DEVELOPMENT OF AN ENTIRE HUMAN HEAD FINITE ELEMENT MODEL BASED ON IN-VIVO MEDICAL IMAGES FOR INVESTIGATION OF SOUND TRANSMISSION

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Auditory discomfort induced by hearing protection devices (HPD) which is related to the value of the sound pressure at the eardrum is one reason that reduces their efficiency. Numerical models prove to be efficient tools to better predict this pressure since they allow for integrating all geometrical and structural complexities of the head-ear-HPD system and go beyond the practical and ethical limits of experiments on living humans. The ultimate goal of this research is to elaborate a finite element (FE) model of a head-ear-HPD system and an associated anatomical phantom to investigate both the air-conducted and bone-conducted sound transmission through ears occluded or not by HPD of earplug type. This paper focuses on the development of the FE head model and its preliminary evaluation. The procedures of geometrical reconstruction and modeling of the head, including the brain, cerebrospinal fluid, skull, and soft tissues based on in-vivo magnetic resonance imaging and cone-beam computed tomography medical images are explained. As head resonances are related to bone-conducted sound, the eigenfrequencies and corresponding mode shapes of the system provide valuable information for interpreting its vibratory response and also for further understanding their impacts on hearing perception. Therefore, as a first step in the FE head model evaluation, a modal analysis and a study of the forced response are carried out using COMSOL Multiphysics 5.4 (COMSOL®, Sweden). Results are compared with available numerical and experimental data in the literature and discussed.

Keywords: finite element head model, vibro-acoustic modeling, in-vivo medical images

1. Introduction

While using hearing protection devices (HPD) is the method of last resort to protect workers from noisy environment, users tend to wear them incorrectly or intermittently because of the discomfort induced by HPD, thereby reducing their efficiency significantly. However, manufacturers lack design tools to fabricate efficient and comfortable HPD due to the insufficiency of knowledge about the links between HPD design parameters and main discomfort sources [1, 2]. Among these sources, the auditory discomfort which is related to the value of the sound pressure at the eardrum is essential. To evaluate this pressure effectively, it is relevant to develop a finite element (FE) model of a head-ear-HPD sys-
tem, which allows to investigate and better understand both the air-conducted and bone-conducted sound transmission paths. Such a system integrating all the physical complexities does not exist presently.

Numerical models based on realistic anatomical geometries have been proposed to investigate the vibro-acoustic behavior of the human head. Some were interested in the head-HPD system, for predicting the sound attenuation [3] and the occlusion effect [4] of HPD of earplug type, for investigating the effectiveness of HPD of helmet type under an impulsive noise by assessment of pressure in the brain [5], and for exploring the different sound transmission pathways in the head-ear-HPD (earplug) system [6]. Others were rather interested in the vibratory behavior of the human head, which have been used to investigate the mechanical point impedance of the skull as well as the acceleration of the ipsilateral and contralateral cochlear bone under a solid excitation [7], and to examine the modal behavior [8] of the system. However, the models are either based on a simplified geometry of the head by considering only the ear canal and its surrounding tissues with the eardrum integrated as an impedance model [3, 4] or reconstructed from cadaver head or ear geometries of which are usually deformed by chemical and physical treatment [4, 6, 7], or obtained by combining structures from different subjects [6, 8]. When considering only the auditory system, it is either not included [5] or simplified [3, 4], or taken from cadavers [4, 6]. For the most advanced studies [5-7], it seems that the models are not validated and calibrated sufficiently. In addition, there are studies involved in the framework of the military research, providing few details concerning the modeling. None of the studies focus on the sound pressure at the eardrum in ears occluded by HPD considering the head in its full complexity. In a word, existing models have limitations both in terms of prediction of the sound pressure at the eardrum of a protected ear of an alive subject and their validation.

To address the aforementioned issues, the ultimate goal of this research is to elaborate a FE model of a head-ear-HPD system and an associated anatomical phantom to investigate both the air-conducted and bone-conducted sound transmission through ears occluded or not by HPD of earplug type. The FE model is based on a complete image dataset of an in-vivo human head including the auditory system with sufficient resolution to take into account the individual characteristics of the scanned head and ears. Experiments on the anatomical phantom and on the volunteer whose head has been scanned make it possible to calibrate and validate the numerical model rigorously. The FE model will be exploited to analyze and predict the vibro-acoustic behavior of the head-ear-earplug system.

The present paper focuses on the development of the FE head model and its preliminary evaluation. The head geometry is obtained from scanning of an in-vivo human head by two different medical imaging techniques: the magnetic resonance imaging (MRI) and cone-beam computed tomography (CBCT). The procedure of the reconstruction in 3D of the anatomical structures involved in the head model is described in section 2. The model evaluation is presented in section 3 with the simulation results discussed by comparing with available numerical and experimental data in the literature.

2. Reconstruction of the head geometry

The geometries of the anatomical structures included in the head model are retrieved from both MRI and CBCT images of one adult volunteer with the approval of the CRCHUM/ÉTS Clinical Research Ethics Boards for the MRI and CBCT scans.

The MRI scan was carried out on the entire head of the volunteer using a Siemens 3T Skyra machine with a 0.6 mm isotropic resolution. This imaging technique is an efficient tool for getting the geometries of the brain and the other soft tissues, such as cartilages, fat, muscles, lymph, skin, etc. However, bones and air have no signal in MRI images and thereby appear both black. As a result, it is only possible to distinguish a part of the skull which is not connected to air, like the frontal bone, the

1 CRCHUM: Centre de Recherche du Centre hospitalier de l’Université de Montréal, Montreal, Quebec, Canada; ÉTS: école de technologie supérieure, Montreal, Quebec, Canada
two parietal bones, and the occipital bone while all the other parts such as the facial skeleton cannot be differentiated.

CBCT imaging technique provides the geometries of the bony structures which are impossible to be distinguished from MRI images. This technique was chosen for its low radiation and high resolution. Two CBCT scans focalized on the auditory system were carried out on the volunteer using a NewTom 5G machine. One field of view (12 cm x 5 cm with a high resolution of 0.15 mm) allowed one to get the geometries of the anatomical structures in the middle ear, especially the ossicles. The second one which is the largest field of view available (18 cm x 16 cm with a 0.3 mm resolution) made it possible to complete the skull structure.

Both MRI and CBCT images were imported separately into the commercial software MIMICS, Materialise (Leuven, Belgium) for semi-automatic 3D segmentation. In the present model, the whole head contour, a part of the skull, the cerebrospinal fluid (CSF), and the brain were segmented from the MRI image while the other part of the skull was segmented from the CBCT image. The human skull is in reality a three-layered sandwich structure, but it is considered to have only one layer for simplification in this study. The cartilages, fat, muscles, lymph and the skin are all considered as soft tissues. The auditory system in the present model is not complete: it includes only the ear canal cavities.

With the 3D structures segmented separately from MRI and CBCT images, the next step is to unite them together respecting the real anatomy. In fact, the cochlea in the inner ear is available in both MRI and CBCT images thus was chosen to be the landmark for registering the others. Superposing the cochlea from the CBCT image to the one from the MRI image got the transformation matrix between the two images. Applying this matrix to the part of the skull obtained from the CBCT image moved it to the right place. However, geometrical errors in the reconstructed 3D structures resulting from artifacts in both images render the superposition not satisfying in some regions. In this case, manual correction is necessary with knowledge of anatomical structures. Then, the commercial software 3-Matic, Materialise (Leuven, Belgium) was used to smooth, reconstruct and simplify the 3D structures in a reasonable degree in preparation of FE modeling. All the reconstructed anatomical structures (see Figure 1) were then imported in COMSOL Multiphysics 5.4 (COMSOL®, Sweden) for developing the corresponding FE head model.

![Figure 1: The 3D anatomical structures reconstructed from MRI and CBCT images. a) The whole geometry with a transparent view; b) soft tissues, c) skull; d) CSF; e) brain](image)

### 3. Head FE model evaluation

#### 3.1 Modal analysis of the head system

As head resonances are related to bone-conducted sound, the eigenfrequencies and corresponding mode shapes of the system provide valuable information for interpreting its vibratory response and also for further understanding their impacts on hearing perception. This subsection presents the modal anal-
ysis of a head model including brain, CSF and skull for comparing with the simulation result of a similar system in [8] which includes brain, CSF, skull as well as cartilages and teeth. In both studies, the soft tissues are not integrated.

Table 1: Parameters of the anatomical structures included in the head system without the soft tissues

<table>
<thead>
<tr>
<th></th>
<th>Young’s modulus, E [MPa]</th>
<th>Poisson coefficient, ν</th>
<th>Density, ρ [kg/m³]</th>
<th>Volume, V [mm³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brain</td>
<td>0.497</td>
<td>0.48</td>
<td>1140</td>
<td>1,436,000</td>
</tr>
<tr>
<td>CSF</td>
<td>1.314</td>
<td>0.4999</td>
<td>1040</td>
<td>332,300</td>
</tr>
<tr>
<td>Skull</td>
<td>8000</td>
<td>0.22</td>
<td>4740</td>
<td>924,300</td>
</tr>
</tbody>
</table>

The corresponding FE model of our reconstructed head system (see figure 2) contains 176,085 10-noded tetrahedral elements. All the material properties are adopted from [8]. The CSF is considered as a solid here. The total mass of this simplified model is 6.36 kg with the defined density for each structure which is in a reasonable range for a human head [9]. The material properties and the volume of each domain are listed in table 1. The base of the skull (see figure 2) is fixed, and the external surface of the system is set to be free. Continuity of stress vectors and displacements is assumed at interfaces between the solid domains.

Figure 2: The FE head system without soft tissues. a) Skull; b) CSF; c) brain

Figure 3 shows the modulus of the structural displacement of the first three modes of the system calculated using the present model. The first mode of the present model at 34 Hz corresponds to an anterior–posterior extension–flexion of the head, the second mode at 56 Hz corresponds to a lateral flexion of the head, and the third mode at 76 Hz corresponds to a vertical axial rotation of the head. This result is in good agreement with that presented in [8]. Higher order modes are local modes and the systems deform in a more complex way (for example, the deformation concentrates in part of the head like the brain). For these modes larger discrepancies are observed which are not presented here. These discrepancies are believed to be the result of geometrical and anatomical differences between the two head models. For example, since structures like the cartilaginous part are not integrated in the present model unlike in the reference [8], local modes corresponding to the deformation which concentrates in the lateral cartilage and septal cartilage are not found.
Figure 3: Modulus of the structural displacement of the first three modes of the model reconstructed in this study

3.2 Forc ed response of the head model

Figure 4: The FE head system with soft tissues. a) soft tissues, b) skull; c) CSF; d) brain

The mechanical point impedance of a head model including soft tissues, skull, CSF and brain is calculated for comparing with that computed on the head system presented in [7] which contains not only the aforementioned structures but also eyes and cartilages. It should also be noted that the three layers of the skull are distinguished in [7]. The corresponding FE model (see figure 4) contains 451,789 10-noded tetrahedral elements. The mechanical material properties including the loss factor of brain, CSF and soft tissues are adopted from [7]. The CSF is integrated as a fluid domain this time rather than a solid one. The material properties of the single-layer skull are taken from [10]. The total mass of the head model is 5.54 kg with the chosen density for each structure which is in a reasonable range of an average human head weight. The parameters of the anatomical structures are listed in table 2. Continuity of stress vectors and displacements is assumed at interfaces between the solid domains and fluid-structure coupling is assumed at interfaces between solid and fluid domains. Similarly as in [7], the external surface of the head model is set to be free. This boundary condition is chosen to duplicate the experimental condition in [11] where the head was placed on a soft pillow for decoupling the head from the support. The mechanical input impedance \( Z_{\text{mech}} \) is defined as the ratio of the excitation force \( F \) and the response velocity \( v \) at the same position and in the same direction as the applied force [7]:

\[
Z_{\text{mech}} = \frac{F}{v}
\]

The force is applied on the forehead position of the skull (see figure 4(b)) at location \( p_0 \) mentioned in [7]. The calculated mechanical impedance is compared with the simulation result presented in [7] and the experimental result of six cadaver heads in [11] (see figure 5). The simulation result of the present model corresponds better to the experimental data in [11] especially in the low-frequency range compared with the simulation result in [7] which exhibits large fluctuations, indicating multiple resonances.
In fact, they were also found by experiments in [11] but eliminated by averaging. In the present model such fluctuations are observed at higher frequencies, which may be due to the simplified model (some anatomical structures are not accounted for and the skull is considered homogeneous). But as mentioned in [7], reasons for these resonances need further investigation. In general, similar tendency is captured between the result of this study and those in [7,11] given the differences in geometry and material properties. Discrepancies between the three results could also be explained by the fact that the vibration transducer and accelerometer used in [11] are modeled as a metal structure at the stimulation position in [7] while in the present study, the force is applied directly on a point at the forehead and the velocity is calculated at the same point.

![Figure 5: Mechanical point impedance of a point at the forehead (see figure 4(b)): a) magnitude, b) phase. Blue solid line: simulation result of the present model; red solid line: simulation result digitized from [7]; green dashed line: average experimental result with error bars indicating ±1/-1 standard deviation digitized from [7].](image-url)
Table 2: Parameters of the anatomical structures included in the head model

<table>
<thead>
<tr>
<th></th>
<th>Young’s modulus, E [MPa]</th>
<th>Poisson coefficient, ν</th>
<th>Density, ρ [kg/m³]</th>
<th>Speed of sound, C [m/s]</th>
<th>Loss factor, η</th>
<th>Volume, V [mm³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brain</td>
<td>0.035</td>
<td>0.45</td>
<td>1000</td>
<td>--</td>
<td>3×10⁻⁴×f</td>
<td>1,436,000</td>
</tr>
<tr>
<td>CSF</td>
<td>--</td>
<td>--</td>
<td>1000</td>
<td>1500</td>
<td>--</td>
<td>332,300</td>
</tr>
<tr>
<td>Skull</td>
<td>7300</td>
<td>0.3</td>
<td>870.23</td>
<td>--</td>
<td>0.01</td>
<td>924,300</td>
</tr>
<tr>
<td>Soft tissues</td>
<td>0.7</td>
<td>0.45</td>
<td>900</td>
<td>--</td>
<td>3×10⁻⁵×f</td>
<td>3,054,000</td>
</tr>
</tbody>
</table>

4. Conclusion and perspective

This paper presented the development of a whole head finite element model for investigating both the air-conducted and bone-conducted sound transmission in the human head through ears occluded or not by HPD of earplug type. As a first evaluation of the proposed model, a modal analysis and a study of the forced response were carried out on the reconstructed head system. The results are rather satisfying compared with the available data in the literature in consideration of the differences in geometry and material properties. Future work involves improving the reconstruction of the various anatomical parts using for example morphing techniques, integrating the full auditory system and calibrating/validating the model using measurements carried out on the volunteer.

REFERENCES