EuroRegio2016
June 13-15, 2016
Porto • Portugal

ADAPTABILITY OF ACOUSTIC CONDITIONING OF A HALL BY VARYING THE HEIGHT OF THE ACOUSTIC ROOF

Pedro J.Blázquez[1], **Juan Cuquejo**[1]

[1] Universidad Internacional de La Rioja (UNIR),
Gran Vía Rey Juan Carlos I, 41. 26002 Logroño, La Rioja, Spain
(pedrojesus.blazquez@unir.net, juan.cuquejo@unir.net)

Abstract

In this paper, we analyze the acoustic behavior of three prototypes of halls, where the only difference between them is the roof. We intend to show that, when a variable roof, conditioned with acoustic materials, is installed, it is possible to obtain, from a single hall, different ones. That is, we can adequate the acoustic conditions of a certain kind of hall modifying the roof, paying attention also to the acoustic conditioning of the hall with lineal roof. For instance, without modifying the roof the hall would be prepared for being a hall for symphonic music, organ music, etc. If we vary the roof to 0.5 meters we achieve a polyvalent hall, for Jazz music, etc. And varying the roof at his maximum (1 meter), we achieve a higher absorption that would be necessary for a hall where concerts or conferences would take place because in these cases, the sound pressure level will be higher.

Keywords: reverberation, roof, variable, conditioning, acoustics.

PACS no. 43.55.+p,43.71.+m,43.75.+a

1 Introduction

1.1 State of the art

At present, several methods for acoustic conditioning have been studied, applying several kinds of materials and methodologies. The aim is reducing reverberation time and improving the acoustic conditioning of multiple halls, using several acoustic indices that will define the features of the studied hall. Researching about materials has improved the quality of the sound. As an example, we could mention the absorbent panels CPA [5-13] that absorb the sound in low frequencies or CBA [14] that absorb the sound until 20 000 Hz, or the Schroeder diffusors [1] that condition and improve the quality of the sound.

During the researching about acoustic conditioning, several different kinds of sound diffusors have been built, with the aim of controlling sound reflection, as asymmetrical diffusors [2]. Also, methods for the placement of absorbent materials have been developed [3] and for calculating the reverberation in a hall with sat audience [4]. One of the materials under research is the microperfored panel (MPP) a promising absorbent of sound [6-7-8-9-10-11]. Another kind of materials under research are the so-called multilayer ones, that consist of a superposition of different types of porous materials and they have a high absorbance capacity [12]. Another of the realms where advances were achieved is in modelling, for instance, in modeling of speech intelligibility [15], which let to correct the speech transmission indices (STI) by means of absorption.

These new developments, both in the realm of acoustic materials and in techniques for their processing, point out the importance of Acoustics, that can be considered one of the main research fields in the realm of acoustic conditioning of rooms. Besides, it shows that Acoustics is basic for conditioning old and new facilities.

1.2 Development of the study

The first part of the work will describe the calculations of reverberation times using Sabine and Eyring methods. With these calculations done in the prototypes, we will compute and analyze the acoustic sonority indices: *Direct SPL Index, Alcons/Articulation Loss Index and RaSTI Index*.

Direct SPL Index comes from the Sound Pressure Level. SPL is defined as 20 multiplied by the common logarithm of the quotient between the root mean square sound pressure and the reference sound pressure (20 µPa, considered as the threshold of human hearing). *Alcons/Articulation Loss Index* is a measure of speech intelligibility. *Alcons* (*Articulation Loss of CONSonants*) value is based in the average percentage of consonants that cannot be understood by hearers (speech intelligibility depends strongly on consonants). *RaSTI* (*Rapid Speech Transmission Index*) is related to Alcons although provides other information. Its values ranges from 0 to 1 (perfect intelligibility).

After this introduction, in section 2 (Description of the model) we will mention the software used in our simulations and we will explain the features of the prototypes that will be analyzed in the paper, defining their structures and the used materials both in the acoustic conditioning and in the rest of the halls. We will also explain what is intended to do with prototypes, that is, the kind of halls they are designed for. In section 3 (Tests and simulations) we will describe the simulations carried out in the prototypes and we will explain the results obtained and their graphical representations. These results and graphs will be analyzed in section 4 (Analysis of results). Finally, in section 5 (Conclusions) we will summarize the conclusions derived from our researching.

2 Description of the model

In order to perform a simulation of acoustic features of the prototypes, we have used the software EASE (*http://ease.afmg.eu/*), a specific package for analysis and simulation of acoustic rooms, since with that program we can define the structural features of the room, absorption coefficients of the surfaces and the sources of sound. EASE let us analyze the prototypes in a global way or from several concrete points where the sound will be heard. By this, precise calculations can be made about reverberation times, speech intelligibility and other parameters needed for an acoustic analysis.

In the analysis carried out in the section *Reverberation Times*, we have used the tool Room RT included in EASE software that calculates the reverberation times using the methods Sabine and Eyring. In the analysis of Acoustic Sonority Indices (*Direct SPL Index, Alcons/Articulation Loss Index and RaSTI index*) we use the application *Area Mapping* (*Standard Mapping – Calculation parameters*) included in EASE package. These parameters will be studied for each of the prototypes.

Below we will explain the features of the three prototypes considered (*Prototype 7.0m, Prototype 7.0.5m* and *Prototype 7.1m*), listing their structural features and the kind of halls or events they would be used for.

2.1 Development of the study: Prototype 7.0m

Prototype 7.0m has a linear roof, that is, the variation of the Unfolding Zone is 0 meters and the only acoustic conditioning received by this prototype is located in the lower part of the Unfolding Zone (upper horizontal surface in this prototype). That conditioning is the use of the acoustic material PYRMID DIF, whose aim is reducing the reverberation times of the lower frequencies (between 100 and 250 Hz). The goal of this prototype is its use in halls devoted to classical music, organ, symphonic music, chamber music, etc.

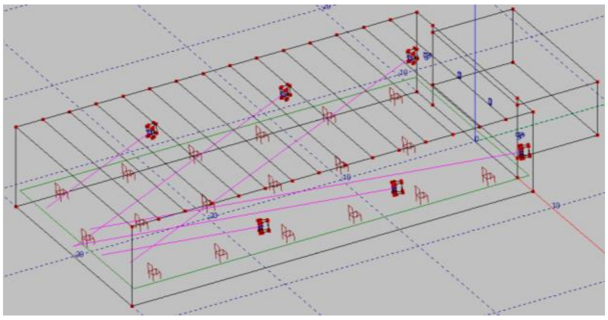

Figure 1 – Tridimensional representation of Prototype 7.0m.

2.2 Development of the study: Prototype 7.0.5m

Prototype 7.0.5m has not a linear roof. The variation of Unfolding Zone is of 0.5m. Acoustic material ABSORBER is used in that case, and it is located in the vertical parts of the Unfolding Zone, in order to lessen the reverberation times produced in the prototypes in a linear way. It is also used the acoustic material PYRMID DIF in the lower part of the Unfolding Zone, whose mission is reducing the reverberation times in the lower frequencies, as mentioned above. The aim of this prototype is the conditioning of polyvalent halls, Jazz halls, etc.

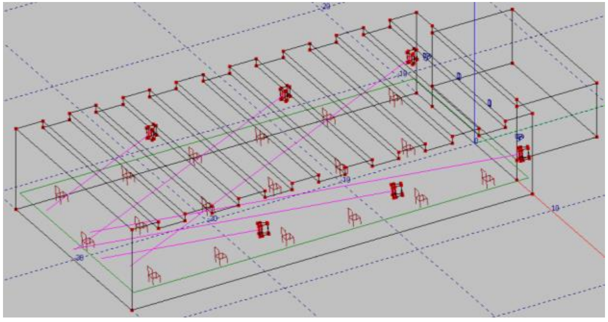

Figure 2 – Tridimensional representation of Prototype 7.0.5m.

2.3 Development of the study: Prototype 7.1m

Prototype 7.1m is the one with the biggest variation. The Unfolding Zone is of 1 meter, and acoustic material ABSORBER is used in that entire zone. That material, as we explained above (*Prototype*

7.0.5m), is located in the vertical parts of the Unfolding Zone. In its lower part we have the acoustic material PYRMID DIF, whose function is reducing the reverberation times of the lowest frequencies. The aim of this prototype is reducing as much as possible the reverberation times produced in the inner part of the hall, in order to ensure a good conditioning for conferences, political speeches, etc.

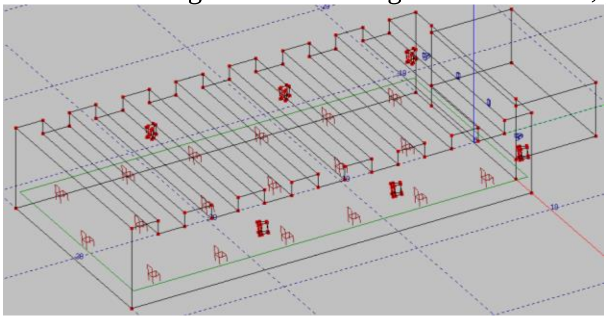

Figure 3 – Tridimensional representation of Prototype 7.1m.

Although the variation in the distances for the roofs stated above are fixed: 0 meters for *Prototype 7.0m*, 0.5 meters for *Prototype 7.0.5m* and 1 meter for *Prototype 7.1m*, these distances are not the only possible ones. The Unfolding zone of the roof can vary from 0 meters to 1 meter, providing then a dynamic roof adaptable to the acoustic features of the events that will take place in the considered hall.

3 Tests and simulations

In this section, we will explain and comment the results obtained from the performed simulations in the prototypes. We will start with reverberation times in the inner part of the prototypes calculations. Then, we will show the results of the simulations of acoustic sonority indices (*Direct SPL Index, Alcons/Articulation Loss Index and RaSTI index*) which will be a good way for evaluating the acoustic characteristics of the prototypes.

In our study, we will emphasis in the result for frequencies of 500, 1000, 2000 and 4000 Hz. 500 Hz is generally considered as the lowest in the range of voice intelligibility and its contribution to speech intelligibility is about 16%. 1000 Hz is considered as an intermediate frequency in voice intelligibility and its contribution to speech intelligibility is about 25%. 2000 Hz is considered as the highest in voice intelligibility and its contribution to speech intelligibility is about 34%. Frequencies above 2000 Hz add “bright” to speech, so we considered studying 4000Hz as a frequency in that range.

3.1 Reverberation times

In this section, we will show the results for the reverberation times when we modify the roof conditioned with the different acoustic materials considered. In order to do that, we will use Sabine and Eyring methods for computing the reverberation times.

Table 1 – Comparison of reverberation times.

Fr (Hz)	LINEAL.S	VARIA.S	VARIA1M.S	LINEAL.E	VARIA.E	VARIA1M.E
100	1,63	1,16	0,89	1,48	1,02	0,76
125	1,63	1,16	0,89	1,48	1,02	0,76
160	1,65	1,17	0,9	1,5	1,03	0,76
200	1,68	1,19	0,9	1,53	1,05	0,77
250	1,7	1,2	0,91	1,55	1,06	0,78

315	1,73	1,21	0,92	1,57	1,07	0,79
400	1,75	1,22	0,92	1,59	1,08	0,79
500	1,77	1,23	0,93	1,62	1,09	0,8
630	1,75	1,22	0,93	1,6	1,08	0,8
800	1,73	1,21	0,92	1,58	1,07	0,79
1000	1,71	1,2	0,91	1,56	1,06	0,78
1250	1,69	1,2	0,91	1,55	1,06	0,78
1600	1,67	1,19	0,9	1,53	1,05	0,78
2000	1,64	1,17	0,89	1,5	1,04	0,77
2500	1,58	1,14	0,88	1,45	1,01	0,75
3150	1,5	1,1	0,85	1,38	0,98	0,73
4000	1,4	1,04	0,82	1,29	0,93	0,71
5000	1,28	0,97	0,77	1,19	0,87	0,67
6300	1,13	0,88	0,72	1,05	0,8	0,63
8000	0,95	0,77	0,64	0,9	0,71	0,57
10000	0,76	0,64	0,55	0,73	0,6	0,49

LINEAL.S Linear roof. Calculated with Sabine	VARIA. S 0.5 meters variable roof. Calculated with Sabine	VARIA1M.S 1 meter variable roof. Calculated with Sabine	LINEAL.E Linear roof. Calculated with Eyring	VARIA.E 0.5 meters variable roof. Calculated with Eyring	VARIA1M.E 1 meter variable roof. Calculated with Eyring

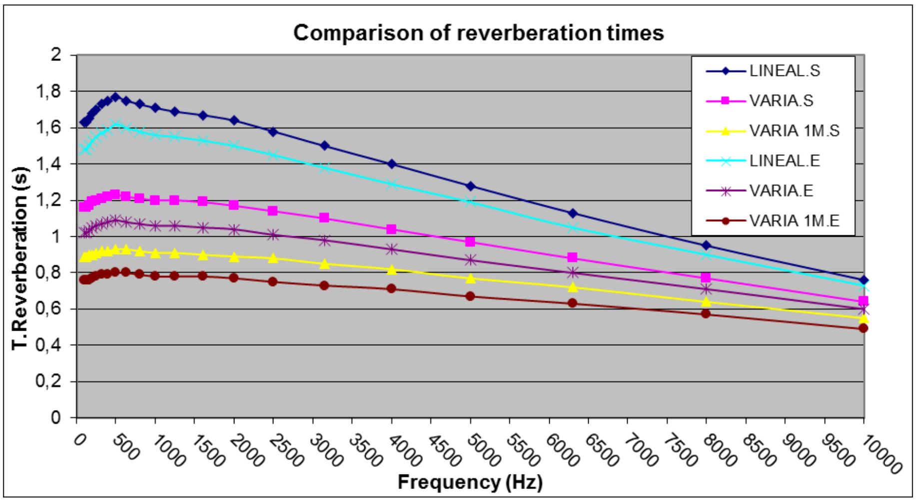

Figure 4 – Reverberation times for each frequency according the variations in the roofs

Table 2 – Comparison of the differences between computed reverberation times.

Fr (Hz)	DF LS-VS (S)	DF LS-V1MS (S)	DF LE-VE (S)	DF LS-V1ME (S)
100	0,47	0,74	0,46	0,72
125	0,47	0,74	0,46	0,72
160	0,48	0,75	0,47	0,74
200	0,49	0,78	0,48	0,76
250	0,5	0,79	0,49	0,77
315	0,52	0,81	0,5	0,78
400	0,53	0,83	0,51	0,8

500	0,54	0,84	0,53	0,82
630	0,53	0,82	0,52	0,8
800	0,52	0,81	0,51	0,79
1000	0,51	0,8	0,5	0,78
1250	0,49	0,78	0,49	0,77
1600	0,48	0,77	0,48	0,75
2000	0,47	0,75	0,46	0,73
2500	0,44	0,7	0,44	0,7
3150	0,4	0,65	0,4	0,65
4000	0,36	0,58	0,36	0,58
5000	0,31	0,51	0,32	0,52
6300	0,25	0,41	0,25	0,42
8000	0,18	0,31	0,19	0,33
10000	0,12	0,21	0,13	0,24

DF LS-VS (S) Difference between reverberation times using Sabine method, between Linear Roof and 0.5 meters variable roof.	DF LS-V1MS (S) Difference between reverberation times using Sabine method, between Linear Roof and 1 meter variable roof.	DF LE-VE (S) Difference between reverberation times using Eyring method, between Linear Roof and 0.5 meters variable roof.	DF LS-V1ME (S) Difference between reverberation times using Eyring method, between Linear Roof and 1 meter variable roof.

3.2 Direct SPL Index

The simulation of Direct SPL Index will denote if there is a good coverage of direct sound or not. We should obtain a value for Direct SPL Index between plus/minus 3 dB.

Table 3 – Results of direct sound for the main frequencies considered.

	500 Hz	1000 Hz	2000 Hz	4000 Hz
Prototype 0m	94,34 dB	93,54 dB	92,62 dB	91,79 dB
Prototype 0,5m	94,2 dB	93,49 dB	92,61 dB	91,72 dB
Prototype 1m	94,03 dB	93,49 dB	92,61 dB	91,72 dB

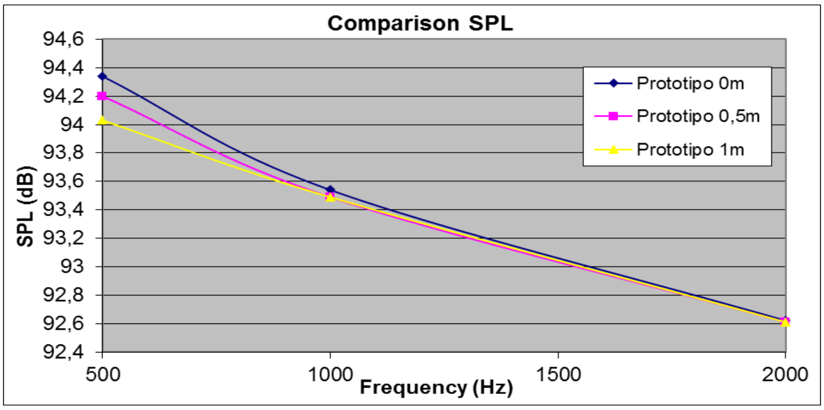

Figure 5 – Graphical representation of direct sound for the main frequencies considered.

3.3 Alcons/Articulation Loss Index

Simulation of the Alcons/Articulation Loss index will characterize the loss of speech articulation received, that is, the loss of intelligibility inside the prototype.

Table 4 – Results of the Alcons Index for the main frequencies.

	500 Hz	1000 Hz	2000 Hz	4000 Hz
Prototype 0m	10,69 %	10,4 %	9,53 %	8,02 %
Prototype 0,5m	8,34 %	8,24 %	7,61 %	6,71 %
Prototype 1m	5,85 %	5,81 %	5,48 %	5,02 %

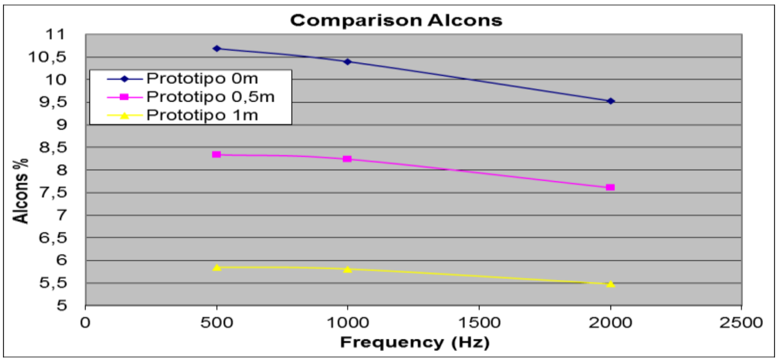

Figure 6 – Comparative Graph for Alcons Index.

3.4 RaSTI Index

Simulation of RaSTI Index will indicate if we have a fast speech transmission and it will measure speech intelligibility.

Table 5 – Results for RaSTI Index for the main frequencies.

	500 Hz	1000 Hz	2000 Hz	4000 Hz
Prototype 0m	0,512	0,517	0,535	0,563
Prototype 0,5m	0,559	0,559	0,575	0,593
Prototype 1m	0,623	0,623	0,633	0,647

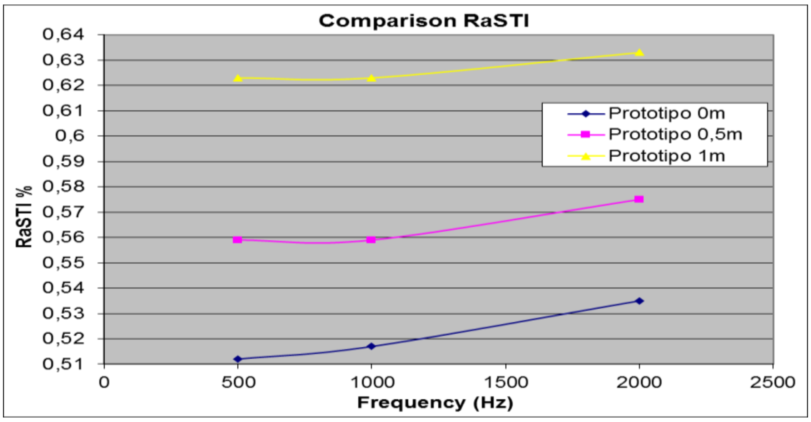

Figure 7 – RaSTI Index comparison for each prototype.

4 Analysis of the results

Below, all the results explained in the last section will be analyzed, in order to reach the aim of this paper: stating the adaptability of the prototypes to different kind of halls.

4.1 Reverberation times

Analyzing the results obtained in the Fig 4 and Tables 1 and 2 from section *Tests and simulations*, we realize that the reduction of reverberation times is not achieved only in low frequencies, but we achieve a much more linear reduction. Paying attention to 0.5 meters variation, we see that the achieved reduction in reverberation time is higher than 0.4 seconds until 3150 Hz and in the variation of 1 meter, that reduction is achieved until 6300 Hz. We obtain also reductions of 0.8 seconds and higher for the most important frequencies. It is also seen that we can reduce reverberation time between 0.84 and 0.6 seconds until 4000Hz, the last reference frequency in this work, for both methods. This indicates that, for a single hall, we can obtain several acoustic conditionings.

Another important fact is that, when the roof is unfolded, a higher linearity will be achieved in the prototypes reverberation times, that is, the difference between the highest and the lowest reverberation time will be smaller (0.87 seconds (Sabine method) and 0.75 seconds (Eyring method) for *Prototype 0m*, 0.52 seconds (Sabine method) and 0.42 seconds (Eyring method) for *Prototype 0.5m* and 0.34 seconds (Sabine method) and 0.27 seconds (Eyring method) for *Prototype 1m*).

4.2 Direct SPL Index

As it can be seen in Fig. 5 and Table 3 shown in the section *Tests and simulations*, when the roof is modified, SPL (Sound Pressure Level) coverage is almost the same, that is, the difference between 500 Hz SPL and the one for 4000Hz is very small (2.55 dB for *Prototype 0m*, 2.48 dB for *Prototype 0.5m* and for *Prototype 1m* 2.31 dB) and the differences between prototypes become negligible (difference between the covering of *Prototype 0m* and the one in *Prototype 1m* is only 0.34 dB). This indicates that the variation in the roof does not affect the values of *Direct SPL Index*. It is observed that, for the three prototypes, the data lies in the range of plus minus 3dB, so we have achieved a sound compensated system inside the halls, one of the desired features for achieving a good acoustic.

4.3 Alcons/Articulation Loss Index

Analyzing the results represented in Fig 6 and Table 4 in the section *Tests and Simulations*, it is observed that Alcons Index decreases considerably (4.84% for 500 Hz, 4.59% for 1000 Hz, 4.05% for 2000 Hz and 3% for 4000 Hz). Such a decrease is one of the goals of the variable roofs design. If we vary the roof, Alcons Index decreases according to the different applications of the hall.

In the first representation (*Prototype 0m)* Alcons Index indicates that we have good speech intelligibility: values are in the range of 7% and 11% (10.69% for 500 Hz, 10.4% for 1000 Hz, 9.53% for 2000 Hz and 8.02% for 4000 Hz). These values are optimal for the kind of halls that would use *Prototype 0m*: classical music halls, organ halls, symphonic halls, chamber music halls, etc., where their reverberation times must be between 1.4 and 2 seconds.

In the second representation (*Prototype 0,5m*), Alcons Index indicates that we have a good speech intelligibility: values are between 7% and 11% (8.34% for 500 Hz, 8.24% for 1000 Hz, 7.61% for 2000 Hz and 6.71% for 4000 Hz). These values are optimal for halls that would use this prototype:

polyvalent halls, Jazz music halls, etc., where their reverberation times would be between 1 and 1.4 seconds.

In the third representation (*Prototype 1m*) Alcons Index indicates that we have really good speech intelligibility: values are between 0% and 7% (5.85% for 500 Hz, 5.81% for 1000 Hz, 5.48% for 2000 Hz and 5.02% for 4000 Hz). Such values are optimal for the kind of halls this prototype is intended to: conference halls, political speeches halls, etc. where their reverberation times would be between 1 and 0.5 seconds.

4.4 RaSTI Index

After analyzing the results depicted in the figure and table (Fig. 7 and Table 5) from the section Tests and Simulations, if we vary the roof more, RaSTI Index considerably increases (0.111 for 500 Hz, 0.106 for 1000 Hz, 0.098 for 2000 Hz and 0.084 for 4000 Hz). This means that, the bigger the variation of the roof, the better the speech transmission will be. This will favor speech intelligibility and will help to fulfill the goal of this work: having different acoustic conditioning in a single hall.

In the first representation (*Prototype 0m*) RaSTI index suggests that we have achieved a good speech intelligibility: values are between 0.45 and 0.6 (0.512% for 500 Hz, 0.517% for 1000 Hz, 5.35% for 2000 Hz and 0.563% for 4000 Hz). These values are optimal for the kind of halls Prototype 0m is intended for: classical music, organ music, symphonic music, chamber music, etc.

In the second representation (*Prototype 0,5m*) RaSTI index suggests that we obtained a good speech intelligibility, since the values are between 0.45 and 0.6 (0.559% for 500 Hz, 0.559% for 1000 Hz, 0.575% for 2000 Hz and 0.593% for 4000 Hz). The values achieved are optimal for the kind of halls this prototype is intended for: polyvalent halls, Jazz halls, etc.

In the third representation (*Prototype 1m*) RaSTI index suggests that we obtained good speech intelligibility: the values are between 0.6 and 1 (0.623% for 500 Hz, 0.623% for 1000 Hz, 0.633% for 2000 Hz and 0.647% for 4000 Hz). The obtained values are optimal for the halls that would use Prototype 1: conference halls, political speech halls, etc. where speech transmission must be fast.

5 Conclusions

As the study shows, we realize that the design of a variable roof can condition a hall for different kind of events, what reduces the need of looking for halls or the unnecessary construction of more halls. Hence, if this kind of variable roof is installed, the halls will be able to be adapted to a certain musical style and halls with the best features for conferences, discussions, political speeches, etc.

After a reflection about the results shown in this work, we realize that the use of variable roofs does not affect negatively to indices like *Direct SPL Index*, since the variations obtained for the mentioned index are negligible. In connection with Alcons Index, it can be noted that the roof variation is favorable, because it improves speech reception, increasing the clarity of the sound in the hall. In the same way, we achieve better speech intelligibility if we take into account the results for RaSTI index.

Due to everything mentioned above, we consider that the installation of a variable roof inside a hall can help to install a sound system in a hall and guarantee the acoustic quality of a certain event.

6 Acknowledgments

This work is partially funded by UNIR Research (*http://research.unir.net*), Universidad Internacional de La Rioja (UNIR, *http://www.unir.net*), under the Research Support Strategy 3 [2015-2017], Research Group MOdelación Matemática Aplicada a la Ingeniería (MOMAIN)".

References

[1] JA Hargreaves y TJ Cox. A transient boundary element method model of Schroeder diffuser scattering using well mouth impedance. 2008. Journal of the Acoustical Society of America.

[2] D'P Antonio y Cox TJ. Sound diffuser for scattering sound reflection, has aperiodic array of diffuser modules, where two modules have same asymmetrical surface pattern oriented in two different orientations, respectively. 2004. Journal of the Acoustical Society of America.

[3] P Kaeseler. Determining modification of acoustic environment by emitting white or pink noise to measure response and compute locations of passive acoustic dampers. 2003. Journal of the Acoustical Society of America.

[4] Nishihara N, Hidaka T y Beranek LL. Mechanism of sound absorption by seated audience in halls. 2001. Journal of the Acoustical Society of America.

[5] HV Fuchs, Zha X, Zhou X y H Drotleff. Creating low-noise environments in communication rooms. 2001. Applied Acoustics.

[6] Sakagami K, Morimoto M y Koike W. A numerical study of double-leaf microperforated panel absorbers. 2006. Applied Acoustics.

[7] M Toyoda, RL Mu y Takahashi D. Relationship between Helmholtz-resonance absorption and panel-type absorption in finite flexible microperforated-panel absorbers. 2010. Applied Acoustics.

[8] O Onen y M Caliskan. Design of a single layer micro-perforated sound absorber by finite element analysis. 2010. Applied Acoustics.

[9] K Sakagam, Nakamori T, M Morimoto y M Yairi. Double-leaf microperforated panel space absorbers: A revised theory and detailed analysis. 2009. Applied Acoustics.

[10] N Atalla y Sgard F. Modeling of perforated plates and screens using rigid frame porous models. 2007. Journal of sound and vibration.

[11] AA Lee, Lee EWM y Ng CF. Sound absorption of a finite flexible micro-perforated panel backed by an air cavity. 2005. Journal of sound and vibration.

[12] FC Lee y WH Chen. On the acoustic absorption of multi-layer absorbers with different inner structures. 2003. Journal of sound and vibration.

[13] HV Fuchs, Zha X, Zhou X y H Drotleff. Creating low-noise environments in communication rooms. 2001. Applied Acoustics.

[14] HV Fuchs, Zha X y M Pommerer. Qualifying freefield and reverberation rooms for frequencies below 100 Hz. 2000. Applied Acoustics.

[15] J Kang. Numerical modelling of the speech intelligibility in dining spaces. 2002. Applied Acoustics.