ON THE INFLUENCE OF THE MATERIAL PROPERTIES OF THE EXTERNAL EAR ON OCCLUSION EFFECT SIMULATIONS

Martin K. Brummund[1], Franck Sgard[1,2], Yvan Petit[1], and Frédéric Laville[1]
[1]Dept. of Mechanical Engineering, École de technologie supérieure, 1100 Rue Notre Dame O., Montréal, Québec, Canada, H3C1K3 martin.brummund.1@ens.etsmtl.ca
[2]Service de la recherche, IRSST, 505 Boulevard de Maisonneuve O., Montréal, Québec, Canada, H3A3C2

1. INTRODUCTION

About 120 million workers worldwide are at risk of developing professional hearing loss (WHO, 2001). Hearing protection devices (HPD) such as earplugs (EP) represent the most frequently used short term solution to protect employees that are exposed to harmful noise levels. Nevertheless, research has also shown that workers often only tend to wear provided EPs for limited amounts of time (Berger, 2000) due to physical and auditory discomfort. One important source of auditory discomfort is the occlusion effect (OE). The OE occurs upon EP insertion and causes an uncomfortable distortion of the perception of the wearer's own voice and an amplification of physiological noises. Numerical modeling can contribute to further our understanding of the sound propagation in the external ear and ultimately the OE's underlying mechanisms. The present study aims at implementing a two-level fractional factorial design to examine how the material properties of the external ear tissues influence numerical predictions of the OE.

2. METHODS

The present study uses a 2D coupled linear elasto-acoustic finite element model for simulation of the OE. This simplified 2D model was developed in a previous study (Brummund et al., 2011) and successfully compared to an equivalent 3D model whose complex external ear geometry was reconstructed using 135 anatomical images of a female cadaver head (images were retrieved from the Visible Human Project® database of the US National Library of Medicine). Furthermore, the 2D model was validated against literature findings (Stenfelt & Reinfeldt, 2007).

2.1 Axis-symmetric model geometry

The axis-symmetric model comprises the domains: ear canal, a skin layer that covers the ear canal walls, a second skin layer that covers the lateral ear canal entrance region as well as soft tissue and bony tissue domains. A silicone EP of known material properties was inserted 7mm into the ear canal.

2.2 Material properties

Implementation of a coupled linear elasto-acoustic model of the external ear requires Young's moduli, Poisson's ratios, densities and loss factors of all tissue domains to be known. To examine the sensitivity of the model's response variable (OE) to varying material property configurations, representative high and low levels must be set for each experimental factor (material properties). This task is very challenging as the material properties of the external ear have, to date, only been sparsely determined. Central values (0) of experimental factors were drawn from the literature. Material properties that could not be found in the literature were approximated using identical tissues in close anatomical proximity which were assumed to be exposed to similar mechanical loading. Afterwards, high (+1) and low levels (-1) were defined by varying each factor ± 20% about its central value.

2.3 Boundary conditions

Outer circumferential (parallel to center axis of ear canal) boundaries of the skin and cartilage domains are fixed. Medial boundaries of the bone (which corresponds to the petrous part) and the skin tissue that surrounds the tympanic membrane are fixed. The lateral surface of the skin tissue that surrounds the ear canal entrance is modeled as free. For open ears, the ear canal entrance is modeled as acoustic radiation impedance of a baffled flat disc. For occluded ears, the lateral earplug boundary is left free. Finally, the eardrum impedance is modeled using a two piston-model (Shaw & Stinson, 1981; Shaw, 1977). A structure borne excitation (1N total force) is applied normally to the circumferential boundary of the bony tissue in both open and occluded models.

2.4 Fractional factorial design (2^k-p)

A 2^12-7 folded saturated factorial design with one replicate and one single block was implemented. The chosen design is of resolution IV. The generators were chosen so that the design is of highest possible resolution and of minimum aberration (Montgomery, 1997). All aforementioned steps were carried out using STATGRAPHICS (STATPOINT Technologies, Inc., USA)

2.5 Simulation of OEs and statistical analysis

The obtained sheet was imported into COMSOL 4.2 (COMSOL, Inc., Sweden). Parametric sweeps were carried out for all property configurations. Open and occluded models were meshed according to the four elements per wavelength criterion using quadratic tetrahedral elements. Obtained transfer function levels between excitation and acoustic pressure at the center of the tympanic membrane were calculated and 1/3 octave band filtered in MATLAB (MathWorks®, USA). Filtered results were imported into STATGRAPHICS TM for post-processing.

3. PRELIMINARY RESULTS

Analysis of variance indicates significant single factor effects for skin (Poisson's ratio, Young's modulus, loss factor), soft (Poisson's ratio, Young's modulus) and bony (Poisson's ratio) tissues. Estimated effect magnitudes vary as a function of frequency. Single factors of skin and soft tissues tend to have positive effects on simulated OEs. Overall, Poisson's ratio and Young's modulus of the skin tissue were estimated to have the biggest effects on the OE data. Statistically significant two factor interactions occurred throughout the entire frequency range. Again, estimated effect magnitudes vary over frequency. Overall, the interaction between Young's modulus and Poisson's ratio of the skin tissue tends to have the greatest estimated effect.

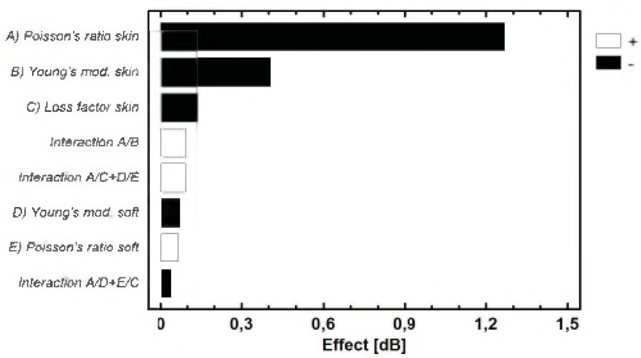

Figure. 1. Pareto chart for OE at 100Hz. All effects were significant (p-Values < 0.05). Filled bars denote positive effects. Empty bars denote negative effects.

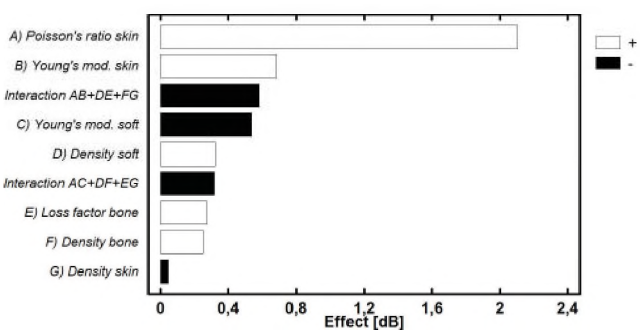

Figure. 2. Pareto chart for OE at 1000Hz. Apart from the skin density, all effects were significant (p-Values < 0.05). Filled bars denote positive effects. Empty bars denote negative effects.

In Figures 1 and 2 Pareto charts are provided. Estimated main effects correspond to the difference between the OE at the high and low levels of the factor when all other factors are kept at their central values. Apart from the density of the skin tissue at 1 kHz, all factors and two factor interactions are statistically significant ($\alpha = 0.05$).

4. DISCUSSION AND CONCLUSION

Skin, soft and bony material properties were found to contribute significantly to simulated OEs. Yet, mostly Poisson's ratio and Young's modulus of the skin tissue tend to exhibit effect estimates which are large enough to cause relevant variations in simulated OE data. These preliminary results suggest an important role of the external ear's skin tissue. This trend is in agreement with experimental findings (Stenfelt et al., 2003) which showed that the non-osseous external ear tissues represent the greatest source of ear canal sound pressure in open ears for frequencies below 2 kHz. Future studies should examine the contribution of the ear canal skin to ear canal sound pressure levels. It should be noted that the authors are anticipating a study to determine material properties of the external ear tissues experimentally. In this context, OE measurements with and without ear canal skin could be carried out. Furthermore, it would be desirable to examine whether relevant higher order factor interactions are existent. This can be achieved via factorial designs of higher resolution or through full factorial designs that consider only the most influential material properties.

REFERENCES

Berger, E. H. (2000). Hearing Protection Device Utilization Around the World. *Spectrum*, *17*(Suppl. 1), 18.

Brummund, M., Sgard, F., Petit, Yvan, & Laville, F. (2011). A simplified axi-symmetric finite element model of the human outer ear to determine the earplug induced auditory occlusion effect. *The Journal of the Acoustical Society of America* (Vol. 130, No. 4, p. 2469). Presented at the 162nd Meeting Acoustical Society of America, San Diego, CA, USA.

Montgomery, D. C. (1997). *Design and analysis of experiments*. New York: John Wiley and Sons.

Organisation mondiale de la santé (OMS). (2001). Le bruit au travail et le bruit ambiant.

Shaw, E. A. ., & Stinson, M. R. (1981). Network concepts and energy flow in the human middle ear. *J. Acoust. Soc. Am.*, *69*(1), 43.

Shaw, E. A. G. (1977). Eardrum representation in middle-ear acoustical networks. *J. Acoust. Soc. Am.*, *62*(1), S 12.

Stenfelt, S., & Reinfeldt, S. (2007). A model of the occlusion effect with bone-conducted stimulation. *International Journal of Audiology*, *46*(10), 595 – 608.

Stenfelt, S., Wild, T., Hato, N., & Goode, R. L. (2003). Factors contributing to bone conduction: the outer ear. *The Journal of the Acoustical Society of America*, *113*(2), 902–913.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support received from the IRSST.