Distribution of free path length as an indicator of the room shape and diffusion of reflections

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Each geometrical form of room is characterized by a certain specific form of free path length distribution. Its shape can be calculated using the ray-tracing analysis. In the global form of the distribution curve, some characteristic shapes can be recognized which are consequence of room geometrical form at micro and macro level. The distribution of free path length can be quantified by some statistical parameters, such as mean value, relative variance, different momentum, etc. Value of all these parameters is dependent of the room geometrical form and nature of reflections at boundary surfaces. In this paper the possibility to use the free path length distribution in prediction and analysis of a room acoustic response is discussed. Variations in the distribution shape and calculated values of its statistical parameters induced by variations in the reflection process are also shown.

1 Introduction

Room acoustic response is influenced by two geometrical properties: global geometrical shape and reflective properties of the interior surfaces (scattering coefficients). These can be indicated as influence at macro and micro level of room geometry.

Influence of geometrical properties on the room acoustic response can be quantified, in general, by the deviation of measured reverberation time values from predicted values obtained using classic statistical mathematical model (Sabine or Eiring formula). Such deviation should be the consequence of factors which statistical theory can not "see", as volume shape and scattering are.

Each geometrical form of the room is characterized by a certain specific shape of the free path length (FPL) distribution. In this sense, global shape of the distribution can be used as specific indicator in prediction of the acoustic response of a room.

Different software tools for prediction of acoustic response in a room by geometrical modeling allowed more detailed insight into the sound field energy movement through room volume. As a result of such calculations, FPL distribution can be obtained for particular room geometry. This can provide analysis of relations between structure of sound paths and geometrical characteristics of a room.

The main objective of this paper is to illustrate room geometrical properties as a factor influencing the acoustic response, and some possibilities to predict this influence by global shape of the FPL distribution.

2 Some previous research

In previous paper of the same authors some form of influence of geometrical properties on room acoustic response were verified [1]. Analysis is based on measurement in the large number of Serbian orthodox churches. The results have shown significant dependence of acoustic response on the church shape. This can be illustrated with one example presented at Fig. 1. Responses shown in diagram are obtained in two extremely different types of church shapes: type 1 with high indentedness and type 2 with minimal indentedness of nearly simple parallelepiped shape.

![Figure 1: Comparison of measured T30 in churches of type 1 and type 2 (the best fit lines for all measured results) and values obtained by Sabine formula (shaded area) [1]](image_url)
Introducing the parameter "shape factor" of the room, defined as:

$$ k = \frac{3 \sqrt{V}}{2 \sqrt{S}} $$

(1)

The basic Sabine formula was transformed to

$$ T = \frac{0.16}{\alpha} k^2 \sqrt[3]{V} $$

(2)

The shape factor is a non-dimensional parameter and has a constant value for each particular geometrical form. Its value does not change with scaling of the room size. The transformation reveals reduced influence of geometrical characteristics of room shape in statistical approach of sound field modeling. According to the calculated values of $k$ for two geometrical types of churches, interval of T30 values are presented in the diagram with shaded area.

The same influence of the geometrical shape was detected both in real churches and in their software models [1]. This proved the influence of room geometrical properties on acoustic response as a factor inherent both in real sound field and in its geometrical model.

Based on such conclusion, further investigation was focused on the experiments with software models concerned relations between room geometry and its acoustic response.

### 3 Acoustic response in various room geometry

For exploring the room geometry influence on acoustic response, large number of software models was prepared. They are organized in several groups. First group were consists of rooms with simple geometrical shape as parallelepiped, cube, prism, ellipse, sphere, and different modification and combination of them. Second group consists of basic parallelepipedic form, but with disturbed regularity by changing proportions or symmetry in them. In third group were rooms with complex form, all made as some combination of plane and spherical surfaces. At last, some models of real concert and theater halls, worship spaces and sport halls were also prepared.

The simulation of sound field in prepared models was realized with the absorption coefficient uniformly distributed through all surfaces, with value set at 0.1. Such setting minimizes absorption influence on room acoustic response, and allows detecting any influence of room geometry on sound field. In the same time, scattering coefficient value was changed, but uniformly distributed at all room interior surfaces.

For all prepared models of different rooms impulse responses were calculated using ray tracing simulation. Simulations were done for different values of scattering coefficient (SC), which varied in the range from 0 to 1 in seven steps (0, 0.1, 0.25, 0.35, 0.5, 0.75 and 1). The reverberation time in all rooms were calculated from these impulse responses. To allow comparing of the results, each calculated value of the reverberation time was normalized to that obtained by Eyring formula for the same room. Results of such calculation are presented on the Fig. 2. Diagram shows deviation of calculated reverberation time from its statistical values for all models as a function of SC.

It is evident from the diagrams that in rooms with different shapes deviations of reverberation time from its statistical value may be positive (larger value of T30 in model than obtained by statistical theory), or negative (smaller values than by statistical theory). All diagrams shown in Fig. 2 are calculated for absorption coefficient value 0.1, and for octave frequency band at 500 Hz, where dissipation in air is negligible. For higher frequencies the deviations appearance should be somehow changed.

The deviations in the diagram depend on global room geometry and scattering coefficient. In many curves, presented in Fig 2, some typical classes of curves with specific trends in deviation as a function of SC value can be recognized. Four such classes are represented by colored curves in Fig. 3. The same color coding is also used in Fig. 2.

First class contains rooms in which deviation from statistical value is positive for all values of SC (red line). In second class are rooms which have the largest value of deviation, up to 30% less than statistical value (blue line). Such maximum deviations are for SC value

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**Figure 2:** Relative value of the reverberation time as a function of scattering coefficient for all analyzed rooms.
in region between 0.2 and 0.4. In third class are rooms showing both positive and negative deviation from statistical value, but limited in interval of ±5% (dark green line). At last, fourth recognized class of rooms with response opposite to the first class, with values smaller than statistical ones, with largest deviation for around SC=0.5 (light green).

4 Free path length distribution in acoustic response analysis

Acoustic response of a room, in general, is determined by its geometrical characteristics, size, shape and scattering, and amount of absorption in it. All possible differences in room response can originate only according to the differences in these two domains, and their mutual dependence. The response is usually determined by interactions of both factors and change of absorption in a room would have different influence in different room shapes. This relation between room properties and its response is schematically illustrated in Fig. 4.

The acoustic response of a room can be described with group of parameters, all derived from the impulse response. Consequently, the parameters are also function of the room geometrical and absorptive features, and their mutual dependence. To identify isolated influence of geometrical shape on a room response, FPL distribution can be considered as a complex quantity which depends purely on geometrical factors, indicated with black arrow in Fig. 4. Basic idea of various room models analysis was to quantify and characterize FPL distributions in them, and so define their possible relations to acoustical parameters calculated from the impulse response.

5 General characteristics of the FPL distribution

The FPL distribution in various rooms has different, sometimes very complex form. In distribution shape there are some characteristic forms and their variations which can be recognized. Nearly all distributions have one or more local maximums. The maximum can have different shape: asymmetrical form with exponential decay to the right, symmetrical form with exponential decay, or Gauss-type form. The maximums can be very pronounced and sharp, or rounded at the top. Beside the appearance of maximums, the FPL distribution in a room can have various probability levels at short paths region. In rooms with complex geometrical form the FPL distribution is superposition of such elements.
demonstrating second class of response (blue line in Fig. 3), FPL distributions are characterized with pronounced asymmetrical maxima. This feature of distributions reveals some disproportions in room dimensions and appearance of large parallel interior surfaces among which most of the sound energy travel.

Rooms which response belongs to the third class, with reverberation time, generally, very near to the statistical value, concentration of paths is in region less than 0.5. Maximum probability values are less than 0.02.

At last, fourth class of room response is characterized with pronounced symmetrical maxima, in most of rooms with maximal value less than 0.2 and lower probability of very short paths.

Experiments were made to explore the influence of SC variations on the FPL distribution. The SC value was changed in several steps from 0 to 1. One example of the result is shown in Fig. 6. The diagram shows that changing of the SC value does not make changes of general distribution shape, but only of relative relations between different path lengths probability. This feature was found in all models.

The FPL distribution can be quantified by various standard statistical parameters, as, for example:
expected value, mean value, variance, median, various momentum, etc. These parameters can be also correlated to room acoustic response. As an illustration, in Fig. 7 mean values calculated from the FPL distribution in the models is presented, normalized to statistical mean free path value. It is obvious that same trends exist as in results of reverberation time from Fig. 3.

Figure 7: Variation of mean value calculated from FPL
distribution for various rooms, normalized to statistical
value of mean free path.

6 Some practical examples

Some demonstration of the FPL distribution analysis
can be illustrated in some examples. Selected was the
room with parallelepipedic shape, but with disturbed
symmetry introducing nonparallel surfaces, as
illustrated with small picture in Fig. 8. According to
the statistical theory, room with such shape, and also
with small value of absorption coefficient, provide
conditions for diffuse sound field. The FPL distribution
for the room is calculated, and also presented in Fig. 8.
It has three symmetrical maximums corresponding to
mean distance of opposite surfaces. These maximums
of probability correspond to the main flows of sound
energy in the room. With uniform change of SC value
for all surfaces the distribution keeps its general shape,
but relative relations between probability values at the
maximums are changing.

As a consequence, there are also differences in
 calculated mean value of free paths and reverberation
time, normalized to their statistical values, as presented
in Fig. 9. The differences are small, less than 7%
which is in harmony to the statistical theory
expectation.

Effects of absorption materials in a room depends on
room shape and, consequently, on FPL distribution.
With the same increase of absorption in room, different
deviations of reverberation time from statistical value
appears in different room shape. For room shape
presented in Fig. 8, deviation of reverberation time as a
function of SC is presented in Fig. 10. Diagrams
present deviation for three different values of
absorption coefficient uniformly distributed at all
surface (black lines), and for two different values of
absorption coefficient applied only at one, auditorium
like, interior surface (red lines).

Figure 8: Distribution of free path length for various
values of scattering coefficient (uniformly distributed
to all surfaces in the room)

Figure 9: Variation of mean value and T30 normalized
to their statistical values.

Some redistribution of energy flow in a room can be
realized with adequate application of SC around the
surfaces in the room. At Fig. 11 some examples of
different SC values are presented. Six different
combinations of SC values introduce changes in FPL
distribution shape, what is a quantifier of differences in
energy flow through the room. Relative changes in
peak values are evident in the distribution curve, were decrease in one maximum produce increase in other. Influence of nonuniform changes of SC value at surfaces around the room from Fig. 11 is shown at Fig. 12. Variations are presented for FPL mean value and for reverberation time value, for the same combinations of SC values as shown in Fig. 11.

Figure 10: Deviation of reverberation time value compared to its statistical value: uniform changing of absorption coefficient (black), and change only at one room surface (red)

Figure 11: Distribution of free path length for various combinations of scattering coefficient at the room surface.

7 Summary

The free path length (FPL) distribution in a room can be in everyday practice an additional source of information in effort to understand or to control the acoustic response. Possible applications of the FPL distribution analysis and knowledge about its correlation with room acoustic response can be in three important branches of room acoustics: in acoustic design, in interpretation of measurement results and in calibration of software models for simulation and prediction of sound field.

Application of knowledge about FPL distribution and its correlation with room acoustic response can be used in acoustic design in several ways. First, in rooms where classic intervention of acoustic design is not allowed, as for example in churches designed in traditional style where implementation of standard absorptive materials is not applicable, FPL distribution analysis can show the way toward possible geometrical intervention for modification of acoustic response. Further, analysis of the FPL distribution can gives information about potential influence of geometrical modifications at micro level, if global room shape is proposed. At last, data obtained from FPL distribution can be used in effort to optimize the usage of absorption in proposed geometrical forms of the room.

Figure 12: Variation of FPL mean value and reverberation time in the room, normalized to their statistical values, for some combinations of scattering coefficients values at the room surfaces.

References

[1] D.Sumarac Pavlovic, M.Mijic, "An insight into the influence of geometrical features of rooms on their acoustic response based on results of measurements in Serbian orthodox worship spaces", submitted for publication