Middle ear vibrations - experimental and numerical study

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Abstract

The paper presents experimental investigations of ossicular chain vibrations using a Laser Doppler Vibrometer (LDV) for the intact and fixed ossicular chain. The modified ossicular chain is used to identify stiffness of tendons and ligaments in modelling process. Moreover, the paper focuses on new methods of signal analysis which is based on recurrence plot technique, besides a typical analysis based on of a transfer function.

Keywords: middle ear mechanics, Laser Doppler Vibrometer

1. Introduction

For more than 50 years middle ear surgery techniques have enabled to improve hearing destroyed by a disease. Despite huge improvement in instrumentation and techniques the results of hearing improvement surgery are still difficult to predict. Variation in anatomy, Eustachian tube malfunction, healing or mucosal disease have a significant impact on the final result. This is why many researchers use the Laser Doppler Vibrometer (LDV) as a tool to measure vibrations of human intact middle ear ossicles [1, 2, 3, 4, 5, 6, 7, 8]. Almost always, the results of measurements are presented as a transfer function between the input signal which usually is a sound pressure and the output one - displacement or velocity of stapes or round window. Some relevant papers report that the intact middle ear has the highest value of the transfer function in the range till 2 kHz with the typical pick at about 0.9 kHz [2, 5, 6] and sometimes at about 4 kHz. The literature research t keeps us convinced that the procedure based only on the transfer function should be completed with a more advanced method which could estimate a kind of ossicular chain vibrations, not only its level. Therefore, this paper has two aims. The first focuses on stiffness coefficients identification, the second on a new technique of ossicles vibration analysis.

The paper is organized as follows: after introduction, in the second section of the paper the authors present a method of the bone specimen preparation and describe experimental methodology. The third part demonstrates the results of a classical transfer function analysis of ossicles vibrations. Next, a new methods of analysis based on recurrence plot technique is used to identify middle ear dynamics. The last section contains concluding remarks.

2. Experimental research

The experiment has been performed at Lublin University of Technology with the support of Medical University of Lublin.

2.1. Temporal bone preparation

Measurements of ossicular chain vibrations are performed on fresh human temporal bone specimen. The temporal bone sample is harvested within 48 hours after death and preserved in a solution of normal saline with 10ml of 10% betadine at 50^oC between measurements. The soft tissue is removed and a standard antromastoidectomy with posterior tympanotomy is performed. The mastoid facial nerve is removed to visualize the stapes arch and footplate. The ear canal is drilled away leaving about 2-3mm of bone around the tympanic annulus. An artificial external ear canal of 25mm length and 9mm in diameter is then attached to the bone with epoxy resin. The artificial canal has two ports. One is for a microphone (ER-7C Etymotic Research) and the other for a sound source (ER2 Etymotic Research) placed about 2mm from the tympanic membrane. The artificial canal is closed with a glass plate to create a sound sealed chamber. Pieces of a retroleflective tape ($0.5mm^2$squares) weighing less than 0.05mg, are placed in the center of the stapes footplate. The temporal bone specimen is then embedded in dental cement and put in a temporal bone holder (Storz).

2.2. Experimental setup

The measurements are performed on an antivibration table inside a sound booth where the specimen with the laser head OFV-534 is placed. The stapes footplate velocity was measured with the Laser Doppler Vibrometer (LDV) system composed of a OFV-5000 controller with a VD-06 velocity decoder (Polytec) and a DD-500 displacement decoder. The OFV-534 sensor head is connected to a joystick operated micromanipulator, which is mounted on the operating microscope. The helium-neon laser beam is directed with the micromanipulator on retroreflective targets on the object of investigations through posterior tympanotomy. Ossicles vibrations are excited by the sound source (ER2 Etymotic Research) and simultaneously sound pressure is measured with the ear microphone (ER-7C Etymotic Research). Additionally sound input signal is amplified with the power amplifier (AP-12 Interacoustics) to produce an adequate signal output. The measurements are recorded using the LMS SCADAS controller.

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2.3. *Experimental procedure*

The human temporal bone is aligned in the optical path of the laser beam and the laser spot is focused on the measured point with a piece of the retroleflective tape. The vibrations are measured at the stapes (S), the oval window (OW), the incus (I), the tympanic membrane (TM). In order to estimate stiffness of ligaments and tendons some ossicles are fixed to the temporal bone with the help of dental cement obtaining following cases:

- intact osicular chain (IOC)
- the malleus and the incus are fixed (MIF)
- the stapes is fixed (SF)
- the incus and he stapes are fixed (ISF)
- all ossicles are free, dental cement is removed (OCR).

Ossicles vibrations are excited by sound stimuli with frequency sweeps from 0.2 to 8 kHz at the $80 - 110$ dB sound pressure level (SPL). According to literature and author's own experimental results, the sound stimuli from 80 to 100 dB SPL gives the near linear response of the ossicles [5] and even in the range of $50 - 110$ dB SPL when round window vibrations are measured [1]. The vibrometer and microphone signals are acquired at a sampling rate of 50kHz.

3. Results of experiment

Vibrations of the middle ear stapes are obtained as results of measurements with the help of LDV. Classical analysis is proposed to estimate stapes vibrations quantitatively and extended research to vibrations qualitatively.

3.1. *Classical analysis*

Firstly, the outcomes of the experiment are presented classically as the frequency response function (FRF) (Fig.**??**fig:frf)) between the input (sound pressure) and the output (vibrations velocity).

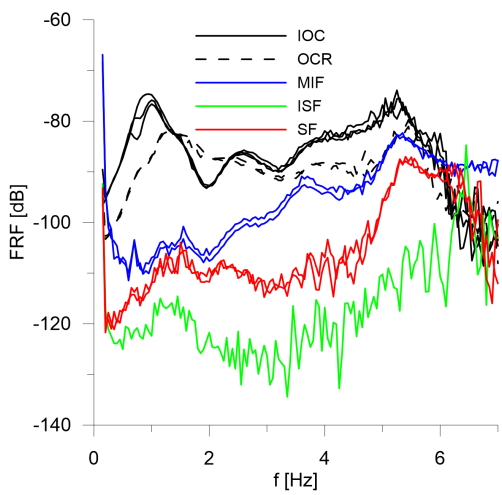

Figure 1: Frequency response function of ossicles vibrations

3.2. *Extended analysis*

A further analysis is performed with the help of recurrence plots (RP) which can be applied to any linear or nonlinear systems and not stationary signals. RP for IOC and MIF are presented in Fig.2. One can notice differences in patterns but more details will be shown in a full paper.

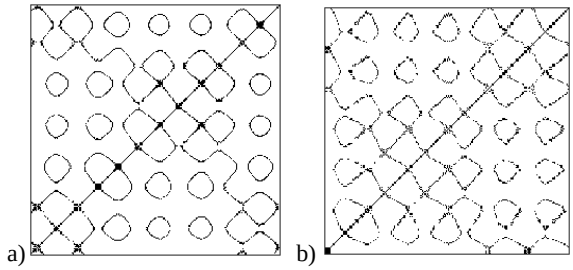

Figure 2: Recurrence plots of stapes velocity a) IOC, b) MIF

4. Conclusions

Fixation of some part of ossicular chain changes the middle ear characteristic which can be measured with the help of the RP technique.

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