ACOUSTICS OF GOTHIC CHURCHES

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ABSTRACT
The acoustic atmosphere of Gothic churches is an important part of their cultural heritage. Mainly, it is formed by rather long reverberation and frequency-depending reflections effected by the columns. Measurements in more than 50 German Gothic churches show a narrow range for mid-frequency reverberation depending on volume being typical for this architectural style but differing for churches with plaster or brick surfaces. The dimensions of the columns lead to the effect that the first high-frequency reflections (coming from side directions) reach the listeners earlier than the low-frequency reflections (coming from above). Some examples will be given how to improve the room acoustic properties for speech and in particular for music without affecting the conservation aspects of the historical buildings.

INTRODUCTION
The Gothic churches to be found in a great number in all European countries represent a huge cultural heritage that has to be preserved very conscientiously. These buildings have been built mainly during the 12th to 14th century for praising god. But their size was not only focused to the demands of masses and other services but often they should demonstrate the richness of the clergy, the parish or community. Therefore, many of the Gothic churches are much larger than necessary for the services *ad gloriam dei*. Furthermore during the following centuries, the modalities of the services varied in a wide range. Originally, clergy and laity were strongly split using their separate parts of the church. Whereas the clergy had comfortable choir-stalls, the laymen had to stand for attending the mass, they assembled around the different altars or close to the priest preaching from the rood screen. Pulpits are to be found not before the 15th century, canopies over the pulpit came into use about 1500.

Caused by Luther's reformation, the sermon got a much higher degree of importance and in this connection, pews for the laymen have been introduced – not only in Lutherian churches, but also in catholic churches. On the other hand, church music became more and more important: During the middle age, there existed only simple liturgic songs and later on monophonic Gregorianic songs that could develop their full sound in the reverberant churches creating a very emotional effect. Particularly in the baroque period, music became more and more polyphonic and the intelligibility of the sung texts became an essential part of the semantic understanding of the service. This changing situation led to changed requirements of the acoustic environment. But even if new churches have been built during all the time, the

Gothic churches kept in use – sometimes with remodelled interior. Therefore the questions arise, whether there are typical acoustic properties of the Gothic churches that have to be maintained under monument preserving aspects and – nevertheless - which possibilities may exist for improving the acoustic situation for listeners as well as for speakers and musicians according to the present demands. As there are great differences in architectural concepts and details of the Gothic churches to be found in different European countries, these questions shall be discussed in the following restrained only to German churches.

REVERBERATION TIME

Mid-frequency Reverberation

As well known, the reverberation time is the most important physical parameter for describing the acoustic behaviour of historic churches since the sound field generated in theses rooms shows a high degree of diffusion – in contrast to many modern churches. The reverberation time including its dependence on frequency is primarily determined by the room bounding surfaces and additionally by furniture and decoration and by the audience. Furthermore, the volume of the room plays an important role. The volume of Gothic churches varies in a very wide range from small village churches with about 1.000 m^3 to large cathedrals with more than 100.000 m^3; for example: the Cologne cathedral has a volume of 235.000 m^3.

As the largest part of the room surfaces consists of plaster or uncovered stones, the roughness and porosity of these areas determines the main part of the sound absorption. In this connection it should be mentioned that the columns or pillars enlarge the entire surface area of the room in a essential way: in most churches the ratio between the area of the walls and the surface of the pillars is in the order of 1 : 0.25 to 1 : 0.3, that means pillars enlarge the wall absorption by a quarter or more; in special cases of extreme thick pillars, the enlargement of the wall surface by pillars reaches the order of 50 %. For mid-frequencies, the typical absorption coefficient of the walls and columns lies between 0.075 and 0.10 if the stones are covered by plaster in a more or less traditional way.

Measurements of the reverberation time in more than 50 (unoccupied) Gothic churches lead to the interesting result that there exists a rather narrow range for the mid-frequency reverberation time that rises with increasing volume from values about 2.5 to 3.8 s at 3.000 m^3 until 9 to 10 s at 100.000 m^3. It can be described by the form:

$$T_m = 4.4 \lg \frac{V}{V_0} - 12,4 \qquad \begin{array}{l} T_m \text{ in s} \\ V \text{ in m}^3 \\ V_0 = 1 \text{ m}^3 \end{array}$$

This form is valid for churches from about 2.000 m^3 to 250.000 m^3; the individual values vary in a range of ± 0.7 s for churches of medium size and of about ± 0.6 s for small and for very large churches. Obviously, this range of the mid-frequency reverberation time is a style-related property of the Gothic churches creating the typical acoustic atmosphere of these rooms.

But there are two groups of exceptions. In Northern Germany, many churches are made by brick and more or less large parts of these stones are uncovered or painted only by porous colour. As brick has a higher porosity than natural stones or plaster, the sound absorption is distinctly higher, typical for mid-frequencies is an absorption coefficient of about 0.13, i. e. about 50 % higher than for plastered surfaces. Measurements lead to the result that the mid-frequency reverberation time of brick churches can be described by

$$T_m = 3 \lg \frac{V}{V_0} - 8.5$$

This form is valid at least for churches having a volume between 3.000 m^3 and 80.000 m^3; the individual values vary by not more than ± 0.5 s. That means in those churches, typical values for the reverberation time are in the order of 3 s for 6.000 m^3 and 5 s for 30.000 m^3.

On the other hand, there are to be found some Gothic churches having a much longer reverberation time than described above as typical. The mid-frequency reverberation time in these churches reaches values up to twice the characteristic values of churches with plastered surfaces. For example in several churches having a volume of about 20.000 m^3, a mid-frequency reverberation time between 9 s and 11.5 s has been measured. The reason for this extremely long reverberation is the fact that these rooms have been restored (after destruction during the war) or renovated later on by using a very tight and unporous plaster and covering paint. Furthermore the furniture and decoration has been reduced to a minimum in a very puristic way. Comparing these extremely long reverberation times with the style-related values mentioned above, one has to conclude that they don't agree with the characteristic acoustic atmosphere typical for Gothic churches.

Frequency Dependence of Reverberation

Besides the mid-frequency reverberation, the frequency dependence of the reverberation time plays an important role for characterising the acoustic behaviour of churches because the variation of the reverberation time with frequency is much more pronounced than in concert halls or opera houses. Caused by the architectural style, hard surfaces prevail and there are only small areas that are fit for vibration like wooden parts of the floor, windows or - seldom - wooden galleries. Therefore, the main tendency of the reverberation curve is increasing to lower frequencies. There has not been found any Gothic church with a reverberation curve decreasing towards lower frequencies as often to be found in baroque churches.

As a measure for this increase, the ratio between the higher value to be found in the 125-Hz-octave or the 250-Hz-octave and the value for mid-frequencies (average of the 500-Hz-octve and the 1000-Hz-octave) shall be considered. Statistically seen, the increase of the reverberation time towards low frequencies varies between 5 and 50 % of the value for mid-frequencies. For churches with plastered surfaces, the increase mostly is concentrated in the range between 1.1 and 1.25, even if higher ratios are to be found. In brick churches, the ratio mainly lies between 1.05 and 1.15, that means in general the rise is little more gentle, but also ratios up to 1.5 occur showing an extremely strong increase of the reverberation time towards low frequencies.

The most important areas for low-frequency absorption are the windows. Usually they consist of stained glass having little thickness; and it is a remarkable fact that the very old platelets often have a thickness in the order of only 1 mm. Later on, little thicker platelets were used. As there is not any closed air cavity behind the vibrating plate, there exists nearly no resonance effect and the sound absorption of the windows includes very low frequencies too. If in our times a second plane is added to windows (for example for sound insolation), a stronger resonance is generated by the combination of stained glass and cavity that tunes the window distinctly higher (up to about 500 Hz!) and the low frequency absorption of the window is reduced.

In Gothic churches, the portion of the window area related to the entire room surfaces (not only walls) varies in a rather wide range from about 2 to 12 %. Accordingly, the influence to the low frequency reverberation is more or less strong. Even if some other architectural details may contribute to the low-frequency sound absorption, a statistical dependence on the window area is to be seen: If the portion of the windows is not more than 4 % of the entire surface area, the increase of the reverberation time towards low frequencies is 25 % and more. Churches with a window portion of 8 % and more show only an increase of less than 10 %; as a remarkable example, the Erfurt Dom Church (volume 33.500 m^3) may be mentioned: it has a window portion of 12 % and an increase of the reverberation time towards low frequencies of only 5 % (Measurement by Tennhardt and Stendel, 1995).

The reverberation time at higher frequencies does not depend as much on the architectural style, as on one hand the porosity and roughness of the mainly used materials and therefore the absorption coefficients do not differ as much, and one the other hand, the energy loss by dissipation increases by frequency. As the influence of the dissipation on the reverberation rises by the volume, the ratio between theses energy losses and the sound absorption by surfaces rises by increasing volume. In the Ulm Münster (volume 105.000 m^3) e.g. the reverberation time for 4000 Hz is 5,7 s when unoccupied; according to Sabine's formula an entire effective absorption area of about 3000 m^2 would be related to this. Considering usual climatic conditions, the dissipation losses in this church would be equal to 2500 m^2, that means that the reverberation time at 4000 Hz would be determined with more than 80 % by the dissipation. Even in medium-sized churches (volume about 15.000 m^3) the influence of the dissipation on the reverberation time at 4000 Hz lies in the order of 30 %.

DIRECT SOUND AND FIRST REFLECTIONS

Influence of Pillars and Columns

In Gothic churches, the propagation of direct sound and first reflections is formed in a special way by the architectural structure of the building; this concerns the pillars and columns that divide the room into three or five naves as well as the shape of the vault. First of all, the direct sound radiated towards the aisles is shadowed by the pillars. Columns and pillars can be more or less thick, usually the ratio between the diameter of the pillars and the open space between them is in the order of 1 : 2 to 1 : 4.5. That leads to the result that 30 to 50 % of the area of the aisles cannot be seen from the position of the speaker; for the sound of the organ, this portion would be still higher. Additionally considering that the direct sound ray which just touches the pillar is attenuated by about 5 dB for medium and high frequencies because of the bending, one can expect that the part of seats where the direct sound is not affected adversely may be greater than the percentage mentioned above. On the other hand, low frequency components will be distributed more equalised over the whole area of the aisles; therefore the clarity as well as the sound colour vary in a high degree.

For listeners seating in the nave, the influence of the pillars on sound is particularly remarkable. As the pillars act as reflectors having limited size, a limiting frequency occurs for an effective reflection. In addition to the size of the reflecting area, the angle of sound incidence and the distance from the reflector to the sound source as well as to the listener influences this limiting frequency: The larger the distances, the higher the limiting frequency (Cremer, 1953). For a sound source on the organ gallery, typical values of the limiting frequency vary between 1000 and 1500 Hz, in case of very thick pillars it can be shifted down to about 750 Hz. Above this limiting frequency, an approximately total reflection can be expected. Below this frequency, the reflected energy is attenuated by 6 dB / oct (Rindel, 1992). If the frequency is lower by a factor of 4.5 of the limiting frequency (i.e. little more than two octaves), the reflected sound energy is attenuated by 13 dB, that means 95 % of the incident sound energy is bent around the pillar; according to the range of limiting frequencies mentioned, this approximately total diffraction occurs below about 250 to 300 Hz. For a speaker in the pulpit or in front of the altar, similar values occur.

For the listeners' impression, this frequency dividing effect is very important. The diffuse high-frequency reflections generated by columns or compound pillars reach the listeners with very short delay. As the width of the nave mostly does not exceed 8 to 9 m, typical delay times for the first lateral reflections of high-frequency components are shorter than 10 ms. By way of contrast, the first low frequency reflections arrive much later: If the sound source is positioned only few steps higher than the audiences, first low-frequency-reflections come from the side walls having delay times about 30 ms and more; if the sound source is located on the organ gallery, first low-frequency reflections come via the vaulting and the delay times can be little shorter, particularly for an rather high located organ it may be in the order of "only" 20 ms but still clearly later than the high-frequency reflections. It seems the effect that the first high-frequency reflections arrive from lateral directions and the first low-frequency arrive later on and from above makes an essential contribution to the special "sacral" atmosphere of Gothic churches (J. Meyer, 2001).

Concerning the sound of the organ, it should be mentioned that the main components of the mixed voices like "Mixtur" or "Cimbel" fall into the range of the high-frequency reflections as well as the articulation noise ("speaking") of all (!) pipes, even in the low stops. That enhances the brilliance of the tutti sound and the clarity of the tone onsets very much. On the other hand, the later reflections of the low frequency components lead – together with the rise of the reverberation time towards low frequencies – to a prolongation of the initial tone development.

Caused by this temporal fine structure of the tonal onset, the low frequency components seem to be softer and weaker, as the experiences of the first New York Philharmonic Hall have shown (E. Meyer and Kuttruff, 1963). That means the loudness of the low frequency components generated in Gothic churches is not as high as to be expected considering only the radiated sound energy and the frequency dependence of the reverberation time.

Influence of vaulting form

Another point of interest is the influence of the different vaulting shapes on the sound transmission via vaulting reflections. Mostly, Gothic churches have so called groined vaults. With many of them the top line in length direction is approximately a straight line over the whole length of the church; there are only four rather small triangular caps drawn down at the pillars. With this kind of vaulting, about 70 % of the vault area are not lower than 0.5 m below the top. That means that the vaulting effects like a plain ceiling with some diffusing elements and there is a good sound propagation by forward reflections reaching the full length of the church. Some churches have top lines in length direction with little stronger arching drawn down by about 1 to 1.5 m from the keystone which is the highest point. Consequently, a larger part of the vault surface is drawn down, only about 20 % are not lower than 0.5 m below the top and a great part is to be found between 1 and 3 m below the top. In such cases, the reflections may be little focused, but they are spread over the whole length of the church too.

Quite another effect happens with so called cambered vaultings, that rise from the keystone to all sides into a higher arch before drawn down to the transverse arch that – even on the length axis of the church - can be about 4 m lower than the highest part of the vaulting. Particularly for the organ sound or other sources on a high gallery, this leads to the effect, that the direct sound runs – even on the middle axis – against vault areas and is reflected steeply down (in the first bay) or backwards (in the other bays). Therefore it can occur that middle and high-frequency reflections reach only the audience sitting in the first two bays (numbered from the organ) and that a the transit to the third bay the sound impression immediately changes towards a less brilliant timbre and reduced clarity. This has to be compensated by the organ maker by a rather sharp intonation particularly in the higher stops.

FEASIBILITIES FOR MODIFICATIONS

Acoustical and Conservatory Demands

Because of the rather long reverberation time of many larger churches, the congregations are often dissatisfied with the acoustic properties and ask for improving. This concerns not only the speech intelligibility that might be improved by loudspeakers, but also the clarity of music. On the other hand, organs need a long reverberation for two reasons: First, the decay time of the organ sound itself is extremely short (100 to 150 ms for 60 dB) and an abrupt end of a chord is very disturbing (the more the louder the chord), and second, a great part of the organ music has been composed considering long reverberation of the room, that applies to German baroque compositions as well as particularly for French romantic music. Extensive research on subjective judgements of the reverberation time resulted in a well defined range for “good acoustics” of unoccupied churches: the lower limit of the mid-frequency reverberation time rises from a value of 1,2 at 1.000 m^3 over 2 s at 3.000 m^3 to 4 s at 20.000 m^3. The upper limit rises from 1.9 s at 1.000 m^3 over 3.3 s at 3.000 m^3 to 5.5 s at 20.000 m^3. Within this range, the upper part is more convenient for music and leads to essential restrictions for speech; it is to be recommended, if church concerts with a great audience play an important role for the congregation.

A comparison of this recommended reverberation range with the style-related range for Gothic churches shows, that a good coincidence exists only for small churches up to 2.000 m^3. With rising volume, the range for Gothic churches exceeds the recommending range, but until 15.000 m^3 the lower part covers the upper part of the recommended range. Above about 15.000 m^3 there isn’t any covering of both ranges. Therefore the question arises, to which extent the reverberation time may be reduced without injuring the (acoustical!) conservatory aspects of historic buildings. A basis for an answer can be the threshold for distinguishing different reverberation times that lies in the order of 5 % for experienced listeners. Therefore one can accept that most listeners might not feel a discrepancy between the optical and the acoustical room impression if the reverberation time is about 10 % below the lower limit of the style-related range, with very large churches (volume about 100.000 m^3) even 15 % below that limit. This concerns not only the mid-frequency reverberation but the low frequencies too, if the ratio remains in the range mentioned above. Of course in churches where the reverberation time essentially exceeds the style-related range, the reverberation time has to be reduced for conservatory reasons.

Some practical solutions

Visual aspects of monument conservation demand that on one hand enduring alterations of the building's substance have to be avoided and that on other hand technical means should be visible as less as possible. Consequently, the number of absorbing materials and constructions suitable for permanent installation is much more limited than in other buildings, and movable elements are of particular importance. Therefore, some examples for permanent (1 – 6) and mobile (7 – 11) solutions shall briefly be listed, more details are to be found in (J. Meyer, 2002):

1. wooden floor over a small cavity in the area covered by pews,
2. floor made by plates of porous stones like basalt-lava,
3. porous sound absorbing plates over a small cavity, covered by special acoustic plaster,
4. thin plywood plates over a small cavity, seamlessly painted,
5. slit absorbers installed at the underside of the pews or chairs
6. double-plate construction of gallery balustrades,
7. cushioned layers on the pews,
8. small cavity filled by mineral wool behind tapestry and paintings,
9. curtains stored in chests and being able to be drawn up (or down) with some distance in front of a wall,
10. free-hanging curtains – if possible doubled with some distance - fixed at traverses and being able to be taken off and stored in movable chests,
11. movable walls like paravents with absorbing back and reflecting front for generating shortly delayed reflections towards singers and musicians.

Sound absorbing plaster directly coated onto the underground and carpets are less suitable in most cases as they absorb only rather high frequencies.

CONCLUSIONS

Gothic churches show a characteristic reverberation behaviour that is related to the architectural style and creates a typical sacral atmosphere. Therefore following the generally accepted rules of monument conservation, it has to be demanded that in those churches the acoustical properties should be maintained or restored in such a way that they fit with the typical range described. These acoustical aspects have to be heeded with the same seriousness as the visual aspects that often exclusively are taken into consideration by conservators. Nevertheless in many cases, there exist technical possibilities to reach better acoustic properties particularly for organ and choir music. On the other hand, one should totally dispense with technical means if it is not possible to reduce the reverberation as much as necessary for getting convenient properties.

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