

Acoustic concert halls

(Statistical calculation, wave acoustic theory
with reference to reconstruction of Saint-
Petersburg Kapelle and philharmonic)

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1. Theories

Today there is no common theory explaining all acoustic processes in rooms. We can select three main theories. It is statistical theory, geometrical theory, wave acoustic theory.

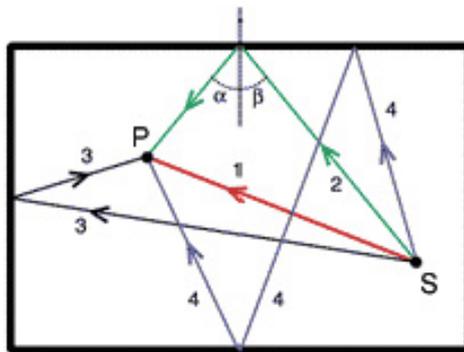
1.1 Statistical theory

This theory consider acoustic processes in halls as gradual recession of energy of waves repeatedly reflected by this rooms barrier. This recession occurs after cancellation of a source of the sound. This process is counted ceaseless in first approximation. It can be represented in linear scale as an exhibitors, and in half-logarithmic scale as straight line. It is necessary to explain, why architectural acoustics gives more attention to transitive (non-stationary) process, than to stationary process (process of the established fluctuations) before analyzing process of sound energy recession in room. Non-stationary process begins after cancellation of sound source. It consists in gradual recession of sounding because of losses of sound energy. It is an echo, or reverberation.

Reverberation essentially influences quality of both speech, and musical sounding. Excessive duration of reverberation leads to the fact that sounding of new syllables of speech sound on a background of the previous fading syllables. The legibility of speech is worsened thus. At a short echo the legibility of speech is quite satisfactory, but such soundings is perceived also as a defect, is especially at recitation. The process of an echo at hearing music has even greater value. Each musical phrase represents a sequence of sound pulses. The tightened echo breaks the perception of music.

1.2 Geometrical theory

The geometrical (beam) theory of acoustic processes in halls is based on laws of geometrical optics. Movement of sound waves is considered similarly to movement of light beams. According to laws of geometrical optics the corner of reflection β is equal to a corner of falling α at reflection from smooth surfaces. The falling and reflected beams lay in one plane. It is true, if the sizes of reflecting surfaces of wave are much longer than wave's length and the sizes of surface's roughnesses are much smaller than wave's length.



Delay of the reflected sound waves is important for acoustical perception. The sound radiated by a source, reaches a barrier (for example, walls) and is being reflected from it. This process is repeated many times. A part of energy is lost at each reflection. The first late pulses come on spectator's places (or in a point of a microphone) after reflection from a hall ceiling and walls.

The direction of initial reflections arrival is also important. If late signals (all early reflections) come to the spectator from the same direction as a direct signal the hearing almost does not distinguish a difference of sound quality in comparison with a direct sound only. It seems, that the sound has not volume. Meanwhile arrival of only three late signals on different directions

creates effect of spatial sounding, despite lacking a process of reverberation. Quality of sounding depends on a direction and a sequence of arrival of late sounds. If the first reflection comes from the frontal side sounding is worsened. If the first reflection comes from the back side sounding is worsened more sharply.

1.3 Wave theory

The echo is considered as attenuation of consecutive lines of the reflected sound pulses which are radiated by a source of a sound in the statistical theory. It is meant, that the form of pulses which is set by a source of a sound remains constant at reflections. Such representation causes doubts. Closed air volume of a room, if its sizes are commensurable with waves length is necessary to be considered as oscillatory system with the distributed parameters which has a spectrum of own (resonant) frequencies. Own fluctuations are the only once to take place in system after cancellation of a source of the sound supporting compelled fluctuations of air in room. They fade in process of absorption of energy. Residual oscillatory process which is earlier imposed by action of compelling external force can not exist in the phenomenon of reverberation. The echo is an own fading fluctuation of an air volume with the frequencies dependent on sizes and form of room.

1.4 Theoretical bases of estimating acoustics of concert halls

The perception of sound by a person is a very complex process. It is required to take into account many factors to create conditions for perception of speech and music in a hall, such as:

- Reverberation time;
- Diffusion of a sound field (homogeneity);
- Articulation;
- Clearness, Spatiality, Loudness, etc.

1.4.1 Reverberation time

Decay of sound energy occurs during some time after deenergizing of sound source in premise as the sound waves, while falling on internal surfaces of a room are only partly absorbed. The significant part of sound waves is reflected in volume of a room.

Reverberation time is the phenomenon of residual sounding in premise after deenergizing of a sound source.

At the end of the last century U. Sabin established, that reverberation of room basically defines its acoustics quality.

Reverberation of room is estimated on time at within which intensity of sound decreases by one million times. This is standard time of reverberation.

Decay of sound intensity one million times corresponds to decrease of sound intensity level by 60 decibels. Optimal time of reverberation is a standard time of reverberation, at which acoustics of a hall appears the best. The premise becomes excessively booming if reverberation time of this premise exceeds optimum value. It especially spoils speech halls as hollowness impairs legibility of speech.

Sounds in premise are devoid of necessary extent, if time of reverberation is less than optimal value. It has a bad effect on acoustics of musical hall.

Value of optimal reverberation time depends on volume and purpose of a hall. Optimal reverberation time will differ in halls with identical volume, but with different purposes. Optimal time of reverberation will be also different in halls with identical purposes and various volumes.

1.4.2 Diffusion of a sound field (homogeneity)

The sound field in room is a result of superimposing of the direct and reflected sound energy available inside. Therefore character of a sound field depends on distribution of these kinds of sound energy on the room's volume. As a rule, energy which goes directly from a source is distributed equally in a room volume. Therefore basically character of a sound field is defined by distribution of the sound energy reflected from internal surfaces of a room. The reflected sound waves can be either useful or harmful.

Useful sound waves do not cause formation of standing waves, focuses and an echo. In this case those waves intensify of sound that it is especially important for the places removed from a source of a sound.

Practically in all rooms useful reflections are reflections from a flat surface of a ceiling which are directed to a spectator's zone of arrangement. So are reflections from surfaces of the lateral walls located at a level of sitting people's heads and from both flat and convex surfaces, taking place near a source of sound.

Concave surfaces and surfaces which are strongly removed from spectators, as well as parallel, well reflecting surfaces can create reflections which break diffusion of sound field (focuses, an echo, standing waves). These reflections are harmful.

Formation of focuses in rooms can make occurs at reflection of a sound from concave surfaces of walls and ceilings. According to position of acoustics requirements availability of focuses is inadmissible in a zone of spectators places, even up to height of 1,5 meters above heads of sitting spectators. If focuses are located above this zone they are not dangerous. Therefore in a ceiling concave surfaces of small radius of curvature can be made.

The ceiling can be concave with radius of curvature of its surface to exceed the height of room more than in 2 times. In this case focuses lay outside of limits of the room, below its floor.

Frequently the back wall of the room is made concave. At definition of its curvature it is necessary to use the same reasons, as at designing ceilings. At calculations the radius of curvature of a back wall should be compared to full length of the room taking into account a stage and a platform if they are available.

1.4.3 Articulation

Process of acoustic perception of speech is considered from the point of view of correct transfer of the semantic information contained in a speech signal. Hence the basic subjective factor determining quality of speech transfer in room is the clearness of speech. Articulation tests which allow to receive clearness in percentage are applied to determine clearness of speech. During tests a test text is transferred in the room with the help of announcer (speaker) or a tape. And spectators write down this text. It is ratio of phonetic elements written down correctly on hearing to total quantity of transferred ones that defines percentage of legibility.

Reliability of clearness estimation results raises with increasing a number of spectators. At the same time the increasing of quantity of spectators results in organizational and economic difficulties, as well as time makes the test longer. The latter circumstance has a bad effect for results as it causes a decrease of spectators and speakers attentiveness, because they are overtired. In the standard rather small group of spectators (20 person) is accepted, that allows to receive statistically reliable results. For the hall with capacity more than 2000 person 2 groups of spectators are involved. If capacity of a hall is more than 5000 person 3 groups of spectators with 20 persons in each group are involved. For reduction of tests time in each group cyclic change of places be carried out each spectator passing from a seat place occupied by him to a place which serial number is one unit bigger. The spectator taking the last place passes to

the first place. The cycle comes to an end, when each spectator has visit (seat down) all places of tests. Places, on which the clearness is defined, should be distributed in regular intervals in a hall, and their quantity should correspond to number of spectators participating in the tests.

It is not only the quantity of spectators that influences greatly the results of defining speech clearness, but also other factors such education, job, social status as well as memory and quickness of mind. In the standard, for reduction of these factors influence articulation tables of syllables as the text for test are used. The age of spectators is limited by age of 35.

1.4.4 Clearness, Spatiality, Loudness, etc.

Clearness is the concept describing division of sounds of separate instruments or groups of instruments in time, is especial at fast passages, and in a sound of simultaneously playing instruments. Criterion of clearness is usually defined as:

$$C_{80} = 10 \lg \frac{\int_{0}^{80.Mc} p^2(t) dt}{\int_{80.Mc}^{\infty} p^2(t) dt}$$

where $p^2(t)$ - square of impact response of a room.

On the other hand, one of the important criteria of hall acoustics is criteria of spatiality. That criterion is usually defined as:

$$R = 10 \lg \frac{\int_{50ms}^{\infty} p^2(t) dt}{\int_0^{50ms} p^2(t) dt}$$

Spatiality is the concept describing sensation of the ratio between force of sound, coming to a place of listening from all directions (except for a direction from a source), and force of the sound coming from a source. Spatiality is the subjective parameter describing sensation of closed space. Usually these criteria define the quality of concert halls acoustics.

Loudness is the subjective concept describing loudness of a source of music playing fortissimo in relation to some expected loudness on a place of listening.

Balance is the concept for an estimation of loudness of separate instruments and groups of instruments in relation to the general loudness of an orchestra. Here many things depend on

experience of the spectator, on his knowledge of composition and his ability to exclude influence of a manner of playing.

Timbre is the concept describing perception of separate components of a sounds spectrum of a musical source on a place of listening. That is how properties of room change a typical timbre of the given source.

The common acoustic impression is the concept covering result of the general subjective estimating of acoustic properties of room on the place of listening. At listening in a hall non-acoustic factors can affect on the common acoustic impression.

Disturbing factors is the concept including all reasons, resulting in worsening of the common acoustic impression on a place of listening. It can be the phenomena of acoustic character (echo, flitting echo, infringement of localization of sound source, distortions of timbre, noise, imperfect playing) and non-acoustic character (a bad view of a platform, insufficient illumination, improper temperature, a draught etc.).

2. Practical part

At the present stage of architectural acoustics development the basic characteristics are: sound reflections structure reverberation time and criteria of spatiality.

2.1 Sound reflections structure

Among acoustics characteristics of premises the most important is the sound reflections structure, determined by its levels and delaying in regard to a direct sound, and also the direction of arriving to a reception point. This characteristic, being local, is closely coherent with all architectural parameters a space: with its size, shape, outlines and interior finish. Development of acoustics measurements methods with using of computer facilities allowed to analyze in details sound reflections structure on the basis of impulse responses registration in an assembly space.

In a general form the impact response $P(t)$ is defined as integral convolution:

$$P(t) = P_0(t) \cdot h(t) = \int_{-\infty}^{+\infty} P_0(\tau) h(t-\tau) d\tau$$

where $P_0(t)$ is an entrance signal (sound pulse raying in a premise); $h(t)$ - impact transitive function of a premise; τ - integration variable

Impact response $P(t)$ can also be determined experimentally. Impact measurements procedure is rather simple. The premise air volume is excited by a short sound impulse, the source of which is usually set on a stage or on a platform. The signal accepted by a microphone in a researched point of the premise is amplified and transferred on an oscillograph or tape recorded for a subsequent processing. The impact response in the given point of the premise gives us pulses arrival sequence relevant to a direct sound and separate reflections from surfaces of the premise.

Allocation of these pulses in time is determined by the premise's geometry and coordinates of reception points and the source of sound, and amplitude and frequency contents are determined by sound-proof and soundspreading properties of interior surfaces. At the impulse measurements it isn't difficult to take into account arrival direction of the most intensive pulses. Thus, with the help of pulse measurements it is possible to get a full picture of sound reflections structure in the given point of the premise.

For sound field stimulation of a premise usually broadband pulses of explosive type (shots, spark categories, breaks of thin shells) are used.

At present time there are two approaches to the reflections structure analysis received on the basis of the impact response. The first is a visual analysis of a structure of the impact response. And three registration types of the impact response are probable: direct response registration $P(t)$, registration of a square response $P^2(t)$ and, at last, reception on the monitor integrated characteristic of the response.

The visual estimation of oscillograms demands a wide experience, therefore its result to a certain degree is subjective. Nevertheless, such estimation is quite common in pulse acoustics research. The pulse oscillogram allows an experienced expert to judge acoustic quality of a place where it is received. On the basis of oscillograms such acoustic defects as an echo and flitting echo can also be revealed.

The second approach to the pulse responses analysis is connected with quantitative estimation.

Practical measurements

Some month ago, two favorite concert halls of Saint-Petersburg (Chapel Hall and Larger Hall of Philharmonic) received the study of acoustic characteristics. As an example, the results of experimental investigations of the Larger Hall of Philharmonic are given here.

The characteristics of hall are:

Number of spectators - 1350 people

Square of the floor – 1319 m²

Total internal volume – 24400 m³,

Specific volume - 18 m³ / man

Measurements of acoustic parameters were made in ten points of the hall according to international standard ISO 3382-98. Impact and sound signals were used for measurement of the reverberation time. It is necessary to note, that the data of reverberation time measurements of impact and sound signals in a normalized range of frequencies had a very high correlation.

The practical method consisted in the analysis of the hall using the special equipment: the adjusted generator created special noise (white noise) which through the amplifier was transferred to the dynamic and was distributed through the hall, then the sound was switched off and a microphone located in the hall a certain time after switching off fixed recession of sound pressure, this information was supplied to a computer and was analyzed, the result was given out as quantitative and graphic parameters.

On the fig 1 we can see, as example, of the results of registration $p^2(t)$ of sound signal.

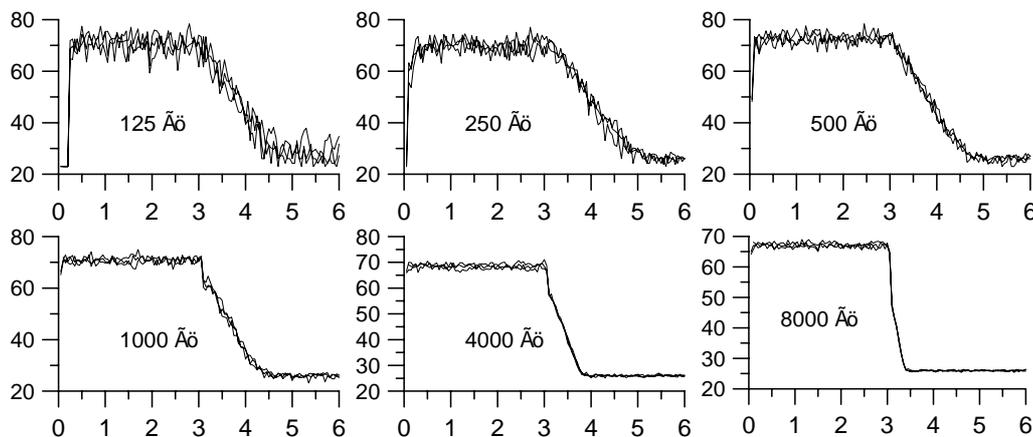


Fig.1. Example of the results of registration $p^2(t)$ of sound signal

These data were used for computation of the reverberation time. The results of computation of the reverberation time are presented on the fig. 2-4.

Standard reverberation time based on classical Sabian's definition, being the most widespread acoustics parameter, however, does not explain distinctions in acoustic conditions of separate places of a hall. Fluctuations of reverberation curves at a standard method of measurement complicate their analysis, in order get to sufficient accuracy at the reverberation time estimation if is necessary to average a number of curves.

Besides using the impulse response for measurement of reverberation process can define the important acoustics parameter such as early reverberation time (decay intensity of sound

energy from 0 up to a minus 5 dB). On the basis of such curves it is possible to receive with the big accuracy reverberation time and other parameters reverberation process.

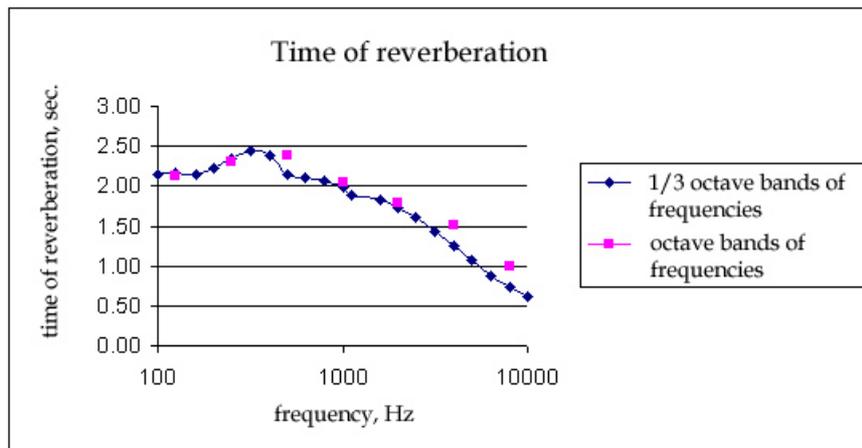


Fig.2 Reverberation time RT_{60} calculated for different bands of frequencies

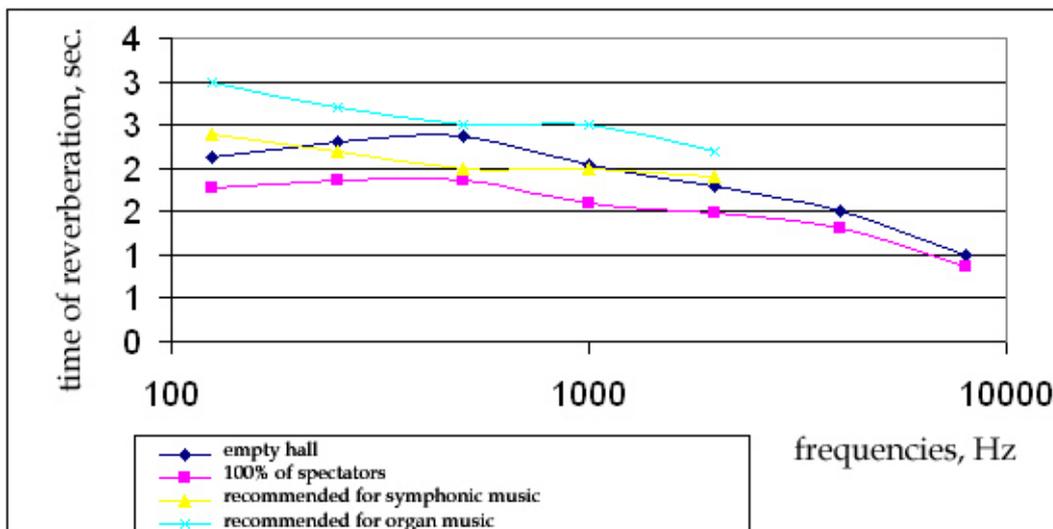


Fig.3. Reverberation time RT_{60} calculated for octave bands of frequencies (shutting off sources of constant noise)

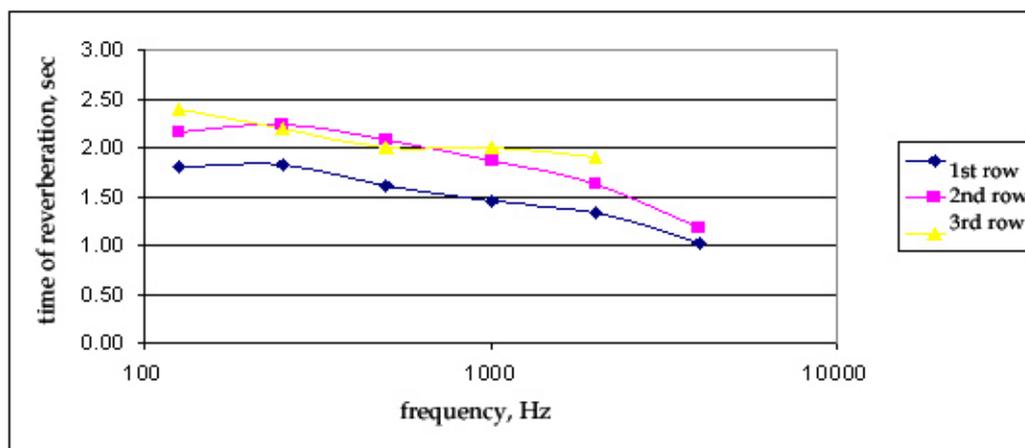


Fig.4. Reverberation time RT_{60} calculated for octave bands of frequencies (impulse response)

Criterion of clearness was defined on the data of the impulse response.

Average values of clearness transparency and recommended range are given in tab. 1.

Table 1.

Average values of clearness of musical sounding on the hall C_{80} , dB

| Frequency, Hz | 500 | 1000 | 2000 | 4000 | 8000 |
|-------------------------------------|-------|-------|-------|------|------|
| Empty hall | -1.50 | -1.07 | -0.46 | 0.38 | 3.18 |
| Recommended values C_{80} , dB | -1÷+3 | -1÷+3 | -1÷+3 | – | – |

Reverberation time – RT_{60} . Values of reverberation time measured for empty hall (in view of an error of measurements) correspond to recommended values for halls of symphonic music.

Average values of time of reverberation in octava and 1/3 octava strips of frequencies are given in tab. 1

Recommended values of an index of clearness lay within the limits of -1...+3 dB.