International Journal of Information, Control and Computer Sciences
ISSN: 2517-9942
Vol:10, No:3, 2016

3D Modelling and Numerical Analysis of Human Inner Ear by Means of Finite Elements Method

C. Castro-Egler, A. Durán-Escalante, A. García-González

***Abstract*—**This paper presents a method to generate a finite element model of the human auditory inner ear system. The geometric model has been realized using 2D images from a virtual model of temporal bones. A point cloud has been gotten manually from those images to construct a whole mesh with hexahedral elements. The main difference with the predecessor models is the spiral shape of the cochlea with its three scales completely defined: scala tympani, scala media and scala vestibuli; which are separate by basilar membrane and Reissner membrane. To validate this model, numerical simulations have been realised with two models: an isolated inner ear and a whole model of human auditory system. Ideal conditions of displacement are applied over the oval window in the isolated Inner Ear model. The whole model is made up of the outer auditory channel, the tympani, the ossicular chain, and the inner ear. The boundary condition for the whole model is 1Pa over the auditory channel entrance. The numerical simulations by FEM have been done using a harmonic analysis with a frequency range between 100-10.000 Hz with an interval of 100Hz. The following results have been carried out: basilar membrane displacement; the scala media pressure according to the cochlea length and the transfer function of the middle ear normalized with the pressure in the tympanic membrane. The basilar membrane displacements and the pressure in the scala media make it possible to validate the response in frequency of the basilar membrane.

***Keywords*—**Finite elements method, human auditory system model, numerical analysis, 3D modelling cochlea.

I. Introduction

THE inner ear is really important for the human being. Lots of routine activities for a *normal life* performance need the use of auditory system. Numerous illnesses and auditory disabilities affect millions of human and the successful of theirs treatments depend on the precision we know the performance of the auditory system. Nowadays, there are still different issues unknown on the ear mechanics.

The state of the art about the human auditory system (HAS) shows how there are still broad fields to be studied, where the mechanical models of the cochlea are built considering the acoustic impedance as an equivalent mechanical impedance of a damped and forced oscillatory system. In [1] is shown a more detailed finite elements model of the inner ear, where is modeled a spiral cochlea with its three cameras and the vestibule. This cochlear model geometry is approximate and its construction takes dimensions and structures published in others papers and it is took into account as an ideal model.

C. Castro-Egler, A. Durán-Escalante and A. García-González are with the Department of Civil Engineering, of Materials and Manufacturing, University of Málaga, Málaga, Spain (e-mail: kcegler@uma.es, antonioduranescalante@gmail.com, tolin@uma.es).

Manual 3D reconstruction of the cochlea was introduced by [2] and additional manual models were subsequently created [3]-[7]. Among these studies, only the study by [5] included tests on a human auditory system. To model a human inner ear with finite elements is needed an accurate geometrical model of its three scales. However, it is difficult to create a faithful geometry of those three scales. In a 3d cochlear reconstruction many 2d images from tomography, magnetic resonances and histologic sections are used. This paper presents a new method to reconstruction of a faithful 3d human inner ear model. The real shape of the different components of the inner ear is got by image processing. So, a realistic finite elements model has been possible to be built this way. To validate this model, basilar membrane displacement and scala media pressure are going to be compared with the results in [8]. The medium ear transfer function, stapes displacement respect to Tympanic membrane pressure, is going to be compared with experimental results. This paper shows the results got for two models: an isolated inner ear and a whole HAS model.

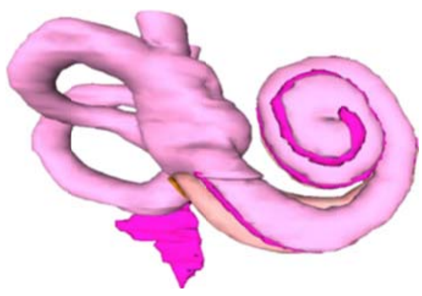
II. Finite Elements Method

The paper *3D Virtual Model of a Human Temporal Bone* by Massachusetts Eye and Ear [9] has been used to create the different subsystems geometry (Figs. 1 and 2), where the 2d morphology of histological sections are related with 3d anatomy of temporal bone. To develop the model, digital images of histological sections and of "structures of interest" segmented anatomical have been used.

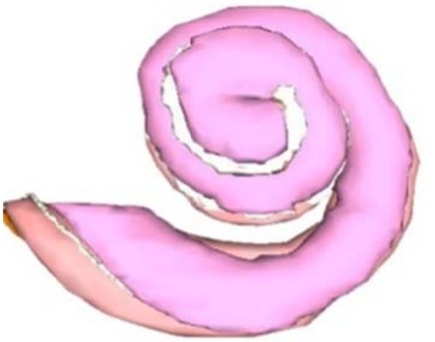
A. Cochlea Geometry

The model part makes up of scala vestibuli (SV), scala tympani (ST), scala media (SM), basilar membrane, Reissner membrane and round window (RW); will be considered as cochlea subsystem (Fig. 1 (b)).

The finite elements model construction of the cochlea is realized from 19 tomography of virtual model, 1mm spaced each other (Fig. 2).



(a)



(b)

Fig. 1 *3D Virtual Model of a Human Temporal Bone* [9]: Cochlea, vestibule and semicircular channels (a); cochlea (b)

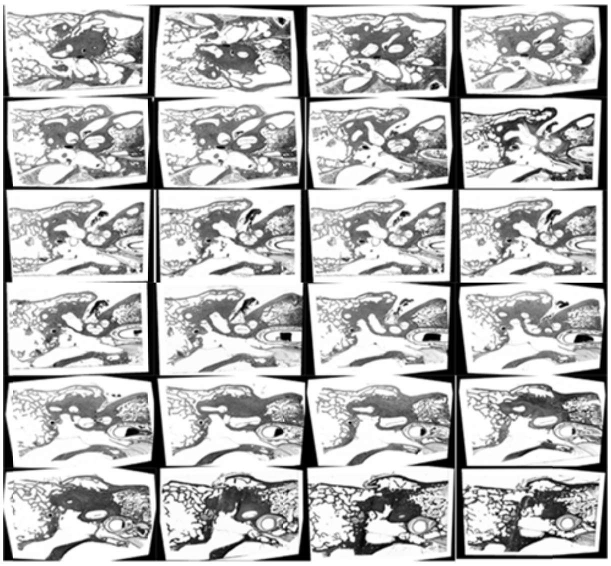
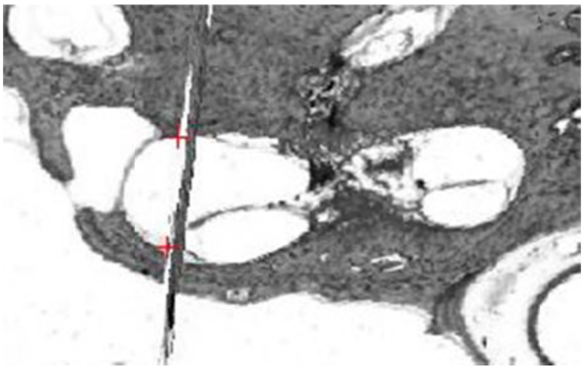
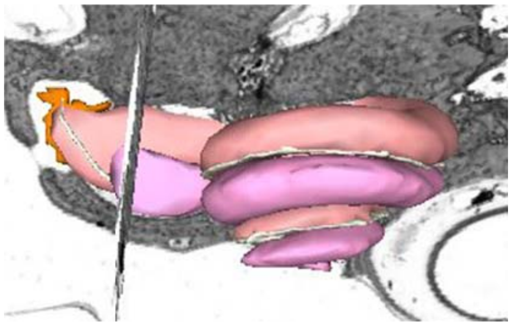


Fig. 2 Tomography got from software 3D Virtual Model of Human Temporal Bone



(a)



(b)

Fig. 3 Obtaining point's process in one section with MATLAB

Firstly, as the images were digital, it has been necessary to use the software MATLAB to get the point cloud which defines the scala vestibuli and scala tympani boundary. This points were exported as (x,y) coordinates into txt file, and then imported to ANSYS. In Fig. 3 is shown the point of one section. However, reproducing the cochlea's spiral shape with those points was not possible. Then, it was required to create some transversal sections along the cochlea. Because of the image information is not sufficient to define its spiral shape, a mesh with hexahedral elements has been developed. The inner and outer cochlea boundaries are defined with the points of the transversal sections to the cochlea trajectory. A set of tomography or maximal and minimal planes parallel to global planes, where is the section to build [X_{max}, X_{min}, Y_{max}, Y_{min}], is determined to get that. With the intersection lines of this set is developed the local plane in each section. Lately, the intersection points of local plane, the virtual model surface or "structure of interest" and the set intermediate planes, are gotten, and these points are imported to ANSYS to create the parameterized dimension of each local plane.

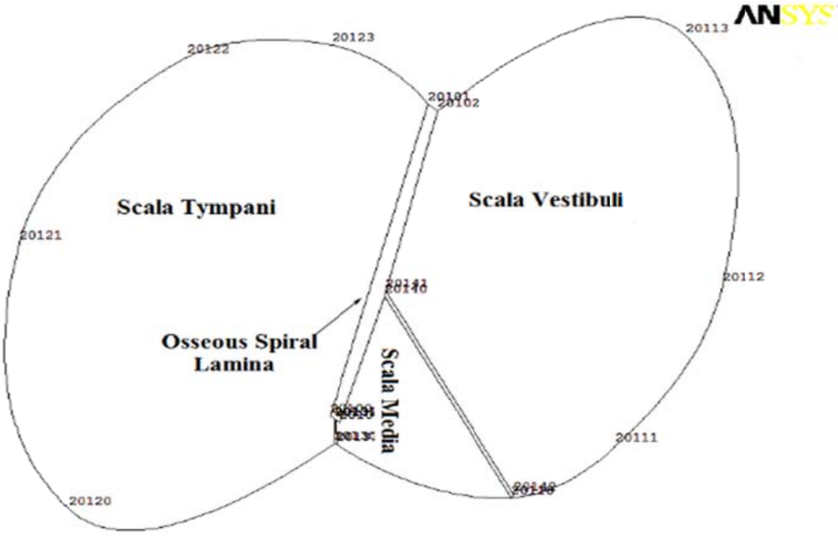
Twenty sections were necessary to define the geometry. Each of these sections shows duct dimensions of the SV, SM and ST. These points are linked with splines in ANSYS (Fig. 4 (a)), and then the 20 sections are acquired (Fig. 4 (b)).

Afterward, the sections were linked each other, developing a spline configuration. The next step was creating surfaces with the splines and after that, volumes with the linking of the surfaces (Fig. 5).

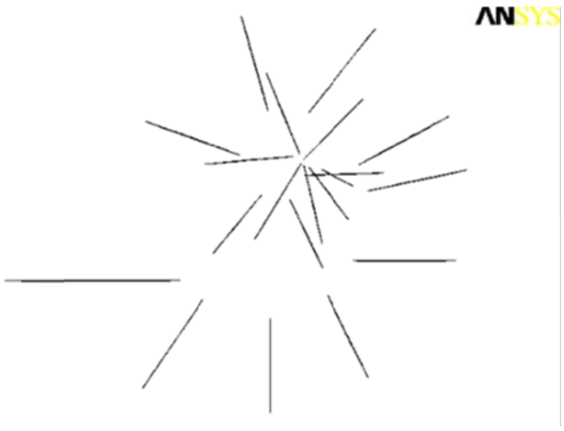
B. Basilar Membrane Geometry

One of the most important goals on this work is the creation of the basilar membrane spiral geometry. Thanks to this membrane, the cochlea can analyze a large frequency range. This membrane divides the scala media and the scala tympani. It is localized on the osseous spiral lamina bottom, which divides the scala tympani from the scala media and scala vestibuli.

The measurement of basilar membrane by means of the images processing with MATLAB had not enough precision for its design. To complete the information, other data have been taken from [10], where the membrane dimensions are exposed (Fig. 6 (a)). The MB modeled is composed by 18 hexahedral volumes, section by section, with a variation in height about 0.1 mm to 0.5 mm from the base to the end and in thickness from 7.5e-3 mm to 2.5e-3 mm. Approximately, it has a curve length of 34 mm (Fig. 6 (b)).

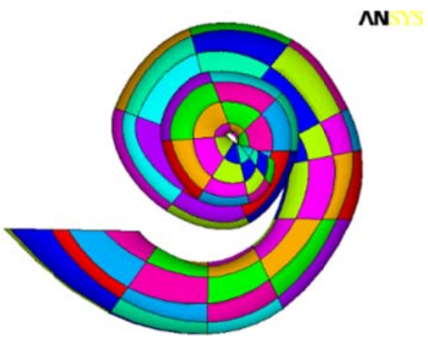


(a)

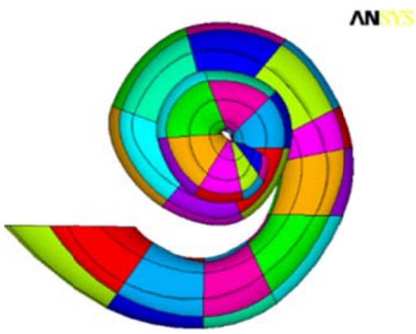


(b)

Fig. 4 Cochlea transversal section in ANSYS (a); 20 cochlea sections in ANSYS (b)



(a)



(b)

Fig. 5 Cochlea surfaces (a); cochlea volumes (b) in ANSYS

C. Reissner Membrane Geometry

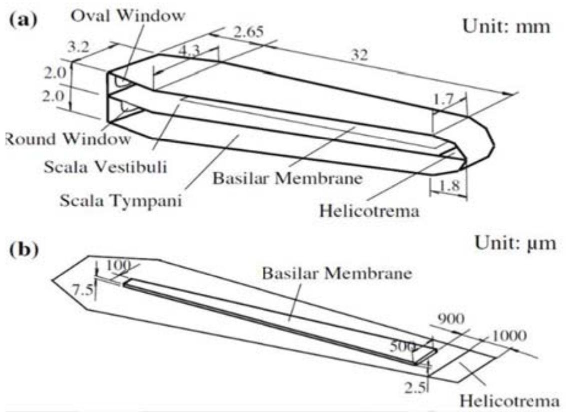
Reissner membrane (RM) divides the scala media from the scala vestibuli. It creates a compartment inside the cochlea plenty of endolymphatic fluid. The geometric construction criterion is the same than the BM. It is made by 18 hexahedral volumes, section by section, with an average width of 1 mm and thickness of 15µm. It is fixed in both extremes by the osseous spiral lamina and the osseous structure that surrounds the cochlea. Approximately, it has a curve length of 34 mm.

D. Helicotrema Geometry

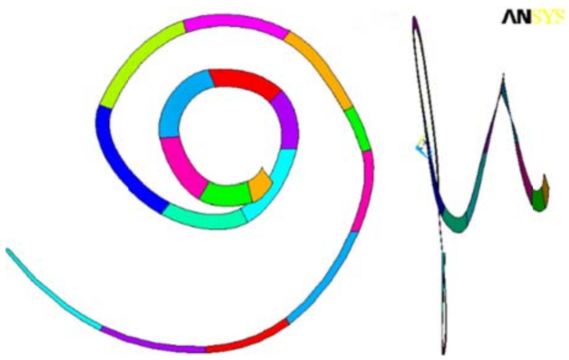
The helicotrema is a cavity situated at cochlea end and connects the scala vestibuli fluid with the scala tympani. Its surface is not seen on tomography, because of this, that parameter is taken from [10] with a value of 1.7 mm^2.

E. Round Window Geometry

The round window is one of the two inner ear openings. It avoids that perilymphatic fluid goes into the inner ear by mean the oval window. It is localized at the beginning of the scala tympani, under the vestibule and does not have direct contact with this last one. It is made as one volume with an average thickness of 40 µm. It has a surface of 2 mm^2, which has been taken from *3D Virtual Model of Human Temporal Bone* images [9].



(a)



(b)

Fig. 6 (a) MB Elongated illustration [9], (b) MB spiral volumes in ANSYS

F. Vestibule Geometry

As the cochlea, the vestibule subsystem geometry has been obtained from the points acquisition of digital images. These points are taken from 16 images cuts with the vestibule "structure of interest". In this case, it only takes into account the boundary (Fig. 7).

With all points obtained and imported to ANSYS, the next step is linking each section points by splines (Fig. 8 (a)). So, 16 sections are generated (Fig. 8 (b)). It will include the sections where the semicircular channels are connected.

G. Oval Window and Annular Ligament of Stapes Geometry

The oval window is the inner ear opening. It is covered by one membrane that is the intersection between inner ear and medium ear. In its periphery is localized annular ligament of stapes. In the model, its geometry is defined as a hexagonal shape, because it is the joining area with stapes in Garcia-González's model [11], [12] which has a hexagonal parallelepiped shape. The oval window is made of a hexahedral volume with a thickness of 100 µm and a surface of about 3.6 mm^2. Annular ligament of stapes encircles the oval window and is made with just one volume 100 µm thick.

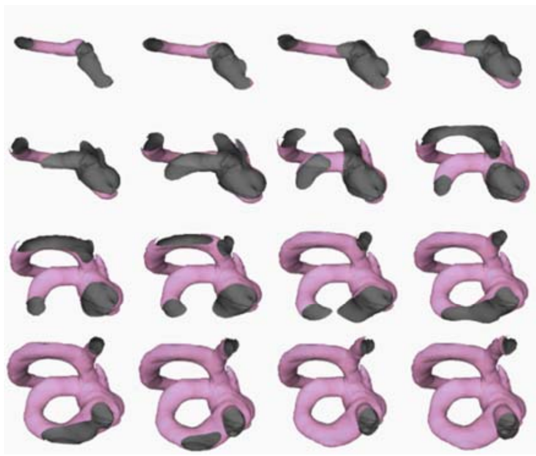


Fig. 7 16 Tomography's cuts form *3D Virtual Model of a Human Temporal Bone* software.

H. Semicircular Channels Geometry

The semicircular channels are the third subsystem in this work. They have been modeled to finish the inner ear geometry. They are developed form sections in the vestibule geometry. For that, the trajectory images of each semicircular channel have been taken, and three transversal and circular sections have been introduced in each trajectory to obtain the beginning sections, which define their geometries.

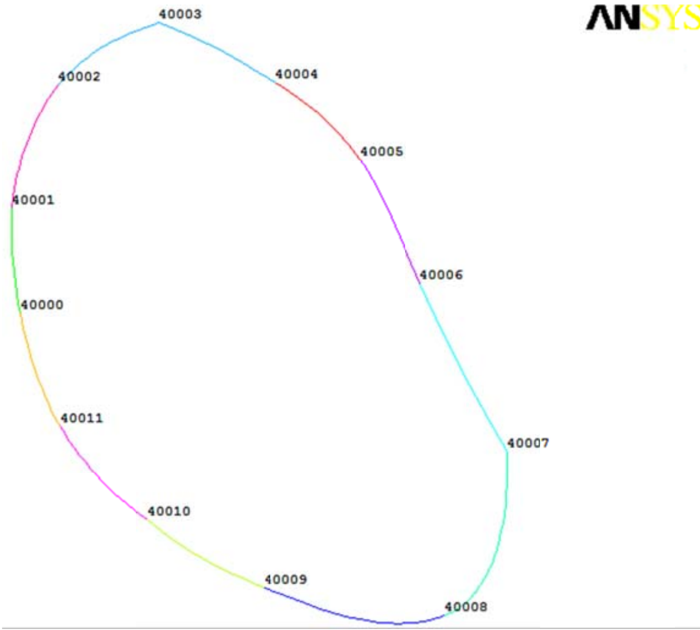
III. Elements and Properties in FEM

In this section, all ANSYS 14.5 elements used and the properties in each element are described.

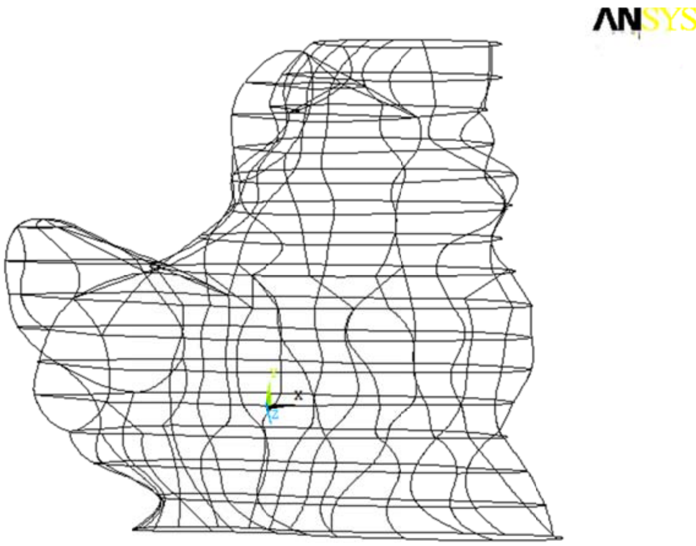
A. Structures: Basilar Membrane, Reissner Membrane and Round and Oval Window

Every membrane has been meshed with hexahedral elements Solid185 in ANSYS 14.5. It uses enhanced strain formulation that avoids the excessive bending stiffness problems specific to these elements.

The basilar membrane is made of 5700 elements, with a size of 30 µm (Fig. 9). The size is limited by membrane geometrics parameters. Then, if the size is reduced, in the base volumes is generated a node group. If the size increases, the elements of the last volumes have a size bigger than the imposed one. ANSYS shows *mesh error* in both cases. BM properties change along its length. Damping coefficient is defined as 0.2 x 10^{-3} s on base and increases linearly to 1 x 10^{-3} sin apex. Young coefficient is 50x10^6 N/m^2 on base, which decrease linearly to 15x10^3 N/m^2 in half, and from that to 3x10^6 N/m^2 in apex. In ANSYS was necessary creating different materials to simulate these properties. Poisson coefficient is fixed as 0.3 and density material as 1x10^3 kg/m^3 [10].



(a)



(b)

Fig. 8 ANSYS images: One vestibule section (a); 16 sections linked by *splines* (b)

B. Fluid: Cochlea, Vestibule, and Semicircular Channels

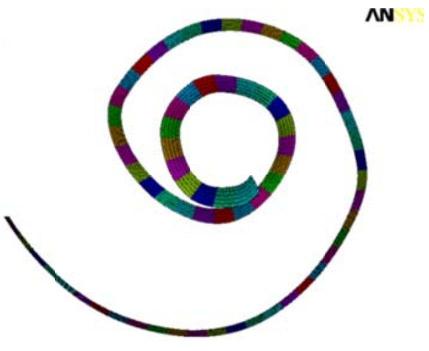
Every cochlea scale, the vestibule, and the semicircular channels have been meshed with the element Fluid30 in ANSYS 14.5. This kind of element is used for modeling the fluid medium and the interface fluid-structure interaction problems. Typical applications include sound wave propagation and submerged structure dynamics. The element is hexahedral, has 8 nodes with four degrees of freedom per node: X, Y, Z displacements and pressure. The starting size is 100 µm. It has been proved numerically the element size could be bigger, because of convergence of the results. Therefore, computational cost can decrease. However, that element size is the appropriate for the suitable transition of elements in the BM mesh size. The mechanical properties are: density 10^3 kg/m^3, sound velocity 1480 m/s and friction coefficient 0.007 [10] (Fig. 10).

IV. Boundary Conditions

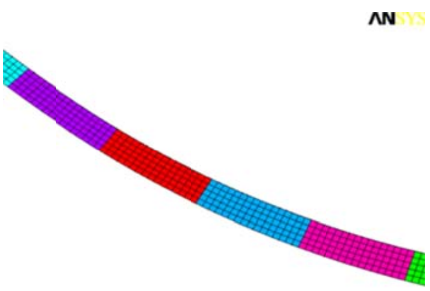
It is necessary define some boundary conditions as realistic as possible in finite elements problems.

A. Cochlea, Vestibule and Semicircular Channels

The external walls of the cochlea, vestibule, and semicircular channels are considered as rigid. For this, all external surface nodes of the volumes are restricted. The bone layer that surrounds those volumes is not modeled, but its effect is modeled as a sound absorption coefficient µ on the channel wall with a value of 0.007. In Fig. 10, this condition is shown as area Fluid-Structure.



(a)



(b)

Fig. 9 Basilar membrane mesh (a); Different materials to basilar membrane (b)

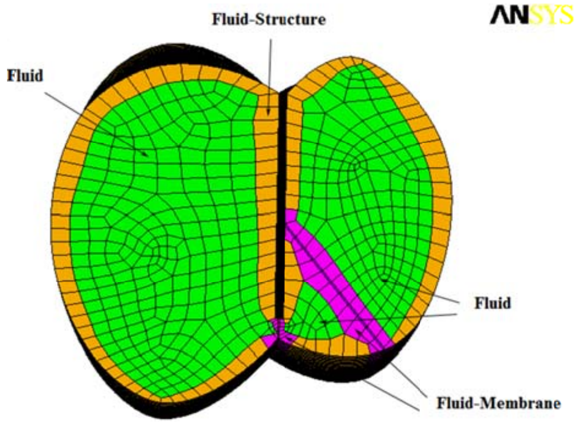


Fig. 10 Detail of cochlea section elements

B. Basilar Membrane and Reissner Membrane

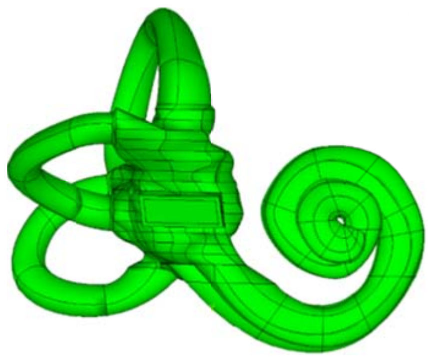
It is considered both of them have two sides in contact with the fluid. In the docking fluid-structure between basilar membrane, scala tympani fluid and scala media is considered a sound absorption coefficient µ of 0.02 (Fig. 10). It is defined the same sound absorption coefficient for the docking between Reissner membrane, scala vestibuli fluid and scala media.

C. Round Window and Oval Window

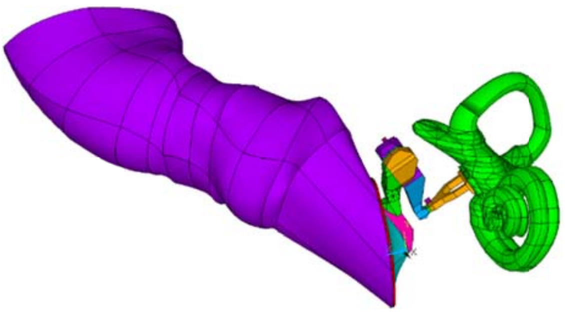
Oval window and round window have one of their sides in contact with fluid. In the docking between round window and scala tympani fluid is considered a sound absorption coefficient of 0.02. This value is the same to RW surface in contact with vestibule fluid. In the specific case of RW are considered the displacements completely restricted in the external frame.

V. Combination of Finite Elements Models

Two different combinations have been made. One simpler model of the isolated inner ear sets up of cochlea, vestibule, and semicircular channels subsystems (Fig. 11 (a)). The second model is more complex, where is included the external auditory channel, tympanic membrane and ossicular chain modeled in [11], [12] (Fig 11 (b)).



(a)

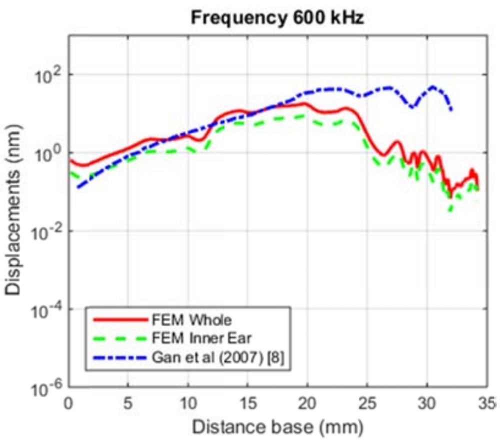


(b)

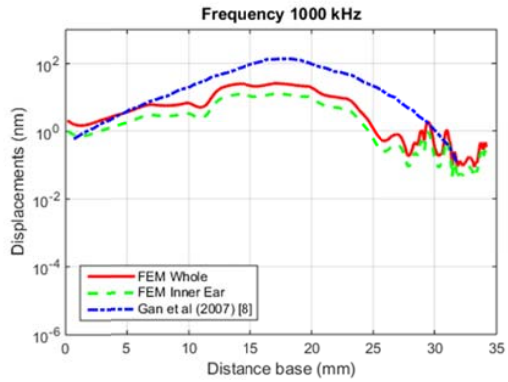
Fig. 11 Finite Elements Models of Cochlea, vestibule and semicircular channels (a); Complex Finite Elements Model: EAC, tympanic membrane, ossicular chain and inner ear (b)

VI. Results

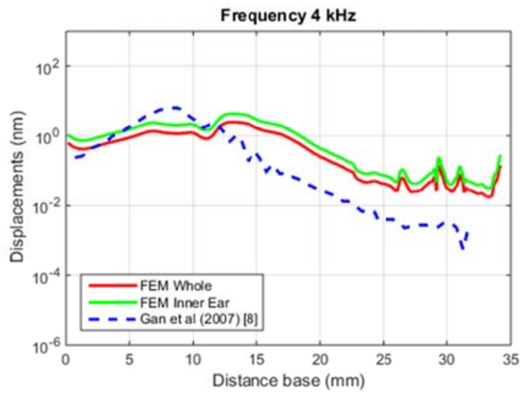
Numerous numerical simulations have been realised using Finite Elements Method (FEM) to validate the developed models. The Numerical Analyses were generated with two models: an isolated inner ear and a whole model of human auditory system. Ideal conditions of displacement are applied over the oval window in the isolated Inner Ear model. The whole model is made up of the outer auditory channel, the tympani, the ossicular chain, and the inner ear. The boundary condition for the whole model is 1Pa over the entrance to the outer auditory channel. The numerical simulations by FEM have been done using a harmonic analysis with a frequency range between 100-10.000 Hz with an interval of 100Hz.



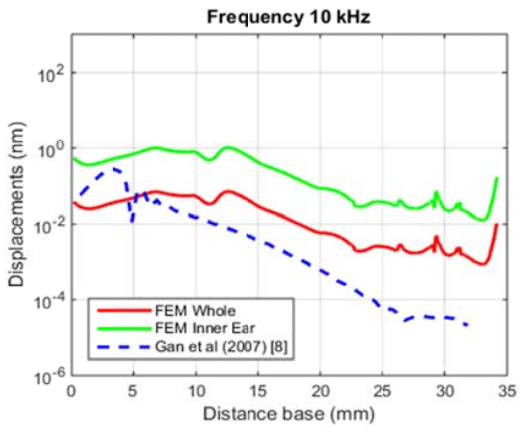
(a)



(b)



(c)



(d)

Fig. 12 Frequency response of basilar membrane absolute displacements. magnitude comparison of two FEM inner ear with Gan [8]; 600 Hz(a); 1000 Hz (b); 4 kHz (c); 10 kHz (d)

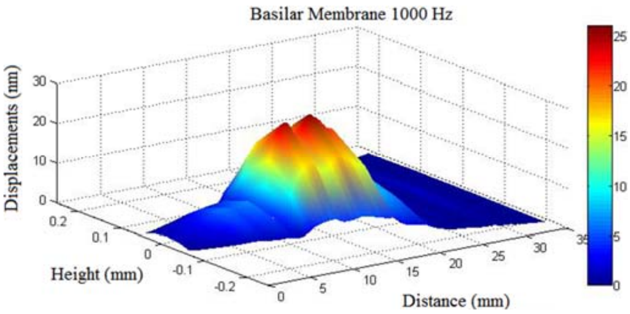


Fig. 13 Plotted on Matlab of whole 3D model, displacement, thickness, and membrane length at 1000 Hz

The results that have been carrying out are:

- Basilar membrane displacements.
- Scala media pressures depending of cochlea length.
- Normalized transfer functions of middle ear with tympanic membrane pressure.

Basilar membrane displacements and scala media pressures are plotted as a function of cochlea length and results of three models are shown: whole FEM, FEM isolated inner ear and Gan's numerical test [8].These have been calculated and plotted along its length obtaining continuity in their results. The post-processed in ANSYS acquires an absolute control of the 8 nodes each element is made to get the relevant results for this study. In Figs. 12 and 14 are plotted the 8 nodes mean of each element, this is the mean behavior of the element.

A. Basilar Membrane Displacements

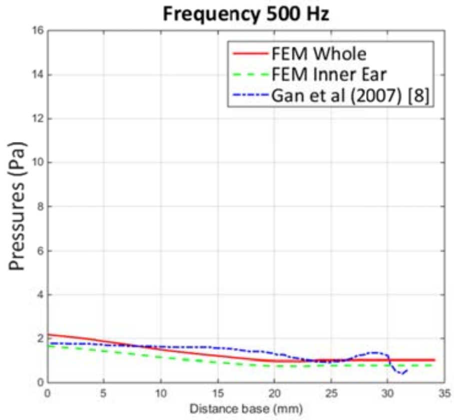
Fig. 12 shows the graphics of basilar membrane displacements in function of its distance to base. It shows as the maximum displacement of basilar membrane goes on from the end of cochlea (low frequencies) to the base (high frequencies). This behavior validates the basilar membrane model with the results and the attained observations [13].The area with the greatest basilar membrane displacement depends on the excitation frequency of the system, which has direct connection with the audible frequencies [13]. It is observed according to frequency increases, the maximum displacement of basilar membrane appears in an area closer to the base (Figs. 12 and 13). There are some differences in the values obtained for whole FEM and inner ear FEM, this discrepancy is due to a stapes turn. This fact produces that the displacement of every point on the foot plate in the isolated model is different to displacement of every point on stapes in whole model test. For all that, it is logic thinking the pressure magnitudes in the cochlea fluid are diverse. Moreover, there are differences in shape and result magnitude between our FEM and Gan's model [8]. It can be for two reasons:

- Different elements on the fluid mesh surround the cochlea.
- Different modeled elements in the two FEM of inner ear.

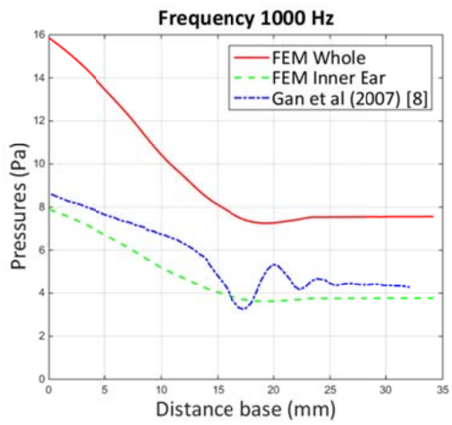
It has been made the 3D plotting of basilar membrane move to see clearly its behavior and the displacements peaks (Fig. 13).

B. Scala Media Pressures in Function to Cochlea Length

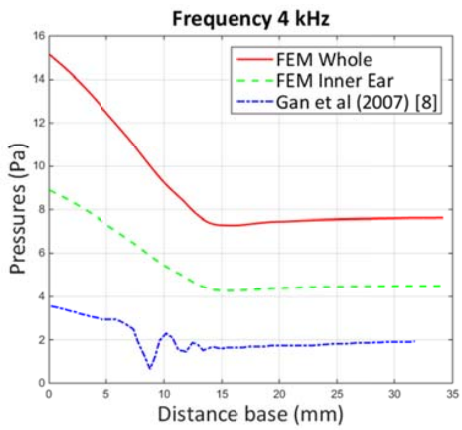
In Fig. 14, scala media pressures are plotted against cochlea length. The fluid pressures are obtained from scala media fluid in contact with basilar membrane. The fluid pressures change from base to end in response to different frequencies. The pressure amplitude decreases to move away from the base (Fig. 14).



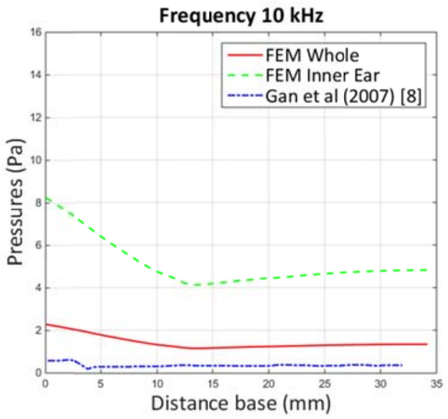
(a)



(b)



(c)



(d)

Fig. 14 Absolute pressures in function of basilar membrane length; 500 Hz (a); 1000 Hz (b); 4 kHz (c); 10 kHz (d)

C. Transfer Functions of Stapes and Umbo Regarding the Tympanic Membrane Pressure

In this paper, is presented the Transfer Functions of stapes and umbo because it has been considered as representative of the effects produces by the fitting together inner ear with the other subsystems. Its localization is shown in Fig. 15.

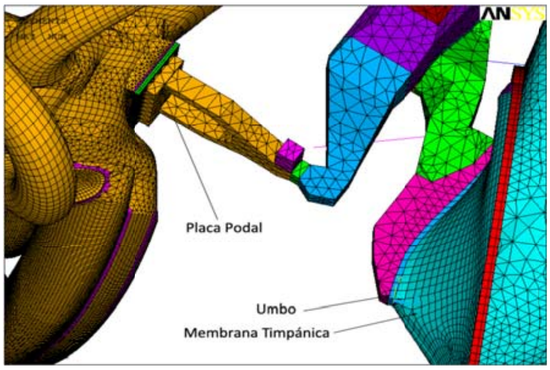
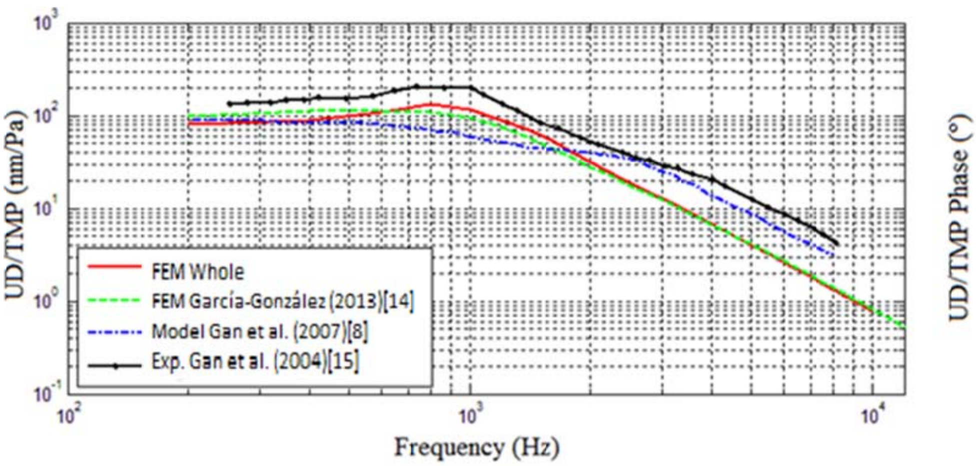


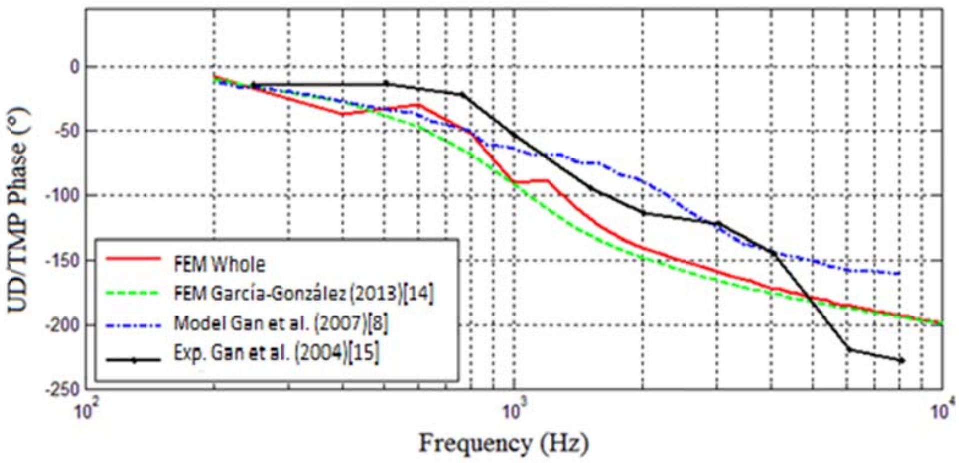
Fig. 15 Umbo, foot plate and tympanic membrane localization

- *Transfer Function Results of Umbo Displacement Versus Tympanic Membrane Pressure (UD/TMP):*

In Fig. 16 (a) is shown a comparative of experimental with FEM results. There is a good correlation between numerical results [8], [14] and experimental [15], both in form and in the peak frequency response, about 700-1000 Hz. In Fig. 16 (b) is shown a comparative of phase, where it can be seen a response valley around of 400 Hz. Here, the whole FEM predicts a lower response than the results in [8], [14], [15]. In frequency range of 500 to 1000 Hz, the model predictions are situated between experimental results [15] and numerical results [8], [14]. If it is compared with a simplify cochlea FEM [8], these results are more approximated in this frequency rank. In range from 1000 to 10000 Hz, the phase is practically equal to numerical model [14].



(a)



(b)

Fig. 16 Normalized umbo displacement with Tympanic membrane pressure (UD/TMP); comparison with magnitude results in [8], [14], [15] (a); comparison with phase magnitude of numerical and experimental results (b)

-Transfer Function Results of Foot Plate Displacement versus Tympanic Membrane Pressure (FPD/TMP):

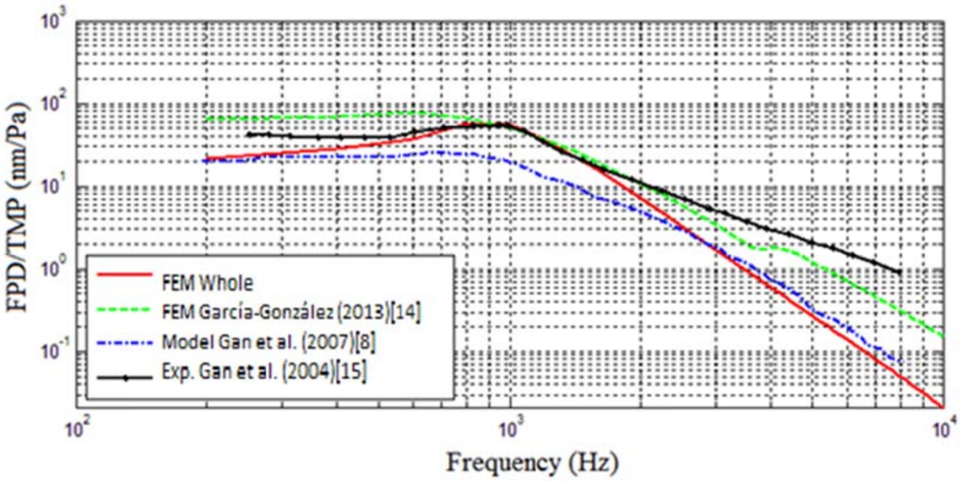
Fig. 8 (a) shows an influence area with the maximum in 1000 Hz, where FEM results move away from numerical model [8] to converge to experimental results [15]; the opposite occurs if frequencies increase. In Fig. 8 (b) is observed one pure resonance in the frequency rank 100-500 Hz in FEM whole and experimental model from [15]. In its final phase, from 3000 to 10000 Hz, it is observed a constant phase lag with a value of 250º. The foot plate is one of the deepest areas into the small inner ear. For this, it is possible data obtained in experimental test are not absolute precision. Because of this, the results in this work are into expected range.

VII. Conclusion

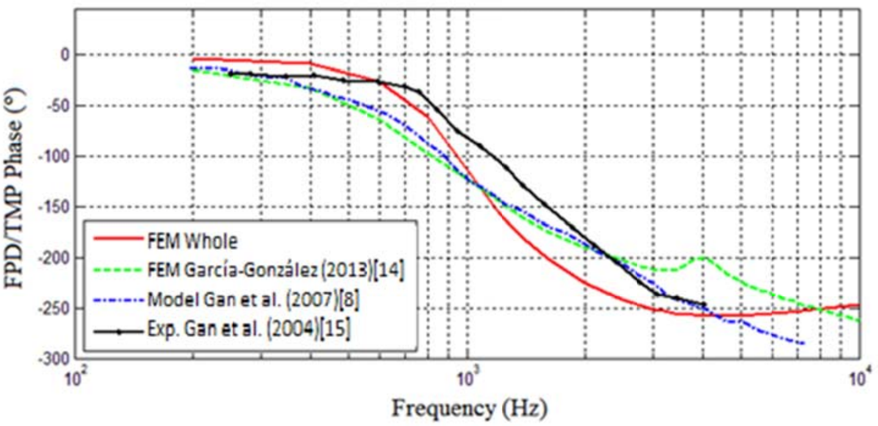
A full model of inner ear has been developed. The model fulfills the displacement conditions of basilar membrane specified in the bibliography. The maximums are moved along the membrane from the base to the end when frequency decreases from 10 kHz to 400 Hz. Basilar membrane response to stimulus is very realistic, because the model has the three cavities: scala vestibuli, scala media and scala tympani.

Secondly, the effects produces by model over outer and middle ear are in agreement with the acceptable ranges.

Finally, the main conclusion is, in both models, whole and isolated model, even if the central point displacement of Foot Plate have the same magnitude, pressures in the inner of the cochlea are not equal.



(a)



(b)

Fig. 17 Normalized Foot Plate displacement with Tympanic membrane pressure (FTD/TMP); Comparison with magnitude results in [8], [14], [15] (a); Comparison with phase magnitude of numerical and experimental results (b)

REFERENCES

[1] R. Z. Gan, X. Zhang, X. Guan. Modeling Analysis of Biomechanical changes of Middle Ear and Cochlea in Otitis Media. Aip Conference Proceedings. American Institute of Physics, 1403, (2011), pp. 539-546.

[2] Voie AH, Spelman FA. 1995. Three-dimensional reconstruction of the cochlea from two-dimensional images of optical sections. Computerized medical imaging and graphics.19:377-384.

[3] Ghiz AF, Salt AN, DeMott JE, Henson MM, Henson Jr OW, Gewalt SL. 2001. Quantitative anatomy of the round window and cochlear aqueduct in guinea pigs. Hearing research.162:105-112.

[4] Hofman R, Segenhout J, Wit H. 2009. Three-dimensional reconstruction of the pigeon inner ear. Journal of Vestibular Research.19:21-26.

[5] Li S-F, Zhang T-Y, Wang Z-M. 2006. An approach for precise three-dimensional modeling of the human inner ear. ORL.68:302-310.

[6] Liu B, Gao XL, Yin HX, Luo SQ, Lu J. 2007. A detailed 3D model of the guinea pig cochlea. Brain Structure and Function.212:223-230.

[7] Wada H, Sugawara M, Kobayashi T, Hozawa K, Takasaka T. 1998. Measurement of guinea pig basilar membrane using computer-aided three-dimensional reconstruction system. Hearing research.120:1-6.

[8] R.Gan, B. Reeves, X. Wang. Modeling of sound transmission from ear canal to cochlea. Annals of Biomedical Engineering. (2007) 35, pp. 2180-2195.

[9] Wang X, Wang L, Zhou J, Hu Y. 2014. Finite element modelling of human auditory periphery including a feed-forward amplification of the cochlea. Computer methods in biomechanics and biomedical engineering.17:1096-1107.

[10] R. Gan, B. Reeves, X. Wang. Modeling of sound transmission from ear canal to cochlea. Annals of Biomedical Engineering, 35 (2007), 2180-2195.

[11] B. J.L. Flores Espejo, A. Durán Escalante, A. García González. Análisis Numérico del Oído Interno Humano con el Método de los Elementos Finitos. XX Congreso Nacional de Ingeniería Mecánica, Málaga, España, (2014).

[12] A. Garcia-Gonzalez, A. Gonzalez-Herrera. Effect of the middle ear cavity on the response of the human auditory system. The Journal of the Acoustical Society of America, 133:5, 3544-2103.

[13] Von Békésy, Georg. Experiments in hearing. Ed. Ernest Glen Wever. (8) (1960).

[14] García-González, Antonio Luis. Análisis numérico de la influencia de la cavidad timpánica en el sistema auditivo humano. Málaga, (2013)

[15] Gan, R., Reeves, B., Wang, X. Three-Dimensional Finite Element Modelling of Human Ear for Sound Transmission. Annals of Biomedical Engineering. (2004), 32, 847-859.