Measurements of stage acoustics in four configurations of an open-air performance acoustic shell

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MEASUREMENTS OF STAGE ACOUSTICS IN FOUR CONFIGURATIONS OF AN OPEN-AIR PERFORMANCE ACOUSTIC SHELL

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ABSTRACT*

Different design recommendations for stage design and parameters for objective measures of the stage conditions have been proposed. They aim to provide the right balance to each musician on stage, consisting in hearing one-self (support) and hearing others (ensemble). These aspects become even more challenging for open-air acoustic shells. The paper presents the case-study of ReS, an acoustic shell developed in the frame of "Villa Pennisi in Musica" Summer School, a "learning by doing"-based workshop approach that promotes the integration of acoustics, digital optimization and technology in an environment that involves musicians with different levels of expertise. This paper focuses on the results of a measurement campaign on five different configurations of the acoustic shell. The design elements related to the reflectors array and sound diffuser have been considered separately and in combination to investigate their effects on the objective stage acoustic parameters that is early and late support (ST_{early} and ST_{late}) and spectral content. To this aim, the musicians' configuration of a *sestetto* has been considered. The results show that ST parameters are little sensitive (differences <1dB) to the presence of the reflectors array and diffuser, however some significant spectral effects could be attributed to these design elements.

Keywords: *stage acoustics, acoustic shell, sound absorption coefficient, impedance tube.*

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1. INTRODUCTION

Acoustic shells [1, 2] have been attractive for different open-air performances from the reuse of ancient spaces [3-5] to other experimental and commercialized solutions [6-7]. Besides the challenging acoustic conditions of the audience, concert halls need to provide a proper acoustic environment to the musicians on stage. This aspect becomes even more challenging for open-air concert halls that generate the main important acoustic reflections through an acoustic shell only. More evidence on the objective and subjective aspects related to the stage design criteria for acoustic shells is still needed. To this aim, this work presents an investigation on the stage acoustics of different conditions of an acoustic shell used for open-air chamber music performances.

Several stage design recommendations proposed in the literature [9-11] highlight that the importance of the stage acoustic environment is two folded: a musician should be able to hear one-self and the others. However, since the process of making music is interactive, the musicians automatically adapt to their environment, which makes it more difficult to find relations between objective and subjective aspects on a stage. A detailed summary of the most important findings on stage acoustics has been presented in Barron [12]. The most used metrics to objectively characterize the stage acoustics, included also in ISO 3382 standard [13], have been proposed by Gade [9, 10]. These are stage support (ST_{early} and ST_{late}) validated based on both laboratory and field experiments. The definition of ST is given as the energy ratio of the reflected energy to the direct sound energy, expressed in decibels. Continuous research on objective and subjective experiments has led to stage acoustical parameters improvement to better relate acoustical design to perception for musicians, i.e. impression of support and ease of ensemble [12, 14]. However, the different needs of various types of musicians and individual preferences make the generalization of the results very difficult and challenging. Moreover, it is highlighted that stage acoustical conditions are very diverse, even within a single hall. Beranek suggested a preferred range of ST_{Early} (-14.4 to -12 dB) based on field measurements and conductors' survey results [15]. In other studies, the range of ST_{Early} simulated and measured using computer simulation and scale model has been reported from -18 to -8 dB, for various hall conditions [16]. Abdou and Guy [17] report tolerance bounds -12 to -8 dB and Bradly [18] reported evidence from 13 halls measurements in the range -14.3 to -9 dB. In summary, the ISO 3382 indicates typical ranges of -24 to -8 dB for ST_{early} and -24 to -10 dB for ST_{late}. It can be observed that there is a wide range of variability and that these parameters still do not have a defined Just Noticeable Difference (JND), which makes it difficult to estimate the significant effects of specific design choices. Moreover, while very often these parameters have been correlated to subjective data in large orchestras on stage [19, 20], while there are several open questions for small and open-air concert halls.

Figure 1. *Sestetto* Stradivari in Villa Pennisi in Musica 2021 Concert: acoustic shell and audience sitting in the garden (upper photo by Flavio Iannello).

This paper focuses on the results of a measurement campaign on four different configurations of an acoustic shell used on the stage for an open-air concert of chamber music (Figure 1). The design elements related to the reflectors array, sound diffuser, and shell boundaries have been considered separately and in combination to investigate their effects on the objective stage acoustic parameters that is early and late support (ST_{early} and ST_{late}) and spectral content. To this aim, the musicians' configuration of a *sestetto* has been considered.

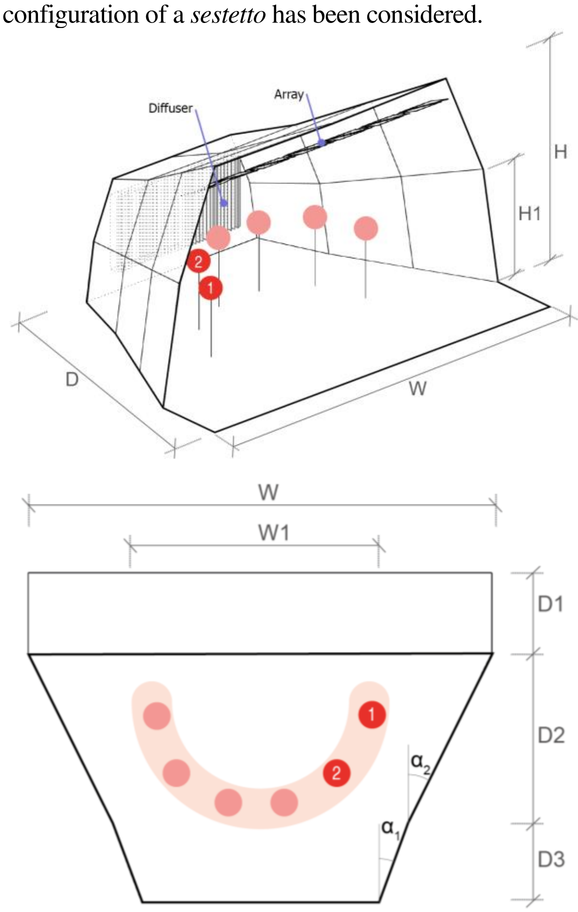

Figure 2. Main geometrical features of ReS: H=4.40m; H1=2.30m; D=5.70m; D2+D3=4.20m; W=7.90m; W1=4.00m; α1=20.4°; and α2=26.5°.

2. METHODS

2.1 Acoustic shell

ReS (Resonant string Shell) has been built since 2012 as part of an architecture and music workshop [21] that takes

place every year in Acireale (Sicily, Italy) in August. The structure has been subject to different iterations and shape optimization each year since then, being part of a pedagogical process that involves different disciplines.
It is an acoustic shell for open-air chamber music concerts and it has been thoroughly described in previous publications [22-24]. The main structure is inspired by a gramophone shape reaching a width of around 8 m at the front and a depth of approximately 5 m. It is built in spruce wood with a reticular load-bearing structure hidden by an inner surface of slatted elements glued together. An array of square HDF (High density Fiberboard) panels [25] and a Schroeder-type diffuser (2.90 x 1.44 m) are mounted over the center-front part of the stage ceiling and rear wall, respectively. The array covers a trapezoidal shaped area located over the musicians at the front part of the stage and is made up of 0.50 x 0.50 m square shaped panels spaced 0.10 m apart. It is divided in two main parts with two orientations: the inner part is made of 13 full and 6 tailor cut panels and is oriented towards the musicians and first rows of the audience; the outer part is made of 14 full and 4 tailor cut panels and is oriented towards the audience.
The main shell is formed by a succession of three hexagonal pyramid trunks measuring approximately 4.3 x 8 m at the proscenium and 2.2 x 4 m at the rear part. The stage has a height of 1 m with respect to the audience level (Figure 3).
The inclination of the planes of the shell is optimized with a MOGA (Multi-Objective Genetic Algorithm) designed with two main objective functions: the first is that of maximizing sound pressure in absolute terms and the second is that of distributing the sound as uniformly as possible over the audience [24]. The acoustics of the audience area will not be discussed in the present work.

2.2 Stage measurements

A common formation for the concerts within this acoustic shell is that of a string sextet, *Sestetto* Stradivari, which includes two violins, two violas, and two cellos. The layout used by the musicians is shown in Figure 1 and 2. Five measured configurations have been tested as shown in Figure 4:

- C0) a reference configuration with only the stage platform and without ReS;
- C1) full configuration with ReS, reflectors array and Schroeder diffuser. This configuration has been indicated as the preferred configuration by the musicians of the *sestetto* through informal interviews;
- C2) full configuration with ReS and without the Schroeder diffuser;
- C3) full configuration with ReS and without reflectors array;
- C4) full configuration with ReS without reflectors array and Schroeder diffuser.

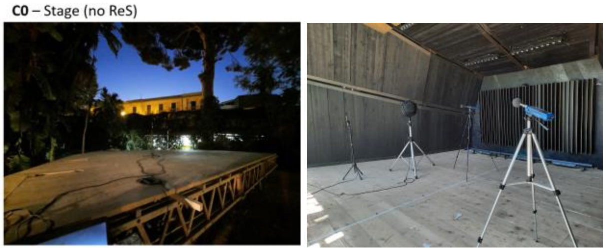

Figure 3. C0) The reference configuration of the stage without ReS and the measurement set-up in C3 configuration.

Figure 4. Four measured configurations: C1) ReS with reflectors array and Schroeder diffuser, C2) ReS without the Schroeder diffuser, C3) ReS without reflectors array and C4) ReS without reflectors array and Schroeder diffuser.

The stage acoustical parameters for the five configurations were measured on an empty stage (Figure 3 and 4). The measurements were conducted with an omnidirectional loudspeaker (B&K type 4296) and omnidirectional microphones (NTI Audio-XL2). As shown in Figure 2, measurement positions were selected such that they could be representative of the exact positions used by the sextet. For this study, the sound source was located at a common position (R1) used by the principal violinist of the sextet in most of the concerts, and in R2 which has been considered for comparisons. Both positions have been considered reciprocally as sources and as receivers. Stage support parameters have bee derived from the impulse responses measured on the stage in R1 and R2. The distance between the sound source and receiver was maintained equal to 1 m and the measurement height was set at 1.35 m from the stage floor. This height is considered as representative of the different instruments played on stage, in particular for the violins. Acoustical parameters, ST_{Early} and ST_{Late}, were calculated from the measured impulse responses using the plug-in AURORA for Audacity [26]. ST_{Early} is defined as the logarithmic ratio between the early reflection energy (80 ms) and the direct sound energy (10 ms). The reflection energy used for stage support late (ST_{Late}) includes late reflections beyond 100ms up to 1000 ms [9, 10]. Both of the ST parameters are averaged over the 250 to 2000 Hz octave bands.

3. RESULTS

ST_{Early} and ST_{Late} results have been presented in Figure 5 for C0, C1, C2, C3, and C4 configurations for both R1 and R2 positions (source in R2 and R1, respectively). It can be noticed that ST_{Early} is within the typical range indicated in the ISO 3382-1, i.e. -24 to -8 dB. The values are between -8 and -9 dB for C1, C2 and C3, and slightly lower than -9 dB for the C4 configuration, which does not have the reflecting array and the rear wall diffuser. The values of this parameter reach -21 dB for C0 when no acoustic shell is used.

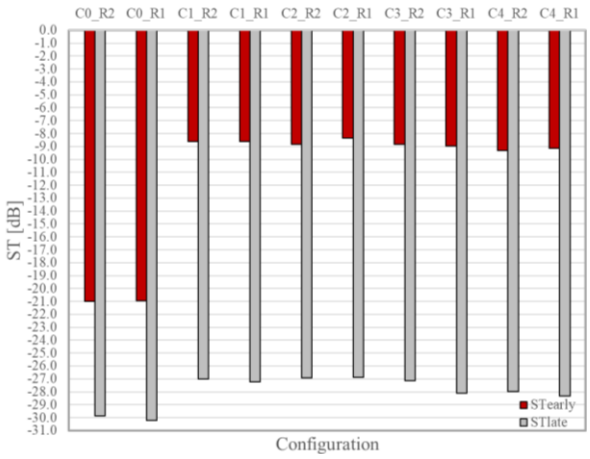

Figure 5. ST_{Early} and ST_{Late} results for C0, C1, C2, C3, and C4 configurations for both R1 and R2 positions (source in R2 and R1, respectively).

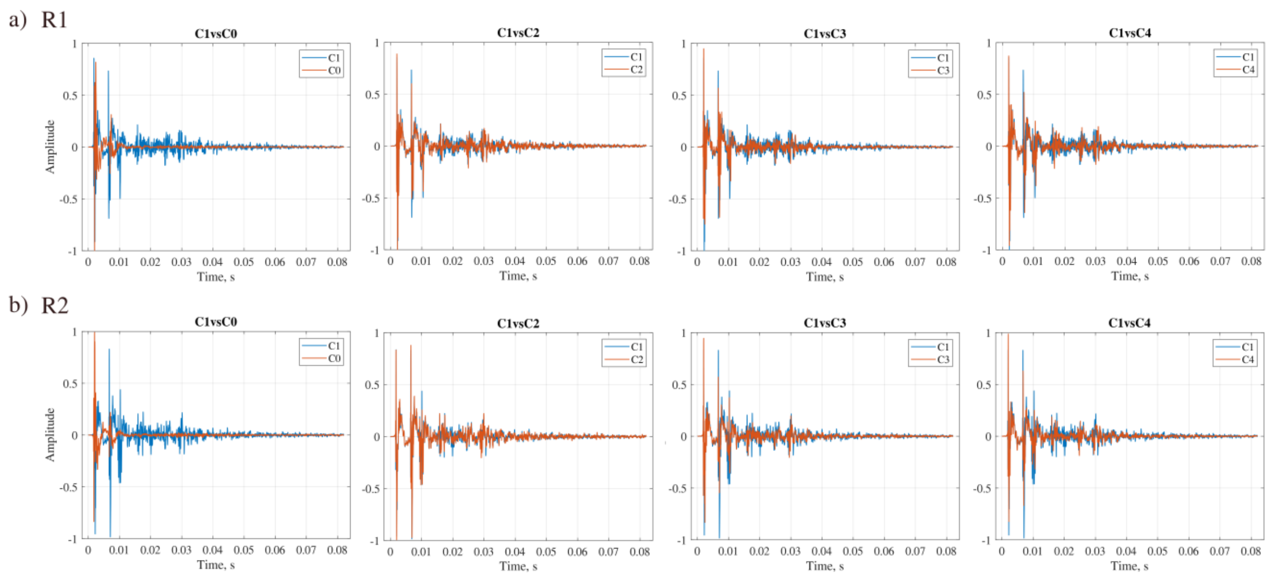

Figure 6. Impulse response comparisons of C1 to C0, C2, C3, and C4 configurations for both R1 and R2 positions (source in R2 and R1, respectively).

ST_{Late} results rely between -27 to -28 dB for C1, C2, C3 and C4. These values are slightly lower than -28 dB for the R1 position for C3 and C4, which are the conditions without the reflecting array. The values of this parameter decrease above -30 dB for C0 when no acoustic shell is used. Overall, the values of ST_{late} result below the typical range indicated in the ISO 3382-1, i.e. -24 to -10 dB.

It can be highlighted that the effects of the presence of the acoustic shell are more evident on the ST_{early}, i.e more variability between the C1-4 configurations with respect to the C0 one is present for this parameter compared to the ST_{late} values. However, the small differences observed for the ST parameters between the C1-4 configurations do not highlight any significant difference on the use of the diffuser and reflecting array.

Given the limited sensitivity of ST parameters to describe the feedbacks of the musicians of the *sestetto* who indicated a clear preference regarding the C1 configuration, it was necessary to investigate the effects of the presence of each element by comparing the temporal and spectral contents in detail (Figure 6 and 7). As mentioned in the introduction, there is still no defined values regarding the JNDs of the ST parameters, which makes it difficult to estimate significant variations.

Both for the temporal and spectral comparisons the C1 (i.e. the preferred condition from the artists) has been used as a reference. The impulse response comparisons have been shown in Figure 6. They present clear differences between C1 and C0 as expected. When comparing C1 and C2, some effects on the density of the reflections due to the diffuser removal could be observed in the timeslot between 0.015-0.025 ms. Similar effects extent to a longer interval when also the array of reflectors is removed (C1vsC3 and C1vsC4). Interestingly the first important reflection at 0.006ms is reduced when both the diffuser and array are removed.

The spectral comparisons (Figure 7) highlight some differences mainly above 1000 Hz. For both R1 and R2 the C1 and C2 conditions seem to be perfectly overlapping throughout the analyzed frequency range. The effect of the presence of the diffuser is not evident in this comparison. Interestingly for R1 also the C4 condition presents a similar trend, while for R2 it highlights important differences above 300 Hz. It shows a decrease of the sound levels in the 300-500 Hz frequency range. Thus, the presence of the array has a significant effect on the spectral content of the impulse response. It can be noticed that the effect of the diffuser is evident when comparing C3 to C4 configuration. The presence of the diffuser flattens the spectrum around the 2500-4500 Hz range. However, it seems to decrease the sound levels in these frequency range.

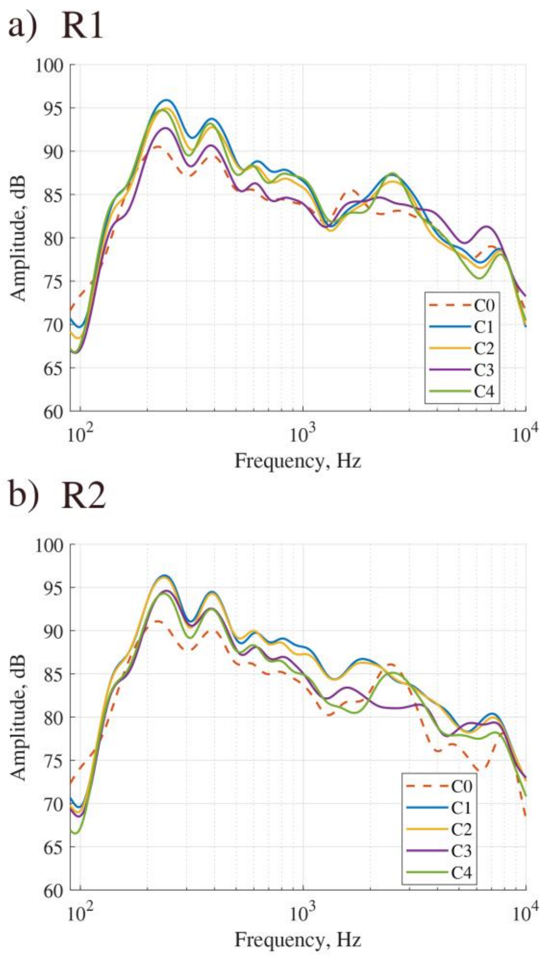

Figure 7. Frequency response for C0, C1, C2, C3, and C4 configurations for both R1 and R2 positions (source in R2 and R1, respectively).

4. CONCLUSIONS

This paper focused on the results of a measurement campaign of the early and late support parameters, ST_{Early} and ST_{Late}, for five different configurations (C0-C4) of an acoustic shell used on the stage for open-air chamber music concerts. The design elements related to the reflectors array, sound diffuser, and shell boundaries have been considered separately and in combination to investigate their effects on the objective stage acoustic parameters and impulse response spectral content. To this aim, the musicians' configuration of a *sestetto* has been considered.

The results showed that the effects of the presence of the acoustic shell are more evident on the ST_{early}, i.e more variability between the C1-4 configurations with respect to the C0 one is present for this parameter compared to the ST_{late} values. The ST_{early} results within the the ISO 3382-1 typical range values, while the ST_{late} is shown to be lower than the higher than the boundary limit (-30 dB). This could be attributed to the open-air performance space condition. Some interesting effects of the array and diffusers presence could be noticed in the comparisons of the spectral content and temporal distribution of the reflections.
However, given that the ST_{early} values and the frequency responses resulted very close to each other (within the measurement accuracy), it might be useful to further investigate the slight differences observed and quantify the effects of the orientation of the loudspeaker on the measurements.
Further subjective investigations could help to gain more evidence on the significance of the observed differences. Moreover, directional microphone arrays could be used to capture spatial information on the reflections arrival at the musicians location.

5. ACKNOWLEDGMENTS

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6. REFERENCES

[1] M. Barron: *Auditorium Acoustics*. London: 2ed. Spon Press, 2003.

[2] J. S. Bradley, "Some effects of orchestra shells," *The Journal of the Acoustical Society of America,* vol. 100, no. 2, pp. 889–898, 1996.

[3] T. Mendez, M. Sassone, A. Astolfi, L. Shtrepi, and A. Van Der Harten, "Multi-Objective Acoustic and Structural design of shell structures for concert halls," *Proc. of the Symposia of the International Association for Shells and Spatial Structures*, (Brasilia, Brasil), 2014.

[4] G. A. Bouvet, L. Shtrepi, E. Bo, T. Méndez Echenagucia, and A. Astolfi, "Computational design: acoustic shells for ancient theatres," *Proc. of the Forum Acusticum* 2020, (Lyon, France), pp.1581–1585, 2020.

[5] M. Palma, M. Sarotto, T. Méndez Echenagucia, M. Sassone, A. Astolfi: "Sound-Strength Driven Parametric Design of an Acoustic Shell in a Free Field Environment", *Journal of Building Acoustics,* vol.21, no.1, pp.31–42, 2014

[6] I. W. Foged, A. Pasold, and M. B. Jensen, "Evolution of an instrumental architecture," *Proc. of the 32nd Education and Research in Computer Aided Architectural Design in Europe (eCAADe) Conference*, (Newcastle upon Tyne, UK), pp. 365–372, 2014.

[7] W. Boning, A. Bassuet, "A room without walls: Optimizing an outdoor music shell to maintain views and maximize reflections," *Proc. of the Institute of Acoustics (IOA)*, (Paris, France), pp. 332–341, 2015.

[8] Available online:
https://www.flanaganlawrence.com/soundforms (accessed on 03/05/2023).

[9] A. C. Gade, "Investigations of musicians' room acoustic conditions in concert halls. Part I: Method and laboratory experiments," *Acustica*, vol. 65, pp. 193-203, 1989.

[10] A. C. Gade, "Investigation of musicians' room acoustic conditions in concert halls II: field experiments and synthesis of results," *Acta Acust. United Acust.*, vol. 69, pp. 249–262, 1989.

[11] T. Halmrast, "Orchestral timbre: comb-filter coloration from reflections," *J. Sound Vib.*, vol. 232, 53–69, 2000.

[12] M. Barron and J. J. Dammerud, "Stage acoustics in concert halls – early investigations," *Proc. of the Institute of Acoustics (IOA),* vol. 28, 2006.

[13] [13] ISO 3382-1:2009: Acoustics — Measurement of room acoustic parameters — Part 1: Performance spaces.

[14] W. Chiang, S. Chen, and C. Huang, "Subjective assessment of stage acoustics for solo and chamber music performances," *Acta Acust. United Acust.,* vol. 89, pp. 848–856, 2003.

[15] L. Beranek: *Concert Halls and Opera Houses: Music, Acoustics, and Architecture*. Berlin: Springer Science & Business Media, 2012.

[16] J. Jeon and M. Barron, "Evaluation of stage acoustics in Seoul Arts Center Concert Hall by measuring stage support," *J. Acoust. Soc. Am.*, vol. 117, pp. 232–239, 2005.

[17] A. Abdou and R. W. Guy, "Spatial information of sound fields for room-acoustics evaluation and diagnosis," *J. Acoust. Soc. Am.*, vol.100, no. 5, 1996.

[18] J. S. Bradley, "Data from 13 North American Concert Halls", Internal Report (National Research Council of Canada. Institute for Research in Construction); no. IRC-IR-668, 1994.

[19] J. Y. Jeon, Y. S. Kim, H. Lim, and D. Cabrera, "Preferred positions for solo, duet, and quartet performers on stage in concert halls: In situ experiment with acoustic measurements," *Building and Environment,* vol. 93, 267–277, 2015.

[20] J. J. Dammerud, M. Barron, and E. Kahle, "Objective assessment of acoustic conditions on concert hall stages – limitations and new strategies," *Proc. of the International Symposium on Room Acoustics (*ISRA), (Melbourne, Australia), 2010.

[21] Available online: https://www.vpmusica.com/ (accessed on 02.05.2023)

[22] S. Di Rosario, B. Parenti, E. Pignatelli, G. Mirra, S. Pone, "ReS, Resonant string shell, development and design of an acoustic shell for outdoor chamber music concerts,". *Proc. of the Institute of Acoustics (IOA),* vol. 37, 2015.

[23] E. Pignatelli, S. Colabella, S. Di Rosario, and S. Pone, "A wooden acoustic shell for open-air chamber music concert," *Proc. of the Symposia of the International Association for Shells and Spatial Structures,* (Amsterdam, Netherlands), 2015.

[24] G. Mirra, E. Pignatelli, and S. Di Rosario, "An automated design methodology for acoustic shells in outdoor concerts," *Proc. of the Conference Euronoise 2018,* (Crete, Greece), 2018.

[25] J.H. Rindel, "Design of new ceiling reflectors for improved ensemble in a concert hall," *Applied Acoustics*, vol. 34, pp.7-17, 1991.

[26] Available online:

http://www.angelofarina.it/Public/Aurora-for-Audacity/ (accessed on 02.05.2023)