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A new spice-like modeling tool for bio- and electro-acoustic systems including thermoviscous effects

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This article illustrates how the fields of acoustics and hearing can benefit from advanced modeling techniques and new simulation tools. A specific toolbox has been developed in a microelectronics-oriented simulation package to better model the middle ear of humans and animals. The human middle ear model of Puria 2008 is used to validate this technique with respect to calculations runned under general purpose mathematical tools. Influence of parameters is viewed in quasi real time enabling model fitting in both time and frequency domains. In 2007 Reeve et al. designed an analog circuit based on Michelsen 1994. Two major simplifications (no thermoviscous effects and no role of a medial septum in-between transverse acoustic tracheae) have been applied. Thanks to weak couplings this model can be subdivided into independent elements such as tubes, cavities or membranes simply connected together. Thermoviscous effects and the role of the septum can now be better investigated and our model reveals interesting feature compared to its historical counterpart.

1 Introduction

The analogy between acoustical or mechanical and electrical systems allows one to define local and distributed parameter equivalent electrical circuits. Such simplified circuits have been widely used to separately model most of the parts of most of known hearing organs: propagation in external media (air and bone conduction as well as signals issued from the vocal organ), external ear where vibro-acoustical phenomena can be better described if thermo-viscous effects are included [1], middle ear and vestibule where couplings can occur, cochlea and neurons where the significant audio information is finally coded into brain-friendly trains of spikes (although complex to our mind).

Beyond the choice of the best description of the physics that drive the behavior of a huge number of anatomical elements, trying to model a whole auditory organ implies to develop a computationally powerful simulation platform including a user-friendly post-processing tool.

1.2 Paper organisation

We first introduce a new dedicated toolbox [2] used here to solve in both time and frequency domains the electro- acoustico- mechanical equations of some bio-acoustic models of a few well-known hearing organs.

In a second part we check the validity of the toolbox through the matching against the results obtained with general-purpose mathematical tools [21] on the model of the human middle ear of O'Connor and Puria [3]. We then discuss the path opened in calculating transient responses.

The level of complexity of a whole auditory system is so high that it is worth studying also less complex systems such as the organs of insects which perform very well when locating certain type of sound sources. In a third part we thus solve the model of the anatomically less complex middle ear of crickets. Thermoviscous effects and vibro-acoustic couplings should not be neglected and some complex equations with frequency dependent coefficients have to be solved thus introducing another interesting level of complexity. Again the toolbox is checked against reference results in the simplest case of a rigid-wall narrow tube then new results are shown based on a known model of the cricket's ear [4].

Finally we draw some perspectives about the toolbox and the joint study of human and animals hearing systems.

2 An optimized acoustic toolbox

It is a common approach for scientists to strip a complex system into sub blocks and study each of those blocks separately in a divide and conquer approach. One point in modeling each of the sub-blocks, is to be able to simulate the full system in order to understand how the different parts of the system interact with each other.

Models can be of very different nature. They can be continuous or discrete time. They can involve digital or analog. They can be defined by equations or a set of experimental points. However an electrical analogy can most of the time – and with no limitation – be found, thus giving access to powerful electronic simulators. Moreover, even very complex models including non-linearity or noise can be built from a limited set of less than a hundred primitives.

This work is based on the use of a software package [2] dedicated to behavioural model simulations of analogue systems such as Radio Frequency circuits, gyrometers or image sensors. This specific package was chosen to address acoustic simulations because of its ability to simulate quickly - yet keeping full analog precision – complex systems including any combination of the following:

- High quality factor devices (up to over 100 000) such as a quartz resonator.
- Repeated patterns (up to 10 000 000) such as pixels in an imager circuit.
- Very different orders of magnitude of time constants (long observation time coupled to high frequency phenomena) as in Radio Frequency circuits or mixed signal circuits.

Moreover for the integration into existing environments and legacy reuse, it can be used in conjunction with other simulators through an Application Programming Interface.

Unlike most Spice like simulators, the calculations do not require any simulation related inputs such as tolerance or minimal simulation step.

It is based on Schematic capture (it comes with libraries of primitives that can be used to build the system model in a hierarchical way) and does not require any Description Language.

For the purpose of modeling a whole biological organ such as the auditory system, the library of primitives was enriched with specific transformers, analogue delay lines, and Bessel functions.

3 Modeling the human middle ear

The literature is fed with equivalent circuits that can be relevant electrical sub-blocks contribution to model the behaviour of an either human or animal hearing system.

Outdoor propagation can be simulated in the time domain using the Transmission Line Matrix (TLM) method [5] which might become useful to analyse binaural hearing in more details.

Among existing outer ear models [1] some can readily be implemented and solved with the new toolbox. Unexpectedly the modeling of the middle ear systems for both humans and animals appeared to be a still open subject as discussed in this paper especially in the time domain.

3.2 About a feedback from cochlea

When modeling the human middle ear a still hot topic is the physics that prevail in the tympanic membrane as will be discussed later but recently the attempt of one author [6] to introduce the feedback of the cochlea in the simulation of the middle ear led to an unexpected result. The model of reference is shown in Fig. (1)

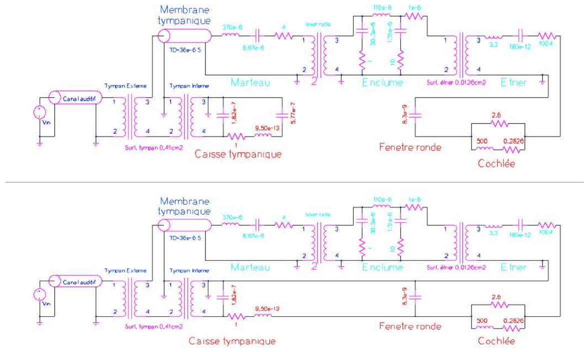

Figure 1: Model of the middle ear chosen in a first attempt to introduce the effect of the feedback of the cochlea on the middle ear behaviour (upper part) and (lower part) the closed loop configuration.

No relevant difference has been found in the simulated behaviour. The model has historically been designed in a sequential view point (from outer to inner) with associated parameters chosen according to the capability to extract values from datas and thus it is inherently "open-loop".

3.3 Method validation, reference model

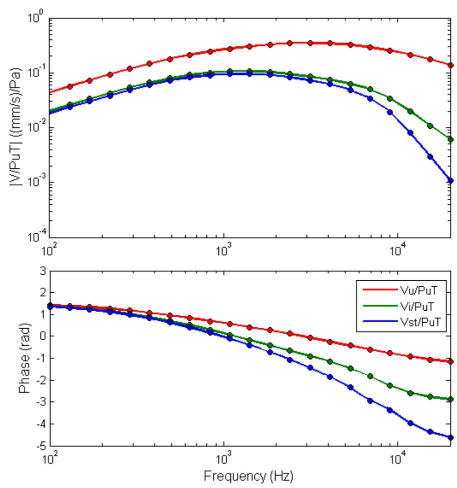

Figure 2: Velocity (V) per unit pressure applied at the tympanic membrane (PuT) (Vu: velocity at umbo, Vi: incus, Vst: stapes). The reference model (lines) is matched perfectly by the implemented toolbox (points).

For the purpose of a future introduction of the influence of the inner ear on the middle ear that would help designing hearing aids and implants the interest arose of using new modeling techniques and a simulation tool developed for microelectronics.

However, it is mandatory to check the validity of the simulation technique itself. This is shown in Fig.(2) with the help of a human middle ear model (see reference [3]) and comparing the simulated results with respect to results from a general purpose mathematical tool [21].

The model [3] used here merely differs from the one used to introduce the feedback [6]: the parameter values have been re-extracted based on statistical measurement done on 16 temporal bones to better fit the speed of the ossicles and of the pressure measured in the outer and middle ear.

To let such a model become compatible with a closed-loop behaviour the question of the values of parameters is raised again. The developed toolbox will be useful as explained in the next part. A complementary method is to extract values from FEM simulation which might be the only relevant method for what concerns the tympanic membrane (TM). A recent review of the TM studied by FEM is found in [7].

3.4 Parameter scrollbars help extracting best fitting values

Daniel Pennac once wrote "the list of parameters, it is the agony of hope". The modeling of biological systems is handicapped by a low access to the right values of reliable parameters since they are hard or impossible to be extracted from measurement procedures. As a consequence models are more conservative in these fields. Moreover the values extracted from experiment might not be so representative of a healthy person or animal since available procedures are often applied post-mortem or after anesthesia where any kind of brain feedback is at least reduced or suppressed.

Parameter extraction with conventional techniques do not benefit from a unique property developed within an efficient post-processing tool [2] and based on the fact that the CPU time is so reduced (thanks to the preliminary high level description of blocs in a library) that the effects of parameter variation on the global response can be directly observed, in quasi real time. It is thus rather easy to define the major parameters and focus on their contribution within a certain range instead of using a predetermined value.

3.5 About propagation delays versus "wave-like" modal effects

It is worth noting here that the modeling of the tympanic membrane itself is still a hot topic whether it is represented in a lumped or in a wave model. Some models like [3] increase the frequency range of validity by introducing transmission lines. Another approach (for example [8]) will consider that modal effects occur whose characteristics are comparable to a propagation of waves without being so. A recent study [9] brings interesting experimental results.

4 Middle ear of small animals

4.2 Solving thermo-viscous equations

In the new toolbox some additional functions used in acoustics such as trigonometric and Bessel functions with complex argument have been added.

The complex impedance can thus be modelled by resistance (real part) and inductance (imaginary part). Frequency dependent parameters are calculated using known frequency of the harmonic source at the input of the circuit. In case of more complex input signal many harmonic sources can be used -their amplitudes and phases being deduced from known complex spectrum of the signal.

The method shall be fully implemented although in our beta-version a script has been written to drive the loop in which the parameter values of the source (frequency, phase and amplitude) were automatically changed as well as the values of the frequency dependent coefficients.

The time domain output signal is then the sum of the output signals of the circuit calculated at each frequency.

4.3 Case of a narrow and closed tube

The simplest geometrical case of a narrow tube (with the radius R and length l) closed at the end has been chosen. Analytical expression of the acoustic field inside the tube can be found in many textbooks (see for example [10]). Improved analytical models of small acoustic ducts (tubes and slits) which accurately accounts for both viscous and thermal losses have been published recently [12].

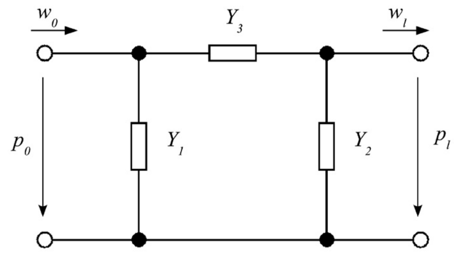

Figure 3: Acoustic equivalent circuit in the form of Π.

The solutions of the linearised version (small harmonic acoustic perturbations are considered) of the Navier-Stokes equation and the Fourier equation for heat conduction under several approximations (quasi-plane wave approximation, radial component of the particle velocity negligible against its axial component, derivatives with respect to axial coordinate of both particle velocity and temperature variation negligible against their derivatives with respect to radial coordinate) give the particle velocity and temperature variation profiles across the tube. Introducing mean values of these profiles into the conservation of mass equation leads to the wave equation for the acoustic pressure in the tube with complex wave-number. The solution of this equation (constants of integration are obtained introducing the volume velocity at the input w_0 and at the output w_l of the tube) can be used to express the acoustic pressure at the input p_0 and at the output p_l of the tube.

Comparison of these expressions with equations describing the equivalent circuit presented in fig. (3) (see [11]) yields the acoustic admittances

$$Y_1 = Y_2 = \frac{j\left(1-K_v\right)}{\omega\rho_0}\pi R^2 k_z \tan\frac{k_z l}{2} \tag{1}$$

and

$$Y_3 = \frac{1-K_v}{j\omega\rho_0}\pi R^2 k_z \frac{1}{\sin k_z l} \tag{2}$$

where the complex wavenumber k_z is given by

$$k_z{}^2 = k_0{}^2 \frac{1+\left(\gamma-1\right)K_h}{1-K_v}, \Re\left(k_z\right)>0 \ and\ \Im\left(k_z\right)<0 \tag{3}$$

where the frequency dependent complex functions involving the thermal and viscous boundary layer effects are

$$K_{h,v} = \frac{2}{k_{h,v}R}\frac{J_1\left(k_{h,v}R\right)}{J_0\left(k_{h,v}R\right)} \tag{4}$$

$J_n(z)$ being the n-th order cylindrical Bessel function of the first kind with the complex argument z and $k_{h,v}$ being the thermal and viscous diffusion complex wave-numbers (see [10] and [12] for details), $k_0 = \omega/c_0$ is the adiabatic wave-number, c_0 is the adiabatic speed of sound, ω is the angular frequency, ρ_0 is the air density and γ is the specific heat ratio. Note that $w_l = 0$ in case of the tube closed at the end.

4.4 Validation of a narrow tube in the time domain versus Matlab results

Using [21] the classic transfer function of the equivalent circuit H(ω) = Y3 / (Y1 + Y3) (see fig. (4)) is calculated and the impulse response h(t) of the circuit is obtained using inverse Fourier transform of the conjugate-symmetric version of the transfer function.

The convolution of the impulse response with the input signal $p_0(t)$ gives the output signal $p_l(t)$ at the end of the closed tube.

Dimensions of the tube are R = 120 μm and l = 10 mm which are close to the one of acoustic tracheae in insects. Sampling frequency is f_s = 1 MHz. Calculation are validated in time-domain (see fig. (5)).

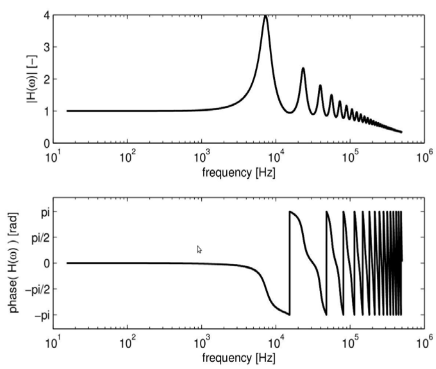

Figure 4: Transfer function of the closed narrow tube (l = 10mm and R = 120 μm)

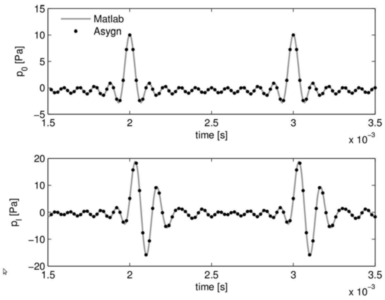

Figure 5: Pressure signals at the input (upper panel) and at the output (lower panel) of the closed tube solved by [21] (gray line) and [2] (black points).

4.5 About pressure difference receivers

Crickets have tympanal ears on their forelegs just below the knees. As shown in Fig. (6) a network of tracheal tubes link them with two other acoustic entrances that are ended by a conical-shaped anatomical component named a spiracle (named Sp.1 and Sp.2). In some species they are always opened but in other ones the outer dimension can be varied. The insect can sometimes open and close them dynamically according to species.

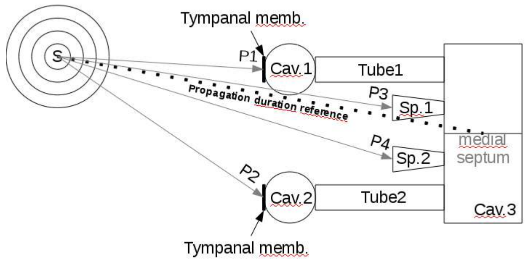

Figure 6: In some insect species such as crickets the tympanal part of the ears are found in forelegs. Coupling means between both ears are seen anatomically. The difference in pathways between the source and the four acoustic entrance are calculated for spherical waves (point source) with respect to an in the body reference distance.

A medial septum is found in the middle of what can be modeled either by a central cavity or by a transverse tube. In 1994 some experiments [13] have demonstrated a role of the medial septum in the directional capability of crickets but the hearing system is usually modeled as a simple pressure difference receiver.

4.6 Middle ear model of the cricket

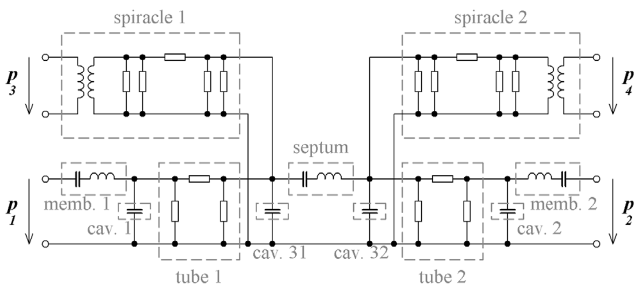

Figure 7: Lumped parameter model of the middle ear of a cricket. The central cavity is divided into two parts with a standard model of the medial septum.

The reference lumped parameter model of the middle ear of the hearing system of a cricket is shown in Fig. (7). The central cavity is divided into two parts with a standard modeling of the medial septum. Datas are taken from [14].

In [14] the parameter values of the septum are chosen so that it introduces no specific role in order to prevent from a resonance to occur that would not be representative of the known biological system.

Our modified model introduces thermo-viscous effects which can not be neglected in long narrow tubes (soft-wall effects will be presented elsewhere). We have also described the conical shape of the spiracles (method to be detailed elsewhere). Finally we added the basic information needed to take into account the Interaural Time Difference (ITD) effect namely the difference in propagation time that exists between a distant point source (spherical wave approximation) and each one of the four acoustic entrance ports according to a reference port located at the medial septum. We thus calculate the pressure in left and right tympanal cavities with no role given to the medial septum.

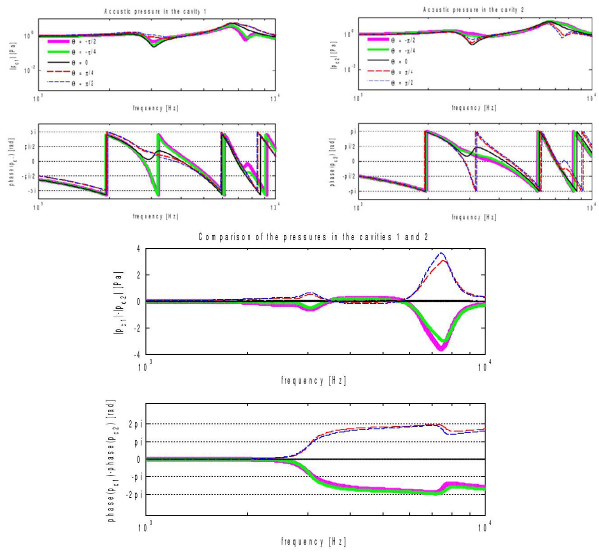

Figure 8: Pressure (amplitude, phase) in tympanal cavities 1 (upper left) and 2 (upper right) as a function of the location of the source (see Fig. (7)). The two signals are then compared (bottom). The parameter angles are 0 (black) $\pi/4$ (green) $-\pi/4$ (red) $\pi/2$ (pink) $-\pi/2$ (blue)

Pressure in tympanal cavities 1 (left) and 2 (right) are compared in Fig. (8) according to the source location. The position of the peaks can be adjusted by modifying the tympanal membrane resonance frequency while using the parameter values given in [14]. A fine dependence to the source location is demonstrated and it might be a requested condition to actually model the effect of the medial septum.

Finally the impulse response of the central mid-cavity “31” seen in Fig. (7) is used as an input signal in [15] (this conference proceedings).

5 Perspectives

5.2 Electro-acoustic systems, MEMS

A simulation tool able to solve all the specific effects that must be accounted for when designing electro-acoustic devices would be useful for the engineers in this field. A specification issued from experts in microphones and speakers as well as in their corresponding MEMS integrated devices has also been taken into account [2].

5.3 Bio-inspired systems, Bioacoustics

The understanding of the auditory and other sensory biological systems led to the fabrication of bio-inspired robots such as http://homepages.inf.ed.ac.uk/bwebb/cricket.

It becomes then possible to reproduce with robots behavioral experiment such as phonotaxis (ability to locate the sound emitted and to orient toward the sound source) [16]. A simulation platform where sub-blocks for both the biological systems and the artificial systems can be found together in libraries shall be usefull for cross-analysis.

5.4 Toward an active brain-controlled middle ear model with feedback

The path has been opened recently in considering the middle ear as a sub-system with its own neural feedback coming from a non auditory part of the cortex [17].

Many electrical equivalent models of the inner ear are found and among them an emerging trend is worth be cited [18] where a computational model of sound translation into neural message at the first auditory synapse is proposed.

Finally when dealing with the neural level, efficient computing leads obviously to using behavioral models [19].

6 Conclusion

A specific toolbox integrated into an efficient time-domain simulation package has been developed that will be useful to simulate auditory pathways from external sound sources to brain processing. It opens a path toward bio-inspired systems [20].

Acknowledgments

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