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Development of a virtual auditorium occupied with virtual manikins used in thermo-acoustic evaluation

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Abstract

In this work a numerical model is applied in the development of a virtual auditorium occupied with virtual manikins. The auditorium geometry, based in a cylindrical methodology, is developed using a geometric numerical model coupled with a CAD system. The thermo-acoustic manikins, based in human body methodology, are developed using empirical and geometrical equation numerical model also coupled with the CAD system. The manikins geometry, using the Human Thermal Response and the Sound Propagation numerical models, is used in the human thermo-acoustic evaluation. The first one evaluates the human temperature and comfort, while the second one, using a virtual binaural manikin, evaluates the direct and indirect sound and calculates the reverberation time. In this preliminary study an auditorium with thirteen rows and ten columns, occupied with 140 virtual manikins, is developed. In the thermal study the human thermal response is evaluated when the indoor air temperature is 25 ºC and the air relative humidity is 50 %. In the acoustic component were selected three virtual manikins, one seated in the stage and two seated in the audience, in opposite positions. The thermal comfort and the acoustic level, in the left and right ears, that the virtual manikins are subjected are evaluated. In accordance the obtained results, the manikins are thermal comfortable and the acoustic level presents slight differences between left and right ear and differences between the two manikins. In accordance with the acoustic path the lateral and, mainly, the ceiling walls reflection show an important contribution in the manikin acoustic level and will be analysed in detail in future works.

Keywords: Auditorium, thermal-acoustic virtual manikin, auditorium geometry, thermal comfort and reverberation time.

1 Introduction

In this work the development of a virtual auditorium occupied with virtual manikins used in thermo-acoustic evaluation is developed and applied. The geometry and the thermo-acoustic numerical model is developed. In the first one the manikin and auditorium geometry and grid generation is developed, while in the second one the manikin comfort, namely the thermal comfort and and indoor air quality, and the acoustic reverberation time methodology is applied.

The thermo-acoustic virtual manikin calculates the environmental variables around the occupants (Conceição et al.[1]), the occupants' thermal comfort (Conceição [2]) and the acoustic level (Conceição et al. [3]). The

manikin geometry and grid generation are developed using numerical equations and the auditorium geometry and grid generation are developed using Computational Aid Design (CAD).
The CAD system is frequently used in several works in acoustic phenomena, as in Jablonska and Czajka [4], Pelzer et al. [5] and Th Kouzeleas [6], and in thermal phenomena.
The building and vehicle surrounding temperature is evaluated through the thermal behaviour numerical models. The first one can be seen in Conceição et al. [7] and Conceição [8], while the second one can be seen in Conceição and Lúcio [9], [10], [11] and [12]. These models are validated in the first one in Conceição et al. [7] and Conceição [8], and in the second one in Conceição and Lúcio [13].
In the applications in vehicles, as Qianmu et al. [14], or in buildings, as Robert et al. [15], is also frequent the use also the CAD techniques.
In the thermal comfort the Human Thermal Response and the Computational Fluids Dynamics are used. In Conceição [2], Conceição [16], Conceição and Lúcio [17], Conceição and Lúcio [18], Conceição et al. [19] and Conceição et al. [20], the Human Thermal Response was developed and applied, while in Conceição et al. [21] the Computational Fluids Dynamics was analysed. The coupling of Computational Fluids Dynamics and the Human Thermal Response were presented in Conceição et al. [22] and Conceição et al. [23]. In the coupling methodology, the input of the Human Thermal Response is used as output of the Computational Fluids Dynamics and the input of the Computational Fluids Dynamics is used as output of the Human Thermal Response.
In the sound propagation several authors developed works, as Schetelig and Rabenstein [24], Savioja et al.[25], Funkhouser et al.[26], Funkhouser et al [27] and [28] and Taylor et al.[29]. These authors analysed in detail the virtual acoustic environments system methodology.
To evaluate the thermal-acoustic phenomena the occupants' thermal phenomena, the internal airflow and the sound propagation are analysed. In the first one the ISO 7730 [30] is applied, while in the third one the reverberation time concept DL [31] is used. One application of this methodology can be seen in Conceição et al [32]. ISO 7730 [30] which considers the Predicted Percentage of Dissatisfied people to evaluate the thermal comfort level, while Conceição et al.[33] and in Conceição et al.[34] consider the adaptive thermal comfort level.
Finally, the air quality level, using the carbon dioxide concentration as indicator of internal air quality, is also evaluated in the thermal-acoustic virtual manikin (see in [35] and in Conceição et al. [36]).
In this work the Auditory Geometric numerical model develop, using a numerical methodology based in cylindrical geometric coordinates, occupied auditorium spaces with complex topologies. In this preliminary study three manikins, two located in the audience and one located in the stage, were developed and used in the reverberation time evaluation.

2 Numerical models

The numerical model considers the integral and differential virtual auditorium and manikin thermal and acoustic response numerical models, namely:

- the integral Auditorium Thermal Response numerical model;
- the integral Human Thermal Response numerical model;
- the differential Computational Fluids Dynamics numerical model;
- the integral Sound Propagation numerical model.

Integral Auditorium Thermal Response numerical model
The integral Auditorium Thermal Response numerical model calculates the air temperature inside the spaces, the temperature on the indoor bodies, the temperature on the transparent bodies and the temperature in the different layers of the opaque surfaces. These variables are used as input data in the:

- Human Thermal Response numerical model;
- Computational Fluids Dynamics numerical model.

Integral Human Thermal Response numerical model

The integral Human Thermal Response numerical model evaluates the body tissue temperature, the clothing temperature, the arterial and venous blood temperature, the skin water vapour and the clothing water vapour. These variables are used as input data in the Computational Fluids Dynamics numerical model.

Differential Computational Fluids Dynamics numerical model

The differential Computational Fluids Dynamics numerical model evaluates the air temperature, air velocity and carbon dioxide concentration around the occupant. These variables are used as input data in the Human Thermal Response numerical model.

Integral Sound Propagation numerical model

The integral Sound Propagation numerical model present graphically the path between the source and the receiver, considering the multi reflections, diffractions and refractions at surfaces of the occupied room, using an image source method. This ray tracing method find the reverberation paths between the source and the receiver. In this numerical model the manikin mouth is used as source and the left and right ears as used as receivers.

The reverberation time is calculated using a regression equation of the sound intensity level evolution, using an exponential equation, when the receiver is located in the left and right ears. The reverberation time is calculated, for the left and right ears, using the necessary time to decay 60 dB from the beginning of the test.

3 Auditorium and manikin geometry generation

The auditorium geometry with complex topology is developed using Computer Added Design techniques, while the occupants' geometry is developed using geometric equations:

- The auditorium geometry, based in a cylindrical geometry coordinates, is generated through a geometric numerical model, using a Computer Added Design philosophy. The auditorium considers the side walls, stage walls, back walls, ceiling, floor and steps.
- The manikin geometry, generated through geometric equations, also uses a Computer Added Design philosophy. The manikin geometry, using 25 elements, considers the head, as sphere, and the neck, chest, upper abdomen, lower abdomen, right upper shoulder, right lower shoulder, right upper arm, right lower arm, right hand, left upper shoulder, left lower shoulder, left upper arm, left lower arm, left hand, right upper thigh, right lower thigh, right upper leg, right lower leg, right foot, left upper thigh, left lower thigh, left upper leg, left lower leg and left foot, as cylinders.

The grid generation of the auditorium and manikin geometry is used in the integral Auditorium Thermal Response numerical model, to evaluate the temperature distribution, the integral Human Thermal Response numerical model, to evaluate the thermal comfort level, the differential Computational Fluids Dynamics numerical model, to evaluate the airflow around the occupants, the Draught Risk and the indoor air quality, and the integral Sound Propagation numerical model, to evaluate the reverberation time and other indexes.

4 Numerical Methodology

In this preliminary study an auditorium with thirteen rows and ten columns, occupied with 140 virtual manikins, is developed (see figure 1 and 2). In the thermal study the human thermal response is evaluated when the indoor air temperature is 25 ºC and the air relative humidity is 50 %. In the acoustic component were selected three virtual manikins, one seated in the stage (left side) and two seated in the audience, in opposite positions (see figure 3), namely:

- manikin seated in the auditorium left side;

- manikin seated in the auditorium right side.

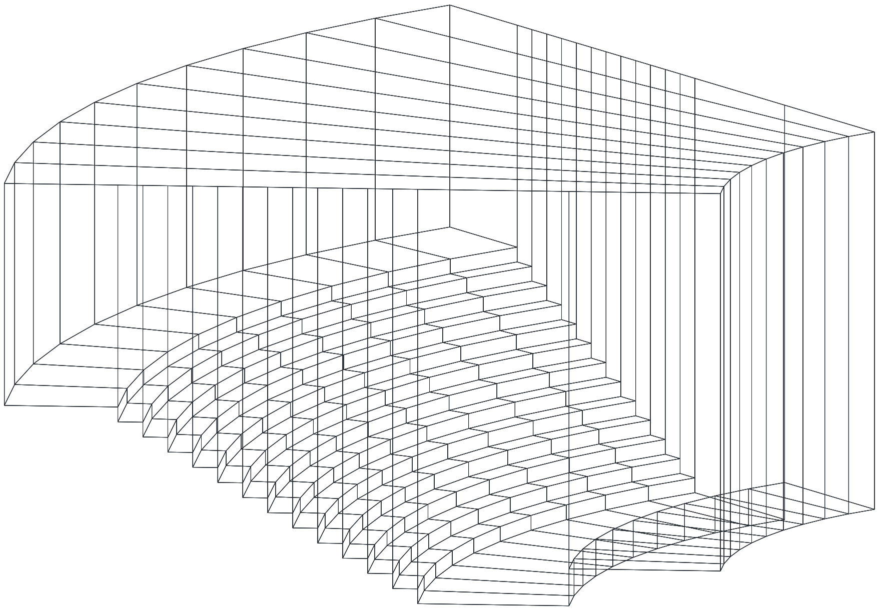


Figure 1 – Scheme of the auditory geometry.

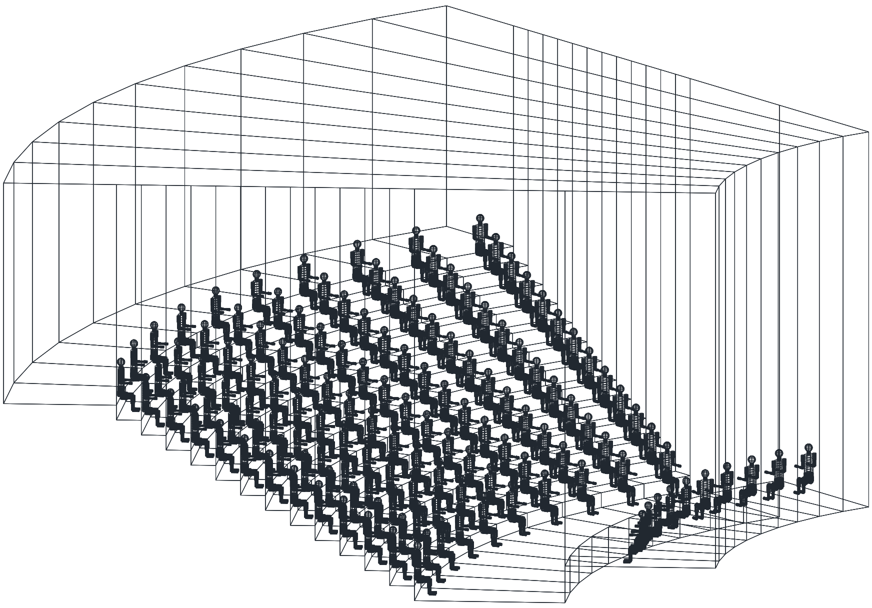


Figure 2 – Scheme of the auditory and thermo-acoustic binaural manikin geometry.

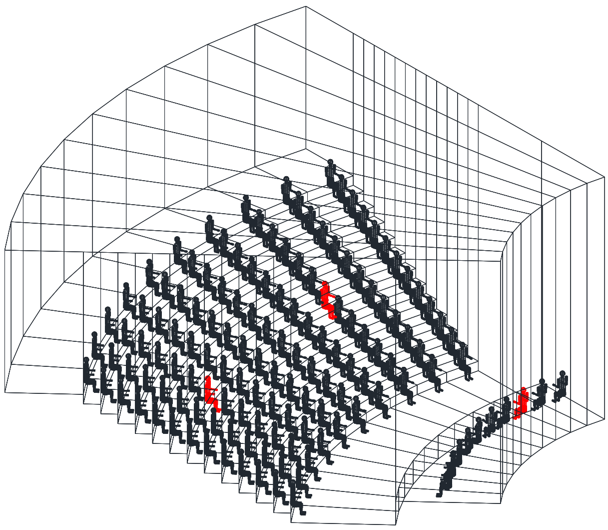


Figure 3 – Virtual manikins (in red) used in the numerical simulation.

5 Results

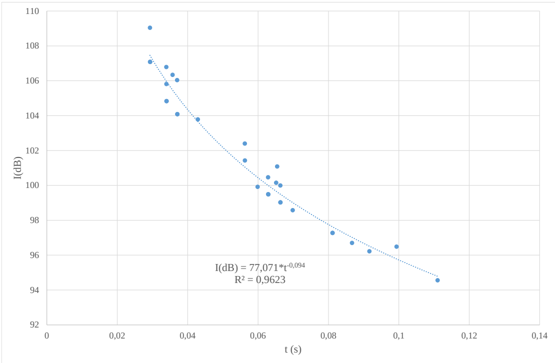
In this section the results of the reverberation time are numerically calculated using a regression of the sound intensity level evolution, using an exponential equation, when the receiver is located in the left and right ears. Thus, the reverberation time is calculated, for the left and right ears, using the necessary time to decay 60 dB from the beginning of the test. In this study the direct, first, second and third reflexion was considered in the numerical calculus.

In figure 4 is presented the dB value and acoustic path in the left ear of the manikin seated in the auditorium left side and in figure 5 is presented the dB value and acoustic path in the right ear of the manikin seated in the auditorium left side. The dB value and acoustic path in the left ear of the manikin seated in the auditorium right side is presented in figure 6 and the dB value and acoustic path in the right ear of the manikin seated in the auditorium right side is presented in figure 7.

Reverberation time calculation when the source is located in the mouth of the occupants and the receiver is located in the left and right ears of other occupants are presented in table 1.

The mean reverberation time is slightly higher for the right virtual manikin than the left virtual manikin. The reverberation time asymmetry verified between the left and right ears is higher for the left virtual manikin than the right virtual manikin and the reverberation time verified in the left ears are higher than in the right ears.

In accordance with the obtained results the walls absorption and reflection are very important in the calculus. In this work the results show that the lateral and, mainly, the ceiling wall show an important contribute in the reverberation calculus.



a)

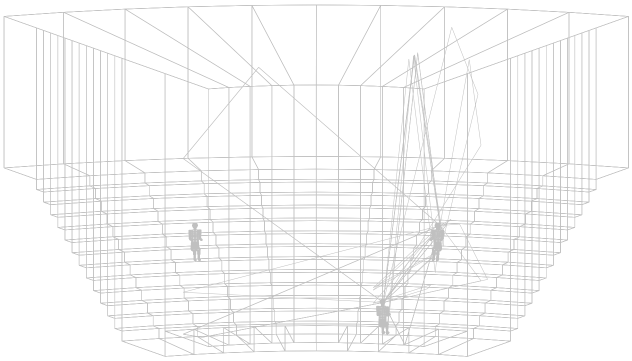
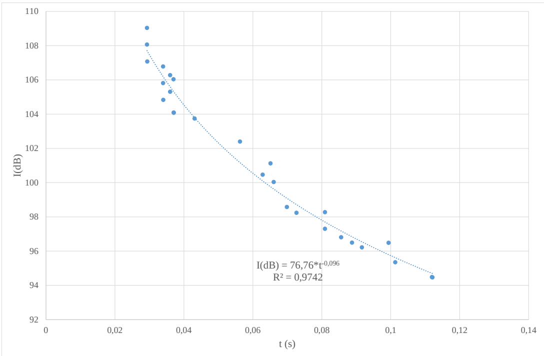

b)

Figure 4 – dB value (a) and acoustic path (b) in the left ear of the manikin seated in the auditorium left side.



a)

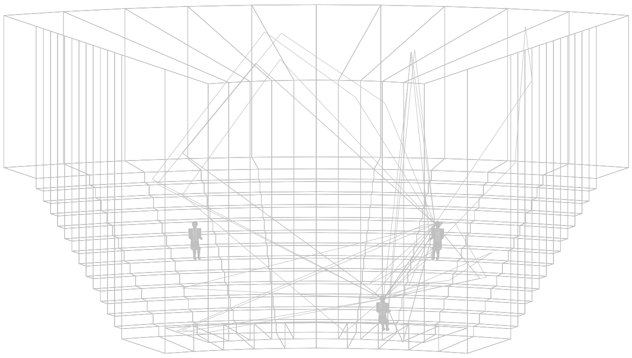
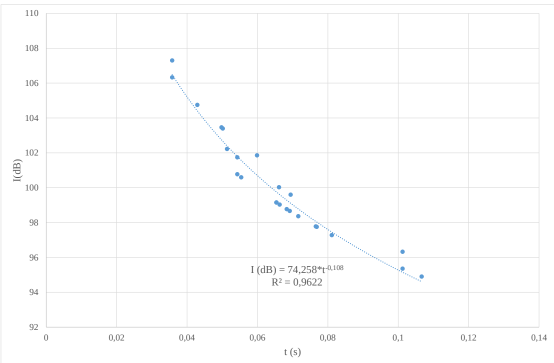

b)

Figure 5 – dB value (a) and acoustic path (b) in the right ear of the manikin seated in the auditorium left side.



a)

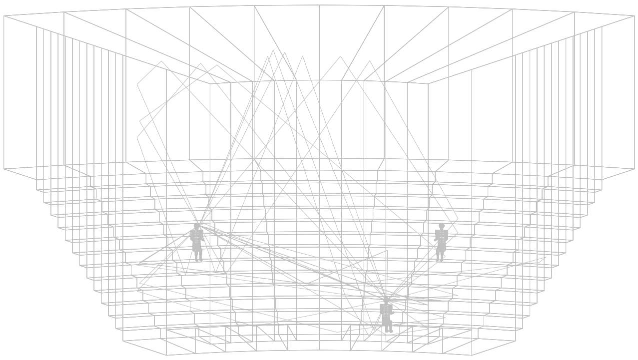
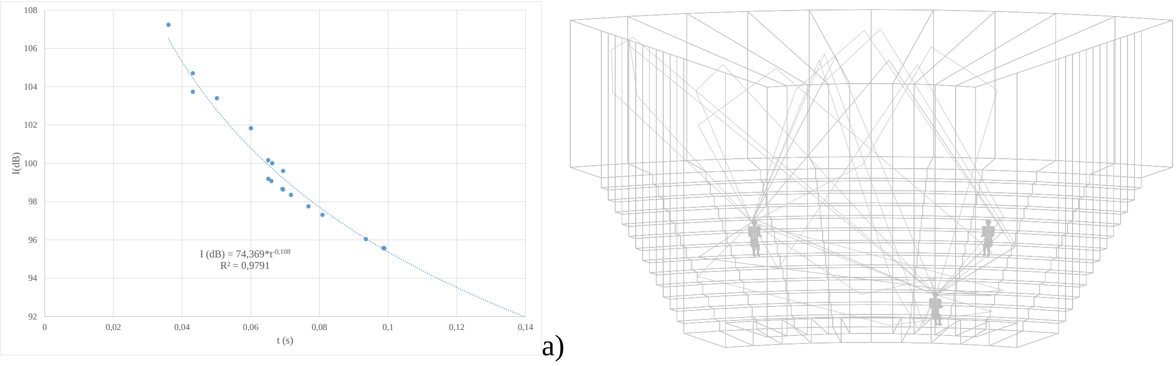

b)

Figure 6 – dB value (a) and acoustic path (b) in the left ear of the manikin seated in the auditorium right side.



a) b)

Figure 7 – dB value (a) and acoustic path (b) in the right ear of the manikin seated in the auditorium right side.

Table 1 – Reverberation time for the two ears manikins.

Location	Equation	Correlation	Reverberation time
Left ear of the manikin seated in the auditorium left side	$I(dB) = 77{,}071*t^{-0{,}094}$	$R^2 =$ 0,9623	0.17624
Right ear of the manikin seated in the auditorium left side	$I(dB) = 76{,}76*t^{-0{,}096}$	$R^2 =$ 0,9742	0.173486
Left ear of the manikin seated in the auditorium right side	$I\ (dB) = 74{,}258*t^{-0{,}108}$	$R^2 =$ 0,9622	0.175484
Right ear of the manikin seated in the auditorium right side	$I\ (dB) = 74{,}369*t^{-0{,}108}$	$R^2 =$ 0,9791	0.175152

In accordance the obtained results the auditory geometric numerical model, developed in this work, is able to develop, using a numerical methodology, occupied auditorium spaces with complex topologies.

In the future this numerical methodology will be used to analyse the influence of the auditory dimension in the reverberation time that the occupants are subjected. The introduction of the fourth and higher reflection will also be considered in the calculus of the reverberation time. The influence of other virtual manikins and the introduction of the upper reflectors panels, to redirect the sound path, will also be analysed.

6 Conclusions

In this work the development of a virtual auditorium occupied with virtual manikins used in thermo-acoustic evaluation is made. In this preliminary study, the Auditory Geometric numerical model is used to develop the space and the manikins. The grid generation is transferred to the thermal-acoustic numerical models in order to evaluate the thermal comfort and reverberation time.
In accordance with the obtained results, the manikins are thermally comfortable and the acoustic path presents slight differences between left and right ear and differences between the two manikins. In accordance with the acoustic path the lateral and, mainly, the ceiling walls reflection show an important contribution in the manikin acoustic level and will be analysed in detail in future works.

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