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ASSESSMENT OF LOW FREQUENCY QUALITY METRICS IN SMALL ROOMS

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In a small room, rectangular or not, eigenmodes cannot be avoided and are part of sound distribution in the enclosure. The aim of the present work is to compare different metrics used in the assessment of low frequency quality in rooms used for critical listening. These parameters differ in the way they consider the magnitude and the spatial distribution of eigenmodes. A figure of merit obtained from a best fit curve over frequency response and acoustic entropy are evaluated in 324 rooms from 30 m^3 to 100 m^3 using a theoretical approach based on the modal decomposition method for a rectangular enclosure. The studied parameters are compared in order to establish similarities and differences among them, as well as their relationship with the Bonello Criteria. Significant correlation between entropy parameters and the figure of merit were found. The Bonello Criteria proved to be a misleading metric for the selection of ideal rooms dimensions used for low frequency reproduction.
Keywords: Eigenmodes, Small Rooms, Acoustic Metrics, Low Frequency

1. Introduction

The quality of room mode distribution in small rectangular rooms has frequently been studied, but there is no clear consensus whether it exists or not ideal dimensions for the low frequency reproduction.

Several authors [1, 2, 3, 4] selected modal density and/or modal spacing using different methodologies. They generally consider that a homogeneous distribution of room modes would lead to a flat spectrum. However, this approach does not take into account the interaction between individual resonances, the source-receiver positions, nor the classification between axial, tangential or oblique modes. Some of these authors proposed ideal room ratios that disregard volume considerations and the interactions between the room response and the stimuli, which have been proved to be misleading [5].

Cox et al. [6] suggested an interesting methodology to optimize room dimensions and source-receiver positions in a room. It is based on a figure of merit derived from the minimum quadratic error of a best-fit curve interpolating the room frequency response from 20 to 200 Hz. The criterion searches for the flattest spectrum. Compared to the previously mentioned parameters, this metric proved to be, through subjective evaluations, a useful parameter to determine room dimensions and sound quality at specific positions inside a room [7].

Over the last decade, several authors demonstrated the need for further study over temporal aspects of resonances and their relation with the perception of room modes [8, 9, 10]. Besides temporal parameters for room evaluation of low frequencies have been proposed [11], this paper only considers frequency metrics.

The present work aims to compare different quality metrics for the low frequency reproduction in rooms from 30 to 100 m^3. Two parameters are proposed for the assessment of low frequency quality in rooms, the spectral entropy and the spectral multiband entropy. They are compared with the criterion of a figure of merit derived from a best-fit polynomial. All the parameters are compared with each other to find correlations and dissimilarities among them and their relationship with the Bonello Criteria.

2. Theoretical Background

2.1 Modal Decomposition Method

The Modal Decomposition Method (MDM) corresponds to the analytical solution of the inhomogeneous Helmholtz equation in a parallelepipedic room. This method can consider the influence between source and receiver positions and damping characteristics of the room. Although this approach is not perfectly correlated to measurements it gives a clear idea of the low frequency response in a room.

The room response at angular frequency (ω), due to a point source excitation with volume velocity (Q), is given by Kuttruff [12]:

$$p(\boldsymbol{r}) = \rho_0 c^2 \omega Q \sum_n \frac{\psi_n(\boldsymbol{r})\psi_n(\boldsymbol{r_0})}{\mathrm{K}_n[2\delta_n\omega_n + j(\omega^2 - \omega_n^2)]} \tag{1}$$

In Eq. (1), ρ_0 is the media density, $j = \sqrt{-1}$, c is the speed of sound and ψ_n are the eigenfunctions depending on source ($\boldsymbol{r_0}$) and receiver ($\boldsymbol{r}$) positions. ω_n is the angular frequency for the mode n, while δ_n corresponds to its damping constant. Finally, K_n is a dimensional constant ($\mathrm{Pa}^2\mathrm{m}^3$).

For a rectangular room, the eigenfunctions are equal to:

$$\psi_n(x,y,z) = C \prod_{q=x,y,z} \cos\left(\frac{n_q \pi q}{L_q}\right) \tag{2}$$

Where, C is an arbitrary constant, and $k_{n_q} = \frac{n_q \pi q}{L_q}$ are the eigenvalues of the function. They depend on the mode number, the dimensions of the room, and the source and receiver position.

2.2 Figure Of Merit

The Figure Of Merit (FOM) is obtained from a best-fit polynomial over the room frequency response. In order to obtain such figure, it is necessary to first interpolate a polynome over the Root Mean Square (RMS) frequency response in a dB scale to evaluate the smoothness of a response. Then, the difference between the RMS magnitude response and the smooth curve are calculated for each frequency bin and a mean value is calculated to deliver a single FOM value. This value is normalized to reach a scale between 0 and 10 dB of mean deviation, corresponding to the range between 1 and 0 in a dimensionless scale. This approach has already been discussed by Wankling and Fazenda in [7].

2.3 Bonello Criteria

The Bonello Criteria [4] include several conditions to evaluate room mode distribution. A significant difference of this criteria compared to previous studies is its dependence on the real dimensions and not on ideal ratios.

To determine if a room is acceptable, the first 48 eigenfrequencies are computed and ordered in ascending manner. Then, the number of modes per third octave bands is calculated, obtaining a density curve. If the density curve increases monotonically, although plateaus might be accepted in case of adjacent bands with equal density, and no modal overlap in any band with less than five modes are found, then the criteria is considered to be fulfilled.

Welti [13] proposed a different approach to the Bonello Criteria by counting the number of violations of either the density curve or modal degeneracy. In this paper, a parameter, Bonello Total, Eq. (3), is considered and takes into account two metrics: Bonello Density and Bonello Degeneracy. They are, respectively, the number of violations of the density curve and the number of overlapping frequencies over a 2 Hz span.

$$Bonello\ Total = Bonello\ Density + Bonello\ Degeneracy \quad (3)$$

This allows a more refined analysis of the criteria, being less restrictive than a simple Pass/Fail analysis.

2.4 Acoustic entropy parameters

The authors of this work propose the acoustic entropy for the assessment of low frequency quality. The entropy can be used in audio analysis to inform the peakness of a Probability Mass Function (PMF). Sound signals, either in time or frequency domain, are first transformed into a PMF before obtaining their entropy values.

Acoustic entropy has been previously used in several fields from the assessment of biodiversity in ecosystems [14] to the identification of transient events in audio signals [15]. In the present work, three models of acoustic entropy are used: the Temporal Entropy, the Spectral Entropy and the Spectral Multiband Entropy.

2.4.1 Temporal Entropy

The first step to obtain the Temporal Entropy (HT) is to transform the signal into a PMF, called $T(n)$. $T(n)$ is calculated by:

$$\mathrm{T}(n) = \frac{|\mathcal{H}\{h(n)\}|}{\sum_{n=1}^{N}|\mathcal{H}\{h(n)\}|} \quad (4)$$

In Eq. (4), $|\mathcal{H}\{h(n)\}|$ is the absolute value of the Hilbert Transform of the discrete impulse response and N the length of the impulse response. Notice that $\sum_{n=1}^{N} T(n) = 1$.

Once the PMF is obtained, the total HT is evaluated by:

$$\mathrm{HT} = \frac{-\sum_{n=1}^{N} T(n)\log_2(T(n))}{\log_2(N)} \quad (5)$$

According to (5), values are limited in the range of 0 to 1. The highest values in the scale are obtained for equiprobable distributions, as any function with an almost constant envelope, like Gaussian noise, while the lowest values are obtained for irregular distributions, as a Dirac Delta function.

2.4.2 Spectral Entropy and Spectral Multiband Entropy

The Spectral Entropy (HF) is defined in a similar way as HT. A PMF for the spectrum, called $S(k)$, is obtained using a similar procedure as in Eq. (4) but taking the power spectrum instead of the Hilbert Transform. Thus, the HF for a complex spectrum is:

$$\mathrm{HF} = \frac{-\sum_{k=1}^{N} S(k)\log_2(S(k))}{\log_2(N)} \quad (6)$$

Equiprobable distributions, for example a flat frequency response, would result in high HF values while an undamped resonance corresponds to low entropy values.

To compute the Spectral Multiband Entropy (MBH), the spectrum is first partitioned into several frames. Each frame is then divided into sub-frames. The energy of each sub-frame is calculated, this corresponds to a smoothing process of the frequency response. Eq. (6) is applied to each frame, omitting the denominator, which is a normalization parameter, resulting in an entropy profile. MBH can then be obtained as a single value from the average of the different frames.

The difference between MBH and HF is that the latter captures a global picture while MBH proposes a more refined analysis.

3. Experimental Procedure

A single source placed in a corner of a room and a receiver at the opposite corner were considered for each of the rooms. Although this condition does not correspond to a real listening configuration it is consistent with previous studies and it better correlates with the conditions assumed by the Bonello Criteria.

324 rooms were considered for the simulations with dimensions in length and width between 2 and 9 m and a fixed height of 2.7 m. The increasing step rates in each dimension were fixed to 0.1 m. From all the possible rooms in this volume range, only those between 30 and 100 m^3 were selected, with an increasing step of 5 m^3. A constant absorption coefficient of 0.05 was considered for the walls.

The MDM was employed to calculate all the room frequency responses with a sampling frequency of 512 Hz and an FFT size of 2048 points. To obtain the temporal response, an IFFT was computed over the frequency response. Then, this response was filtered using a bandpass FIR filter from 20 to 180 Hz with 61 taps.

For the frequency related parameters, like the FOM, the HF and the MBH, the spectrum obtained via the MDM was limited from 20 to 180 Hz. All the calculations were performed over this range of frequencies, which corresponds roughly to three octaves.

The MBH was analysed using three different configurations, which are classified according to their frame size. Table 1 summarizes their length.

Table 1: Frame size for the MBH parameters

Parameter Name	Frame Size
MBHT	Third octave resolution for 31.5 to125 Hz octave bands
MBH12	12 Hz frames with constant bandwidth with no overlap
MBH2450	24 Hz frames with constant bandwidth and 50% overlap between frames

The frame sizes are here proposed by the authors since there are no previous studies that suggest an ideal frame width or overlap degree that may consider perceptual factors. The sub-frame size was determined by calculating the ideal spacing between two resonances predicted by the HT. This parameter is correlated with decay time, so it is expected that the HT will tend to predict the smallest decay produced by the interaction between two close resonances. Finally, the MBH related parameters were normalized to entropy values obtained by an equiprobable distribution for each frame.

4. Results

The mean value and standard deviation for each parameter considering every room are displayed in Table 2.

Table 2: Mean values and standard deviation for the 324 rooms.

	Mean	Standard Deviation
FOM	0.5229	0.05435
HF	0.8823	0.01483
MBHT	0.8156	0.03453
MBH12	0.8127	0.03056
MBH2450	0.8259	0.02829

In general, the entropy parameters result in higher values than the FOM but with less deviation. The HF shows that values are compressed in a smaller scale compared to the other values. This is probably due to the general approach that the HF follows.

The correlation between the FOM and the entropy parameters were calculated. Table 3 shows the Pearson's correlation coefficients.

Table 3: Pearson Correlation Coefficient for the FOM against the entropy parameters.

	HF	MBHT	MBH12	MBH2450
FOM	0.348**	0.524**	0.572**	0.673**

** p < 0.01

Statistical significance was achieved in each case. The HF has a weak interaction with the FOM, however, as the more refined definitions using frame subdivision were included, correlation tends to increase reaching a significant correlation with the MBH2450.

To further investigate the correlation, dispersion diagrams were created and analysed for each case. Judging from the correlation values and the dispersion plots, the selection of the frame bandwidth in the MBH parameters affects directly its results. For example, the highest correlation between entropy values was achieved between the MBH and the MBH12 ($r = 0.590$, $p < 0.01$) while the MBH2450 achieved moderate interaction with the MBH ($r = 0.468$, $p < 0.01$) and slightly higher with the MBH12 ($r = 0.535$, $p < 0.01$). This poses the question whether there is an optimum frame bandwidth for this frequency-based parameter.

Furthermore, the linear regression models show that no clear correlation between variables can be obtained. For example, the highest coefficient of determination was 0.453 for the FOM against the MBH2450 parameter. It highlights the existence of contrast cases. A subjective based study should be performed in order to determine if a parameter is better to determine the low frequency quality characteristics or in order to determine if there are noticeable variations between this responses. An analysis of this two cases was performed, one with the FOM variable and the MBH2450 constant, and vice versa. Values for the FOM and the MBH2450 parameters are shown in the labels of Fig. 1.

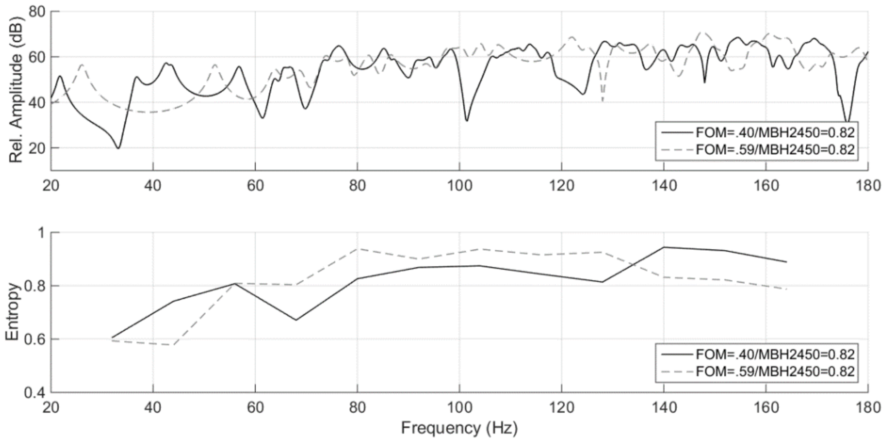

Figure 1: Contrast between variable FOM and constant MBH2450. Frequency response (above) and entropy profile (below). Room dimensions are 6.6 x 2.5 x 2.7 m and 4.7 x 7.9 x 2.7 m for the highest and lowest FOM values respectively.

From Fig. 1 visual evaluation the FOM variation seems to be justified. Entropy parameters seem to evaluate more peaks than notches. It can be observed, for example, for the last frame where a deep notch around 176 Hz is present for the solid curve. In the entropy calculation notches are informed from subsequent peaks, this is only valid for the cases where an anti-resonance is followed by a resonance as in the region from 63 to 75 Hz for the solid curve. Fig. 2 presents the opposite contrast case.

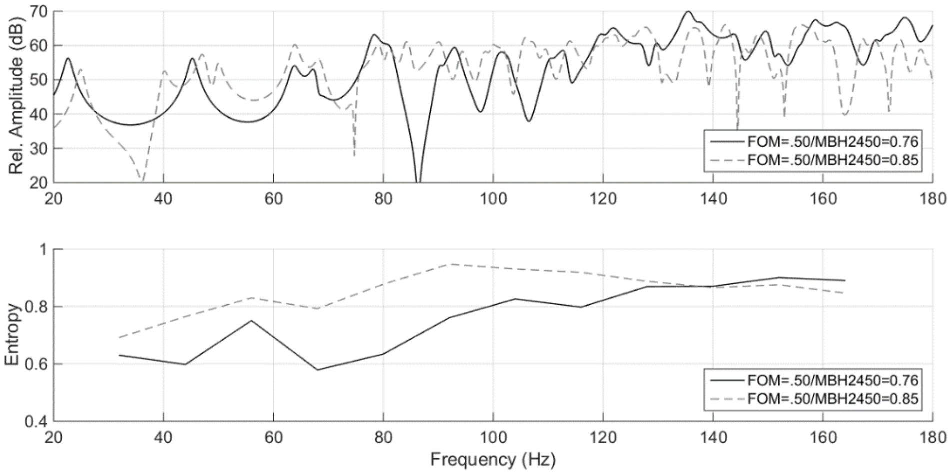

Figure 2: Contrast between constant FOM and variable MBH2450. Frequency response (above) and entropy profile (below). Room dimensions are 4.3 x 6.9 x 2.7 m and 7.6 x 2.2 x 2.7 m for the highest and lowest MBH2450 values respectively.

Fig. 2 shows that a clearer picture of the judgement of peaks by entropy parameters is obtained. In the region from 80 to 120 Hz, high entropy values are registered for one room in comparison to the other response. It seems to be a more regular pattern in frequency distribution, so further analysis between modal density and entropy parameters should be performed. It would be interesting to study if variations in this profile can be distinguished through a subjective test. Considering a single value for the MBH is not enough and deviation between frames should be informed. Finally, a constant bandwidth might not be the best choice for entropy parameters, since it does not follow the increase in modal density as frequency rises, resulting in a less detailed analysis between subsequent resonances.

In either case, the correlation among these metrics shows that a very general tendency can be established for best versus worst cases, which is a good starting point to compare these parameters to the Bonello Criteria. Besides, the apparent relation of entropy parameters with density might lead to a more fair comparison.

4.1 Bonello criteria

Eq. (3) was considered to test the Bonello Criteria. The values for each room were computed and a correlation analysis was performed. Table 4 shows the linear correlation coefficients between the Bonello Total and the frequency-based parameters.

Table 4: Correlation analysis between Bonello Total and Frequency-based parameters

	FOM	HF	MBHT	MBH12	MBH2450
Bonnello Total	-0.176**	-0.063	0.045	-0.157**	-0.231**

** $p < 0.01$

HF and MBHT show respectively that the correlation with the Bonello Total criteria is not significant. The two parameters previously compared with each other, the FOM and the MBH2450, achieve low correlations with the Bonello Total criteria of 0.176 and 0.231 respectively with a significance level of $p < 0.01$. For these two metrics boxplots were created as it is shown in Fig. 3. It can be observed that the standard deviation is high, although a tendency for the mean values of FOM and MBH2450 can be seen. Standard deviation values and quartile ranges show that the Bonello Criteria does not seem to give a clear result about room quality of low frequency. In fact, the best rated rooms for the FOM present violations of the Bonello criteria. The MBH2450 gives high values for the Bonello Total values of 0. The highest rated room (of 6.6 x 5.6 x 2.7 m) falls in this category, being similar in dimensions (7 x 5.3 x 2.7 m) to those recommended in IEC 60268-13 [16]. It seems to be a good point for the Bonello Criteria, however, the standard deviations show that it might be a misleading metric for quality classification of rooms at low frequencies.

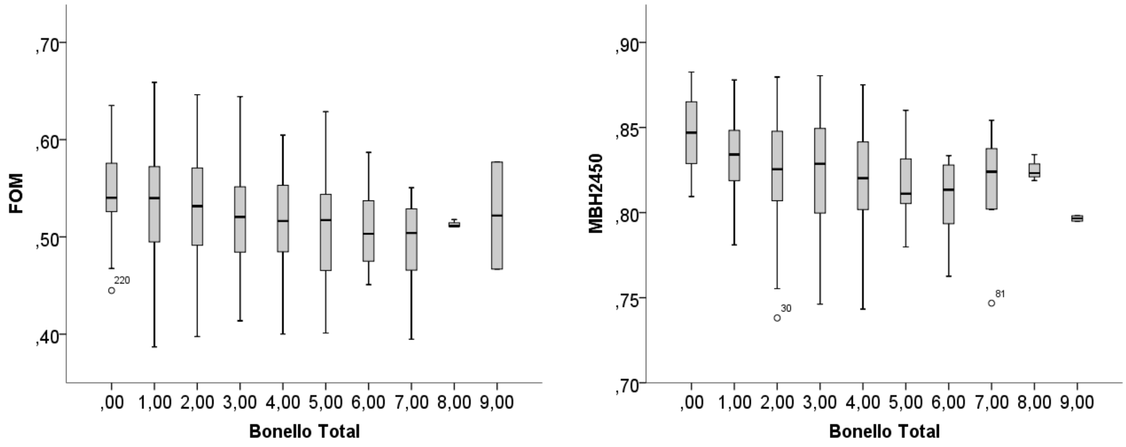

Figure 3: Boxplots for FOM (left) and MBH2450 (right) against Bonello Total.

5. Discussion and Conclusion

The present work presented the evaluation of several metrics related to the assessment of low frequency reproduction quality in small rooms. Entropy parameters were proposed as alternatives for the evaluation of modal response in a rectangular room. Correlation between the entropy parameters and the FOM was performed showing significant correlations with MBH metrics.

Several questions concerning the entropy parameters still have to be analyzed. First, this research did not determine if there is an ideal bandwidth for the MBH, considering both sub-frames and frames. A correct bandwidth could define better the fine frequency analysis and establish if the entropy profile is a useful parameter in the identification of resonances Secondly, the importance of peaks instead of notches of the entropy functions needs further analysis and possibly a redefinition of MBH. For example, phase or group delay changes could be considered to identify anti-resonances.

Although the FOM showed to be a useful metric in the assessment of low frequency quality, its definition could be seen as too general since it evaluates the global deviation of the spectrum. Besides, no weighting is applied to notches and peaks in the frequency distribution, this should be considered in a redefinition of the parameter. The interaction between resonances could possibly be taken into account by entropy profiles and then related to the FOM's results.

Under the assumptions considered by Bonello of a coupled source-receiver system, it seems that this criterion does not always perform a good estimation of the low frequency reproduction quality. It highlights the fact that more robust parameters should be developed to characterize small rooms in this range of frequencies.

Finally, the simple approach employed here should be extended for the whole room using a grid of receptors and different source positions. This point is currently being investigated.

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