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DIAGNOSIS OF HEARING IMPAIRMENT BY OHCs GAIN FACTOR DETERMINATION

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Abstract: The pressure applied to the basilar membrane is transmitted to the outer hair cells, which act on the cilia and back on the basilar membrane. The interaction of basilar membrane and outer hair cells is a nonlinear, non-local active system. Active amplification and nonlinear saturation terms as additional forces triggered by the outer hair cells and acting on the basilar membrane, can be seen as generated by nonlocal feed-forward longitudinal interaction. A model based on sound amplification method is proposed and studied to enhance the ability of the hearing impaired.

Key words: sound vibrations, hearing impaired, cochlea, basilar membrane, OHCs gain.

1. INTRODUCTION

Hearing is a branch of science concerned with the physiology of sound, perception and relates with the field of processing and interpreting the sound signals and their disorders. Human ear detecting variations of the surrounding pressure and translating variations in air pressure into neural activity for our perception and interpretation of sound. The ear can be divided into main sections such as outer ear, middle ear and inner ear [2].

The cochlea is the part of the inner ear where acoustic signals are transformed into neural pulses which are then signaled to the brain. These signal processing capabilities are achieved by a mechanism involving interaction of elastic material components immersed in fluid. The stapes' motion that reaches it through the middle ear is converted into motion of the fluids of the cochlea and the subsequent creation of a traveling wave moving along the basilar membrane (BM). The BM plays the role of a frequency analyzer. Location on the basilar membrane when maximum amplitude reaches are named the characteristic place (CP), which correspond to the unique input frequency. The frequency corresponding to the CP is called the characteristic frequency (CF). Formula of CP based on the frequency, as in [3] is:

$$CP(f) = 3.5 \left(1 - 4.83^{-1} \cdot \log \left(\frac{f + 0.45}{0.456} \right) \right) \quad (1)$$

Where: f is the frequency [Hz]. The domain size is on the order of centimeters (cm).

The basilar membrane is the base for the sensory cells of hearing, the hair cells. There are two types of hair cells: the outer and inner hair cells (OHCs and IHCs). OHCs drives oscillations in the cells length and provide an "active" feedback amplification. They are responsible of the nonlinear response of the BM. The OHC force is saturate if the BM motion increases in magnitude [3]. A common cause of hearing loss is a lack of sensitivity of OHC due to aging or frequent exposure to loud noise. Hearing aids attempt to provide amplification to sounds according to the loss at hearing threshold [1]. The IHCs transform the sound vibrations in the fluids of the cochlea into electrical signals sent via the auditory nerve to the auditory cortex. In this research, we focus on the major role of OHCs for cochlear mechanism [4].

1.1 Cochlear mechanism

The cochlea consists of three parts: scala vestibuli, scala tympani and scala media (Figure 1.). An inward motion of the stapes into the scala vestibuli causes movement of the

incompressible fluid from the scala vestibuli into the scala tympani. After the fluid passes through the helicotrema at the apex of the cochlea, the round window membrane bulges out to accommodate the increased amount of fluid in the scala tympani. A motion of the stapes away from the scala vestibuli causes fluid to move from the scala tympani into scala

vestibule and the membrane of the round window to consequently bulge inwards. The motion of the inner ear fluid caused by the inward and outward motions of the stapes creates a traveling (transverse) wave motion along the BM [2].

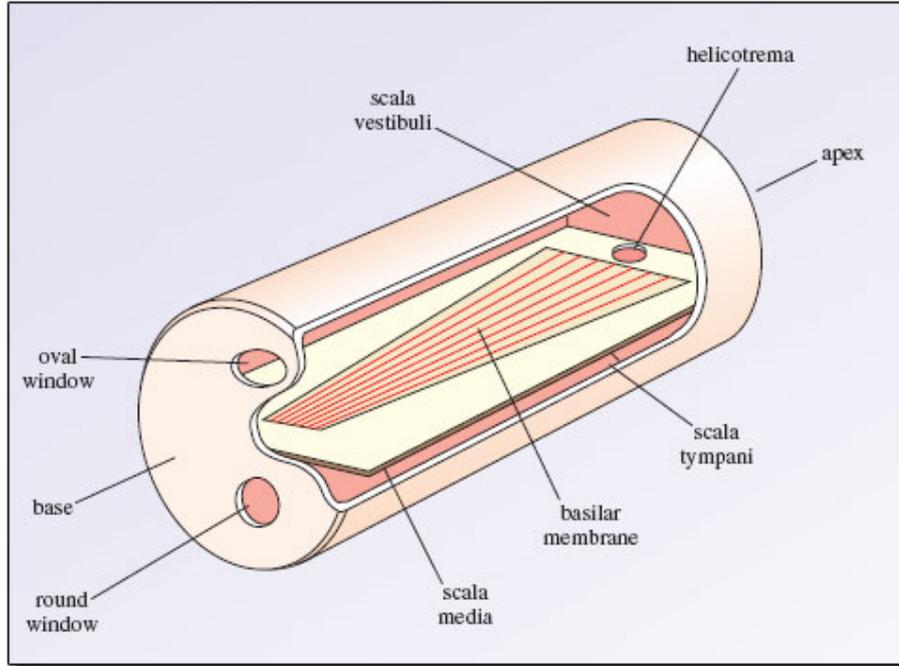


Fig. 1. Unrolled cochlea [6]

The pressure applied by the OHCs on the BM is assumed to be proportional to the total pressure acting on the BM. The total pressure acting on the BM is transmitted to the cilia, which in turn acts on the OHCs and back on the BM. The force on the BM is transmitted to the cilia depicted in Figure 2.

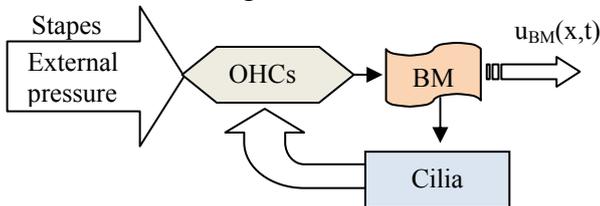


Fig. 2. Feed-forward model of OHCs ($u_{BM}(x,t)$ – BM displacement).

The OHCs provide an amplification function, increasing the amplitude of the incoming sound wave. The high gain of the cochlea is a result of the force applied on the BM by the OHC's. Thus, the OHC's can be

considered as the cochlear amplifiers [5]. High BM velocity will decrease the OHC's gain ($\gamma(x)$). A low BM velocity will increase the OHC's gain. As a result, the BM velocity will tend to be constant. OHC gain is the relative density of healthy OHCs per unit area along the cochlear duct. Its value ranges from 0 to 1. A normal, healthy cochlea is assumed to have a gain of $g(x)$ is 0.52. If $g(x)$ is below 0.52 the ear functions are impaired [3].

2. MATHEMATIC DETERMINATION OF OHCs GAIN FACTOR

Mathematical determination of OHCs factor is based on one-dimensional nonlinear nonlocal model developed by Cohen and Furst (2004) [3]. Let x be the longitudinal coordinate determinate by (1) for a certain frequency and t the time variable. It define $x = 0$ at the basal location (stapes), and $x = L$ at the cochlear most apical location. L represents the uncoiled cochlear length ($L \approx 3.5\text{cm}$). Let p_f be the

difference in the pressure which pulls the mass of the fluid through the scala vestibuli and through the scala tympani, respectively. The equation for $p_f(x,t)$ is [3]:

$$p_f(x,t) = \frac{x^3}{6} \ddot{u}(x,t) \quad (2)$$

where:

- $p_f(x,t)$ - difference of fluid pressure [Pa];
- $\ddot{u}(x,t)$ is vertical acceleration of the scala media, which represents the elastic partition the scala vestibuli and the scala tympani [nm/s²].

Kim and Xin (2005) [3] developed a dynamic model of BM using mass-damper-spring system. According to this model, the equation of pressure on BM is:

$$p_{BM} = \rho_m \ddot{u}(x,t) + c(x) \dot{u}(x,t) + s(x)u(x,t), \quad (3)$$

where:

- p_{BM} is BM pressure [Pa];
- ρ_m represents the BM density, $\rho_m=0.05\text{g/cm}^2$;
- $c(x)$ is the BM damping per unit length [N·s/cm] in the following form:

$$c(x) = 0.25 \exp(-1.2x) - 0.018, \quad (4)$$

- $s(x)$ is the BM stiffness per unit length [N/cm] in the following form:

$$s(x) = 4\pi\rho_m \left(0.456 \exp\left(4.83 \left(1 - \frac{x}{L} \right) \right) - 0.45 \right)^2. \quad (5)$$

Using non-linearity of cochlea model was described OHC force saturation.

The pressure that acts on OHCs can be calculates as:

$$p_{OHC} = p_s (L - x), \quad (6)$$

where:

- p_{OHC} represents OHCs pressure [Pa];
- p_s is the sound pressure at the stapes [Pa].

According to [3];

$$p_{OHC} = p_{BM} - p_f, \quad (7)$$

Knowing the pressure p_{OHC} [4] it can be determined the gain factor $\gamma(x)$ with following equation:

$$\gamma(x) = \frac{\dot{p}_{OHC} + 6280 \cdot p_{OHC}}{\alpha_1 \cdot u(x) + \alpha_2 \cdot \dot{u}(x)} \quad (8)$$

where:

- $\dot{u}(x,t)$ is vertical velocity [nm/s];
- α_1 - coefficient [N²s/g]:

$$\alpha_1(x) = -\frac{c(x) \cdot s(x)}{\rho_m}, \quad (9)$$

- α_2 - coefficient [N/(cm·s)]:

$$\alpha_2(x) = c(x) \cdot \omega_{OHC}, \quad (10)$$

- ω_{OHC} - characteristic frequency of OHC [Hz].

3. MathLab Simulink DETERMINATION OF OHCs GAIN FACTOR

Equations by Section 2 have been transposed in MathLab Simulink software using particular blocks related to each mathematical operation.

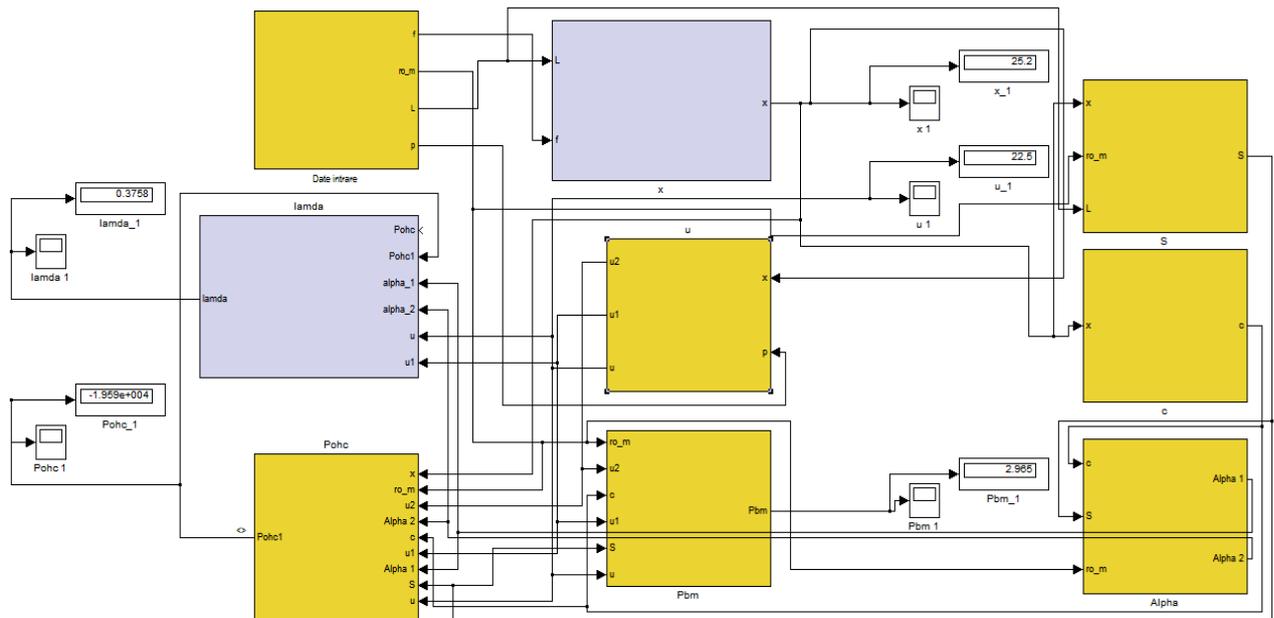


Fig. 3. MathLab Simulink program of OHCs gain determination

4. RESULTS

If the external pressure level is 50 dB, 200 Hz frequency then it results 0.47 OHCs gain

factor. Time variation of BM pressure, OHC pressure and BM displacement is presented on followings:

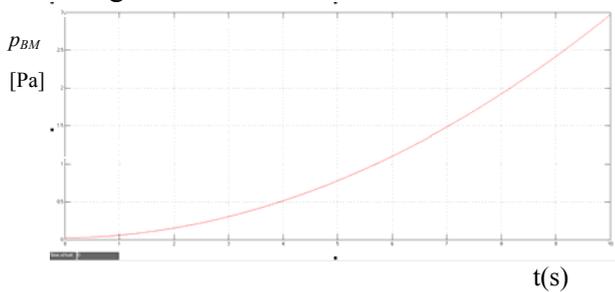


Fig. 4. Time variation of BM pressure.

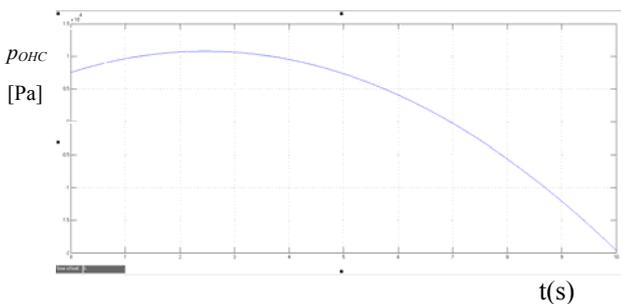


Fig. 5. Time variation of OHC pressure.

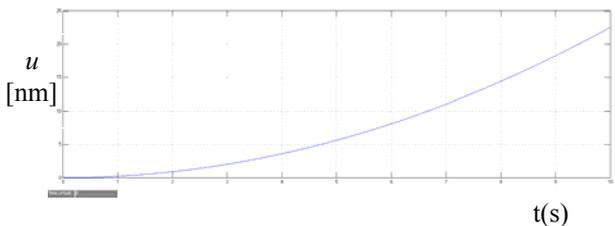


Fig. 6. Time variation of BM displacement.

5. CONCLUSION

An impaired ear has raised hearing thresholds and less frequency selectivity. The active parameter $\gamma(x)$ was obtained using BM-

OHC system model. If the output's amplitude is large, the OHCs gain factor decreases, conversely, if the output's amplitude is small, the gain increases.

6. REFERENCES

- [1] Erixon E., Högstorp H., Wadin K., Rask-Andersen H., *Variational anatomy of the human cochlea: implications for cochlear implantation*, US National Library of Medicine National Institutes of Health, pp. 14-22, doi: 10.1097/MAO.0b013e31818a08 e8, SUA, 2009.
- [2] Gan R. Z., Sun Q., Feng B., Wood M.W., *Acoustic-Structural Coupled Finite Element Analysis for Sound Transmission in Human Ear - Pressure Distributions*, Medical Engineering & Physics, Vol. 28, Issue 5, pp. 395-404, June 2006, Ed. Elsevier, Oxford, UK, 2006.
- [3] Kim Y. S., Xin J., *A Two-dimensional Nonlocal Feed-forward Cochlear Model and Time Domain Computation of Multitone Interactions*, SIAM J. Multiscale Modeling and Simulation, DOI.10.1137/040612464, Vol. 4, Nr. 2, pag. 664-690, China, 2005.
- [4] Levron Y., *A cochlear AGC model, proposing a new type of cochlear non-linearity*, A thesis. Master of Science in Electrical and Electronic engineering. The Iby and Aladar Fleischman faculty of engineering. Tel-Aviv University, Israel, 2007. www.eng.tau.ac.il
- [5] *** www.math.uci.edu
- [6] ***<http://en.wikipedia.org>

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Diagnosticarea deteriorării auditive prin determinarea factorului de amplificare a OHC

Rezumat: Presiunea sonoră aplicată membranei bazilare este transmisă celulelor ciliate externe, care acționează asupra speriocililor, presiunea rezultată revenind asupra membranei bazilare. Interacțiunea dintre membrană și celulele ciliate externe este descrisă de un sistem neliniar, nelocal. Amplificarea activă, saturația neliniară și forțele celulelor ciliate externe de declanșare ce acționează asupra membranei bazilare pot fi considerate rezultate ale interacțiunii longitudinale nelocale de tip feed-forward. Pentru relevarea deteriorării abilității auditive, este prezentat modelul ce are la bază amplificarea sonoră.

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