

Acoustics and spatial sound distribution in the theatre comunale in Bologna, Italy

Manfren, Massimiliano; Nastasi, Benedetto; Merli, Francesca; Vodola, Vincenzo

Publication date

2020

Document Version

Final published version

Published in

Proceedings - Building Simulation Applications, BSA 2019

Citation (APA)

Manfren, M., Nastasi, B., Merli, F., & Vodola, V. (2020). Acoustics and spatial sound distribution in the theatre comunale in Bologna, Italy. In G. Pernigotto, F. Patuzzi, A. Prada, V. Corrado, & A. Gasparella (Eds.), *Proceedings - Building Simulation Applications, BSA 2019: 4th IBPSA-Italy Conference* (pp. 239-244). (Building Simulation Applications; Vol. 2020-June). Free University of Bozen Bolzano.

Important note

To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy

Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

Konferenzbeiträge / Atti / Proceedings

Building Simulation Applications BSA 2019

4th IBPSA-Italy Conference
Bozen-Bolzano, 19th–21st June 2019

Edited by

**Giovanni Pernigotto, Francesco Patuzzi,
Alessandro Prada, Vincenzo Corrado, Andrea Gasparella**

bu,press

bozen
bolzano
university
press

Scientific committee

Ian Beausoleil-Morrison, Carleton University, Canada
Jan L.M. Hensen, Technische Universiteit Eindhoven, The Netherlands
Gregor P. Henze, University of Colorado Boulder, USA
Ardeshir Mahdavi, Technische Universität Wien, Austria
Athanasios Tzempelikos, Purdue University, USA
Reinhard Radermacher, University of Maryland, USA
Francesco Asdrubali, Università degli Studi Roma Tre, Italy
Paolo Baggio, Università degli Studi di Trento, Italy
Maurizio Cellura, Università degli Studi di Palermo, Italy
Cristina Cornaro, Università degli Studi di Tor Vergata, Italy
Vincenzo Corrado, Politecnico di Torino, Italy
Andrea Gasparella, Free University of Bozen-Bolzano, Italy
Livio Mazzarella, Politecnico di Milano, Italy
Adolfo Palombo, Università degli Studi di Napoli Federico II, Italy

Students Tutoring Scientific Committee

Fabian Ochs, Universität Innsbruck, Austria
Matthias Schuss, Technische Universität Wien, Austria
Alessia Arteconi, Università Politecnica delle Marche, Italy
Ilaria Ballarini, Politecnico di Torino, Italy
Annamaria Buonomano, Università degli Studi di Napoli Federico II, Italy
Marco Caniato, Free University of Bozen-Bolzano, Italy
Francesca Cappelletti, Università IUAV di Venezia, Italy
Gianpiero Evola, Università degli Studi di Catania, Italy
Francesco Patuzzi, Free University of Bozen-Bolzano, Italy
Giovanni Pernigotto, Free University of Bozen-Bolzano, Italy
Anna Laura Pisello, Università degli Studi di Perugia, Italy
Alessandro Prada, Università degli Studi di Trento, Italy

Organizing committee

Paolo Baggio, Università degli Studi di Trento, Italy
Marco Baratieri, Free University of Bozen-Bolzano, Italy
Marco Caniato, Free University of Bozen-Bolzano, Italy
Francesca Cappelletti, Università IUAV di Venezia, Italy
Vincenzo Corrado, Politecnico di Torino, Italy
Andrea Gasparella, Free University of Bozen-Bolzano, Italy
Norbert Klammsteiner, Energytech G.m.b.H./S.r.l -Bozen, Italy
Fabian Ochs, Universität Innsbruck, Austria
Francesco Patuzzi, Free University of Bozen-Bolzano, Italy
Giovanni Pernigotto, Free University of Bozen-Bolzano, Italy
Alessandro Prada, Università degli Studi di Trento, Italy
Fabio Viero, Manens – Tifs, Italy



This work—excluding the cover and the quotations—is licensed under the Creative Commons Attribution-ShareAlike 4.0 International License.

Cover design: DOC.bz

© 2020 by Bozen-Bolzano University Press

Free University of Bozen-Bolzano

All rights reserved

1st edition

www.unibz.it/universitypress

ISSN 2531-6702

ISBN 978-88-6046-176-6

Acoustics and Spatial Sound Distribution in the Theatre Comunale in Bologna, Italy

Massimiliano Manfren – University of Southampton, United Kingdom – m.manfren@soton.ac.uk

Benedetto Nastasi – Delft University of Technology, The Netherlands – benedetto.nastasi@outlook.com

Francesca Merli – University of Bologna, Italy – francesca.merli8@unibo.it

Vincenzo Vodola – University of Bologna, Italy – vincenzo.vodola2@unibo.it

Abstract

The acoustic quality of concert halls is extremely relevant for the modeling and simulation of the global music experience and for improving the acoustic design of music spaces. Furthermore, the acoustic characteristics of historical opera houses are considered to be one of the most important intangible elements of the cultural heritage of Italian history. An important Italian opera house is the theatre “Comunale” in Bologna (designed in the 18th Century by Galli Bibiena), and has a particular characteristic: the shape of the balconies and the materials with which they were constructed are different from those of a classical Italian opera house. This special feature of the balconies affects the listening conditions related to the position of sound sources on the stage and in the orchestra pit. This study investigates the acoustic properties of this important theatre in order to reproduce the sound properties by means of a 3D auralization. For describing the spatial sound characteristics of the hall, an experimental campaign was carried out. An omnidirectional, pre-equalized sound source was installed in the orchestra pit and on stage, and a dummy head was put in several listening positions on the balconies and in the stalls, accomplished with a B-format (soundfield) microphone. Moreover, the special features of the ACF (autocorrelation function) and the IACC (InterAural Cross Correlation) and other acoustic parameters were measured experimentally in order to reproduce them in the listening room “Arlecchino” at the laboratory of University of Bologna, by means of the Stereo Dipole and Ambisonics technique. The main results from the experiments are reported in this paper.

1. Introduction

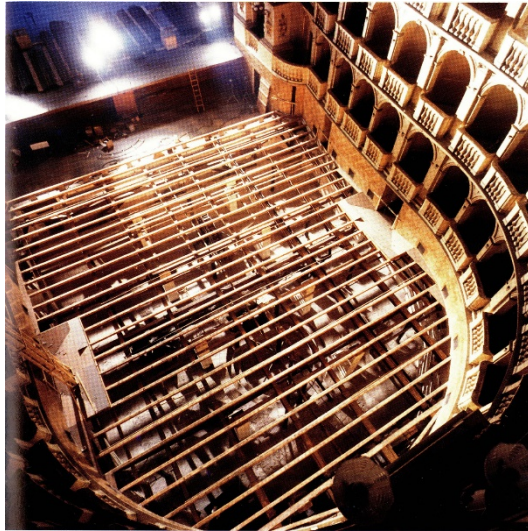
It is well known that the acoustic properties of opera houses and concert halls are extremely important for determining the global sensation that is experimented by listeners and musicians. Since the 1970s, with the work of Gerzon (1975) and subsequent research (Farina and Tronchin, 2005 and 2013; Tronchin, 2013; Tronchin and Coli, 2015), the sound properties of the special opera house have been considered to be of equal importance to ancient musical instruments (Tronchin et al., 2020). Therefore, cultural heritage is composed by their acoustical properties too apart from the architectural features. The theatre “Comunale” in Bologna is an important Italian opera house and has a particular characteristic: the shape of the balconies and the materials with which they were constructed are different from those of a classical Italian opera house. This special feature of the balconies affects the listening conditions related to the position of sound sources in the stage and in the orchestra pit. The aim of this paper is to investigate the acoustic properties of this important theatre with the purpose of reproducing its characteristics by means of a 3D auralization.

2. Materials and Methods

2.1 Historic Background of the Theatre

The Teatro *Comunale* in Bologna was designed by the architect Antonio Galli Bibiena, one of the most active architects for music venues in the 18th Century, and inaugurated in 1763. From the beginning

of the design process, Galli Bibiena considered a different shape of theatre to that of the typical horseshoe shape, namely a bell shape. Thus, the *Comunale* of Bologna was the first example of a special "phonic" shape conceived by Galli Bibiena, and was followed by the Teatro Scientifico in Mantova and the Four Horsemen Theatre in Pavia. At that time, however, this idea was not supported by other physicists and acousticians.



(a)



(b)

Fig. 1 – (a) The device below the floor of the stalls and (b) the hall

The *Comunale* also had other specific characteristics: the brick structure of the main hall was one of the most important innovations and was used instead of a wooden structure, in order to reduce the

risk of the theatre being damaged or destroyed in a fire. The theatre also had two major innovations in balconies and stalls. The balconies were designed to allow the owners to customize the walls, colour the walls, change the interiors, etc. The floor of the stalls was equipped with a special device: it could be lifted to the height of the stage by a special mechanism. There would have been a large cavity, with musicians and singers on the same level; Bibiena believed that the movement of the floor would enhance the intelligibility of the singers. This mechanism was active until 1820.

1.2 The Acoustic Measurements

A measurement campaign was undertaken in order to properly describe the spatial sound characteristics of the hall, with a special focus on the stage and orchestra pit and the relationship between the perception of the sound of the musical instruments and their characteristics in the stalls and balconies (Farina et al., 1998; Farina and Tronchin, 2000; Shimokura et al., 2011; Tronchin, 2012; Tronchin and Coli, 2015). Then, in a further step, the ACF (autocorrelation function) and IACC (InterAural Cross Correlation) and other acoustic parameters were calculated from the impulse responses thanks to the Stereo Dipole and Ambisonics techniques, in order to reproduce them in the listening room "Arlecchino" at the laboratory of University of Bologna.

The instruments used are::

- on the stage and in orchestra pit, an omnidirectional, frequency-equalized sound source (namely LookLine);
- at the receiver's positions (Neumann KU-100) to measure binaural impulse responses and parameters, a dummy head;
- in the theatre, similarly to the dummy head, a Soundfield microphone (MK V) probe. For calculating the monoaural and 3-dimensional parameters, a four-channel output was adopted.

An exponential, 30-second-long sine sweep (chirp) was played by the omnidirectional sound source and, to store the signals from the microphones, a 20-bit 96 kHz 8-channel sound board was utilized. The measurements were taken in 25 different positions, from stalls to balconies, as shown in Fig. 2.

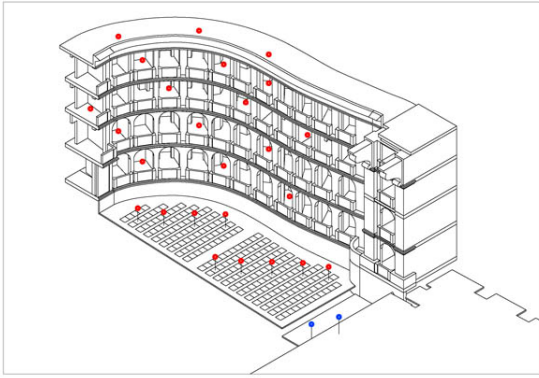


Fig. 2 – The points for measurements in red dots in the *Comunale*

Then, the authors used a numerical simulation model. On the stage the sound source was put and the measurements were repeatedly moved to the orchestra pit. To calculate the strength spatial maps at 1 m a reference position was added. Some additional measurements were carried out with the sound source to evaluate the different impulse responses during the 3D auralization process (Binaural and B-formats) including floor effects for sound insulation (Caniato et al., 2016 and 2018).

The mono-aural parameters, such as reverberation time, center time and clarity, were calculated considering the W channel from the Soundfield microphone, as well as spatial parameters, such as LE and LF and the B-format Impulse Response. The measurement of binaural parameters was taken by the dummy head, such as the IACC (Farina et al., 2013). In addition, the discovery of virtual acoustics in the theatre (Tronchin, 2013) was made possible by the B-format impulses obtained through the Soundfield and the bi-induction responses by the dummy head, crucial for retrofitting (Caniato et al., 2015 and 2019; Fabbri et al., 2014; Fabbri and Tronchin, 2015; Tronchin and Fabbri, 2017; Tronchin and Knight, 2016; Tronchin et al., 2014 and 2016).

3. Results

The results from the measurements are briefly reported in the following paragraphs. Various acoustic parameters were calculated from the measurements. Table 1 reports the average values of the acoustic parameters measured in the theatre. The results show that the position of the sound source from the stage and the orchestra pit modifies the parameters. As mentioned above, a sound source with a directivity pattern was also used during the measurements. For further analysing the influence of both the position of the sound source and its directional patterns, the results for a specific position in the stalls are shown in the graphs.

Table 1 – Values obtained in the Teatro Comunale of Bologna with reference to the positions of the sound source on the Stage

Frequency	C50 [dB]	C80 [dB]	D50 [%]	Ts [ms]	EDT [s]	T20 [s]	LF
63	-5.2	-1.7	26.2	179.9	2.1	2.3	0.94
125	-5.3	-1.5	25.0	154.2	1.8	2.0	0.81
250	-2.6	0.6	36.5	117.8	1.6	1.8	0.81
500	-2.4	0.6	37.6	111.3	1.6	1.7	0.78
1k	-2.8	0.2	35.3	114.7	1.6	1.6	0.78
2k	-3.1	0.2	34.1	113.1	1.6	1.6	0.68
4k	-2.4	1.2	37.4	94.9	1.3	1.3	0.58
8k	1.1	4.6	55.8	58.5	0.9	1.0	0.48

The *Teatro Comunale* gives an overall impression of the sound of typical Italian opera houses. The reverberation time at mid frequencies was approximately 1.4 s. The acoustics of the orchestra pit, however, differ significantly from the stage. These differences are particularly significant in the stalls rather than on the balconies. Variations in acoustic parameters could be seen specifically in the initial part of the impulse responses (less than 100 ms), as depicted in the graphics reporting the values of the acoustic parameters measured in one specific position not far from the orchestra pit. The energetic parameters (i.e. clarity) showed a significant difference from the stage with the orchestra pit whereas the position of the sound source, effected

by the fence, induces a diffuse sound field with no direct sound from the source to the receivers (which was clearly perceived by the receiver) and the orchestra pit. Including the reverberation times, the sound source from stage to pit was significantly different. The estimated Early Decay Time was affected more than the RT30, due to its longer decay time. In some cases, the variation of EDT also ranged from 0.5 s at mid-frequencies to 0.2 s in RT30.

Table 2 – Values obtained in the Teatro Comunale of Bologna with reference to the positions of the sound source on the Pit

Frequency	C50 [dB]	C80 [dB]	D50 [%]	Ts [ms]	EDT [s]	T20 [s]	LF
63	-0.2	3.5	49.1	112.4	1.0	2.1	0.8
125	-8.7	-0.8	17.7	148.5	1.7	2.0	0.7
250	-4.3	2.1	31.2	110.8	1.4	1.7	1.0
500	-4.2	1.3	32.0	108.2	1.4	1.6	1.1
1k	-3.4	0.8	34.5	110.9	1.6	1.6	1.0
2k	-3.0	1.0	35.3	104.1	1.5	1.5	0.8
4k	-1.7	2.2	41.1	86.7	1.2	1.3	0.6
8k	2.1	5.9	59.9	54.0	0.7	0.9	0.5

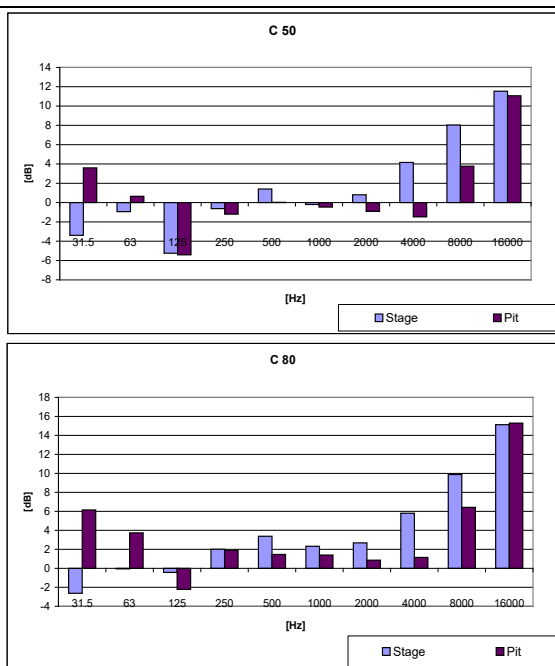


Fig. 3 – Values of Clarity measured in stalls (14F), in the Teatro Comunale of Bologna, Italy

Additional analysis consisted of a variety of sound source positions and directivity patterns. Some acoustic measured parameters in the hall are shown in Figs 6 to 8. There were remarkable variations in these parameters.

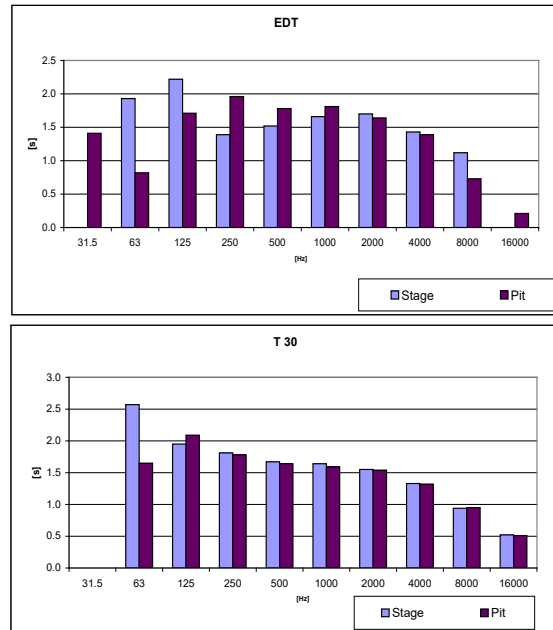


Fig. 4 – Values of Early Decay Time and Reverberation Time measured in stalls (14F), in the Teatro Comunale of Bologna, Italy

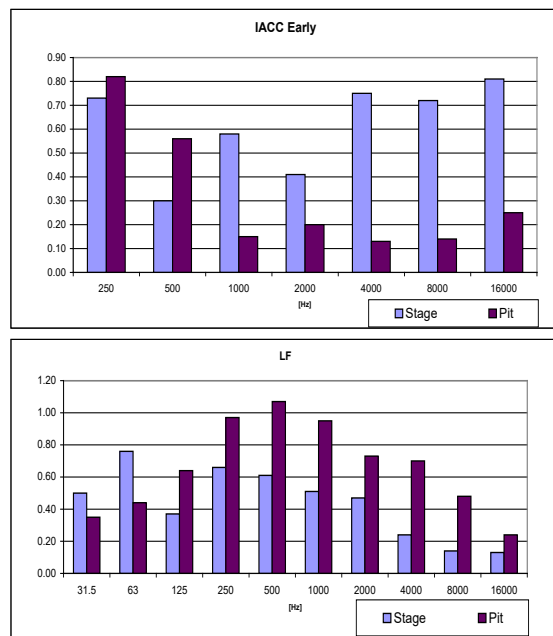


Fig. 5 – Values of InterAural Cross-Correlation and Lateral Fraction measured in stalls (14F), in the Teatro Comunale of Bologna, Italy

Even the *clarity* of the sound source changed considerably. Only the reverberation time with sound sources remained relatively stable. However, the analysis of the variation of the IACC led to the identification of differences of between 0.15 and 0.075 at the frequency of 2 kHz, depending on the sound source.

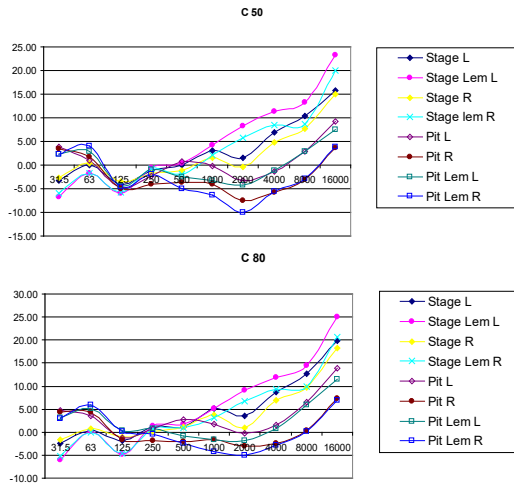


Fig. 6 – Values of Clarity measured in stalls (14F) with different sound sources and positions in the Teatro Comunale of Bologna

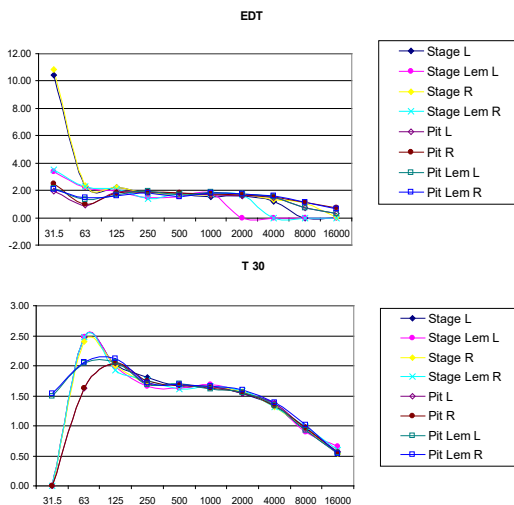


Fig. 7 – Values of Reverberation Time measured in stalls (14F) with different sound sources and positions in the Teatro Comunale of Bologna

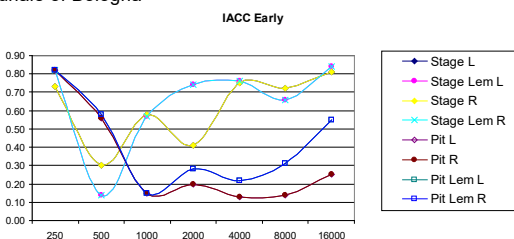


Fig. 8 – Values of IACC measured in stalls (14F) with different sound sources and positions in the Teatro Comunale of Bologna

This was not a surprise because the first 80 ms of the impulse response (IACC) were considered in the calculation, i.e. the component of the binaural impulse responses that was heavily dependent on the different characteristics of the sound sources and their positions.

4. Conclusion

In conclusion, based on the results discussed in this paper, it is possible to state that the Teatro Comunale presents the typical sound characteristics of Italian-style opera houses. Yet, the acoustics of the stage and the orchestra pit were found very different. This fact makes unique this opera house.

Acknowledgement

The authors acknowledge the help of Enrico Reatti and Lamberto Tronchin for their collaboration during the experimental measurements.

References

Caniato, M., F. Bettarello, L. Marsich, A. Ferluga, O. Sbaizero and C. Schmid. 2015 "Time-dependent performance of resilient layers under floating floors." *Construction and Building Materials* 102(1). doi: 10.1016/j.conbuildmat.2015.10.176

Caniato, M., F. Bettarello, C. Schmid and P. Fausti. 2016 "Assessment criterion for indoor noise disturbance in the presence of low frequency sources." *Applied Acoustics* 113(1): 22–33.

Caniato, M., S. Favretto, F. Bettarello, C. Schmid. 2018. "Acoustic Characterization of Resonance Wood." *Acta Acustica united with Acustica* 104(6) 1030–1040. doi: 10.3813/AAA.919269

Caniato, M, F. Bettarello, C. Schmid, P. Fausti. 2019. "The use of numerical models on service equipment noise prediction in heavyweight and lightweight timber buildings." *Building Acoustics* 26(1): 35-55. doi:10.1177/1351010X18794523

Fabrizi, K., L. Tronchin and V. Tarabusi. 2014. "Energy retrofit and economic evaluation priorities applied at an Italian case study."

- Energy Procedia* 45: 379-384.
doi:10.1016/j.egypro.2014.01.041
- Fabbri, K., and L. Tronchin. 2015. "Indoor environmental quality in low energy buildings." *Energy Procedia* 78: 2778–2783. doi: 10.1016/j.egypro.2015.11.625
- Farina, A., A. Langhoff, and L. Tronchin. 1998. "Acoustic Characterisation of "virtual" Musical Instruments: Using MLS Technique on Ancient Violins." *Journal of New Music Research* 27(4): 359-379. doi:10.1080/09298219808570753
- Farina, A., and L. Tronchin. 2000. "On the "Virtual" Reconstruction of Sound Quality of Trumpets." *Acustica* 86(4): 737-745.
- Farina, A., and L. Tronchin 2005. "Measurements and reproduction of spatial sound characteristics of auditoria." *Acoustical Science and Technology* 26(2): 193-199. doi.org/10.1250/ast.26.193
- Farina, A., and L. Tronchin. 2013. "3D Sound Characterisation in Theatres Employing Microphone Arrays." *Acta Acustica United with Acustica* 99 (1): 118-125. doi:10.3813/AAA.918595
- Gerzon, M. 1975. "Recording Concert Hall Acoustics for Posterity." *Journal of Audio Engineering Society* 23(7): 569.
- Shimokura, R., L. Tronchin, A. Cocchi, and Y. Soeta. 2011. "Subjective Diffuseness of Music Signals Convolved with Binaural Impulse Responses." *Journal of Sound and Vibration* 330 (14): 3526-3537. doi:10.1016/j.jsv.2011.02.014
- Tronchin, L. 2012. "The Emulation of Nonlinear Time-Invariant Audio Systems with Memory by Means of Volterra Series." *AES: Journal of the Audio Engineering Society* 60(12): 984-886.
- Tronchin, L. 2013a. "Francesco Milizia (1725-1798) and the Acoustics of His Teatro Ideale (1773)." *Acta Acustica United with Acustica* 99(1): 91-97. doi:10.3813/AAA.918592
- Tronchin, L. 2013b. "On the Acoustic Efficiency of Road Barriers: The Reflection Index." *International Journal of Mechanics* 7(3): 318-326.
- Tronchin, L., M.C. Tommasino and K. Fabbri. 2014. "On the cost-optimal levels of energy-performance requirements for buildings: A case study with economic evaluation in Italy." *International Journal of Sustainable Energy Planning and Management* 3: 49-62. doi:10.5278/ijsepm.2014.3.5
- Tronchin, L., and V. L. Coli. 2015. "Further Investigations in the Emulation of Nonlinear Systems with Volterra Series." *AES: Journal of the Audio Engineering Society* 63(9): 671-683. doi:10.17743/jaes.2015.0065
- Tronchin, L., M. Manfren and L. C. Tagliabue. 2016. "Optimization of building energy performance by means of multi-scale analysis – Lessons learned from case studies" *Sustainable Cities and Society* 27: 296-306. doi:10.1016/j.scs.2015.11.003
- Tronchin, L., and D. J. Knight. 2016. "Revisiting Historic Buildings through the Senses Visualising Aural and Obscured Aspects of San Vitale, Ravenna." *International Journal of Historical Archaeology* 20(1): 127-145.
- Tronchin, L., and K. Fabbri. 2017. "Energy and Microclimate Simulation in a Heritage Building: Further Studies on the Malatestiana Library." *Energies* 10(10). doi:10.3390/en10101621
- Tronchin, L., M. Manfren, V. Vodola. 2020a. "The carabattola - vibroacoustical analysis and intensity of acoustic radiation (IAR)." *Applied Sciences* 10(2), 641.
- Tronchin, L., M. Manfren, V. Vodola. 2020b. "Sound characterization through intensity of acoustic radiation measurement: A study of persian musical instruments." *Applied Sciences* 10(2), 633.
- Tronchin, L., M. Manfren, V. Vodola. 2020c. "Sound characterization through intensity of acoustic radiation measurement: A study of persian musical instruments." *Applied Sciences* 10(2), 633.
- Tronchin, L., F. Merli, M. Manfren. B. Nastasi. 2020d. "The sound diffusion in Italian Opera Houses: Some examples." *Building Acoustics*, in press. doi:10.1177/1351010X20929216