NONLINEAR 3D AURALISATION IN THE ACOUSTIC DESIGN OF OPERA HOUSES

L Tronchin DIENCA – CIARM, University of Bologna, Italy

1 ABSTRACT

The 3D auralisation of rooms has been thoroughly analysed in last decades. The most-used methods to recreate the acoustics of a room are based on measuring or simulating its impulse responses (3D or binaural). Once the IRs have been obtained, it is possible to recreate, by using linear convolution, the output signal that the system will generate when it is physically driven by any input signal. This method gives great results if the system is linear and time-invariant but it is not satisfactory in other cases, when it cannot be considered completely linear, such as during the emulation of musical instruments, which could be used in the 3D auralisation of rooms.
The Arlecchino listening room at University of Bologna, based on stereo-dipole and Ambisonic systems, has been upgraded to nonlinear convolution, by means of a new numerical tool which uses the Volterra series.
This new technique has been utilised during the acoustic design of the new Teatro Galli in Rimini, which is going to be reconstructed after its destruction during II World War. The acoustics of the new theatre, which follows the rule “where it was, how it was”, has been studied and virtually presented in the listening room by means of binaural IRs, considering the linear and nonlinear convolution with IRs of musical instruments previously measured at CIARM.

2 INTRODUCTION

The proper understanding of sound perception in a theatre could be retrieved considering the acoustics of the room (measured or simulated) and reproducing its effects in a listening room by means of 3D Auralisation. The “Arlecchino” listening room at University of Bologna could reproduce the sound perception by means of Ambisonics and Stereo Dipole since 2002 and 2005 respectively [1], [2]. The use of a dummy head and a Soundfield microphone, allow determining and measuring the spatial sound distribution in rooms for auralisation [3], [4], [5], capturing binaural and B-format IRs.
In recent years, the development of a new measuring technique which is able to measure impulse responses and distortions [6], [7], [8], allows separating the linear IR that is responsible of the acoustics of halls and theatres, and evaluating the distortions of nonlinear sound devices and musical instruments. Moreover, starting from the measurements of the IR and distortions, under certain constraints, it is possible to measure the acoustic behaviour especially of some kinds of musical instruments utilized in music performances [9] that could be emulated for 3D auralisation experiments.
This method has been firstly developed and utilized for emulating the sound emission in flutes and violins [16], and in this paper it has been applied during the acoustic design in the reconstruction of the new Teatro Galli in Rimini, Italy [10].

3 NONLINEARITIES IN ACOUSTIC PERCEPTION

Any complex tone "can be described as a combination of many simple periodic waves (i.e., sine waves) or partials, each with its own frequency of vibration, amplitude, and phase." [11]. A harmonic (or a harmonic partial) is any of a set of partials that are whole number multiples of a common fundamental frequency [12]. This set includes the fundamental, which is a whole number multiple of itself (1 times itself). The relative amplitudes of the various harmonics primarily determine the timbre of different instruments (see Figure 1). The ratio of these harmonics (and therefore the timbre) generally varies during the execution of a note if it is played with different dynamics: that's one reason why raising the volume of a *pianissimo* performance is not the same as listening to it if played *fortissimo*. Thinking as the instrument as if it was a black-box (i.e. a system) these behaviours let us understand that it has the key features to be classified as nonlinear.

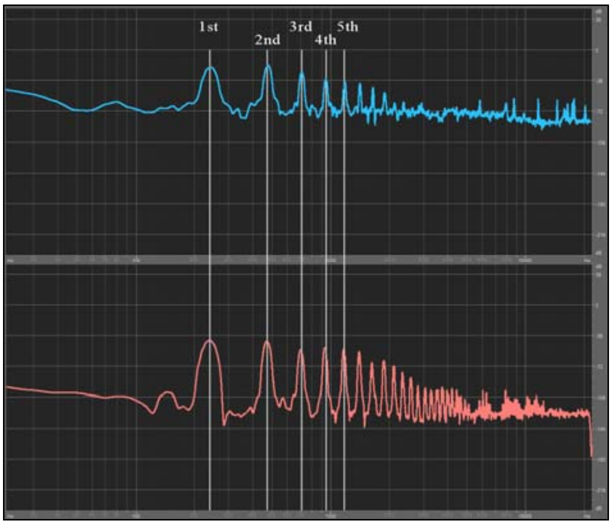

Figure 1: A#3 harmonics played by trombone (blue) and guitar (red)

A nonlinear system could be described as a system that could add harmonics to the waveform it is fed with and/or vary harmonics ratios based on the volume of the stimulus: a system that alters therefore the basic waveform. The nonlinear system is a system that exhibits distortions. Encyclopedia Britannica defines the distortion as "*any change in a signal that alters the basic waveform or the relationship between various frequency components*" and adds that "*it is usually a degradation of the signal*". Distortion is usually unwanted but in some cases it became the key feature of some analog devices or musical instruments. A way to formally represent the input-output relation in such kind of systems has been developed by Vito Volterra (1860-1940) in 1887.

3.1 Volterra series

The input-output relation of a continuous time-invariant system with memory may be represented by Volterra series, as reported in equation (1):

$$y(t) = k_0 + \sum_{n=1}^{\infty} \frac{1}{n!} \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} k_n(t_1, t_2, \ldots, t_n) x(t - t_1) x(t - t_2) \cdots x(t - t_n) dt_1 dt_2 \cdots dt_n \qquad (1)$$

The k_n term is called n^{th} order Volterra kernel and can be seen as a higher order impulse response of the system. If only the 1st kernel differs from zero, the Volterra series reduce to the input-output relation of a time-invariant linear system with memory (i.e. the output is the convolution between input and the impulse response of the system). If the nonlinear part is purely algebraic and that memory effects reside only in the linear part of the system equation (1) can be rewritten as equation (2) where the terms 1/n! have been included in the respective k_n

$$y(t) = k_0 + \sum_{n=1}^{\infty} k_n(t) * x^n(t) \qquad (2)$$

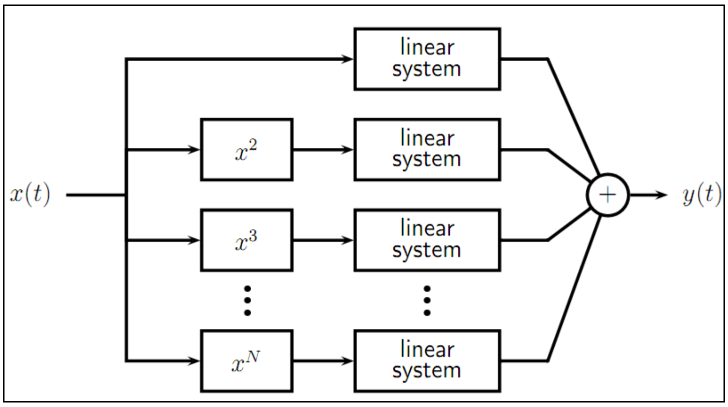

Figure 2 Nonlinear system model

Figure 2 shows a representation of the equation (2), the term k_0 has been neglected because it represents a DC component. As reported in [3], [4] and [5] it is possible to experimentally obtain, by measuring a nonlinear system, the kernels $k_n(t)$ of equation (2) and afterwards use them to recreate the output. The more the model in figure 2 matches with the real nonlinear system way of work, the more the emulation will be faithful.

3.2 Measurement technique (Synchronized Swept-Sine)

There are different possibilities to emulate the sound emission of nonlinear systems. These possibilities are influenced by the measurement technique that is utilized to obtain the necessary information for the virtualization. The kernels obtained following [7], [8] and [9] should not be directly employed to synthesize the nonlinear system because of phase problems. This limit was noticed and controlled employing proper FIR filters by the author [16]. Moreover in [17] a modified version of ESS was presented: it has been precisely designed to contrast these phase errors. The Synchronized Swept-Sine's equation is shown in (3) and (4).

$$x_s(t) = \sin\left\{2\pi L\left[\exp\left(\frac{f_1 t}{L}\right) - 1\right]\right\} \qquad (3)$$

$$L = round\left(\frac{T\ f_1}{\ln\left(\frac{f_2}{f_1}\right)}\right) \qquad (4)$$

The difference with ESS resides in the addiction of the constraint of zero-crossing in time domain waveform when starting frequency (f_1) duplicates, triplicates, ... its value, Figure 3 (left).

3.3 Nonlinear systems virtualization

In order to emulate the nonlinear behaviour of musical instruments or audio devices for 3D real-time auralisation, a special tool was developed and firstly presented in [16]. The Volterra Convolver VST plug-in was developed in C++ environment and JUCE framework, and could emulate up to 5 orders of distortions in real-time. A screenshot is represented in figure 3 (right).

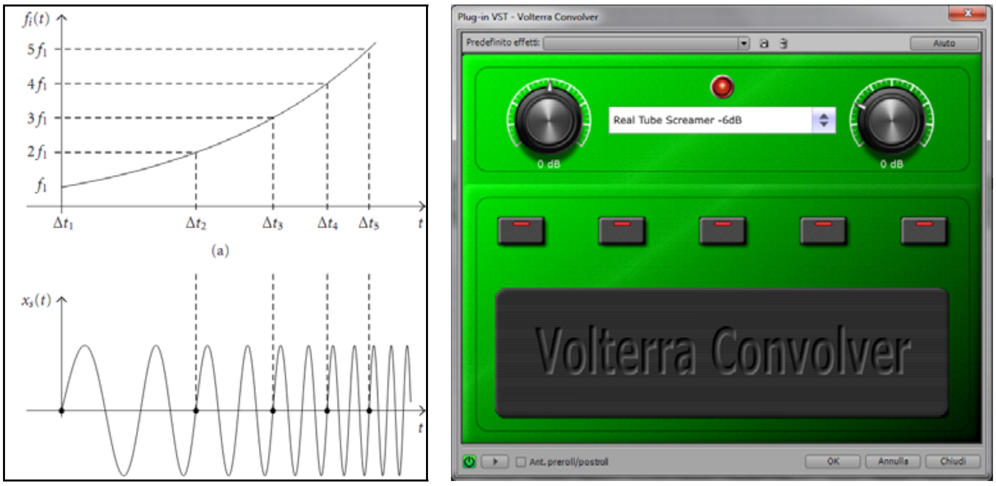

Figure 3: Synchronized swept-sine (left)) and the real-time VST Volterra Convolver (right)

Because of the need of correct phase responses the synchronized swept-sine measurement technique has been chosen in this work as input signal to measure the distortions and to calculate the kernels for the nonlinear convolution. In this manner, the nonlinear effects of musical instruments have been added to the linear component, as previously shown [13], [14].

4 THE CASE STUDY: THE "TEATRO AMINTORE GALLI"

The history of the "teatro Amintore Galli" in Rimini, on the Adriatic coast, is similar to the histories of other theatres in Italy. The theatre was opened in August 16th, 1857. The theatre had a semi-circular shape, similar to the horse-shoe shape that typically distinguishes the Italian theatres, and it could host about 800 people. Perhaps one of the most interesting characteristics of the theatre was the number of columns between the second and third order of the boxes, which characterised the hall (see figure 4).

The Teatro Galli represented for a long time an important building in the town, since it is located at the main square in the city centre (Piazza Cavour), between the Roman bridge and the Roman arch of the town. After its destruction during the Second World War, all the cultural and musical events of the town were forced to move to other buildings, much less fascinating that the Galli, and located not in the city centre of the town.

Since the 1950s, when Rimini became the most important and populated coastal centre in Italy, the local Municipality started a debate, which involved the most outstanding cultural personalities of the town and of the cultural community in northern Italy, in order to decide which could have been the suitable solution for the reconstruction of the theatre.

In 1995 an international competition for the new theatre was launched. The project of arch. Natalini *et al*. was chosen. It proposed a totally new building, completely different from the Poletti theatre of

1857. This solution was presented to the city, but immediately a large number of cultural personalities expressed their doubts of the project.
Moreover, after the burning of the two Italian theatres in Bari (the theatre Petruzzelli) and especially La Fenice in Venice, many other people disagreed with the project of the architect Natalini.

Figure 4: The theatre in 1910 (left), after the bombing of 1944 (centre) and the new hall (right)

At the beginning of the new millennium, accordingly with the Regional and National authorities on cultural heritage (the Regional Supervisors and Ministry of Cultural Affairs), a new project was developed, following the rule “as it was, where it was”, in the same way as the theatres Petruzzelli and Fenice were rebuilt after the burning. This new position completely cancelled the previous hypothesis.
The new theatre includes many enhancements in the main hall, in the balconies and in the orchestra pit. The results obtained from the 3D numerical model that was developed for the acoustic design of the teatro A. Galli in Rimini, recently presented [10], are reported in table 1.

Freq. [Hz]	63	125	250	500	1000	2000	4000
T20	2.7	2.0	1.6	1.5	1.6	1.5	1.1
EDT	2.2	1.6	1.3	1.2	1.2	1.2	1.0
C50	-2.2	-0.7	0.5	1.0	1.0	1.2	2.6
C80	-0.1	1.4	2.1	3.1	3.0	3.1	4.7
D50	37.8	45.9	52.9	55.9	55.9	56.7	64.8
Ts	142.2	103.9	82.5	75.1	75.8	73.4	54.9
G	5.1	3.8	2.3	2	2.1	2	1.3
RaSTI		0.65	0.69	0.7	0.7	0.7	0.75

Table 1: Averaged parameters simulated in the Theatre A. Galli in Rimini

5 THE AURALISATION

5.1 The stereo-dipole rendering

One of the most useful procedures that could be used for the auralisation experiments is the stereo-dipole playback system [15]. It is a two-loudspeakers-based system that enables the reconstruction of the sound characteristics of any auditorium or theatre in a properly designed listening room, provided that the cross-talk paths between the two loudspeakers are avoided, and their frequency responses are flattened by means of a special set of digital inverse filters.
The calculation of the digital inverse filters requires special care. The acoustic treatment in the listening room, especially on the floor, and the position of the loudspeakers, could compromise the

excellent quality of the system. Any changes in the room require a recalculation of the inverse filters.
Using the stereo-dipole system, it became easier to merge video and sound together in a movie, which could be played with a simple movie player, and displaying a perfect reproduction of architecture and sound in the listening room where the digital filters have been calculated and applied. On the other hand, the sound reconstruction requires that the loudspeakers should not be moved in any way from their original position, unless a new set of digital filters would be calculated and applied. The stereo dipole also allows a rather fair sound reproduction with normal stereo home systems.

Figure 5: The stereo-dipole technique: software settings for playback

In addition, the stereo-dipole technique allows for a perfect sound reproduction of virtual rooms. Using the aforementioned numerical model of the theatre, it was possible to calculate the binaural impulse responses that were later utilised in the stereo-dipole sound reproduction (figure 5).
The calculation of the binaural impulse responses here utilised was firstly described in 2000 [18].

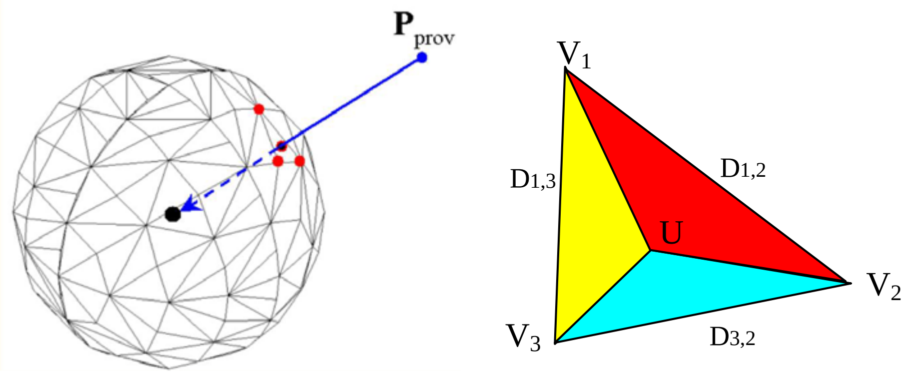

Figure 6: Calculation of the interpolation of HRTFs during the acoustic simulation.

The point P represents the position of the early reflection after the last impact with the room. During the acoustic simulation in the room the early reflection in the impulse responses can be recorded. The time delay and the angles of last impact (cosine) up to 10 (and even more) early reflections are stored. With reference to the azimuth and elevation angle of the receiver, the ray coming from the point P intersects a sphere in a point U, which lies inside a triangle having vertexes V_1, V_2 and V_3 (figure 6). These three vertexes represent the position of the Head-Related Transfer Functions (HRTFs) measured on a Kemar dummy head at MIT, Boston (MA).

The calculation of the HRTF for the point P is based on the interpolation between the three HRTFs corresponding to each vertex, using the three triangular surfaces as a weighting coefficient.

6 THE VIRTUAL MODEL FOR 3D AURALISATION

During the acoustic design, a 3D model was realized for visual purposes (figure 7). The final solution for the theatre has been rendered by means of a 3D auralisation.

Figure 7: Rendering of the new Teatro A. Galli

A short movie, which illustrates the architectural design, has been realised. The audio of the file has been obtained by means of convolution between dry music and the binaural impulse responses obtained from the simulations, which could properly render the diffuseness in the main room [19, 20], both using normal Stereo and Stereo-Dipole audio.

7 CONCLUSIONS

The possibilities given by 3D auralisation allow recreating and reproducing the sound effects that would be present in a room. By means of stereo-dipole and ambisonics, the full 3D reconstruction of the sound characteristics of a theatre could be realised in a listening room. These reconstructions could be enhanced by adding the nonlinear components (distortions) to the virtual reconstruction of the soundboards or bodies of violins or trumpets, as shown in previous papers. In this way, by means of the 3D auralisation and nonlinear emulation of musical instruments, in the acoustically controlled listening room “Arlecchino” at the University of Bologna, it could be appreciated the architecture of the theatre Galli in Rimini.

8 ACKNOWLEDGEMENTS

The author would like to thank Mr Giorgio Guidotti, Ms Giulia Parantelli and Mr Andrea Venturi for their precious help at the computer desk for the realisation of the 3D model of the theatre and for their assistance at the Arlecchino listening room and the nonlinear virtualisation.

9 REFERENCES

1. L. Tronchin, V. Tarabusi, A. Giusto, The realization of Ambisonics and Ambiophonics listening room "Arlecchino" for car sound systems evaluation, 21st AES Conference on architectural acoustics and sound reinforcements - St. Petersburg, Russia (2002)
2. L. Tronchin, G. E. Curà, V. Tarabusi, "The enhancement of the Arlecchino listening room: adding Stereo Dipole to Ambisonics", in: AA.VV., Proceedings of Forum Acusticum 2005, Budapest, Opakfi, 2005, pp. 2469 – 2474.
3. A. Farina, L. Tronchin, 3D Impulse Response measurements on S. Maria del Fiore Church. Florence. Italy, Proc. of 16th International Congress on Acoustics, Seattle, USA (1998)
4. A. Farina, R. Ayalon, Recording Concert Hall Acoustics for Posterity, 24th AES Conference on Surround Sound. Techniques. Technology and Perception – Banff. Canada (2003)
5. A. Farina, L. Tronchin, 'Measurement and reproduction of spatial sound characteristics of auditoria', Acoustical Science and Technology, 26(2), 193-199 (2005)
6. A. Farina, Simultaneous measurement of impulse response and distortion with a swept-sine technique, 110th AES Convention, Paris (2000)
7. A. Farina, A. Bellini, E. Armelloni (2001). "Non-Linear Convolution: A New Approach For The Auralization Of Distorting Systems". Proceedings of the 110th AES Convention, 2001 May 12-15 Amsterdam, The Netherlands
8. A. Farina. "Advancements in impulse response measurements by sine sweeps". 122th AES Convention, Vienna, Austria, 5-8 May 2007
9. A. Farina, L. Tronchin: "Measurements of time-invariant not linearity in musical instruments", Proc. of ISMA2007, International Symposium on Musical Acoustics, Barcelona, Spain, 2007
10. L. Tronchin: The reconstruction of the Teatro Galli in Rimini: the acoustic design. Proc. of ISRA2010, International Symposium on room Acoustics, Melbourne, Australia, 2010
11. W. F. Thompson: Music, Thought, and Feeling: Understanding the Psychology of Music. p. 46 (2008).
12. J. R. Pierce: "Consonance and Scales". in Perry R. Cook. Music, Cognition, and Computerized Sound. MIT Press, (2001)
13. A. Farina, A. Langhoff, L. Tronchin: Acoustic characterisation of "virtual" musical instruments: using MLS technique on ancient violins Journal of New Music Research, 27(4), 359-379, (1998)
14. A. Farina, L. Tronchin: On the "virtual" reconstruction of sound quality of trumpets, Acustica United with Acta Acustica, 86(4), 737-745, (2000)
15. O. Kirkeby, P. A. Nelson, H. Hamada, "The "Stereo Dipole" - A Virtual Source Imaging System Using Two Closely Spaced Loudspeakers" J.Audio.Eng.Soc. 46(5), pp. 387-395, (1998)
16. L. Tronchin, A.Venturi (2010). "The use of Volterra series for simulating the nonlinear behaviour of musical instruments" Proceedings of the Second Vienna Talk on Music Acoustics, Vienna 19-21 September 2010
17. A. Novak, L. Simon, P. Lotton, F. Kadlec. (2009). "Modeling of nonlinear audio systems using swept-sine signals: application to audio effects". Proc. of the 12th Int. Conference on Digital Audio Effects (DAFx-09), Como, Italy, September 1-4, 2009
18. L. Tronchin, A. Farina, M. Pontillo, V. Tarabusi: The calculation of the impulse response in the binaural technique, Proc. of 7th International Congress on Sound and Vibration (ICSV), Garmisch, Germany, (2000)
19. R. Shimokura, L. Tronchin, A. Cocchi, Y. Soeta: Subjective diffuseness of music signals convolved with binaural impulse responses, Journal of Sound and Vibration, in press (2011) http://dx.doi.org/10.1016/j.jsv.2011.02.014
20. L. Tronchin, R. Shimokura: Effectiveness of 3D auralisation to evaluate room acoustic enhancement in theatre restoration. Proc of 6th International Conference on Auditorium Acoustics, IOA, Copenhagen, Denmark, 2006