Reverberation Radius in Real Rooms

Miomir Mijić and Draško Mašović

***Abstract* — A reverberation radius, also called a critical distance, is an important parameter in sound reproduction. Statistical approach gives a simple formula for its calculation, and some simple methods for its measurement were described in literature. To measure the critical distance in real rooms, a more accurate method is proposed. This paper is concerned with that method. Accuracy of the method was analysed and the results of critical distance measurement in several rooms of different sizes and acoustical characteristics are presented.**

***Keywords* – critical distance, reverberation radius, room acoustics, sound reproduction.**

I. INTRODUCTION

REVERBERATION radius in a room, or a critical distance as usually named in audio literature, is the distance from a sound source in the room at which the level of direct sound, in the process of its wavefront spreading, becomes equal to a reflected sound level. For a good perception of sound information the listener must be inside the reverberation radius around the sound source. That is why the name "critical distance" has been introduced and it is an important parameter in sound reproduction.

The value of critical distance is usually calculated by using the basic relations of the statistical model of sound field. This leads to the simple and practical expression usually given in textbooks [1], [2]:

$$r_c = 0.057\sqrt{\frac{\gamma V}{T}}\ , \qquad (1)$$

in which r_c is critical distance in (m), V is the room volume in (m^3), T reverberation time in (s) and γ directivity factor of the sound source. The formula (1) is valid along the axis of the source where it gives a maximum intensity.

The statistical model of sound field in rooms assumes a homogeneous and diffuse sound field. This is valid in rooms when the average absorption coefficient is low enough. In real rooms that is not always the case, especially in recording studios and acoustically designed rooms for speech (classrooms, amphitheatres). Critical distance in them can be significantly different from the one theoretically estimated by formula (1).

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There are several methods for measuring critical distance described in literature, and all presume a homogeneous and diffuse sound field. They are based on two measured values of sound level: one far enough from the sound source where a reflected sound confidently dominates, and another one near to the source where a direct sound confidently dominates. The simplest procedure in literature is called "measurement by phonometer" [3]. At first, a sound level is measured very close to the sound source, so that a reflected sound is negligible compared to a direct sound. Then a measuring microphone is moved away from the source in a specified direction, and when a sound level becomes sustained at one value (a reflected sound starts dominating over a direct one), that distance is considered to be the critical distance. The main disadvantage of such a procedure is the uncertainty of determination of the place where a reflected sound becomes equal to a direct one. The method can be acceptable only when the critical distance is measured roughly.

There is a somewhat more precise method which also includes the measurement of sound level in a near and far sound field [1]. Assuming a spherical wavefront, the critical distance is calculated using formula:

$$r_c = r_r \cdot 10^{(L_r - L_R)/20}\ , \qquad (2)$$

where r_r is the reference distance from the source at which near field measurement is made, L_r is a sound level at that distance and L_R is a sound level in a far field.

One of the problems of using this method is that the first measurement is made very close to the source (recommendable at few tenths of centimetres where a direct sound dominates for sure). If the microphone is too close to the source whose dimensions are unnegligible, the wavefront at that point is not spherical, so the law by which a sound level declines with the distance is different from that for a point source. If the microphone is placed too far from the source, domination of a direct sound is not guaranteed. There is also a problem with the measurement of sound level in a far field, because in some circumstances a direct sound is not negligible and affects the total sound level even at considerable distances. This is the case in small rooms with great absorption, and such are most music studios. Influence of the direct sound grows when the source is directional.

Methods of critical distance measurement considered in literature assume that statistical theory is valid, according to which a reflected sound level is constant across the room. In real rooms this is not the case for a few reasons. First, a homogeneous sound field is hard to achieve in reality. The level of reflected sound in real rooms usually declines with the distance from the source. The literature presents the so-called revised theory of statistical model, which takes this fact into account [4]. Second, in rooms with a small reverberation time, that is with relatively small energy of the reflected sound, variations in the structure of the first reflections across the room can have significant influence on the reflected sound level, and consequently on the critical distance. Finally, resonant frequencies of the room and generating standing waves can also influence the sound level at low frequencies.

Standard methods for impulse response measurement in the room, used in everyday practice, enable a more precise analysis of direct sound zone in real rooms. This paper presents a method for determination of critical distance, based on recorded impulse response. The method was used for measurement of critical distance in a few real rooms, chosen so that a wide range of volumes and acoustical characteristics is covered. Results are used to analyse errors in critical distance estimated by the statistical theory, i.e. formula (1).

II. Proposed Method for Critical Distance Measurement in Real Rooms

The method described here is based on the implementation of some of the common techniques for recording of impulse response in rooms (MLS, sweep, impulse excitation). That is a standard procedure carried out in a relatively simple way. In a recorded impulse response it is possible to determine in time domain the boundary between signals of direct and reflected sound.

Based on that, for each point around the sound source where the impulse response is recorded, the energy ratio of the direct and reflected part of impulse response can be calculated. By repeating the recording of impulse response at various distances from the sound source, in each record the ratio of the direct and reflected part of energy can be found.

Over the set of measured values of direct and reflected sound ratio, realised along one radial direction departing from the sound source, it is possible to fit the curve which represents the variation of the ratio as a function of distance. The assumption has been made that the wavefront is spherical, and the energy of direct sound has an exponential decay with increasing the distance. If a reflected sound has a constant level through the room, as defined by the statistical theory, the curve of direct and reflected sound ratio (difference of their levels) also has to show an exponential decay in its initial part. Interpolation accuracy depends on the number of available values measured on different distances from the source. A larger number of measuring points gives a more accurate interpolation. In the interpolation the exponential curve is assumed and the minimum mean square error method is used. The value of critical distance is determined as the distance from the source at which the interpolated curve of direct and reflected sound ratio approaches 0 dB value. Beyond that point, in a far field, direct to reflected sound ratio has negative values.

For this procedure two programs have been developed in MATLAB for necessary calculations. The first calculates the direct and reflected sound ratio for each recorded impulse response, based on manually determined their boundary in time. The second program carries out the interpolation of exponential curve and calculates the value of critical distance, as a point where the curve crosses 0 dB.

The advantage of proposed method for critical distance measurement is in the fact that at points where the impulse response is measured neither direct nor reflected sound should dominate. Accuracy of the result depends only on the capability for precise determination of the boundary between the direct and reflected sound in the recorded impulse response. Accordingly, the risks of measuring in the near field of the source, or the insufficient domination of reflected sound at greater distances from the source, are minimised.

III. Analysis of Proposed Method Accuracy

The proposed method for critical distance measurement includes several factors that can affect its accuracy. The first cause of error is the difficulty to recognise the point on time axis in the impulse response where the boundary between the direct and reflected part is. In this method that boundary is determined visually over the diagram of broadband impulse response, and it is later used for all octaves. There is always some small interval of time the loudspeaker membrane takes to settle after excitation (speaker's intrinsic reverberation). It extends the duration of direct sound and sometimes can overlap with the beginning of reflected sound. Accuracy in determination of the boundary between direct and reflected sound can affect the result of measurement. As an illustration, Fig 1 shows an impulse response recorded in a room, 1.5 m from a speaker. Because of the speaker's intrinsic reverberation and fast coming of some reflected energy, exact position of the end of direct sound is not easily recognizable.

In order to examine the effect of variability in the determination of direct sound boundary, the direct and reflected sound ratio of the impulse response shown in Figure 1 is calculated for several chosen boundaries, varying from 1.5 ms to 4.5 ms. The results are given in Table 1. Variations of direct and reflected sound level ratio, as a function of a chosen direct sound duration, are negligible in the highest analysed octave. They become more significant at lower frequencies, and in octave 125 Hz they are about 3 dB. However, for durations of direct sound between 2.5 ms and 3.5 ms variations are small. Thus the analysis shows that the speaker used in this experiment has the duration of emitted direct sound about 2.5 ms, but small variations in the chosen position of the boundary toward the reflected part of impulse response do not affect the result significantly.

The second cause of potential errors comes from the fact that the critical distance is calculated from the acoustic centre of the source, i.e. the central point around which the wavefront expands. When a speaker is used as the source, its dimensions are not negligible to the wavelengths of emitting sound, so the wavefront in its vicinity is not ideally spherical. The acoustic centre of the speaker is usually positioned several centimetres inside the speaker cabinet, depending on its construction. That can produce an error when calculating the distance between measuring points and the source and consequently in the calculation of critical distance.

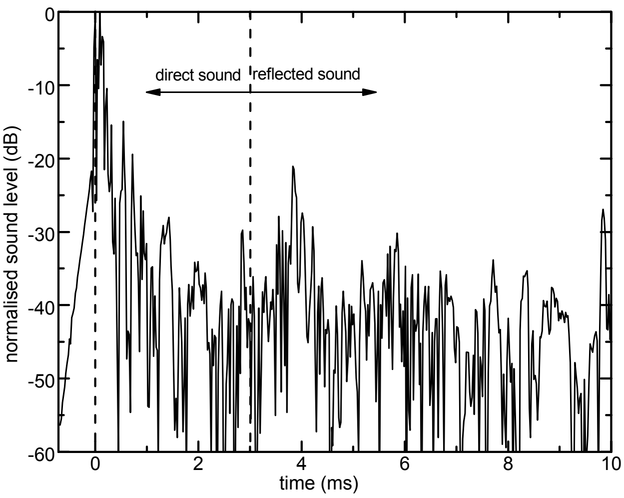

Fig. 1. The beginning of a recorded impulse response (the first 10 ms).

TABLE 1. THE EFFECT OF DIRECT SOUND DURATION ON DIRECT AND REFLECTED SOUND RATIO IN DECIBELS.

octave	***1.5 ms***	***2.5 ms***	***3.5 ms***	***4.5 ms***
125	-10.82	-8.06	-8.23	-8.42
250	-5.24	-4.35	-4.11	-3.50
500	-3.54	-4.02	-4.00	-4.01
1000	-1.06	-0.93	-0.87	-0.48
2000	1.92	1.86	1.93	2.38
4000	5.36	5.37	5.40	5.67

The third cause of potential errors comes from the fact that each record of impulse response is made with a limited dynamic range of the signal. That is why the determination of the impulse response end, i.e. the end of the period of time in which reflected energy comes, can also potentially cause some error in the measured value of critical distance. It is experimentally shown that with a dynamic range over 40 dB small variations in the chosen location of reflected sound end do not affect the calculated value of reflected sound level.

The interpolation of the curve is more accurate when the number of measuring points is greater. Variations of critical distance value in regard to the number of measuring points are examined in case of one of the analysed rooms. The impulse response recording is made at eight points with the first at a distance of 0.5 m from the speaker and each of the following at a 0.5 m larger distance. The difference between critical distance values obtained by the interpolation over all of the eight points and over merely three of them is within the limits of ±3 %.

The deviation of measured values from interpolated direct to reflected sound ratio curve is less than ±2 dB, and standard deviation is between 0.5 dB at high and 1 dB at low frequencies. According to the inverse square law of spherical wavefront spreading, the expression follows:

$$\frac{J_{dir}}{J_{refl}} r^2 = const. \qquad (3)$$

where J_{dir} is the intensity of direct sound at the distance r, and J_{refl} is the intensity of reflected sound. When this expression is applied for critical distance, it can be estimated that direct and reflected sound ratio variation of +1/-1 dB causes the change of critical distance value of about –11/+12%. This result gives the interval of error which the results of proposed method have. Consequently, the value measured in the proposed method is somewhere in that interval around the obtained value.

IV. MEASUREMENT OF CRITICAL DISTANCE IN SOME ROOMS

The measurement of critical distance was carried out by described method in four selected rooms of various sizes, acoustic properties and functions. Their volumes vary from 50 m^3 to 500 m^3 and reverberation times range from 0.4 s to 2.4 s. Thus selected rooms cover a wide range of characteristics of the rooms in which critical distance might be of interest. The description of measuring procedure carried out in the rooms and the obtained results are given below.

A. Procedure of measurement

In all rooms impulse response measurement was carried out using the MLS technique. Sampling frequency was 44.1 kHz, and sequence length was adapted to the length of impulse response in each room. Monitor speaker JBL *Control 1* was used as a sound source. In every room the loudspeaker was located in accordance with the purpose of the room. In the case of a control room, the speaker was in the place of one of monitor speakers, and in the other analysed rooms near the centre of the room, about 1.5 m above the floor. A standard measuring microphone was used as the receiver.

For all analysed rooms, the reverberation time and critical distance are calculated in six octave bands (125, 250, 500, 1000, 2000 and 4000 Hz). Octave at 8000 Hz was not considered due to a strong directivity of the speaker in this band.

In each room the impulse response was recorded at several distances from the speaker along its axis, from 0.5 m to the maximum possible distance in room in 0.5 m steps. Thus the set of direct and reflected sound ratio values was obtained for each room, over which the interpolation was performed and the critical distance was calculated.

B. Room 1

This room is rectangular, its dimensions are 8.5 x 8.3 x 4.3 m and its volume is 303 m^3. It is a classroom, but with no acoustic treatments in the interior. All four walls and the ceiling are solid, and the floor is covered with parquet. The only significant absorption is on upholstered chairs (backs and seats). Thus, the measured reverberation time is relatively long, with the value of about 1.7 s at middle frequencies. The speaker was located near the centre of the classroom, and its axis was directed along the longest axis of the room. The measured values of reverberation time and critical distance are shown in Table 2. The table also contains the theoretical values of critical distance calculated by formula (1).

TABLE 2. REVERBERATION TIME AND CRITICAL DISTANCE MEASURED IN ROOM 1.

frequency	*T*	*r_c measured*	*r_c theoretical*
125 Hz	1.58	0.53	0.80
250 Hz	1.88	0.84	0.80
500 Hz	1.80	0.97	1.03
1000 Hz	1.69	1.38	1.34
2000 Hz	1.49	2.02	2.02
4000 Hz	1.32	3.06	2.55

C. Room 2

Room 2 is a laboratory room which is also frequently used as a classroom. It has a rectangular parallelepiped shape, with dimensions 5 x 4 x 2.5 m and volume of 50 m^3. There is an intense acoustic treatment in it in the form of a suspended ceiling made of highly absorbing panels. The absorption coefficient of ceiling material is $\alpha > 0.9$ at middle and high frequencies. The side walls and the floor are hard. Measured reverberation time at middle frequencies is about 0.5 s. During the measurement of critical distance the loudspeaker was positioned in the centre of the room, and the measurement was carried out along its longest axis. Results are shown in Table 3. The same table shows the theoretical values of critical distance calculated by formula (1).

D. Room 3

This room is a control room of a music studio. Its base is slightly irregular in shape, but the room can be approximated by a parallelepiped of dimensions 6.5 x 8 x 3.2 m, and volume 166 m^3. There is a usual acoustic treatment for such a function of the room, so the reverberation time is about 0.4 s at middle frequencies. During the measurement the speaker was placed at the front end of the room, approximately in the line between the existing monitor speakers. Measurements are carried out along the central axis of the room. The results are given in Table 4. The same table shows the values of critical distance calculated by formula (1).

TABLE 3. REVERBERATION TIME AND CRITICAL DISTANCE MEASURED IN ROOM 2.

frequency	*T*	*r_c measured*	*r_c theoretical*
125 Hz	0.73	0.50	0.52
250 Hz	0.60	0.56	0.83
500 Hz	0.52	0.78	1.03
1000 Hz	0.43	1.09	1.27
2000 Hz	0.43	1.51	1.83
4000 Hz	0.45	1.77	2.21

TABLE 4. REVERBERATION TIME AND CRITICAL DISTANCE MEASURED IN ROOM 3.

frequency	*T*	*r_c measured*	*r_c theoretical*
125 Hz	0.55	0.51	1.00
250 Hz	0.50	1.14	1.15
500 Hz	0.39	1.99	1.64
1000 Hz	0.40	2.63	2.03
2000 Hz	0.39	3.49	2.93
4000 Hz	0.35	4.99	3.67

E. Room 4

The fourth room is a relatively large classroom. Its dimensions are 14 x 8 x 4.5 m and the volume is 504 m^3. It is not acoustically treated and all surfaces are hard. The measured reverberation time at middle frequencies is about 2.3 s. During the measurement the speaker was placed in the axis of the room, far enough from all walls, and recording of impulse response was carried out along its longest axis. The measurement results are shown in Table 5. The same table shows the values of critical distance calculated by formula (1).

TABLE 5. REVERBERATION TIME AND CRITICAL DISTANCE MEASURED IN ROOM 4.

frequency	*T*	*r_c measured*	*r_c theoretical*
125 Hz	2.43	0.84	0.83
250 Hz	1.51	1.20	1.15
500 Hz	2.11	1.24	1.23
1000 Hz	2.37	1.51	1.46
2000 Hz	2.29	2.12	2.10
4000 Hz	1.86	3.36	2.76

V. DISCUSSION

Rooms in which critical distance was measured cover a relatively wide range of sizes and reverberation times (volumes from 50 m^3 to 500 m^3 and reverberation times from 0.4 s to 2.4 s). Among the analysed rooms there is a control room with intensive acoustic treatment, a room with an extremely irregular distribution of absorption and a large room with minimum absorption and all surfaces made of hard materials. Thus, rooms selected for the analysis cover a wide range of possible circumstances in which the size of direct sound zone can be important.

The ratio of theoretical values of critical distance to the values measured in analysed rooms is graphically shown in Figure 2. The diagram represents all values from Tables 2 – 5, in four rooms and in six octave bands, 24 points in total. The line $r_{c\ measured} = r_{c\ theoretical}$ is also drawn in the same diagram. It is obvious that in the area of small values of r_c, below 1 m, measured values scatter around theoretically estimated values in both directions. Results show that dispersion is smaller for larger values of r_c , but then all measured values exceed a theoretical value calculated for the same room by formula (1). This fact verifies the integrity of „revised theory" which states that the level of reflected sound decreases with the distance from the sound source [3]. That theory explains why the critical distance estimated according to the statistical theory is slightly lower than actual values.

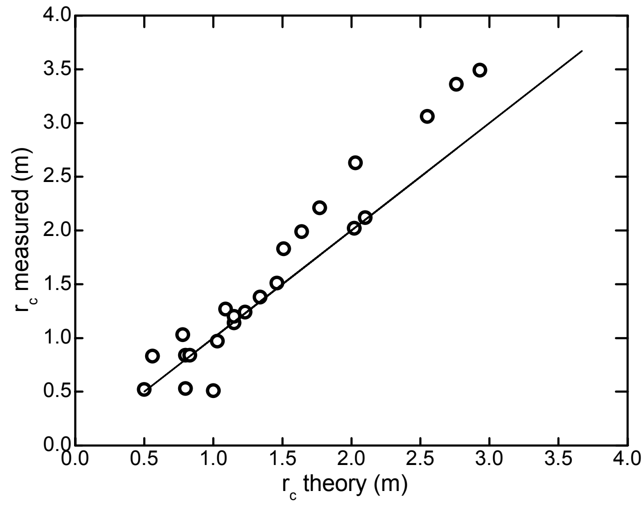

Fig. 2. The ratio between theoretical value of critical distance according to formula (1) and measured value.

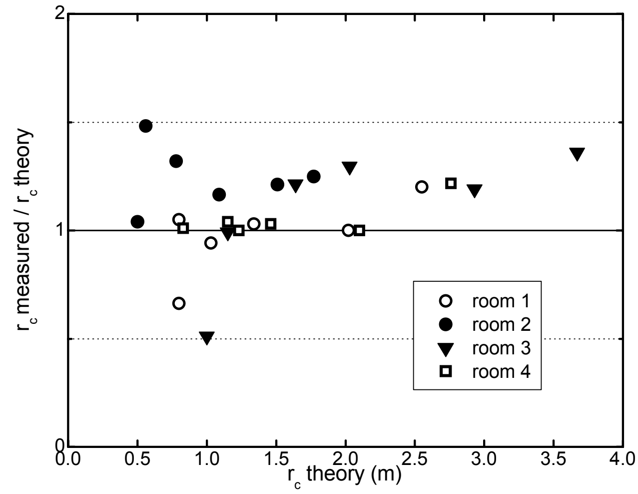

Fig. 3. Normalized measured value of critical distance as a function of theoretically estimated value by formula (1).

In order to quantify the relation between measured and estimated values more clearly, the normalization of ratio between the measured value of r_c and the theoretical value defined by expression (1) is introduced. The result is graphically shown in Fig. 3. Different symbols in the diagram represent values measured in different rooms. It is obvious from Fig. 3 that in room 2 all measured values are higher than theoretical. That is a room with a relatively short reverberation time (only 0.5 s) and a significantly irregular distribution of absorption materials (only on the ceiling). In room 1 four of six measured values are very close to theoretically estimated values. This is a large classroom with a reverberation time of 1.7 s.

In order to examine the possible influence of frequency on variations in the size of direct sound zone, the normalized values of critical distance measured in all four rooms as a function of frequency are shown in Figure 4. It can be seen in this diagram that at low frequencies, in octave at 125 Hz, the measured values of critical distance are close to, or lower than theoretical values. The largest negative deviation of measured values is also in this octave, reaching -50%. This can be explained by wave phenomena in the room, i.e. effects of standing waves. Under some circumstances the standing waves can make the level of reflected sound higher than theoretically expected, which will cause a lower value of critical distance. The largest deviations of measured values in higher octaves are about ±30%.

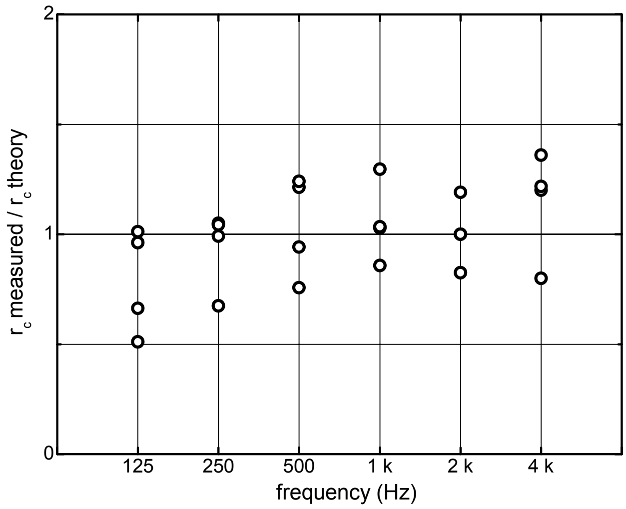

Fig. 4. Normalized value of measured critical distance as a function of frequency.

In an effort to further determine the factors which can affect measuring the actual values of critical distance, Figure 5 shows the deviation of normalized critical distance value measured in the room, as a function of reverberation time. It can be seen in the diagram that with increasing values of reverberation time the difference between measurement and theory reduces.

In order to examine differences between measured and calculated values more clearly, Fig. 6 shows the absolute values of relative difference Δ. It is obvious that when reverberation time in the room is longer than 2 s, Δ is relatively small. For lower values of reverberation time in the room, Δ increases. In the zone below 0.7 s there are circumstances when the difference between measured values and theoretically estimated values is up to ±50%. In Fig. 6 this trend is graphically shown by a line, below which are all measured values.

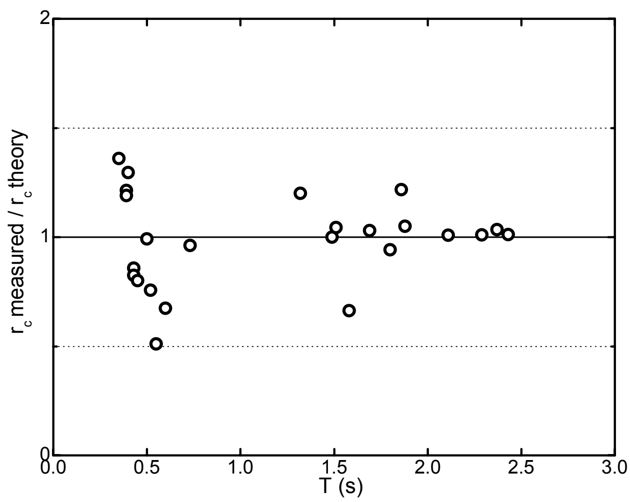

Fig. 5. Normalized value of measured critical distance as a function of reverberation time.

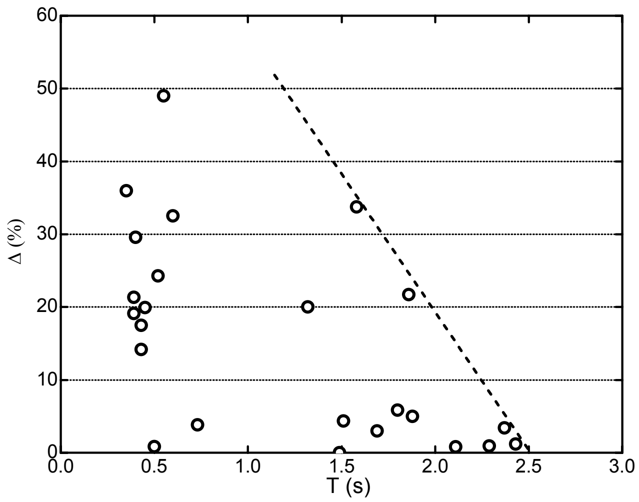

Fig. 6. Absolute value of difference between measured and theoretical value in percents, as a function of reverberation time.

VI. Conclusion

The method for critical distance (reverberation radius) measurement based on recording of impulse response, described in this paper, is more precise than the methods suggested in literature. In those methods direct and reflected sound are determined by measurement of sound level at points where the domination of one of the two is assured. When the domination of direct sound in a near field or reflected sound in a far field is not significant, these methods produce an error. In the method proposed in this paper, a maximal error in critical distance measurement is about ±10%, which is considered acceptable in engineering practice.

The proposed method was used for the measurement of critical distance in four real rooms, with volumes in the range from 50 to 500 m^3, and reverberation time from 0.4 to 2.4 s. Measurement in four rooms and six octaves provided a set of 24 critical distance values on which conclusions are based.

The results of measurement have shown that in the room with a short reverberation time, the well known theoretical formula (1) for the calculation of critical distance causes potentially a large error, up to ±50% of the real value in the room. This is, to some extent, an expected result, considering the statistical model of sound field and its initial limitations. From a practical point of view, an important conclusion is that in studio rooms, with short reverberation times as default (due to the acoustic design requirements), deviations from theory are the largest. Consequently, the use of theoretical expression (1) in acoustic design of studio rooms is not reliable.

The fact that in cases of large critical distances, above 2 m, measured values in four rooms are systematically larger than theoretical is important for design of sound reinforcement systems. This modifies the common theoretical consideration of the maximum allowed distances between listeners and speakers.

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