/1 oct.)	1.84	1.82	0.08	0.13		

The average and maximal absolute differences for both parameters are given in Table 2. Maximal changes of C_{80} at 125 and 160 Hz are less than the JND and they are comparable with the changes at 500 and 1000 Hz. The variations of the C_{80} at 125 and 160 Hz can be related to ordinary experimental dispersion taking place in the considered measurements, and not to the effect of the resonators.

Similar results are found for EDT. The average values of the absolute difference are less than the JND at all frequencies, although the maximal deviations are slightly greater the standard JND and much smaller JND found in [37]. As in the case of C_{80} , the maximal changes of EDT at 125 and 160 Hz, at which we seek the effect of the resonators, and at 500 and 1000 Hz, at which the effect is not expected, are similar. Therefore, the possible changes of acoustic parameters of the hall because of the resonators is smaller than the accuracy of the executed measurements.

4. Discussion

The use of built-in vessels in Russian architecture has been illustrated by several examples. It should be noted that the use of such vessels was very popular in the middle ages and later, and they are found in many cities throughout the European part of Russia. Today, there are no systematic descriptions of this architectural technique in different regions or special research devoted to the history or archeology of the known buildings with vessels. The churches in Moscow and Pskov considered here have shown great difference in dimensions of the vessels and their positions in the building. Of course, it is not possible to give a complete overview of this issue in only one paper; therefore,

several significant examples were selected to demonstrate the widespread of the acoustic vessels in Russia.

The technology of application of the vessels into the building came to Russia from Byzantium, but there they had never been used as an acoustical treatment. Russian builders probably did not know Vitruvius's treatise in the middle ages, since its first known translation into Russian was made only in the 17th century. So we can assume that the development of the use of vessels in construction practice into acoustical application was an independent achievement of the Russian architectural school.

The most surprising difference from the known European examples is the number of vessels in Russian churches. It reaches several hundred in relatively small churches with a volume of 1000–2000 m³. The record holders for this parameter are the buildings by the Pskov school of architecture, which reached its peak in the 15th and 16th centuries. Today, we can count more than 300 vessels in the Church Nikoly so Usokhi, but, perhaps before the 19th century, the record belonged to the Kalozha Church in Grodno. Because of the destruction that began in 1853, today it is impossible to determine how many vessels were in the Kalozha Church before.

There is even a concert hall equipped with acoustic vessels in Russia. It is the Rachmaninov Concert Hall in the Moscow Conservatory. This chamber-music hall has 29 vessels, which, according to many singers, are one of the reasons for the good acoustics in the hall. In situ measurements were carried out in the hall and included the study of the vessels. It has been found out that they behave like resonators and their natural frequencies are in the range 120–176 Hz. At the same time, the measurements did not reveal any influence of the resonators on the acoustic parameters of the hall. Possible changes in the parameters are below both the measurement accuracy and the threshold of human perception of sound. This last result coincides with many previous investigations [6,7,9,10,17,19].

5. Conclusions

The phenomenon of acoustic vessels in Russia is unique and differs from the European one; it still requires deeper historical and archeological research. There is no reliable information that the Russian builders had any empirical knowledge of acoustics, some historians suggest that it was just an interior design technique, whereas in Europe the acoustic pots were inserted according to empirical rules [2].

Although there is only a small hope of proving the acoustic efficiency of the vessels, their use in modern buildings can remain an excellent tradition that goes back deep into the past.

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