11th World Congress on Computational Mechanics (WCCM XI)
5th European Conference on Computational Mechanics (ECCM V)
6th European Conference on Computational Fluid Dynamics (ECFD VI)
July 20 - 25, 2014, Barcelona, Spain

Statistical Calibration in a Human Middle Ear FE Model

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Key Words: *Model Calibration, Statistical Validation, Human Middle Ear.*

A role of middle ear is to match impedances between air in ear canal and fluid in inner ear. Finite element models for the middle ear are used to investigate the dynamic characteristics of the middle ear [1]. However, the material properties that should be known for the analysis using the finite element method have numerous uncertainties, which lead to large uncertainties in the middle ear dynamic characteristics. The authors developed a finite element model for a Korean middle ear that was based on the high-precision geometry data and material properties from published articles [2]. The performance of the developed FE model exhibited good agreement in the low frequency bands, but it deviated from the measurement data in the high frequency bands. Thus, the validity of the developed FE model should be estimated quantitatively and updated for better performance in the high frequency bands. In this study, the validity of the FE model for a middle ear is quantitatively estimated using statistical percentiles estimation and a novel validation metric. The material properties of the FE model that have a significant influence on the tympanic membrane responses are also updated using an optimization technique.

The middle ear FE model consists of three ossicles (malleus, incus, and stapes), a tympanic membrane, tendons, and ligaments as shown in Fig. 1. The umbo displacement transfer function (UDTF) was defined as a frequency response function of the umbo displacement due to the unit sound pressure on the tympanic membrane. In order to calculate the UDTF using the FE model, the nodal displacements of the nodes in the umbo region of the tympanic membrane were averaged when a unit sound pressure was applied on the tympanic membrane in the frequency domain. Because the uncertainties of the input parameters propagate into the UDTF through the FE model, the responses calculated using the FE model become a distribution of which information can be represented using the probability density function (PDF). The experimental data available from the literature was the means and two percentile values (10^{th} and 90^{th}) of the measured UDTF along the frequency axis. In order to assess the FE model based on the experimental data, the PDF of the UDTF should be obtained using a probability analysis. The eigenvector dimension reduction (EDR) method was used with a 2N+1 sampling scheme in order to obtain the PDF of the UDTF that results

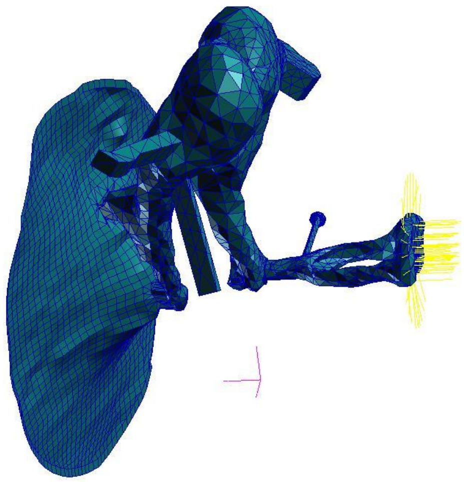

Fig. 1 An FE model for middle ear.

from the FE model parameter uncertainties [3].

A validation metric was defined in order to compare the mean and two percentile values (10th and 90th) between the experiments and the calculated UDTFs, as follows:

$$\phi(f)=\left((G^m_{p_{10}}-G^e_{p_{10}})^2+(G^m_{\mu}-G^e_{\mu})^2+(G^m_{p_{90}}-G^e_{p_{90}})^2\right)^{1/2}, \quad (1)$$

where G is the UDTF, f is the frequency, the superscripts m and e refer to the FE model and experiment, respectively, and the subscripts μ, p_{10}, and p_{90} are the mean, 10th percentile (10% CDF), and 90th percentile (90% CDF), respectively. The calibration parameters, which are composed of stiffness-related and density variables, were selected using the analysis of variance (ANOVA) for the material properties of the middle ear FE model. The geometrical shapes and dimensions of the middle ear FE model were assumed to be deterministic because those were obtained from the high-precision CT scanning. The results of the ANOVA showed the amount of contributions on the UDTF due to the variabilities of the potential calibration parameters. The relation between the physical experiments and the FE model outputs can be formulated as $y^e(\mathbf{x})=y^m(\mathbf{x},\boldsymbol{\theta})+\delta(\mathbf{x})+\varepsilon$ where $y^e(\mathbf{x})$ is the measurement data, $y^m(\mathbf{x},\boldsymbol{\theta})$ is the FE model output, $\delta(\mathbf{x})$ is a bias FE model error, and ε is the measurement error.

Through minimizing a validation metric, the calibration parameters are updated in order to enhance the performance of the middle ear FE model. Figure 2 shows the statistical properties of the UDTFs (mean, and 10 and 90% CDF points) with the calibrated parameters compared with those of the initial FE model and the measurement data. The calibrated FE model by the proposed method shows good agreement with experimental data, which demonstrates the effectiveness of the statistical calibration method.

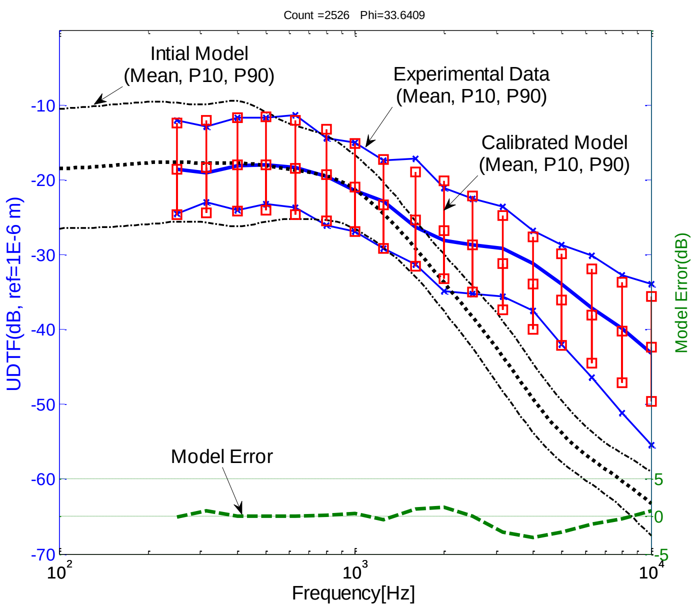

Fig. 2 UDTF calculated by the calibrated FE model.

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