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ACOUSTICS OF THE RUSSIAN TENT-SHAPED TEMPLES

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The construction of the tent-shaped temples is a separate direction in the history of the Russian church architecture. The volumetric and planned solutions of these templates differ greatly from the mostly widespread in Russia five-dome churches and cathedrals with the cross-like plan. For that reason the investigation of the acoustics of the tent-shaped temples seems to be important. The results of acoustic measurement done in several tent-shaped temples are analyzed. The most old and well-known stone temples – the Church of the Ascension at Kolomenskoje and St. Basil's Cathedral (Red Square, Moscow) were studied in most details. Computer models of the most wide-spread forms of the tent-shaped temples were also analysed. As a result some common conclusions on the acoustics of these temples were given.

Acoustics of the Russian Orthodox churches became an object of the systematic scientific study only several years ago. At first the acoustic conditions of the five-dome temples with the cross-like plane were studied [1,2]. It was a correct decision because such temples are mostly typical in Russia as for the relatively small churches and for the large cathedrals as well. But several very different forms of the temples were also used. Among these trends one of the most interesting is the construction of the tent-shaped temples (TST) with the tower-like main body of the church. Such stone TST firstly appeared in XVI century. The historians of the Russian architecture studied TST very detailed. There are a lot of architectural studies on the subject and special monographs (for example, see [3] with a wide bibliography). In this paper the acoustics of TST which were built during XVI-XVII is studied. This period is certainly the most typical and important for TST. Just during these two centuries there were built the most outstanding and well-known TST including the unique architectural monuments.
Some data on the most well-known Russian TST is given in table 1. In this table L is the largest plan dimension of the main body of the church and H is the height of the church. The column "Form of TST' shows the modification of the church's form from it's lower part to the highest one. In this column the following abbreviations are used: T – tetrahedron; O – octahedron; TR – tent-shaped roof; C – cupola.

Table 1.

The name of TST	Date of construction	Form of TST	L, m	H/L
Church of the Ascension at Kolomenskoje (AK).	1532	T-O-O-TR	8.5	5.6
Intersession Church in St. Basil's Cathedral, Red Square, Moscow (IC).	1555-1561	O-O-O-TR	8.2	5.5
Church of the Beheading of St John the Precursor at Dyakovo (ID)	1547	O-O-O-C	8.7	3.7
Transfiguration Church at Ostrov (TO).	XVI –XVII	T-O-TR	8.9	3.8
Church of Resurrection at Gorognja (RG).	XVI	O-TR	9.5	3.0
Znamensky Church at Dubrovitsi (ZD)	1690-1704	T-O-O-O-C	8.2	3.4
The upper summer Church of the Intersection at Fily (IF).	1693-1694	T-O-O-O	8.8	3.2
Tower of Ìenshikov, Moscow (TM).	1701-1707	T-T-O-O	7.2	3.6

It's necessary to estimate the typical forms of the plans of TST. Three such forms (quadratic, octagonal and quadratic with 4 semicircular or three-petal exedrae) are shown in fig. 1. Of course, in several TST there are some deflexions from these forms. For example, in IC and ID only the main bodies of the temples are taken into account. The exedrae in these churches are separated from the main volume by the icon-stands and are of little importance from the acoustical point of view. In TO

the lowest tetrahedron is enlarged on the southern and northern sides. In TM a small trapeznaya (meal-room) adjoin the lowest tetrahedron. In AK the tetrahedron is also enlarged a little on the southern, northern and western sides.

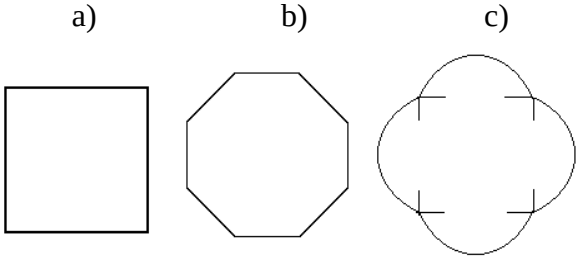

Fig. 1. Typical plans of TST.

Nevertheless it's possible with confidence to note the following general architectural tendency of THT that were built in XVI-XVII centuries. The small dimension of TST plan (L) is typical. In most cases this dimension is between 7-10 m. Above the main basement several more narrow bodies are located that forms the tower-like form of the church. The most wide spread solution is the octahedron (or several more narrow octahedrons) covered by a tent-shaped roof. In the most clear view this tendency is seen in RG. This church has a form of a simple octahedron covered by the tent roof with a small 8-windowers octahedron ("drum") at the very top. TST may be divided into two groups according to the mentioned general tendency. The first group includes the most large churches (AK and IC) for which H/L>5. The second group includes all other churches that are characterised by smaller dimensions. The ratio H/L is about 3.0-3.7 for this group. It's also possible to estimate 3 mostly typical forms of TST that are shown in fig.2.

Six computer models based on 3D representation of TST were made. Three of them corresponded to the typical forms of TST given in fig.2. The other models represented 3 real TST (AK, IC, IF) and were done in more details. The results of acoustical computer simulation were compared with the acoustical measurements that were done in the empty churches and partly published earlier [4-6]. The analyses of this data lead to some common conclusions on the acoustics of TST

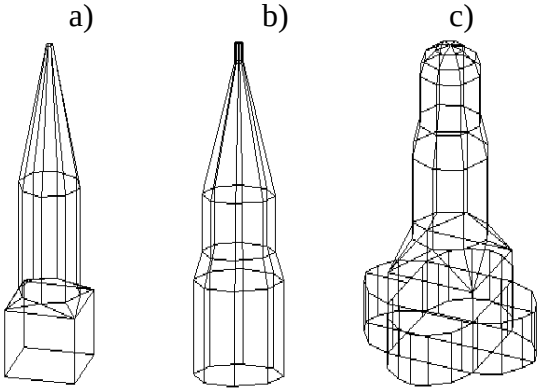

Fig. 2. Typical forms of TST.

1. The reverberation time RT60 is very high in the largest TST. The volume of AK is equal to V=1700 m^3. That is about 2 times less than in 5-dome Trinity Cathedral in Kostroma (V=3200m^3 [1]). And the values of RT60 in AK are about 2 times larger (see rows 1 and 4 in table 2). Even in considerably larger 5-dome cathedrals of Moscow Kremlin (the Cathedral of Assumption, V=11500m^3 and the Cathedral of Archangel Michael, V=6600 m^3) the values of RT60 [2] is less than in AK. Such values of RT60 depend greatly on the inner attire of TST. For example, IC has the volume of V=1670 m^3 that is very close to the volume of AK. But the values of RT60 in IC are much smaller than in AK (see rows 1 and 2 in table 2). This is caused mainly by the large wooden icon-stand that was installed in IC. During the measurements in AK in this church there was no icon-stand and the room was

completely empty with only several wooden benches on the floor. Still shorter reverberation time was estimated in more lower TST with exedrae on the sides of the tetrahedron. For example, in IF (see row 3 in table 2) RT60 is equal to 1.4-1.7 s at middle frequencies. In this case the huge icon-stand with 8 rows of icons and various wooden decorative structures as well influenced greatly on the sound absorption in the church. It should be noted that there is no large increase of RT60 at the low frequencies in IC and IF that is typical for 5-dome churches and cathedrals. This fact deals with the large surface of windows in IC and IF that absorb sound energy at the low frequencies. The surface of windows in AK is much smaller in comparison with IC and IF.

The values of RT60, s. **Table 2.**

	Temple in which the Measurements were done	Frequencies of the octave bands, Hz					
		125	250	500	1000	2000	4000
1	AK	10.0	8.2	7.4	5.0	3.6	2.6
2	IC	4.9	5.0	4.4	3.8	2.2	1.3
3	IF	1.9	1.8	1.7	1.5	1.4	1.2
4	The Trinity Cathedral in Kostroma [1]	5.5	4.8	4.0	3.6	2.8	2.1

2. The problem of speech intelligibility is of the great importance in Russian Orthodox churches. In general the speech intelligibility in TST is better than in 5-dome churches. The measured values of RASTI and another speech criteria – D50 lead to this conclusion. In the main tetrahedron of IC the measured values of RASTI are equal to 0.50-0.72 and in IF RASTI=0.52-0.66. Such values correspond to speech intelligibility from fair to good. Of course this result is caused mainly by the very small dimensions of TST where the distance between the sound source and the receiver is not more than 8 m. In the presence of the audience the reverberation time will be some shorter and even better speech intelligibility is expected. The listening tests confirmed this proposal. Only in AK the low values of RASTI=0.32-0.45 were estimated. But as it was mentioned above, this TST during the measurements was completely empty and without the icon-stand. Such case is not typical for the Orthodox churches.

3. The structures of sound reflections in TST were studied in more details. A good coincidence was estimated between the results of the measurements and the computer simulation. The results showed that there are many early high-level sound reflections and the density of these reflections is high. This is caused mainly by the sound reflections from the lower parts of the walls (tetrahedron or octahedron). None late high-level sound reflections that may cause audible echo were fixed during the measurements and listening tests. The impulse response was additionally calculated from computer models for the placement of both the sound source and the receiver in the central part of the rooms. Although this placement is not typical for the Orthodox churches, it seems to be the most “dangerous” due to the possible concentration of sound by the tent-roof. It was estimated from the calculations that in such a case some late sound reflections are fixed with a delay about $\tau \approx 2H/c_0$ (where c_0 is the speed of sound in air). While dealing with the form of the church shown in fig. 2a, these are the reflection of the type: sound source-T-O-TR-TR-O-T-sound receiver. In another words, the sound wave from the source is rising up to the top of the church while reflecting from the walls and then is coming down to the receiver. In spite of the large time delay these reflections did not cause the audible echo. They are also not fixed on the measured impulse responses as an exceeding (“hump”) over the monotonous structure of the sound decay. It seems, the reason of this situation is due to the large number of the high-level reflections from the lower parts of the walls that fully masked the mentioned large-order reflections with the delay $\tau \approx 2H/c_0$. In the central part of AK the values of RT60 above 500 Hz are about 0.5 s larger than in the other parts of the church. This result confirmed that the reflections with $\tau \approx 2H/c_0$ which were found by computer simulation are really present and have some influence upon the sound field in TST.

It should be noted as a conclusion that acoustics of the TST in noticeably better in comparison with the large Orthodox 5-dome churches and cathedrals with cross-like plan.

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