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Crossover frequency estimation from statistical features of a room transfer function

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Abstract

In certain practical situations one faces the problem of choosing the most suitable approach to analyze the sound field in a room. For acoustically small rooms, a modal approach is of higher importance, as opposed to acoustically large rooms, when statistical considerations provide more useful models. In the context of reverberation rooms, an important issue to be dealt with relates to the diffusion of the sound field. Although the evaluation of how close the field is from being diffuse is under discussion, it seems to be accepted that such a condition isn't reached under a crossover frequency, also referred to as the "Schroeder Frequency". This paper presents the investigation of procedures based on statistical features of rooms' Transfer Functions aiming the experimental determination of such a frequency. Real and imaginary parts of transfer functions are analyzed with Kurtosis, while the phase is analyzed with a proposed measure. Results from measurements performed in a large (108.5 cubic meter) and in a scaled (1.48 cubic meter) reverberation rooms are presented, as well as results from analytical solution from three shoebox rooms with the same volume, but different symmetry degree. Both measures presented comparable results, showing possible, and potentially more precise practical approaches.

Keywords: Crossover frequency, Schroeder frequency

1 INTRODUCTION

When using geometrical acoustics algorithms, one needs an estimation of the frequency above which such an approximation for studying the sound field is valid. In other cases, when designing a reverberation room for instance, it is important to guarantee enough modal overlap in order to provide an acceptable degree of homogeneity to the sound field, or supposedly to fulfill a necessary condition for the sound field to be diffuse.

In such situations, Schroeder's equation may be used in order to estimate such a frequency. For deriving this equation, an important amount of research was accomplished since the early 1950's, as reported in papers by Schroeder (1,2), Kuttruff, Thiele (3), among other important members of the acoustical researchers' community. The equation was derived based on the analytical solution of the wave equation for shoebox rooms, and further adjusted after measurements and analysis of rooms with generic geometry. As found in most of the text books, this is

$$f_{Schroeder} = 2000\sqrt{\frac{T}{V}}, \tag{1}$$

where T is the reverberation time in s, and V is the room's volume in m^3.

For many, however, there are some doubts of how to use this equation when the reverberation time varies as a function of the frequency. And, although it is known that room's geometry has an influence which is considerably smaller than the influence from volume and reverberation time, to which extent it is valid not to consider that?

In some situations, as during the design of a reverberation chamber for measuring sound insulation, for example, ISO 10140 (5) suggests that the natural frequencies of the room should be as evenly separated as possible. The main reason is supposedly to provide a more homogeneous, and isotropic sound field. This has a relation with the crossover frequency, and it would be very useful to develop measures that, besides reverberation time and volume, were also able to indicate the influence of room's geometry in this respect. In fact, there is an approach which is based on the analysis of the standard deviation of the sound pressure level, and to the sound level decay over the space. The present work proposes also the use of statistical features as a way of verifying the crossover frequency. In this case, however, the distribution of values of a single transfer function is used. Average over space is taken in order to provide more clear results.

Based on stochastic models of a room transfer function as described by Schroeder and Kuttruff (5), and by Polack (6), it is assumed that, above the crossover frequency, the probability distribution functions of real and imaginary parts are normal. Therefore, Kurtosis is used as an indicator.

As a consequence of the normally distributed values of real and imaginary parts of a transfer function, the value distribution of magnitude is given by a Rayleigh function, while phase values follow an uniform distribution. Because of that, a simple measure is presented for the analysis of the phase signal.

There may be a relation between crossover frequency and diffuse sound field, in relation to isotropy, in the sense that the former is necessary (not sufficient) condition to be transposed for the latter to be feasible. The same is true also in the time domain, above a critical time, according to Jot, Cerveau and Warusfel (7) , and DeFrance and Polack (8). However, as pointed out by Jeong (9), such a relation is still not clear, and although not focused in the present work, should be kept in the background.

2 METHODS

A room's transfer function may be described in cartesian or polar coordinates, as follows:

$$H(f) = X(f) + iY(f) = R(f)e^{i\phi(f)}, \tag{2}$$

where X represents the real part, Y represents the imaginary part, R is the magnitude, and ϕ represents the phase. It may be shown, for instance as given by Papoulis (10), that if X and Y are considered random variables with a probability which follows a normal function, the probability density function of R will be given by a Rayleigh function, and the probability of ϕ will be given according to an uniform function. These relations, and the conclusions from the authors cited previously, serve as basis of the measures described in this section.

2.1 Kurtosis

Kurtosis is a statistical moment of forth order, and related to the peakedness or tailedness of a population distribution. It has been used as an indicator of the normality of a distribution in several situations for a long time, such as the integrity of roller bearings. More recently, Jeong (11) found a correlation between the degree of diffusion of a sound field, and Kurtosis of an initial portion of a room's impulse response.

It is given by, in the normalized version:

$$K = \frac{E(p-\mu_p)^4}{\sigma_p^4} - 3, \tag{3}$$

where p, in the present case, is the real $X(f)$ or imaginary $Y(f)$ part of a room transfer function at a given frequency, μ_p is the mean value within a frequency window, and σ_p is the standard deviation of values in the same frequency window. When Kurtosis approaches 0, the population under analysis is likely to present a normal distribution.

A similar procedure as the one described by Jeong (11) was adopted initially for the present work, except for the frequency filtering, and the fact that it is applied in the frequency domain. Such a procedure consists of taking a population of 800 points from the real part of a room's transfer function, and computing the Kurtosis. This

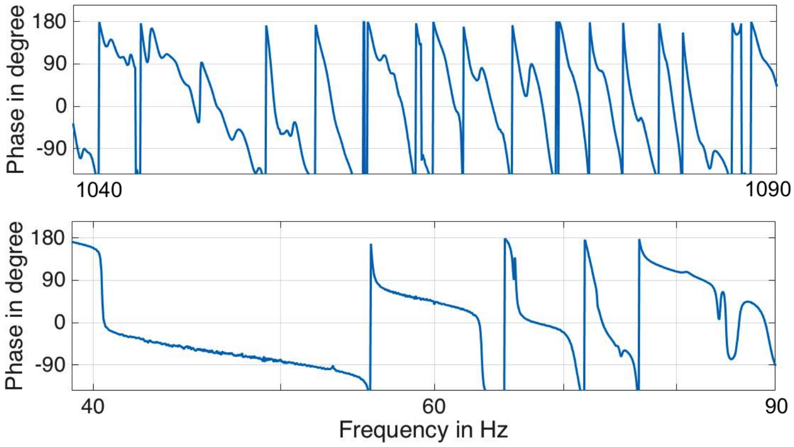

Figure 1. Room's transfer function within a 50 Hz window, at low (bottom), and high (top) frequencies. From measurements in a $108.5m^3$ reverberant room.

is performed for a sliding window and the values are plotted against frequency. An average curve is generated from a collection of room transfer functions obtained for different source-receiver combinations. The frequency above which Kurtosis values are smaller than 2 is kept as a possible value for the crossover frequency.

The analysis is repeated for the imaginary part, and the possible values for the crossover frequency are compared. The larger of them is considered as the final result for the crossover frequency. For the sake of better visualizing the result, the population size is reduced in some cases, after checking if this does not compromise the analysis.

2.2 Phase analysis though the maximum difference from an ideal uniform distribution, observed in histograms

Because above the crossover frequency phase values assume a distribution given by a very simple function, a measure has been developed as described in the following.

At first, as many of the readers have already observed, the phase of a room's transfer function at very low and very high frequencies is similar to those shown in Figure 1.

A histogram may be built from segments (bands) as those shown in Figure 1. One has to define the histogram resolution, and normalize the population counting, expressing it in percentage. Exemplary histograms for low and high frequencies, for an angle resolution of 20 degrees are shown in Figure 2.

The red line indicates the percentage of points if the distribution was perfectly uniform. The proposed measure is the maximum difference found in each frequency band under analysis to the reference value of a perfect uniform distribution. Note that this value is related to the angle resolution.

Such a measure is further referenced to as the "maximum deviation from the uniform distribution". A histogram resolution which was found to be adequate is actually of 18 degrees, which leads to the situation that 5% of the population should fall in each angle interval. The analyses presented in this work were performed in frequency bands of the same (constant) length, equal to those used for computing Kurtosis, and also through a sliding window. A frequency-dependent curve with values of the maximum deviation from the uniform distribution is generated and an spatial average computed, just as described in the procedure based on the Kurtosis.

As frequency increases, the curve tends to fluctuate around a minimum value. The frequency above which the fluctuation is considered to be small is is declared to be the crossover frequency.

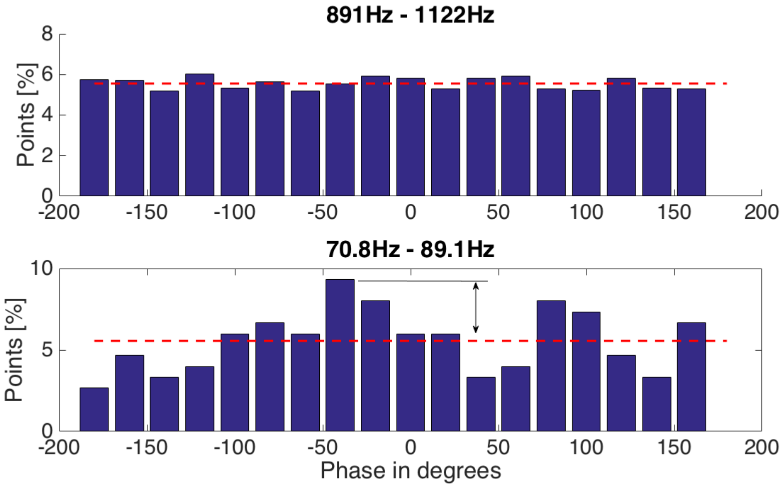

Figure 2. Histograms from analysis of room's transfer function phase at low (bottom), and high (top) frequencies. The red lines indicate the population counting in the case of a perfect uniform distribution. The proposed measure is indicated in the graphic displayed at the bottom.

3 ROOMS

The procedures described in the previous section were applied to measured signals and signals generated by an algorithm based on the analytical solution of sound propagation problem in a shoebox room. The real and the hypothetic rooms are described in this section.

3.1 Measured rooms

One of the rooms tested was a reverberation room constructed in reduced scale with the goal of being used for scattering coefficient measurements. Its volume is 1.48 m^3, and two pairs of walls are non-parallel. This scale-model room is equipped with a semi-automated mechanism that moves the microphone and the sound source. The sound source is a cubic structure with a loudspeaker mounted on each side, and was driven by a power amplifier with a flat frequency response. Measurements were performed for three source, and four microphone positions. Two situations were set-up: the empty room, and the room with an absorbent foam covering almost the total area of the floor.

In all measurements, a 1/2 inch measurement microphone was used, along with a sound card (RME Multiface II) set to a sample frequency of 48kHz. The ITA-Toolbox, which runs on Matlab, was used for measuring through a deconvolution technique with sine sweeps as excitation signal. A dodecahedron loudspeaker system was used in measurements performed in the real scale room.

A set of rooms built to perform sound insulation measurements were also used. Measurements were performed at first with no closing between them, such as to compose a room with total volume of 108.5 m^3. In this case, only one source position was used, and the microphone was placed in twenty different positions.

3.2 Hypothetical rooms

A computer routine based on the Green's function of rectangular rooms (normal mode model), as presented in (12), was used for computing transfer functions of three hypothetical rooms with same volume, and different symmetry degrees. A cubic room with all dimensions set to be 5 m, a room with dimensions 10 vs. 5 vs. 2.5 m^3, and a room with dimensions 7.974 vs. 5.819 vs. 2.694 m^3 were idealized. The latter one is supposed to have optimal dimensional relations, such as to provide an uniform distribution of natural frequencies, based on

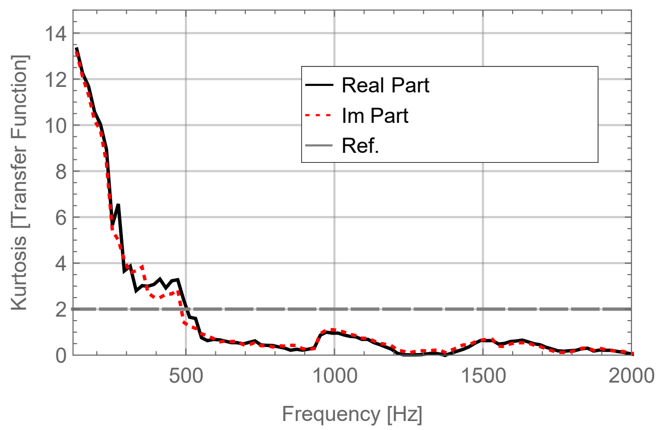

Figure 3. Average Kurtosis of real and imaginary parts from 15 transfer functions measured in the larger ($108.5m^3$) room.

(13), and is for now on be denominated "optimal room". These rooms have the same volume (125 m^3), and were initially set to present a reverberation time of 10 s, such that the Schroeder frequency is easily computed, and results to be 566 Hz.

The reverberation time of the optimal room was varied from 10 to 5, 2, and 0.2 s, in order to observe the variation on the measures proposed in this work.

One source position and fifteen receiver positions were used in order to obtain the transfer functions for each room. Care was taken to compute a number of modes used as basis for obtaining reliable transfer functions up to the maximum frequency of analysis. Receiver positions were also set to be at a minimum of 0.8 m from each other, and from any surface. The critical distance was also observed for setting the source-receiver distance.

4 RESULTS

4.1 From measured rooms

Kurtosis analysis of the larger ($108.5m^3$) room is shown in Figure 3. Kurtosis of real and imaginary parts, spatially averaged, are shown simultaneously. From such a plot, the resulting crossover frequency is 504 Hz. The Schroeder frequency estimated from measured reverberation times, and the room's volume, lies within the 1/3 octave band with central frequency in 400 Hz.

The curve generated by the maximum deviation from uniform distribution is displayed in Figure 4, and the crossover frequency according to this measure is approximately 275 Hz.

Kurtosis analysis from transfer functions measured in the scale-model reverberation room resulted in a crossover frequency of 1520 Hz, when the room is empty, and 720 Hz, when the floor is covered with an absorptive foam. The Schroeder frequencies estimated from measured reverberation times lie in the 1/3 octave frequency bands with central frequency in 1600 Hz, and 1000 Hz, respectively, for the different absorption conditions.

The analysis from the maximum deviation from the uniform distribution led to crossover frequencies of approximately 1250 Hz, when the scaled reverberant chamber is empty, and of 590 Hz, when the absorbent foam covers the floor. Figure 5 presents the curves related to this measure for both situations. As one may observe, when absorption is introduced, the minimum value for this measure tends to increase.

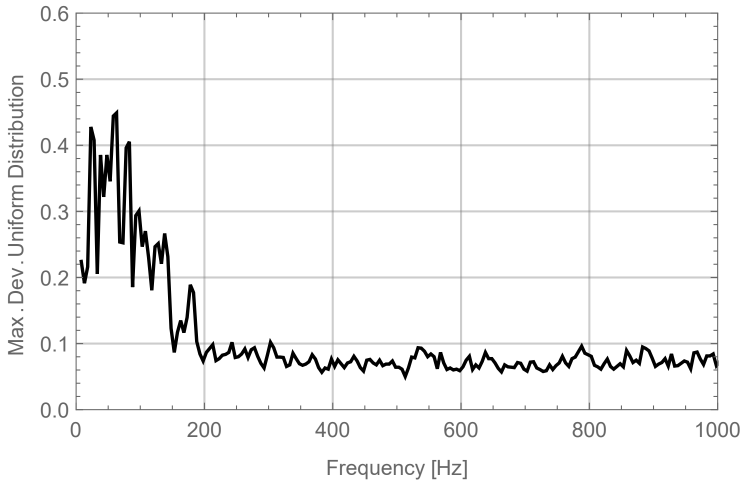

Figure 4. Maximum deviation from uniform distribution averaged from 15 transfer functions measured in the larger ($108.5m^3$) room.

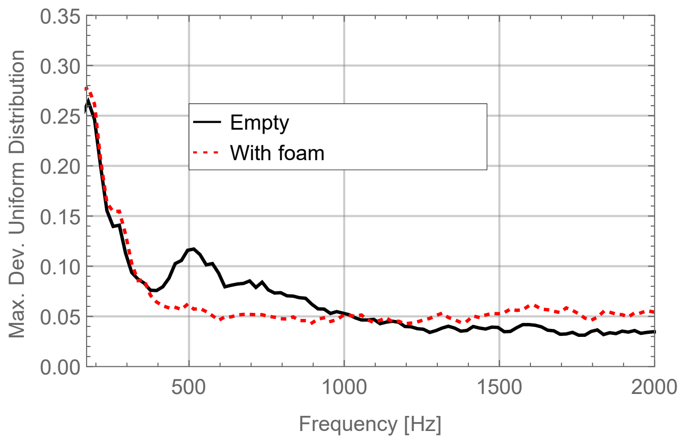

Figure 5. Maximum deviation from uniform distribution averaged from 12 transfer functions measured in the scale model of a reverberation room ($1.48m^3$), with (continuous line), and without absorptive foam (dotted line).

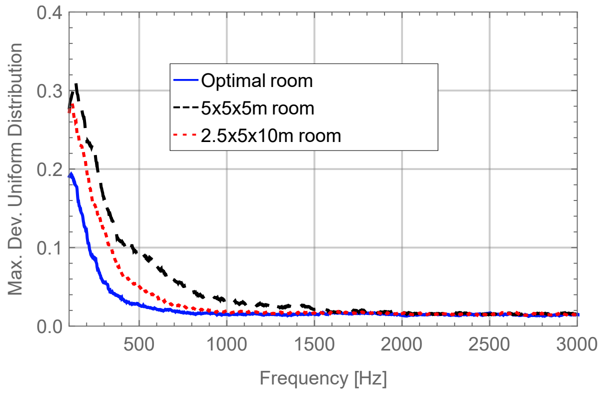

Figure 6. Maximum deviation from uniform distribution averaged from 15 transfer functions for three idealized rooms with same volume (125 m^3), and reverberation time (10 seconds).

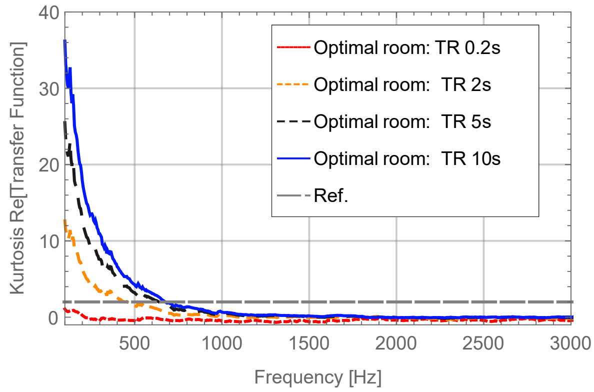

Figure 7. Kurtosis averaged from 15 transfer functions for the optimal room, with different reverberation times.

4.2 From normal mode model

The maximum deviation from the uniform distribution as a function of frequency, for the rooms previously described, with a reverberation time of 10 seconds, is shown in Figure 6. The curve for each room is an average from 15 processed transfer functions.

In order to illustrate the effect of absorption on the measures, frequency-dependent curves obtained for the Kurtosis analysis are presented in Figure 7. While the curve for the optimal room with 0.2 seconds of reverberation time stays always below the reference value of 2, the "background noise" value observed in the phase analysis increases substantially. Im both cases it was not possible to assess a crossover frequency value.

The crossover frequencies obtained through the Kurtosis, and phase (in parenthesis) analyses, for the rooms with different geometries were: 1580 Hz (1600 Hz), for the cubic room, 1070 Hz (1200 Hz), and 670 Hz (750 Hz) for the optimal room. These values may be compared to the 566 Hz for the Schroeder frequency. For the optimal room, with reverberation time set to 5, and 2 seconds, the results were: 635 Hz (700 Hz), and 450 Hz (600 Hz), respectively.

As observed, Kurtosis presented results for the crossover frequency larger than the phase analysis for the experimental investigations, while the contrary was observed for the cases generated through analytical responses.

5 CONCLUSIONS

The measures proposed in this work provided coherent results to what would be expected in relation to natural frequency spacing, and modal overlap in rooms' transfer functions. At first, results for the crossover frequency from measurements performed in two rooms with very different volumes and geometry were obtained, and are in the same range as estimated through Schroeder's equation. Results from transfer functions obtained through a normal mode model for rooms with same volume and reverberation time show that the measures are capable of capturing effects attributed to the symmetry degree of their geometry. The measures provide different results, and while the one based on Kurtosis analysis may be regarded as the most complete one, a further investigation and discussion about the one based on the phase analysis seems to be worth of being accomplished. Results from que measurements performed in the room with and without absorptive material may be regarded as an example of how the effect of lowering the crossover frequency is not necessarily correlated to an increase of isotropy (diffusion) of the sound field.

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