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Measuring Mixing Time in non-Sabinian Rooms: how scattering influences small-room responses

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ABSTRACT

The goal of this work is to optimize a DSP tool for extrapolating from room impulse response information regarding the way in which the transition between early reflections and late reverberation occurs. Two different methods for measuring this transition (usually referred as mixing time, t_{mix}) have been found in literature, both based on statistical properties of acoustic spaces. Appropriate changes have been implemented and the algorithms have been tested on I.R. measured in 8 different environments. Particular attention is given to non-Sabinian environments such as small-rooms for music. It has been also measured a relationship between sound diffusion and t_{mix}, showing how the presence of scattering elements contributes to lower t_{mix} altering the statistical properties of I.R.

1. INTRODUCTION

The room impulse response (R.I.R.) of a reverberant space is composed of three elements: direct sound, early reflections and diffuse reverberation. The early reflections are a set of discrete events whose density increases until individual reflections can no longer be discriminated and/or perceived. After a sufficient period of time, the echo density will be so great that the arriving echoes may be treated statistically. The transition time from early reflections to late reverberation is called Mixing Time [1]: therefore this instant divides a deterministic section from a stochastic one, because the time domain response can only be Gaussian if a sufficient number of reflections overlaps at any time along the response [2]. Theoretical definitions of mixing time are usually related to geometrical dimension of the room: in particular, the common defintion of t_{mix} is directly proportional to its volume ($t_{mix} = \sqrt{V}$) [3]. The main concern with theoretical definitions is that only geometrical aspects of the room are taken into account and other key elements for defining room acoustics characteristics (sound absorption and diffusion) are not included in this kind of physical model.

Two different methods to study the statistical properties of impulse responses have been found in scientific literature: the former proposed by Abel and Huang in [4], and the latter by Stewart and Sandler in [5]. Both these methods take a sliding window over an I.R. and when the distribution of the samples within the window is Gaussian, the transition between deterministic early reflections and stochastic late reverberation can be considered accomplished. The instant that marks this transtion is definied as mixing time. Further details will be given in section 3. Appropriate changes to these methodologies were implemented in this study in order to optimize an useful tool for the analysis of room acoustic properties. The modified algorithms have been tested on a variety of I.R. measured by the authors in 8 environments different for dimensions, sound absorption characteristics and utilization. Particular attention is given to non-Sabinian environments, rooms with small dimensions and heavy sound absorption, where Sabine's assumptions about diffuse sound field cannot be considered fulfilled.

This work is a further step inside the research about measurements in non-Sabinian enclosures for music carried on by the Acoustic Engineering Studio "Suono e Vita", reported in [6] and [7]. In fact music production business dynamics have moved most of the production phases to personal and project studios. This fact gives acousticians smaller 'cavities' to study and optimize. The idea is to provide engineering tools for in-deep knowledge of time and frequency domain properties of small acoustic spaces.

In section 2 some basic statistical properties of room acoustic will be reviewed. In section 3 the two algorithms will be analyzed and in section 4 the contribution of the authors to improve the reliability of the developed tool will be reported. Then in sections 5 and 6, the case studies, used in this work, and the analysis of results will be reported.

2. STATISTICAL PROPERTIES OF ROOM ACOUSTICS

According to Kuttruff [8], the echo density (D_e - average number of reflection per second) is proportional to the square of time t, such as

$$D_e(t) = 4\pi c_0^3 \frac{t^2}{V} \quad (1)$$

where c_0 is the speed of sound in [m/s] and V is the volume of the room in [m^3]. For longer times, echo density becomes large, suggesting to use a statistical approach to the problem. The time domain response can only be Gaussian if a sufficient number of reflections overlap at any time along the response [2]. Polack in [3] tried to give a mathematical definition linked to the resolution of the auditory system. According to this definition, the Mixing Time is the earliest time when N=10 reflections overlap within the characteristic time resolution of the auditory system, taken equal to Δt = 24 ms [9]. Eq. (1) leads to:

$$t_{mix} \approx \sqrt{V} \quad [\text{ms}] \quad (2)$$

where t_{mix} is the mixing time expressed in [ms] and V is the volume of the room in [m^3]. Polack used the mathematical theory of billiards [10] to reach this result. The essential requirement is ergodicity (the term ergodic is used to describe a dynamical system which has the same behaviour averaged both over time as well as over space), which requires that any given echo trajectory in space will eventually reach all points in space. However, Joyce [11] showed that the ergodicity assumption is determined by the shape of the enclosure and the surface reflection properties. Non-ergodic shapes will exhibit much longer mixing times, and will not lead to the same results that Sabine reported in terms of reverberation time (non-Sabinian rooms), according to Joyce [11]. Spaces with low reverberation time would be not ergodic because there is insufficient time for mixing. In this work, objective measurement procedures have been applied also to non-Sabinian rooms in order to study the transition to a Gaussian state: it is demonstrated that this state is accomplished.

3. LITERATURE MIXING TIME MEASUREMENT METHODS

In order to obtain an objective measurement of t_{mix}, two different methodologies found in scientific literature have been used. The first approach is proposed by J.S. Abel and P. Huang in [4], while the second one is proposed by R. Stewart and M. Sandler in [5]. In the following paragraphs, implementation details of these methods will be exposed.

3.1. Echo Density Measure

The J.S. Abel and P. Huang work [4] aims to create a simple and robust measure of reverberation echo density. The authors defined a curve, called *echo density profile* $\eta(t)$, that represents the increasing rate of echo arrivals in a measured impulse response. Once the room is sufficiently mixed, the impulse response taps take on a Gaussian distribution irrespective of the actual reflection density. The authors measure echo density as a function of time: over a sliding I.R. window, the proposed echo density measure $\eta(t)$ counts the fraction of impulse response taps lying outside the window standard deviation and normalizes by that expected for a Gaussian distribution. It is formulated in this way

$$\eta(t) = \frac{\frac{1}{\mathrm{erfc}\left(\frac{1}{\sqrt{2}}\right)}}{\delta+1} \sum_{\tau=t}^{t+\delta} 1\{|h(t)| > \sigma\} \qquad (3)$$

where $h(t)$ is the room impulse response (assumed to be zero mean), $\delta+1$ is the window length in sample, σ is the window standard deviation given by the formula

$$\sigma = \sqrt{\frac{1}{\delta+1} \sum_{\tau=t}^{t+\delta} h^2(t)} \qquad (4)$$

$1\{\cdot\}$ is the indicator function (returns one when its argument is true and zero otherwise), and $\mathrm{erfc}(1/\sqrt{2}) := 0.3173$ is the expected fraction of samples lying outside a standard deviation from the mean for a Gaussian distribution.

Reflections arriving separated in time or in level skew the tap histogram away from its limiting Gaussian form, and the percentage of taps outside a standard deviation is a computationally simple indicator of this skew. The echo density profile increases over time to around one: the presence of a few prominent reflections results in a low echo density value, since they contribute to a larger standard deviation and consequently to a smaller number of samples classified as outliers. By contrast, an extremely dense pattern of overlapping reflections approximating Gaussian noise will produce a value near one. Abel and Huang propose to define the beginning of the late field (i.e. the Mixing Time) as the point in time when the echo density profile $\eta(t)$ first attains a value of one [4].

3.2. Kurtosis Measure

R. Stewart and M. Sandler in their work [5] underline the fact that, for some type of rooms, it is difficult to identify the point in time when it can first be assumed that the room is mixed, using a measure of dispersion like the measure proposed by Abel in [4]. Stewart and Sandler propose to use a measure based on higher order statistics. They focus their attention on kurtosis (fourth order cumulant) for the following reason: if a set of random variables are jointly Gaussian, then all information about their distribution is in the moments of an order less than or equal to two; it can be interpreted that cumulants of an order greater than two measure the non-Gaussian nature of a time series or, stated otherwise, cumulants of Gaussian random processes equal zero for order greater than two. With this assumption, if the normalized kurtosis of the window impulse response is zero, it can be asserted that the distribution of the sample inside the window is Gaussian. Hence the kurtosis can be calculated (in its normalized version) with the formula

$$k = \frac{E(x-\mu)^4}{\sigma^4} - 3 \qquad (5)$$

where E( ) is the expectation operator, μ is the mean and σ^2 is the standard deviation. Similar to the procedure used for the echo density profile $\eta(t)$, also in this case kurtosis is calculated for each sliding window over the impulse response and the process creates a curve (called here $k(t)$). This curve, in its normalized version, starts with values around one and gradually goes towards zero as the degree of gaussianity of sample inside the window increases.

In Figure 1 an example of the output of the two curves applied to an impulse response can be seen. The red line shows the I.R. itself, the blue line the echo density curve $\eta(t)$ and the green line the kurtosis curve $k(t)$. There are also three vertical lines: the black one represents theoretical value of t_{mix} obtained as the square root of the volume of the room, while the blue vertical line is t_{mix} measured with $\eta(t)$ and the green on is t_{mix} measured with $k(t)$.

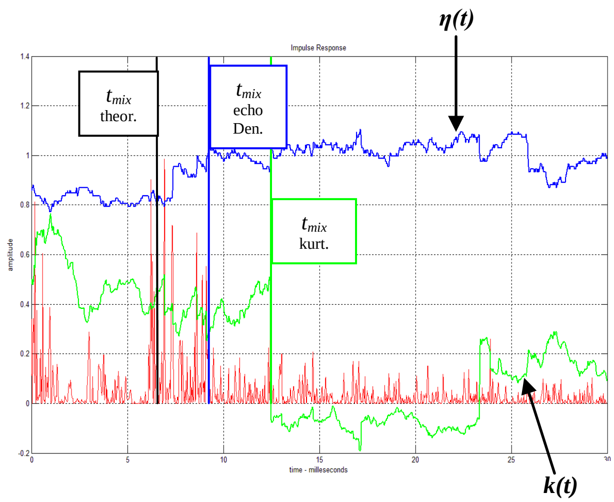

Figure 1 Example of plot of the two curves (first 30 ms)

4. METHODOLOGY IMPROVEMENTS

4.1. Window Length Selection

These methodologies for measuring mixing time present the problem of selecting the analysis window length. Although the profile of the curve remains almost the same, if the window size changes [4], the value obtained for t_{mix} may be very different from each other. While Stewart [5] uses a fixed window length of 30 ms without giving details about this choice, Abel [4] gives some explanation about that: a short window length naturally includes few impulse response taps and thus is expected to have a relatively high variance about its local mean. While using a shorter window leads to a larger Echo Density profile variance, the profile produced will be more responsive to short-term echo density changes but the window should not be made so short that it does not contain any reflections [4]. Abel proposes to use a window length of 20-30ms since it is long enough to provide good statistics and contain at least a few reflections within each window [4]. Another suggestion about fixed window length is due to [12], proposing a 24ms window length because it is the characteristic time resolution of the auditory system.

During our analysis, made on rooms with different dimensions and absorption characteristics, it became clear that there is no “perfect size” for the window size, but it is necessary to find a way to define window length related with the particular characteristics of the room under analysis and with a physical meaning. In order to have a window long enough to provide good statistics and contain at least a few reflections but not too long, in order to avoiding loose short-term changes, this paper proposes to use a window length related to the concept of mean free path $\bar{l}$, i.e. the average distance a ray of sound travels inside a room before it encounters an obstacle [8]. The proposed window length is given by the following formula, where $\bar{l}$ is converted in [s]:

$$L_{win} = \frac{\bar{l}}{c} = \frac{4V}{cS} \quad [\mathrm{s}] \qquad (6)$$

where V is the volume of the room and S is the total surface area enclosing the room. In this way the presence of a set of reflections inside the window is ensured and furthermore it is extremely easy to calculate quantity strictly related with the room: it results in longer windows for big rooms and shorter ones for small-rooms. This means working with windows 4.82 to 24.6 ms long. Olive and Toole works on first reflection perception [13] demonstrate the ability of the human ear to perceive changes also below its integration time, justifying our choices. This choice works well for rooms in which the acoustic treatments are placed on the boundaries: this still has to be tested on rooms with suspended diffusers affecting the volume in an undetermined way due to shadowing, inevitably reducing the mean free path [14].

4.2. Mixing Time Instant Selection

Observing results given by a number of curves it has been observed that limiting attention on the first time in which *η(t)* and *k(t)* attains the values of one and zero respectively is not always useful. The usual behaviour of the two curves is starting around their initial values, gradually increasing (or decreasing in the case of *k(t)*) as the process became more diffuse, reaching values around one (or zero) and remaining stable around these two values. Sometimes the two curves, more often in non-Sabinan rooms, may exhibit some spurious transitions above (or below for *k(t)*) the fixed threshold in the first part of the I.R. It is clear that considering these temporary transitions as t_{mix} would be largely wrong. In order to improve results reliability, the following arrangement is proposed: starting from the candidate time instant as t_{mix}, an I.R. window of the same length of analysis window is taken and a computation of mean and standard deviation of that window is performed. If the mean of the values inside the window is included in a small interval around one or zero and with small standard deviation the time instant identified can be considered as reasonable value for t_{mix}, otherwise the value is discharged.

5. CASE STUDIES

The mixing time measurement algorithms described here have been tested on eight rooms with different characteristics about geometrical dimensions, utilization, sound absorption and diffusion. In Table 1 the analyzed rooms are listed with their volume and reverberation time T_{30}.

Room	Volume	T_{30}
1- RSI Auditorium	4200	1.54
2- Reverberation Chamber	177.2	2.62
3- RSI Broadcast Mobile Studio	17.6	0.19
4- Control Room 1 (not treated)	44.8	0.98
5- Control Room 2	30.2	0.30
6- Rehearsal Room	108.9	0.31
7- Control Room 3	42.7	0.20
8- Recording Room	51.1	0.61

Table 1 Case studies

For each room have been used at least six different impulse responses measured with the exponential sine sweep method [15]. Case 1 and 2 (auditorium and reverberation chamber) are Sabinian rooms while all the other examples are small-rooms that can be considered non-Sabinian. Particular attention has been given to two particular cases: the Rehearsal Room (Reh6 from now on) and the Recording Room (Rec8). These two cases present removable QRD diffusers that allowed us to test the t_{mix} measurement procedures with different settings of sound diffusion. In order to investigate the relationship between scattering and mixing time, several experiments have been repeated, specifically designed for the present research.

5.1. Description of experimental measurement settings

As can be seen on Figure 2, in Reh6 there are 3 sound diffusers (QRDs): three different sets of measures have been arranged. The first set of measurements has been made with QRD1 and QRD2 left untouched: in this way the surface covered by diffusers is the 7% of the walls surface area; the second set has been accomplished with both diffusers covered with absorbing and reflecting panels in order to eliminate their diffusive effect (surface covered by QRD = 1%); the third set has been completed instead with one diffuser left untouched (QRD1) and the other (QRD2) "eliminated" (surface covered by QRD = 4%).

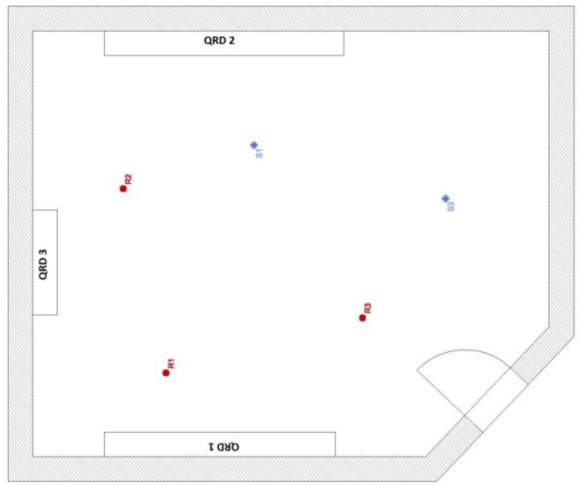

Figure 2 Rehearsal Room – Reh6

For what concerns Rec8 (Figure 3), the QRDs are placed in two sides of the room facing each other. At one side there are three fixed QRDs while at the other side the QRDs were removable, so three different sets of measures were performed: the first one with no removable QRD (surface covered by diffusers is the 4% of the walls surface area), the second one with four QRDs (11%) and the last one with six QRDs (14%). In this way it has been possible to investigate the behaviour of the two measurement procedures, changing the amount of sound diffusion present inside the room. In Fig.2 and 3 the positions of the measurement microphone are marked in red and the positions of the dodecahedron loudspeaker used as source for the impulse response measuring process are marked in blue. During the study of room Rec8, it has been noticed that the appropriate positions for sound source and measurement microphone should be all inside the "diffuser region", i.e. the portion of the room volume bounded by QRDs diffusivity geometrical polar responses, where the influence of sound diffusers is effective.

In the next section the results obtained by the application of the two algorithms to the I.R. of the rooms listed in Table 1 will be examined. Particular attention will be given to Reh6 and Rec8 where the relationship between scattering and mixing time is highlighted.

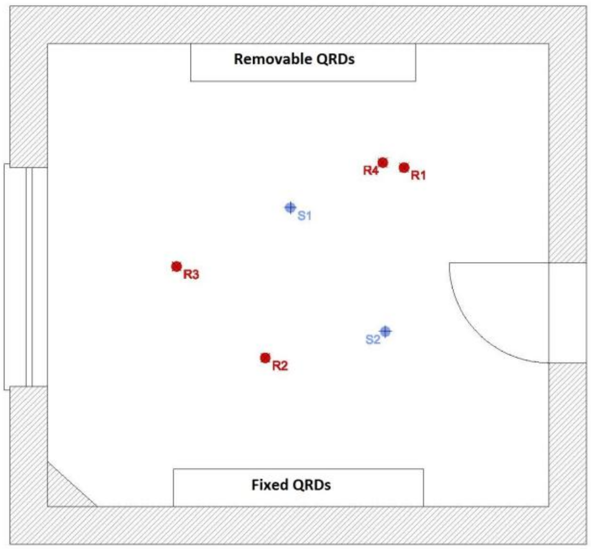

Figure 3 Recording Room – Rec8

6. ANALYSIS OF RESULTS

6.1. Mixing Time Measurement

This attempt to develop a software tool for the objective measurement of t_{mix} gives demonstrates the experimental evidence of a well-known assumption in non-Sabinian spaces theory. In Table 2 the theoretical values of t_{mix} and the value measured with the echo density curve *η(t)* are reported as well as and the ones measured with kurtosis curve *k(t)* (the reported value is the mean value of the measured values for each impulse response). As can be seen, for Sabinian rooms (case 1 and 2), theoretical and measured values are almost the same while, for non-Sabinian rooms, measured t_{mix} is longer than the theoretical ones. In fact, within non-Sabinian spaces, the classical definition of mixing time tends to lose significance.

It is interesting to notice that the t_{mix} parameter is still measurable even in clearly non-Sabinian spaces: this occurs because in these rooms, even with small dimensions, after a certain time, the samples of the impulse response tend to Gaussian distribution anyways and the two algorithms can produce consistent curves. There is still a transition to stochastic behaviour, but the fast energy decay sets the room behaviour outside classic assumptions. Then it can be also concluded that the difference between theoretical and measured mixing time can be considered a useful instrument to evaluate the degree of sabinianity of an acoustic space: the more measured values are different from a theoretical one, the less sound field assumption can be considered fulfilled. This statement is the first part of the research, whose results are expressed in [16] with tests performed on rooms from 1 to 5 of Table 2.

Room	$\sqrt{V}$	*η(t)*	*k(t)*
1- RSI Auditorium	64.8	65.9	69.3
2- Reverberation Chamber	13.3	12.7	17.1
3- RSI Mobile Studio	4.1	6.1	6.7
4- Control Room 1	6.7	17.7	19.9
5- Control Room 2	6.2	13.8	15.1
6- Rehearsal Room	10.4	9.92	12.5
7- Control Room 3	7.1	15.2	15.3
8- Recording Room	6.54	8.33	9.99

Table 2 Mixing Time measurement results in [ms]. For Reh6 and Rec8, the t_{mix} value in the case of minimum number of QRDs is reported.

6.2. Mixing Time and scattering

As has been exposed in paragraph 5, the tests performed in Reh.6 and Rec.8 were specifically designed to investigate the relationship between mixing time and sound diffusion. In Tables 3 and 4 are reported the t_{mix} values obtained in the three different sets. The second column indicates the percentage of wall surface covered by sound diffusers.

Room – Reh.6	%diff	*η(t)*	*k(t)*
D1- Complete Diffusion	7%	5.13	6.62
D3- Intermediate Situation	4%	7.01	10.4
D2- Complete Absorption	1%	9.92	12.5

Table 3 Rehearsal Room (Reh.6)

Room – Rec.8	%diff	*η(t)*	*k(t)*
D1- 3 QRDs	4%	8.33	9.99
D2- 7 QRDs	11%	7.48	7.70
D3- 9 QRDs	14%	6.72	8.52

Table 4 Recording Room (Rec.8)

With both these measurement sessions, a close bond between scattering elements inside the room and mixing time is established. Diffusive elements, such as QRDs, contribute to lowering the time necessary to complete the transition between the deterministic and the stochastic part of the impulse response. In Reh.6 the lowering effect on mixing time caused by the presence of sound diffusion is particularly evident (t_{mix} is halved in the case of complete diffusion compared to its value with complete absorption) because the QRD involved in the comparison (QRD1 and QRD2 in Figure 2) are large in size. In Rec.8 the lowering effect is less marked because the room itself is smaller than Reh.6. Then there are 3 QRDs that are always present inside the room and the dimensions of the single QRD are lower than in Reh.6 case, but it is always interesting to notice that a decrease of t_{mix} is still verified. So the proposed measuring tool can be considered a reliable instrument for measuring the changes in the ratio between diffusive and specular reflections in real rooms.

Furthermore it can be noticed that in Rec.8, the increasing of diffusive elements brings the measured values of t_{mix} closer to the theoretical one. Something similar happens also for Reh.6 where the case of complete diffusion gives even lower measured values than the expected ones, for both curves. So an experimental evidence of the fact that the presence of diffusive elements modifying establishment of diffuse sound field is provided, reducing in a remarkable way the degree of non-Sabinianity of any acoustic space, even if it is small.

6.3. Discontinuities on kurtosis curves

Although the two curves, $\eta(t)$ and $k(t)$, show similar performances on the measurement process of mixing time, the curve $k(t)$ based on kurtosis displays an interesting behaviour: at some particular reflections during the I.R., very sharp discontinuities correspond as can be seen in Figure 1 as well as in Figure 4. This behaviour is also present in echo density curves $\eta(t)$ but in a much less evident way. This phenomenon appears often in a large number of analyzed impulse responses. After repeated tests and detailed analysis, in order to exclude mathematical problems or algorithmic artifacts, it became clear that discontinuities have a precise meaning: a discontinuity appears because the reflection is followed by a stochastic I.R. segment at least as long as the analysis window. In order to generate this phenomenon, the I.R. segment following the discontinuity reflection, has to contain only sparse reflections, lower in amplitude respect to the one that generated the discontinuity. In fact, in the first time instant where the outstanding reflection is no longer contained in the analysis window, the curve becomes Gaussian.

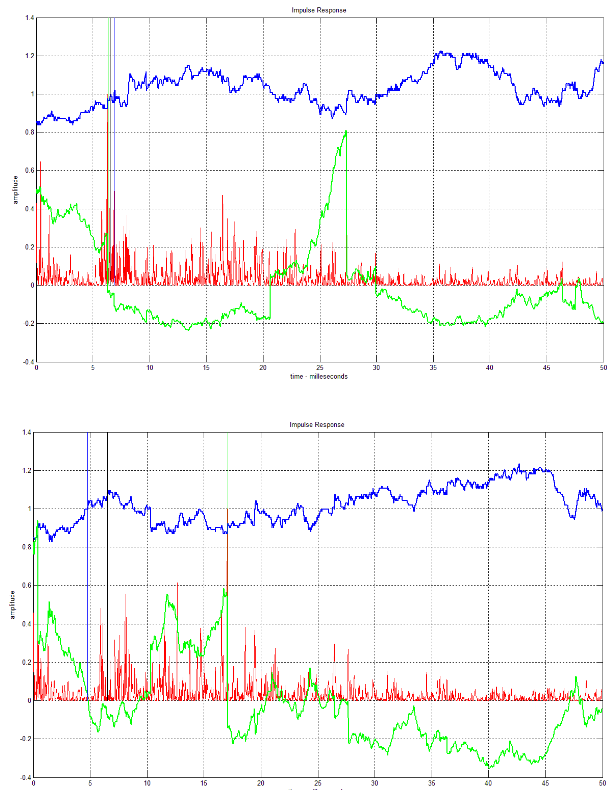

Figure 4 Examples of sharp discontinuity on $k(t)$

Psychoacoustic aspects related to discontinuities remain to be investigated, in order to understand whether or not these reflections take on a special role in the perception of sound, for example renewing the precedence effect, as referred in [13]. It would be interesting to understand if groups of reflections, followed by "Gaussian segment", affect the perceived acoustic space more than individual reflections. What is interesting to notice up to now is that these discontinuities are not instrument artifacts but statistical events with a precise meaning, strictly related with the distribution of reflections inside the room under analysis.

6.4. Sound diffusion and microphone position

Analyzing the case of Recording Room num.8, it can be observed another interesting behaviour of the kurtosis curve (again, the same behaviour is present in the echo density curve but it is less evident due to its limited "dynamic range"). Inside this room, 4 different positions of the measurement microphone and 2 different positions of the source have been used to record I.R.

Figure 5 The kurtosis curve generated for each receiver position are superimposed. From the top: 3 QRDs case, 7 QRDs case and 9 QRDs case.

As can be seen on Figure 5, where the *k(t)* curves generated for each I.R. are superimposed for the three different QRDs settings, the profile of the curves is similar regardless of the receiver position. This behaviour is particularly evident for Rec.8 because the reciprocal positions of sources and receivers are all inside the "diffusers region". This means that in small-rooms, where an extensive use of diffusive elements is made, the statistical properties of echo arrivals are almost the same for each position. This is another evidence of the beneficial effect in the use of sound diffusers inside small-rooms. It can be also noticed how, by increasing the number of QRDs, the curves become more regular, more Gaussian (remember that, for *k(t)*, when the curve is "around zero", the sample inside the window are Gaussian distributed): this is what would be expected in a diffuse field.

7. CONCLUSIONS

In this work a useful tool for detailed analysis of room impulse responses has been optimized and studied. This software tool is able to measure mixing time and to generate curves useful to understand statistical acoustic properties of a space. Tests made on different I.R.s show how, for non-Sabinian spaces, t_{mix} measured values diverge considerably from theoretical ones. However there is evidence that a transition from deterministic to stochastic does still take place and that scattering helps stabilize and modify it. Moreover the profile of the curves shows that, for this kind of environments, it is useful to go beyond the common concept of mixing time: in small-rooms, groups of reflection can be followed by "Gaussian segments" without outstanding reflections, but this transition often cannot be considered definitely accomplished. Then it would seem more appropriate to focus on groups of reflections instead of "single reflection", on "segment of Gaussianity" instead of a sharp separation between deterministic early reflection and stochastic late reverberation. Discontinuities in the kurtosis curves described in 6.3 are a clear evidence of it, giving a new viewpoint for time domain analysis of I.R. Furthermore, the relationship between mixing time and sound diffusion has been investigated: experimental measurements reveal, with objective evidence, how the presence of sound diffusers (QRD) lowers mixing time helping the establishment and stabilization of diffuse sound field also in clearly non-Sabinian spaces. Accurate positioning of QRDs creates a "diffuser region" where every position of the receiver relative to the source becomes equivalent from a "reflection arrivals" point of view. Thinking about application in music recording, it appears clear that creating a "diffuser region" inside a small-room can greatly help the quality of multi-microphone-recording: the beneficial effects of sound diffusion in music recording are well known to sound engineers, but in this paper, they have been demonstrated with objective measurements. Further research has to be done to confirm the psychoacoustic relevance of the relationship between mixing properties and sound diffusion. Establishing a relationship between statistical behaviour of groups of reflections and human perception, would open new points of view in the time domain analysis of small acoustic spaces.

8. ACKNOWLEDGMENTS

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