AURALIZATION OF ROOM USING DIGITAL WAVEGUIDE MESH

Vilela, Ana Paula Freitas, ana04nte@hotmail.com
Machado, Mateus Lichfett, mateus_lichfett@hotmail.com
Miranda, Ricardo Fortes de, rfmiranda@mecanica.ufu.br
Duarte, Marcus Antônio Viana, mvduarte@mecanica.ufu.br

Universidade Federal de Uberlândia – UFU

Abstract. *One of the main difficulties in designing acoustic environment is the different characteristics of each enclosure, for example, churches, auditoriums, theaters, etc. A series of considerations (in relation to geometry, sound propagation and sound source characteristics) increases significantly the calculations. Financially, it is interesting that during the project it is possible to analyze the acoustic behavior of these locations and thus avoiding future expenses with noise control. Through the auralization it is possible to create virtual reverberant environments which allow characterizing the sound field. Among the many numerical techniques available in literature, the digital waveguide mesh seems to be an efficient tool, because of the algorithm simplicity and the quality of the results. This method is based on the behavior of acoustical waves. A set of equations that governs the phenomenon through sampling points called scattering junctions are solved numerically. To simulate such field, the room impulsive response (RIR) at a membrane was simulated. The objective of this study is the construction of a computational tool that simulates a virtual environment in which an acoustic wave propagates and interacts with the obstacles. The results obtained can be used with success to characterize real environments.*

Keywords*: Auralization, Digital Waveguide, Room Impulse Response*

1. INTRODUCTION

Nowadays, due to the advance of computational technology, it is possible to simulate innumerous physicals phenomenon, using numerical techniques. The acoustic area, in particular, has many algorithms which can simulate the acoustic field, including the wave propagation and its interaction with obstacles. However, one of the great challenges of reverberant acoustic environment designers is to find an efficient method that represents the sound intensity levels.

Among the techniques used for sound propagation simulations, the following ones are outstanding: methodology based on geometry where sound has the same behavior as light rays; statistical models which shape the statistics properties of sound intensity; and frameworks based on sound wave behavior with numerical simulation related to the wave equation. The third method showed to be more efficient for studying which simulates reverberation fields. It is possible to observe and manipulate the interaction of sound waves with obstacles defining its reflection, absorption, diffraction, transmission, etc. The digital waveguide mesh showed to be efficient by the simplicity of the algorithm and by the results obtained, Vilela and Fortes, (2008).

An acoustical system can be characterized by the impulsive response. Various parameters of these environments can be calculated from these responses, Gerges (2000). The great advantage of this method is the possibility to convolute the impulse response with other type of audio input and output signal like the virtual room simulated by Murphy *et al.* (2001).

2. DIGITAL WAVEGUIDE FORMULATION

As the proper name suggests, the digital waveguide mesh are virtual devices that guide the wave movement and characterizes the average propagation. They are a digital implementation of the wave equation's solution, representing the sum of two parcels which correspond to the waves that move in opposite directions (Moura, 2005) as shown in "Fig.1".

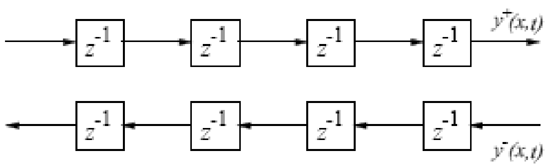

Figure1: Bidimensional delay. *Z* represents a transport function of the wave properties

Figure 1 represents a transfer function to transport the wave properties from one extremity to the other. The arrow indicates the two directions of the movement. The sum of these two movements characterizes the solution of the problem.

The points where the waveguide connect are called scattering junctions. "Figure 2" shows the general case of the scattering junction J with N neighbors.

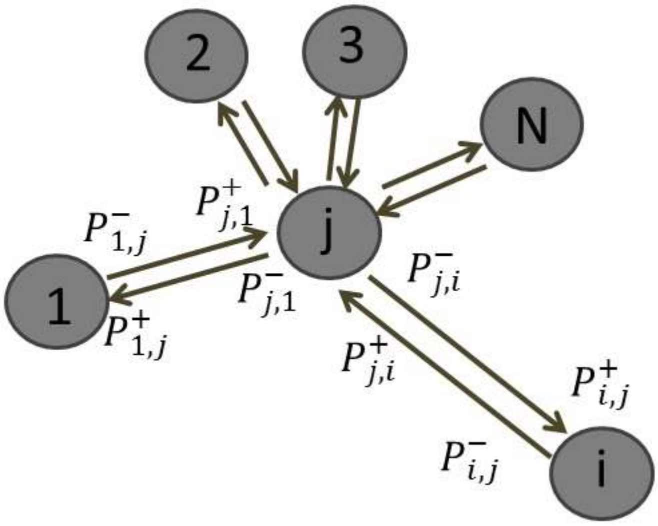

Figure 2: A general scattering junction J with N connected waveguides for i=1,2,…,N

Where:

$p_{i,j}^{+}$ represents the incoming signal to junction I along the waveguide from the opposite junction J.

$p_{j,i}^{+}$ represents the outgoing signal from junction I along the waveguide to the opposite junction J.

The delay elements are bi-directional and so the sound pressure is defined as the sum of its input and output signals like shown in Eq.(1):

$$p_i = p_i^{+} + p_i^{-} \tag{1}$$

The propagation velocity $\boldsymbol{v_i}$ is equal to the pressure p_i divided by impedance $\boldsymbol{Z_i}$. The propagation at a scattering junction with $\boldsymbol{N}$ connected waveguides should obey the following conditions.

1- The sum of the incoming velocities v^{+} should be equal to the sum of the outgoing velocities, v^{-}:

$$\sum_{i=1}^{N} v_i^{+} = \sum_{i=1}^{N} v_i^{-} \tag{2}$$

2- The sound pressure of the neighbors should be equal to the pressure at the junction:

$$p_1 = p_2 = \dots = p_i = \dots = p_N \tag{3}$$

Using Eq. [2] and [3], the sound pressure at a scattering junction can be expressed by Eq. (4):

$$p_J = \frac{2\sum_{i=1}^{N}\frac{p_i^+}{Z_i}}{\sum_{i=1}^{N}\frac{1}{Z_i}} \tag{4}$$

To model the wave propagation, bi-dimensional or tri-dimensional mesh structures are constructed. For each case, the calculation at the scattering junction is expressed by Eq. (5)

$$p_i^- = \left(\frac{2}{N}\sum_{j=1}^{N} p_j^+\right) - p_i^+ \tag{5}$$

Where ***N*** is the number of neighbors of each node. Note that the value of *N* is not related to the dimension of the mesh, that is, *N* is not necessarily 2 for the bi-dimensional case, or 3 for the tri-dimensional case.

3. DIGITAL WAVEGUIDE MESH – SQUARE WAVEGUIDE (SWG)

To generate bi-dimensional mesh various models are described in literature, among them are Square Waveguide (SWG) and Tingle Waveguide (TWG). In SWG each junction is connected to four adjacent junctions by four digital waveguides as shown in "Fig. 3":

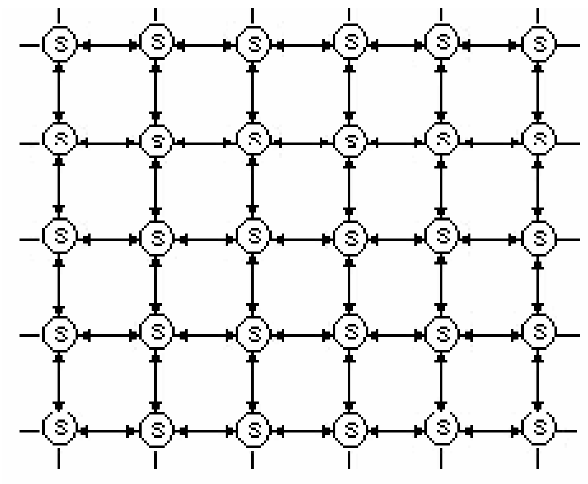

Figure 3: SWG mesh.

The mathematical model applied to the scattering junction is expressed by the following equation:

$$p_J(n) = \frac{1}{2}\left[\sum_{i=1}^{4} P_i(n-1)\right] - P_j(n-2) \tag{6}$$

3.1. Update Frequency

The update frequency of an N-dimensional mesh is:

$$fs = \frac{c\sqrt{N}}{dx} \tag{7}$$

Where ***c*** represents the sound speed in the medium and *dx* is the spatial sampling corresponding to the distance between two neighboring nodes. The approximate values stands for a typical room simulation (*c=430m/s, N=2*). The same frequency is also the sampling frequency of the resulting impulse response.

4. DETAILS OF NUMERICAL MODELING

Before entering in detail in the physical model, some particularities imposed during simulation will be shown.

4.1. Boundary Conditions

In modeling of physical systems, an important parameter to be analyzed is the boundary conditions which describe what happens at the boundary of the physical system in consideration (Campos, 2003). In digital waveguide mesh modeling, the boundary points are treated as boundary nodes as their positions define the limits of change of propagation medium. However, due to the special discretization of the nodes, errors can occur, when the physical boundary does not coincide exactly with the boundary nodes and these surfaces are usually represented by approximations. To avoid this, the boundary nodes are positioned in such a way that the impedance discontinuity can be represented as shown in Fig. 4.

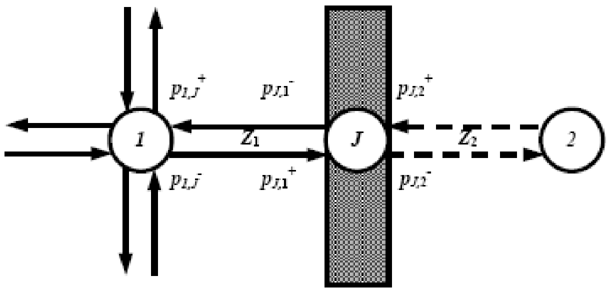

Figure 4: Representation of a scattering junction showing an impedance discontinuity

In Figure 4 the mediums 1 and 2 correspond to the left and right sides, respectively. The junction *J* that represents the impedance discontinuity was positioned on the obstacle and the boundary condition model is based on Eq. (8).

$$p_1^+ = rp_1^- \tag{8}$$

It is important to emphasize that the index of reflection depends on the frequency, in other words, the acoustic impedance of the materials assumes different values according to the frequency. At the boundary, where change of impedance occurs, a unique waveguide has two scattering junctions with different impedance values as shown in Figure 4. In this case the index of reflection varies according to the change of impedance and its value is defined as:

$$r = \frac{Z_2 - Z_1}{Z_2 + Z_1} \tag{9}$$

To model the sound sources using digital waveguide mesh, an excitation is generated in the mesh to reproduce the injection of sound energy (Smith, 1993). In this study to model the room acoustics, a sound source is simulated by the injection of a signal, generally sine wave in a unique node, representing a point source.

4.2. Sound Attenuation by Air

In room acoustic modeling wall absorption is the main cause of energy dissipation. But in practice there is a significant fraction of absorption by air, which increases with frequency. The sound absorption by the propagation medium depends on a series of factors, such as distance, temperature, humidity and others. In practice, the most important factor is the temperature variation (Savioja, 2000).

5. AURALIZATION

Auralization is a term used for the techniques that render audible a sound field through mathematical or physical modeling of the sound source, the acoustic space and the listener (Savioja *et. al*.,1995; Campos, 2006). The acoustic response perceived by the listener in a space varies according to the source and receiver positions. The direct room impulse response rendering technique is based on Binaural Room Impulsive Responses (BRIRs), which can be obtained from simulation or from measurements. Figure 5 shows the BRIRs schematically, where the signal received in each ear by listener (r1 and r2, left and right ears, respectively) is represented by signal H1 and H2.

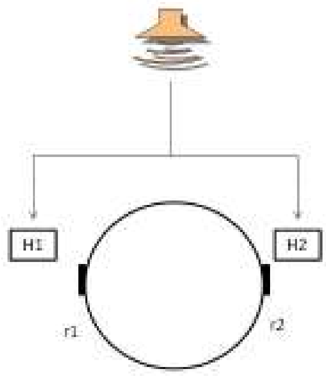

Figure 5: Reception of audio using BRIR technique

Computers simulations can be used to create different kinds of geometry and generate the spatial and temporal data describing the acoustical behavior of the room (Savioja, 2000). The signal obtained by the sensor (*h1*) is convolved with another input signal (*f*), as shown in Eq. 10.

$$(h_1 * f)(t) = \int_0^t h_1(\tau) * f(t-\tau)d\tau \qquad (10)$$

6. RESULTS

To evaluate the acoustic quality of an enclosed space, it is necessary to verify the qualitative and quantitative characteristics of the noise present (Gerges, 2000), that is, to calculate the impulse responses associated to the paths between the sources and the receivers (Vilela et al., 2009). The room impulsive responses analysis is the response function of the room subjected to an impulse of sound. Some parameters to simulate real variables such as room size, source location, position of receivers and coefficients absorption were used.

A 6 x 4 [m^2] membrane with an obstacle subjected to an impulsive response was simulated. The source has set at position (3.00, 3.00) and the receivers were set at position (5.50, 3.55) and (5.50, 3.70), respectively. The obstacle was positioned at x = 4 [m] and y = 1.8 to 4 [m]. Figure 6 shows the situation schematically.

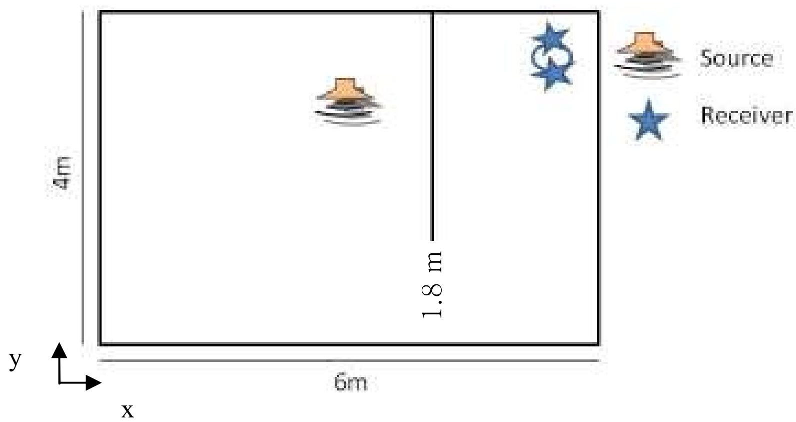

Figure 6: Audio reception using BRIR technique

A square mesh topology was used and the source generated a signal with an amplitude of 1 [Pa], a frequency of 4.096Hz, varying absorption coefficient to represent the bands of 125, 250, 500, 1000, 2000 and 4000Hz. The total simulation time to capture the reverberant field was 5 seconds. The source was active for $2.44e^{-004}$ [s], which represents a Dirac Delta input. The update frequency of the mesh was adjusted to 16.384 Hz. The obstacles absorption coefficients were configured according to Table 1.

Table 1. Hypothetic values of absorption coefficient

Frequency Band	Absorption Coefficient (%)
63	3
125	5
250	10
500	12
1000	15
2000	17
4000	20

Figures 7 to 9 show the interaction of the sound waves with the obstacles. Figure 7 shows the instant when the sound source is turned on.

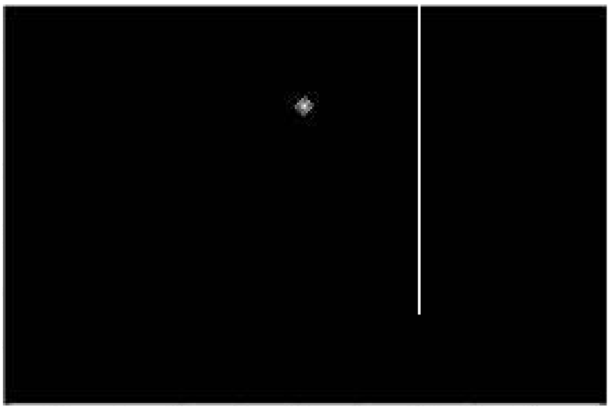

Figure 7: Instant when the sound source is turned on (the white line represents the obstacle)

Figure 8 shows the interaction of the wave with the obstacle. At this instant, the information has not yet reached the receiver.

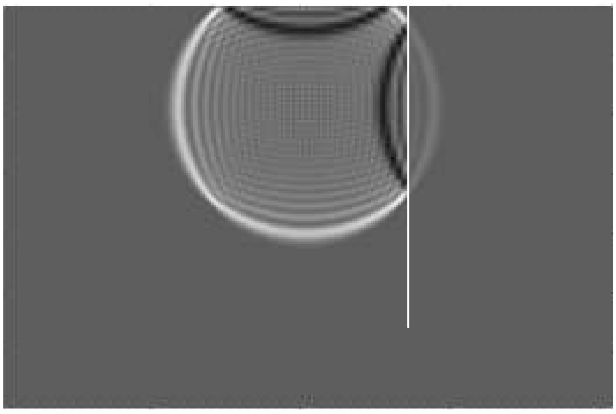

Figure 8: Waves hitting the obstacle

Figure 9 shows the time that the waves are contouring the obstacle and the signal propagates into the other side of the membrane, where the receivers are.

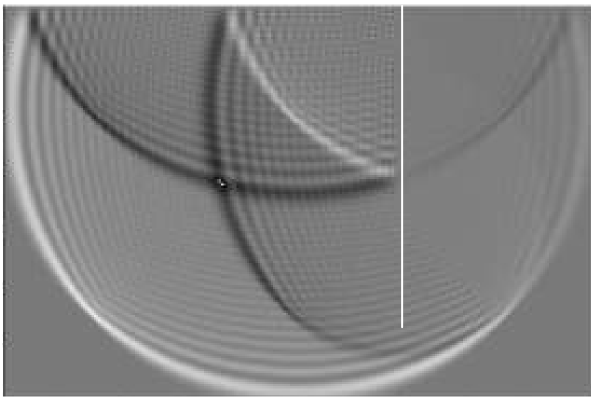

Figure 9: Waves contouring the obstacle

After the source is turned off, the sound energy begins to dissipate due the presence of obstacles. Figure 10 shows the behavior of the BRIRs on receivers at coordinates (5.50, 3.55) and (5.50, 3.70) of the room, which are represented by the colors blue and red, respectively, for three absorption coefficient (for frequencies 63 Hz, 500 Hz and 4Kz, respectively shown in Table 1).

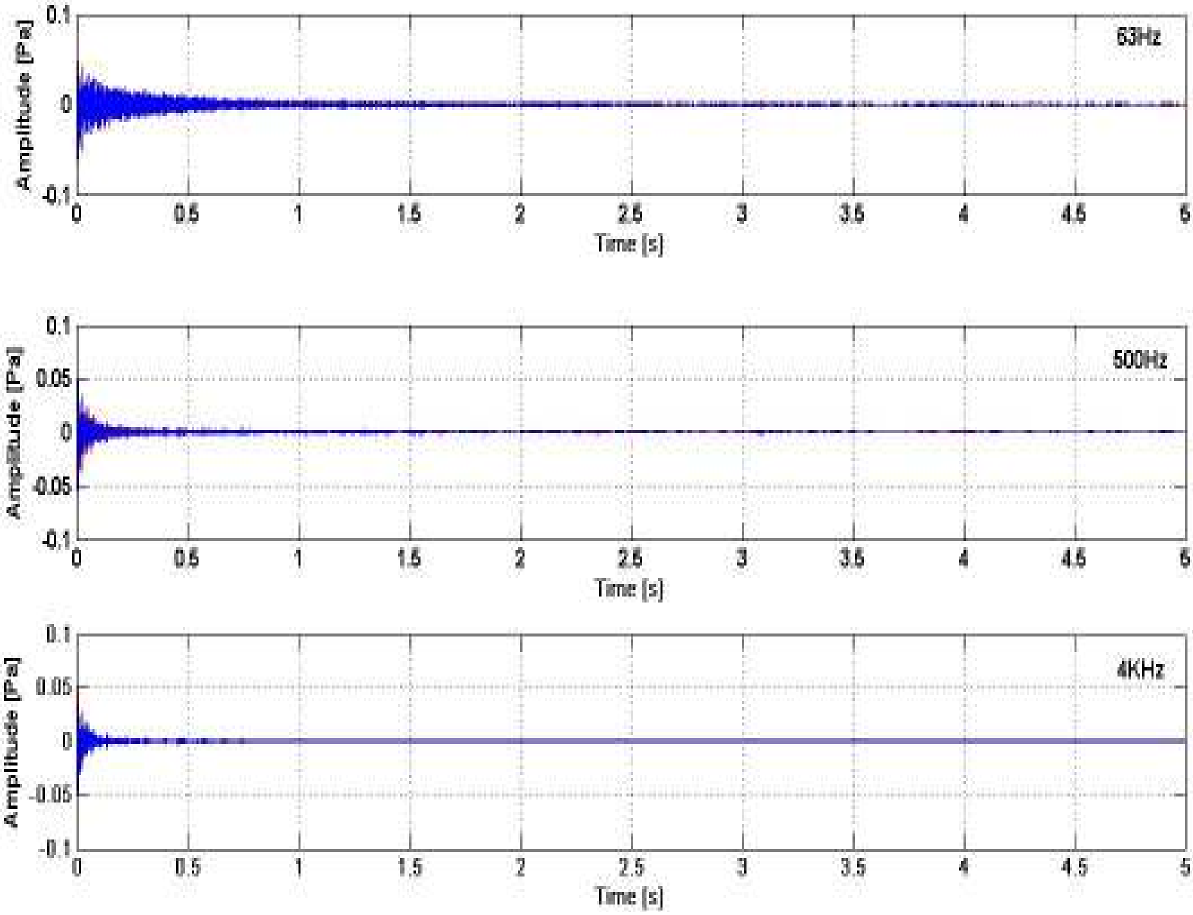

Figure 10: Audio reception of using BRIRs technique

Note that the signal is more attenuated at frequency of 4Khz, because the absorption coefficient was configured in 20%, while in 63Hz the signal is less attenuated with absorption coefficient of 3%.

Although the auralization is used only in three-dimensional cases, this work explores some parameter of this technique to estimate the sound convolved in this membrane. The BRIRs was calculated six times, varying the absorption coefficient to represent different bands of frequency. Each signal has been filtrated by an octave-band filter and the sum of filtrated components was convolved with other audio signal. Fig.11 shows the original signal and the result of convolution.

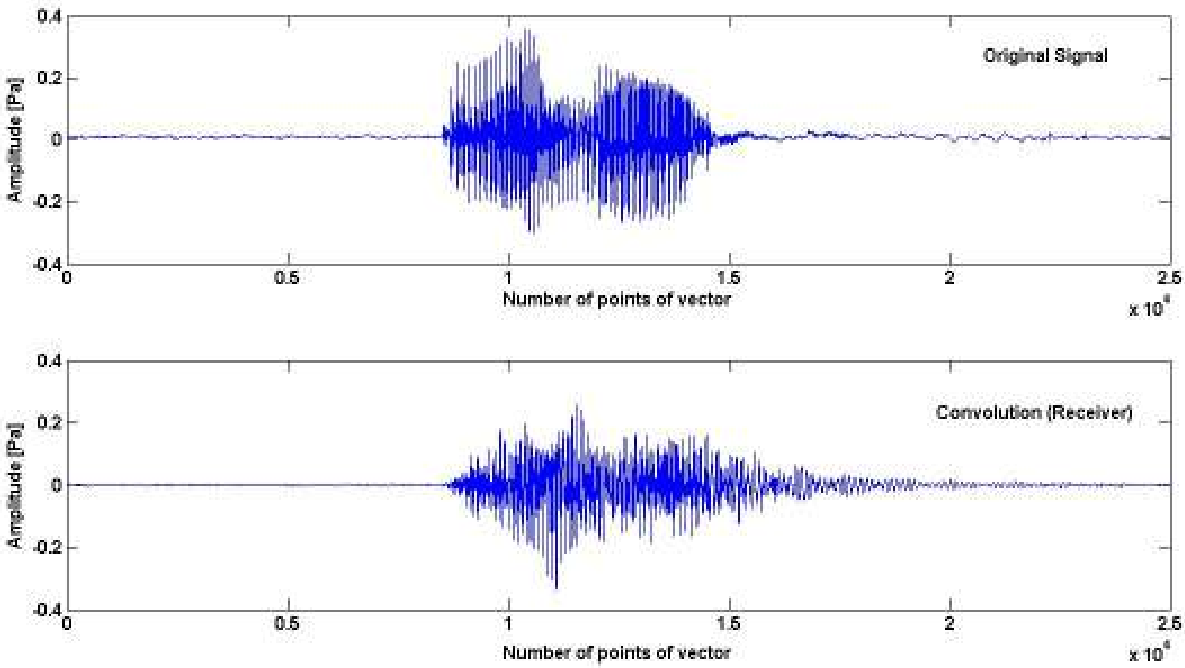

Figure 11: Original signal and convolved signal, respectively

7. CONCLUSION

This work investigated the Digital Waveguide Mesh for acoustic room simulation for a bi-dimensional case. Although auralization technique is generally used in 3D case, this work investigated the quality of room impulsive response, using bi-dimensional Digital Waveguide Mesh methodology, characterizing different absorption coefficient. The room impulsive response was obtained by a square waveguide mesh, which has an input of Dirac Delta signal and simulates a membrane with obstacles. Six different signals were simulated, varying the absorption coefficient from 3% up to 20%, to represent the behavior of a wave in different frequency bands. After recording the signal in two different points of the membrane (near to each other), representing the Binaural Response Room, each signal was filtered by an octave band filter and the sum of filtrated components was convolved with other audio signal. The result obtained was a digital behavior of the sound inside the membrane in the same way it was listened by the receiver.

However, the kind of mesh analyzed has some restriction due to the discretization of the wave propagation paths in only two directions and does not collect information efficiently, since the waves propagate in all directions. To reduce this error, it is possible to get more number of points or change the mesh geometry, for example a triangular mesh.

Nevertheless, the use of Digital Waveguide Mesh showed good results in simulation of reverberant spaces. Each signal with 5 seconds of simulation, took about 10 minutes to acquire the results, while the same physic phenomenon when using Finite Element Method (FEM) each signal took more than 10 hours to be processed. Its outstanding advantage is the modeling simplicity, where the information is collected using the medium impedance, making possible to simulate more complex geometries, obtaining efficient and accurate results.

This research concludes that Digital Waveguide is feasible to auralization of rooms, and in a future work a tridimensional case will be considered.

8. ACKNOWLEDGEMENTS

The authors are grateful to Universidade Federal de Uberlândia, Faculdade de Engenharia Mecânica-Laboratório de Vibrações e Acústica for the infra-estructure and to Capes, Fapemig and CNPq for financial support.

4. REFERENCES

CAMPOS Guilherme: Modelação Acústica 3D por Malhas de Guias Digitais de Ondas. Associação Portuguesa de Engenharia de Áudio, 2006.

CAMPOS Guilherme: Three-Dimensional Digital Waveguide Mesh Modelling for Acoustic Simulation PHD Tesis, 2003.

GERGES S.N.Y Ruído: Fundamentos e Controle - Florianópolis : NR Editora, 2000.

MOURA H. G. Simulação da Propagação de Ondas Acústicas Através de uma Malha de Guias Digitais de Ondas. Dissertação em Engenharia Mecância pela Universidade Federal de Uberlândia. Uberlândia-MG Brasil, 2005.

MURPHY D.T, NEWTON C.T.C. e HOWARD D.M. Digital Waveguide Mesh Modelling of Room Acoustics: Surround-Sound, Boundaries and Plugin Implementation. Proceding of the COST G-6 Conference on Digital Audio Effects - Limerick, Ireland, 2001. - December 6-8.

Savioja L e al et Waveguide Mesh Method for Low Frequency Simulation of Room Acoustics. Procedings of the 15th International Congress on Acoustic (ICA), Trondheim, Norway. - 26-30 de Junho de 1995. - pp. 637-641.

Savioja Lauri Modeling Techniques for Virtual Acoustics. PHD Tesis. - 2000.

SMITH J.O. Physical Modeling with Digital Waveguides. Center of Computer Research in Music and Acoustics (CCRMA) 1993.

Vilela A.P.F, Miranda R.F. e Duarte M.A.V. A Comparasion between Digital Waveguide and Finite Element Method. COBEM. - Gramado-RS Brazil, 2009.

Vilela A.P.F, Miranda R.F. Simulação Baseada no Comportamento da Onda Acústica usando Guias Digitais de Ondas. CONEM. – Salvador-BA Brasil. 2008.

5. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.