Modelling of sound transfer in middle ear with SMA element

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Abstract

The human middle ear contains three ossicles: malleus, incus and stapes. The ossicles form a sound conduction system which transmits sound from the external ear to the fluids of the inner ear. The ossicles are connected to each other by incudomallear and incudostapedial joint. The ossicular chain is supported by two muscles: the tensor tympani muscle attached with its tendon to the handle of the malleus, and the stapedius muscle attached to the stapes neck or posterior crus. The malleus is also firmly connected to the tympanic membrane while stapes is attached to the bony walls of the oval window by annular ligament forming stapediovestibular junction. Such a complex bio-system is modelled in the literature from the last half century. The first study in this field was published in 1961 by Mőller [1] where also the first scheme of middle ear mechanism was proposed. Next, a similar model was investigated by Zwislocki [2]. In both publications, authors used an electrical circuit to analyse middle ear system.

In the last decades mechanical models are developed where ossicles are represented by lumped masses, connected with springs and dashpots. In the literature, one can find three or four degrees of freedom (dof) model and sometimes even six dof but always they are linear. Usually these models focus only on kinematics of an intact middle ear however hardly ever, dynamics models are built. Here, a nonlinear three dof model of middle ear is proposed, which next is rebuild to system with prosthesis made of shape memory alloy (SMA).

The human middle ear mechanism can be presented as a 3dof model consisting of three lumped masses suspended with seven springs and dashpots (Figure 1) [1]. The three ossicular bones: malleus, incus, and stapes are represented by masses m_M, m_I, m_S, respectively. The malleus (m_M) is jointed with a tympanic membrane (TM) with spring and dashpot k_{TM} and c_{TM}. An anterior malleal ligament (AML) suspending the malleus is simulated as spring k_{AML} and dashpot c_{AML}. The malleus is connected with the incus by incudomalleal joint (IMJ) represented by spring k_{IMJ} and dashpot c_{IMJ}. Next, the incus and stapes are supported by posterior incudal ligament (PIL) and annular ligament (AL) that are modelled as springs with stiffness k_{PIL} and k_{AL}, and dashpots c_{PIL} and c_{AL}. The incudostapedial joint (ISJ) is shown as spring k_{ISJ} and dashpot c_{ISJ}. Finally, the stapes motion is transferred to cochlea (C) which stiffness and damping is simulated by spring k_C and dashpot c_C. The spring force of annular ligament F_{AL} has a linear part $k_{1AL}x_S$ and nonlinear $k_{2AL}x_S{}^2 + k_{3AL}x_S{}^3$, then:

$$F_{AL} = k_{1AL}x_S + k_{2AL}x_S{}^2 + k_{3AL}x_S{}^3 \quad (1)$$

The proposed model is governed by three differential equations of motion in the form presented below:

$$\begin{aligned} &m_M\ddot{x}_M + k_{TM}x_M + k_{AML}x_M + k_{IMJ}\left(x_M - x_I\right) + c_{TM}\dot{x}_M + c_{AML}\dot{x}_M + c_{IMJ}\left(\dot{x}_M - \dot{x}_I\right) = Q\sin\omega\tau \\ &m_I\ddot{x}_I + k_{IMJ}\left(x_I - x_M\right) + k_{PIL}x_I + k_{ISJ}\left(x_I - x_S\right) + c_{IMJ}\left(\dot{x}_I - \dot{x}_M\right) + c_{PIL}\dot{x}_I + c_{ISJ}\left(\dot{x}_I - \dot{x}_S\right) = 0 \\ &m_S\ddot{x}_S + k_{ISJ}\left(x_S - x_I\right) + k_C x_S + k_{AL}x_S + k_{2AL}x_S{}^2 + k_{3AL}x_S{}^3 + c_{ISJ}\left(\dot{x}_S - \dot{x}_I\right) + c_C\dot{x}_S + c_{AL}\dot{x}_S = 0 \end{aligned} \quad (2)$$

For the system parameters identified in experimental tests the natural vibration frequency are found as follows: f_1= 0.97 kHz, f_2= 5.59 kHz, f_3=43.8 kHz. The first and the second are the most important because they cover the audibility range. Results of the numerical analysis of the resonances are depicted in Figure 2, where A_M, A_I and A_S means the amplitude of malleus, incus and stapes respectively. The dashed line represents unstable solutions.

In medicine practice middle ear destruction of a ossicular chain can be caused by chronic otitis media. In this case usually middle ear prostheses can be applied to reconstruct connection between stapes and malleus or tympanic membrane.

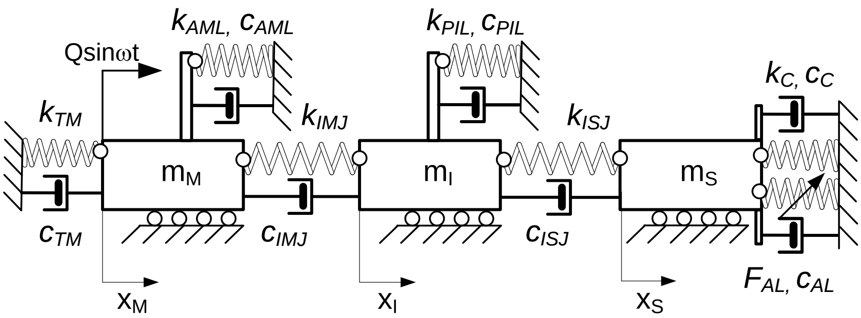

Figure 1: Three degree of freedom model of human middle ear.

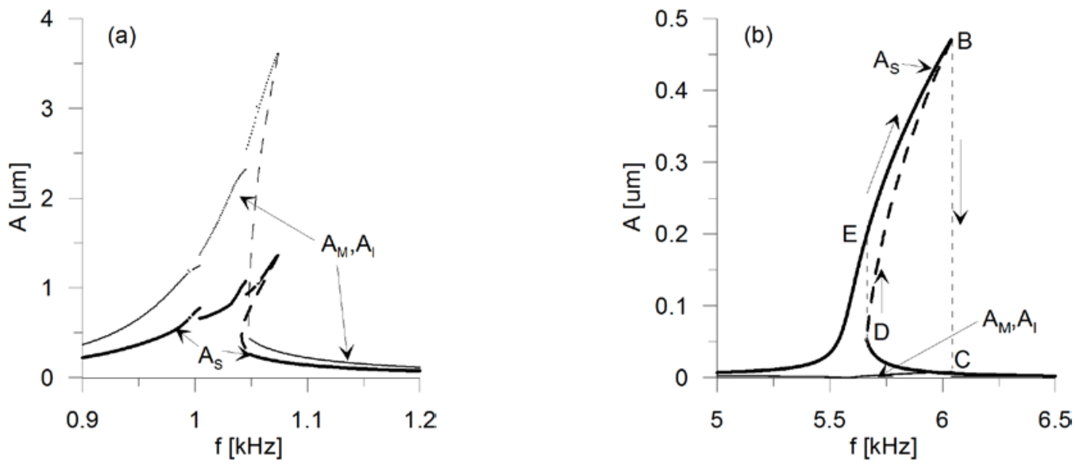

Figure 1: Resonance curves of middle ear model, the first resonance at 1kHz (a), the second resonance at 5.5kHz.

Adjustment of the prosthesis size and location is one of the main problem occurring during implantation. Therefore, a new concept of smart prosthesis is proposed here to improve the process. The smart prosthesis can be made of shape memory alloy (SMA) and its characteristic is given by the stress (σ) polynomial of the strain (ε) [2,3]:

$$\sigma = a_1(T - T_M)\varepsilon - a_2\varepsilon^3 + a_5\varepsilon^5 \quad (3)$$

where, a_1, a_2, a_3 are the material constants, T is temperature and T_M is phase temperature. More information and description of model dynamics will be given in a full paper.

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References

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