Acoustic design of voice booths in open plan offices by modal analysis

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ABSTRACT
In the past years, due to the popularity of open plan offices the need for enclosed spaces meant for concentration moments, small meetings of two people or even for phone meetings is increasing. In order to provide adequate rooms to these types of activities, voice booths are been implemented on office spaces. However, these booths are normally very small with volumes under 15 cubic meters.
In Brazil, it has been noticed an increase in the usage of voice booths in open plan offices. However, voice booths demand a great quality of the sound, especially when it comes to the intelligibility of the human voice. Still they have an acoustic field remarkably different and unknown compared with normal meeting rooms, which hinders the acoustic design since acousticians do not have enough parameters to design these rooms. Therefore, this paper investigates the sound behavior of booths by studying the modes distribution and the coloration present in a considerable amount of existing rooms in order to determine parameters to guide the acoustic design of these spaces.
1 INTRODUCTION

Offices with open plan configuration are being widely used in the recent years due to the necessity of increasing worker density and collaboration between coworkers and also to have more flexibility. Which works perfectly for these purposes however is not the best structure to increase productivity since the level of distraction caused by noises is normally high in open plan offices [1]–[3]. Considering that a higher level of privacy or quietness is regularly needed by workers, enclosed spaces started being implemented inside open plan offices [4].

Specifically in Brazil, offices are adopting voice booths as the missing enclosed spaces to fulfill the lack of privacy and concentration in the open plan office areas. Through its work, Harmonia Acústica¹, which is a company of acoustic consultants that have developed acoustic design for over 150 office buildings in Brazil in the last 3 years, has been noticing a raise in the usage of voice booths in Brazil lately. It is estimated that approximately 67% of the designs developed by Harmonia had voice booths.

Voice booths are being used when workers do not want to disturb other people around them and when there is a need for a quieter place for:

- Higher concentration on some specific activity;
- Small meetings of two people / private conversation;
- Video/phone calls.

All these types of activities are usually destined to one or two people maximum, consequently the room designed for them is very small (Fig. 1). The voice booths commonly used in office spaces in Brazil have volumes under 15 cubic meters.

When the purpose of the voice booth is exclusively for the worker’s concentration and isolation, there is not a lot to consider when it comes to the acoustic conditioning of the room. However, voice booths are frequently used for more than one type of activity, which usually includes traditional phone calls, small meetings of two people and video conferences.

Therefore, essentially all main activities of voice booths demand a great quality of the sound and intelligibility of human voice [5].

However, voice booths still have an acoustic field remarkably different and unknown when compared with normal meeting rooms because of its reduced volume. Considering that dimensions of small rooms are equivalent to audible low frequencies wavelengths, it is necessary to be conscious about resonance and other possible sound effects. Because the smallest the room the higher the chances of the resonances occur in the range of frequencies that may hinder the spectrum of the voice.

¹ www.harmoniaacustica.com.br
Most of the studies made in the small rooms acoustics field so far are destined to small studios that are significantly bigger than the 15 cubic meter booths [6]–[8]. The BBC Research Department study [6] for example, investigated coloration in BBC’s listening rooms and talk studios that had its dimensions considered small. Still their volumes varied between 30 and 120 cubic meters, which represent at least the double of the volume of this study’s object.

For this reason, this paper tries to expose and bring attention to the subject since there are insufficient studies about the acoustic field of such small rooms.

2 OBJECTIVES

This study will compare existing parameters and criteria for acoustic conditioning of rooms in order to investigate which of them and/or if they are applicable to voice booths. As a result, new parameters can be developed, and acoustic design of voice booths will be facilitated.

3 METHODOLOGY

In order to achieve these objectives, this study will make a series of analysis about the modes distribution, coloration and reverberation time in 24 existing voice booths (Table 1). Typical layouts of booths under study are shown in Figure 1.

Table 1 – Full dataset of voice booths under study

<table>
<thead>
<tr>
<th>Voice booths under study</th>
<th>Dimensions</th>
<th>Room Volume (m³)</th>
<th>Absorbing Material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Length</td>
<td>Width</td>
<td>Height</td>
</tr>
<tr>
<td>Voice Booth 1</td>
<td>2.38</td>
<td>1.82</td>
<td>2.90</td>
</tr>
<tr>
<td>Voice Booth 2</td>
<td>2.38</td>
<td>1.82</td>
<td>2.60</td>
</tr>
<tr>
<td>Voice Booth 3</td>
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<td>Voice Booth 6</td>
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<td>Voice Booth 7</td>
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<td>Voice Booth 8</td>
<td>2.40</td>
<td>1.79</td>
<td>2.50</td>
</tr>
<tr>
<td>Voice Booth 9</td>
<td>2.44</td>
<td>1.78</td>
<td>2.60</td>
</tr>
<tr>
<td>Voice Booth 10</td>
<td>2.44</td>
<td>1.78</td>
<td>2.60</td>
</tr>
<tr>
<td>Voice Booth 11</td>
<td>2.18</td>
<td>2.07</td>
<td>2.65</td>
</tr>
<tr>
<td>Voice Booth 12</td>
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</tr>
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<td>2.49</td>
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<tr>
<td>Voice Booth 16</td>
<td>1.18</td>
<td>1.34</td>
<td>2.49</td>
</tr>
<tr>
<td>Voice Booth 17</td>
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<td>1.67</td>
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<td>Voice Booth 19</td>
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<td>1.80</td>
<td>2.50</td>
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<td>Voice Booth 20</td>
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<td>1.48</td>
<td>2.50</td>
</tr>
<tr>
<td>Voice Booth 21</td>
<td>2.36</td>
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<td>Voice Booth 22</td>
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<tr>
<td>Voice Booth 23</td>
<td>1.73</td>
<td>1.84</td>
<td>2.50</td>
</tr>
<tr>
<td>Voice Booth 24</td>
<td>2.56</td>
<td>1.48</td>
<td>2.90</td>
</tr>
</tbody>
</table>
3.1 Criteria

- Modal Distribution:
  The modes distribution are being analyzed according to Bonello’s modes criterion [8] which analyses the frequencies up to 250Hz divided into 1/3 octave bands. To meet Bonello’s modes criterion it is necessary to maintain the modal density rising in a way that the number of modes never decrease if the frequency increases. Each 1/3 octave band should have the same amount of modes as the preceding one or at least the same number (Fig. 2).

- Coloration:
  Coloration is one of the parameters considered in this study to evaluate the sound quality of voice booths because it is a sound effect that may modify the frequencies response in the human voice spectrum inside of a voice booth, and in many cases decrease the acoustic comfort.
In this paper, the voice booths’ coloration analysis is based on two different criteria: Gilford and Bonello’s coloration criterion.

According to Gilford’s study [6] coloration occur when axial modes are isolated and they are separated more than 20Hz from their neighbors.

In Bonello’s opinion “(…) it is desirable to have all modal frequencies in a critical band at least 5% of their frequency apart.” [9].

3.2 Statistical models

Each of the analyzed voice booths had its modes calculated according to the equation:

\[ f = \frac{c}{2} \cdot \sqrt{\left(\frac{m}{x}\right)^2 + \left(\frac{n}{y}\right)^2 + \left(\frac{p}{z}\right)^2} \]

3.3 Subjective test

In order to develop a subjective test to obtain sound quality results, one of the existing rooms was modeled in the room acoustics commercial software AFMG EASE® v 4.4 with “Aura” module and an auralization was developed with the “Ears” module.

The “Aura” module of EASE is a tool used for acoustic simulation algorithms, which uses a hybrid system that mixes both ray tracing, and image source methods.

“Ears” is the model where it is possible to obtain the impulsive response of the room and convolve an anechoic sound file into an auralization simulating the sound field of a room.

In the subjective test, one of the existing voice booths was simulated in EASE considering two scenarios:

- Scenario 1: Simulation of the real conditions of one of the voice booths;
- Scenario 2: Simulation of the same voice booth of “Scenario 1” with acoustic treatment.

This simulation has two main objectives. The first one is to study acoustic treatments that will contribute to the control the critical frequencies. The second objective is to understand if the acoustic treatments suggested in this study are effective when it comes to the human perception.

20 Volunteers listened to the auralization of both scenarios 1 and 2 twice. Each time the simulations had the same conditions except that the sound source was a different human voice for each simulation. Each volunteer was asked which one of the scenarios have the most pleasant acoustic field and they voted according to their preference.

3.3 Field measurements

All voice booths analyzed in this study had its RT measured in situ according to the ISO 3382-2 [10].

4 RESULTS AND DISCUSSION

4.1 Modal Distribution

The modal distribution analysis according to Bonello’s modes criterion divides the voice booths into two groups (Fig. 3 and 4). Only 35% of the studied voice booths meet this criterion
and this division between rooms with good and bad modal distribution is very important to the correlation study of modes, coloration and reverberation time.

Fig. 3 – Number of modes by bandwidth for each voice booth that meet Bonello’s modes criterion.*

Fig. 4 – Number of modes by bandwidth for each voice booth that do not meet Bonello’s modes criterion.*

* Due to equal dimensions between some of the studied voice booths, a few of the curves presented in the graphs above are coincidental.
4.2 Coloration frequencies

In order to quantify the frequencies up to 350Hz that present coloration, all modes and frequencies with coloration of each voice booth were calculated. The mean number of frequencies with coloration in the studied voice booths according to both Gilford and Bonello’s modes criteria is shown in Table 2.

Table 2 – Average number of coloration in the studied voice booths according to Gilford and Bonello’s criteria.

<table>
<thead>
<tr>
<th></th>
<th>Average number of frequencies with coloration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gilford</td>
<td>5.78</td>
</tr>
<tr>
<td>Bonello</td>
<td>56.1</td>
</tr>
</tbody>
</table>

The same analysis presented in Figure 5 was made to each of the studied voice booths. This coloration evaluation indicates that 97.5% of the first modal frequencies with coloration according to Gilford’s criterion are out of the human voice spectrum, which is usually above 100 Hz. When the objective is the acoustic design of the room, this result indicates that it is more significant to act starting with the second modal frequency with coloration.

However, it is not possible to interpret the data extracted from Bonello’s coloration criterion in the same way. According this criterion the mode spacing is so small and there are so many colorations happening that it is not possible to consider so many modal frequencies in the design of a room (Fig. 5). In such manner, it is possible to say that Bonello’s coloration criterion is not conclusive when it comes to find the right frequencies to act on the acoustic design.

Usually modes separated from their neighbors by intervals greater than 20Hz are more audible [6]. Consequently, taking measures to minimize their resonances in the room would be more precise and efficient than acting on all the coloration frequencies pointed by Bonello's coloration criterion. For this reason, it is assumed that Gilford’s criterion for coloration is more suitable to be used as a parameter in the acoustic design of voice booths.
Fig. 5 – Comparison between frequencies with coloration according to Gilford and Bonello’s modes criteria in voice booth 13.

4.3 Reverberation Time (RT)

In order to evaluate if the RT is some way associated to the modes and coloration frequencies of the voice booths a series of correlation studies were developed.

The first investigation is related to the modal distribution of the voice booths. Gathering the rooms with good modal distribution in one group and the ones with bad modal distribution in another group an analysis was made by comparing the values of their RT measured in situ.

Fig. 6 – Reverberation time values of the studied voice booths measured in situ.
The graph (Fig. 6) demonstrates that the rooms with good and bad modes distribution according to Bonello’s modes criterion (Fig. 3 and 4) do not have any contrast between them when it comes to the reverberation time in high frequencies. Contrarily, in the voice booths that do not meet Bonello’s criterion, there is a higher dispersion of the RT in the low frequency and scarcely in the middle frequency range.

The next analysis is related to the coloration frequencies of the voice booths according to Gilford’s coloration criterion. When it comes to the correlation between coloration frequencies and RT, the graph presented in Fig. 7 has the regions with a higher concentration of coloration frequencies highlighted in grey.

![Reverberation time x Frequencies with coloration graph](image)

*Fig. 7 – Reverberation time values in the frequencies with coloration according to Gilford’s criterion.*

The Fig. 7 shows RT values very scattered and because of that it is not possible to presume any tendency on the behavior of RT that relates to the colorations frequencies in voice booths.

Considering voice booths dimensions are so small, changing their modal distribution through modifying their proportions is rarely possible. So, still in the attempt to investigate the RT influence on the sound quality of the voice booths, a subjective test was performed as described earlier in this paper.

The objective of this simulation is to change the voice booth modal response by including elements in the room that will contribute to the control of frequencies between 125Hz to 315Hz which are critical regions already pointed out earlier in the study (Fig. 6) as coincidental to the spectrum of the voice. And at the same time, the simulation aims to perform a subjective test to
analyze if this acoustic treatment of the voice booth is effective when it comes to the human perception.

This treatment was executed through a membrane absorber calculated to act on the critical frequencies of this specific voice booth. The volunteers listened to the auralization of both scenarios 1 (simulation of the real room) and 2 (voice booth with acoustic treatment) twice (with two different voices as sound sources) and were asked to vote which scenario has the most pleasant acoustic field according to their opinion.

![Subjective Test's Results](image)

**Fig. 8 – Subjective test’s results.**

The graph (Fig. 8) is relevant because it demonstrates that people have a tendency to prefer the “Scenario 2”. Which indicates that preference for voice booths with acoustic treatment in the frequencies pointed out as critical by this study analysis.

Even though in order to have a more precise conclusion more studies need to be developed in the future, all analysis presented in this study demonstrate that there is a possibility that the RT may be one of the parameters to evaluate the quality of the voice booths for human voice.

5 CONCLUSIONS

The results of this paper investigation show that when it comes to the analysis of the acoustic field of voice booths, all methods have some type of limitation.

Even so, Gilford’s coloration criterion proved to be the most satisfactory one to be used as a coloration analysis parameter for voice booth acoustic conditioning. Still, according to his criterion, this study shows that for the acoustic design of voice booths it is more significant to act starting with the second modal frequency with coloration because it is the first coloration mode in the spectrum of the human voice.

The studies herein presented also show that the RT values in the low frequency region are dispersed. In such manner, the colorations analysis and the subjective test’s result indicate that
voice booths should have their RT treated through the use of sound absorbing materials for the low frequency region, such as membrane absorbers.

In conclusion, all the presented results indicate that RT can be one of the main parameters to evaluate the quality of voice booths when combined to modal analysis as mentioned before. So, for making acoustic design of voice booths easier, RT is an important and interesting parameter to be used since its measurement methods are simple, easy to perform and there are established standards to give procedures to be followed in the verification measurements. And in order to verify if the voice booth’s modal behavior is according to the design, the frequency response of the booths can be verified. In this conference, a method for performing this measurement in situ is presented, as well as the effects of using acoustic treatment on different spectrum regions [11].

6  FURTHER WORK

Further work should be developed with additional correlation studies with more measurements in situ and modal analysis data. Along with questionnaires and more subjective studies to investigate further what these parameters and criteria really mean when it comes to human perception. And to verify if they provide the right information to established to acoustic design parameters for voice booths.

7  REFERENCES