Effect of Nonlinear Electromechanical Coupling in Implanted Middle Ear

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Summary. The nonlinear electromechanical coupling between the middle ear structure and the implantable hearing device is analysed in order to explain combined dynamics of human middle ear, body of an implant and electric circuit that powers the implant. Numerical simulations of a lumped mass model shows harmonic, subharmonic and even chaotic vibrations for chosen range of excitation frequency.
Keywords: middle ear implant; implantable middle ear hearing device; electromechanical coupling

Introduction

Probably more than one third of people over 65 years of age suffer from clinically significant hearing deficits. Only a mild to moderate hearing loss can be improved by conventional hearing aids. Patients with hearing loss of approximately 50 to 90 dB may receive greater benefit from other, more technologically advanced devices such as implantable middle ear hearing devices (IMEHDs shown in Figure 1a). IMEHDs can be used for both conductive and sensorineural hearing loss, therefore they are becoming more and more popular nowadays. A typical IMEHD consists of three parts: a microphone, a signal processor and a floating mass transducer (FMT) [1,2,3]. The literature of the subject usually reports clinical studies on the application of IMEHDs in various medical cases. The effect of mass loading the ossicles with a FMT, an influence of different coupler types and various techniques of FMT implantation are investigated. However, widespread clinical research does not go together with theoretical investigation. Undoubtedly, there is a lack of biomechanical model that could explain the behaviour of the human middle ear with an implant and especially an influence on mechanical part of the system on electrical circuit and vice versa. Therefore here, a nonlinear electromechanical coupling between the middle ear structure and the IMEHD is analysed.

Results and Discussion

The model of implanted middle ear (Figure 1b) consists of three masses that represent the malleus (m_M), the incus (m_I) and the stapes (m_S). The masses are connected to each other and to the temporal bone by the joints (IMJ – the incudo-malleal joint, ISJ – the incudostapedial joint) and ligaments (AML – the anterior malleal ligament, PIL – the posterior incudal ligament, AL – the annular ligament). Damping and stiffness properties of the elements are denoted as c and k, respectively, including the cochlea (c_c and k_c), and the tympanic membrane (c_{TM}, k_{TM}). The stapes is excited by the FMT consisting of a magnet (M_m) suspended in a metal case (M_c) with dashpots (c_m) and springs (km). The magnet is moved by electromagnetic field generated by an electrical circuit with resistance R and conductance L supplied by a voltage source $U(t)$. E_{EM} denotes the electromotive force that generates an electro dynamic force (P) acting in the mechanical subsystem. The FMT is fixed to the incus long process with a clip whose linear damping and stiffness coefficients are denoted as c_{CLIP}, k_{CLIP}. The electromechanical coupling is described as α.

(a) (b)

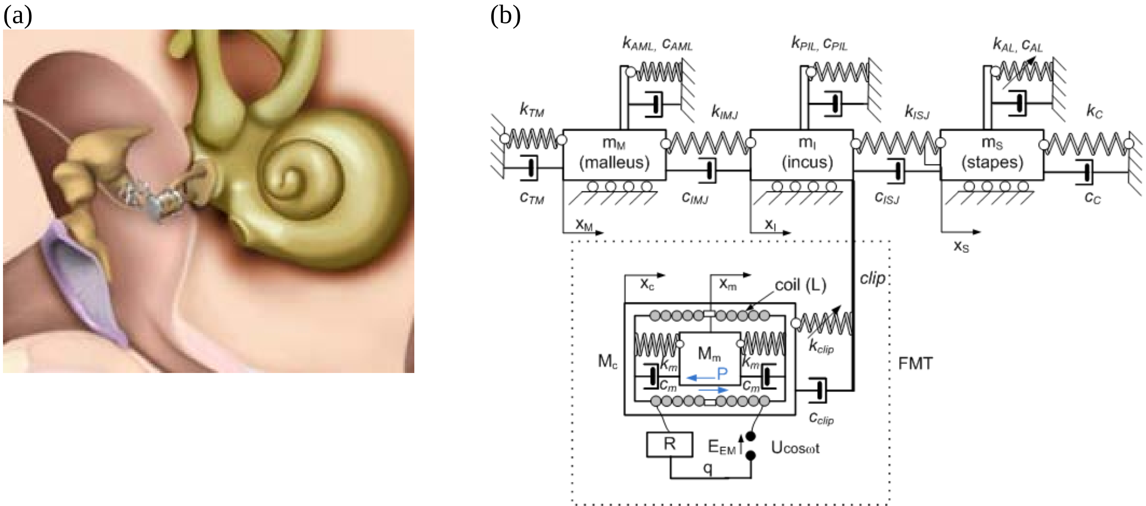

Figure 1: Schematic view of the middle ear with a floating mass transducer (a), lumped mass model of implanted middle ear (b).

Then, the governing differential equations of the IME are as follows

$$
\begin{aligned}
&\ddot{x}_M m_M + \tilde{k}_{11} x_M + \tilde{k}_{12} x_I + \tilde{c}_{11} \dot{x}_M + \tilde{c}_{12} \dot{x}_I = 0 \\
&\ddot{x}_I m_I + \tilde{k}_{21} x_M + \tilde{k}_{22} x_I + \tilde{k}_{23} x_S + \tilde{k}_{24} x_c + \tilde{\beta}_{24} (x_I - x_c)^2 + \tilde{\gamma}_{24} (x_I - x_c)^3 + \tilde{c}_{21} \dot{x}_M + \tilde{c}_{22} \dot{x}_I + \tilde{c}_{23} \dot{x}_S + \tilde{c}_{24} \dot{x}_c = 0 \\
&\ddot{x}_S m_S + \tilde{k}_{32} x_I + \tilde{k}_{33} x_S + \tilde{c}_{32} \dot{x}_I + \tilde{c}_{33} \dot{x}_S + \tilde{\gamma}_3 x_S^3 = 0 \\
&\ddot{x}_c m_c + \tilde{k}_{42} x_I + \tilde{k}_{44} x_c + \tilde{k}_{45} x_m + \tilde{c}_{42} \dot{x}_I + \tilde{c}_{44} \dot{x}_c + \tilde{c}_{45} \dot{x}_m - \tilde{\beta}_{24} (x_I - x_c)^2 - \tilde{\gamma}_{24} (x_I - x_c)^3 - \tilde{\beta}_{45} (x_c - x_m)^2 + \tilde{\gamma}_{45} (x_c - x_m)^3 = \alpha \dot{q} \\
&\ddot{x}_m m_m + \tilde{k}_{54} x_c + \tilde{k}_{55} x_m + \tilde{c}_{54} \dot{x}_c + \tilde{c}_{55} \dot{x}_m + \tilde{\beta}_{45} (x_c - x_m)^2 - \tilde{\gamma}_{45} (x_c - x_m)^3 = -\alpha \dot{q} \\
&L\ddot{q} + R\dot{q} + \alpha(\dot{x}_c - \dot{x}_m) = U_0 \cos(\omega t)
\end{aligned}
\tag{1}
$$

where

$$
\alpha = \alpha_0 - \alpha_1 (x_c - x_m)^2 \quad or \quad \alpha = \alpha_0 e^{-n|(x_c - x_m + d)|} \sin[w(x_c - x_m + d)] \tag{2}
$$

(a) (b)

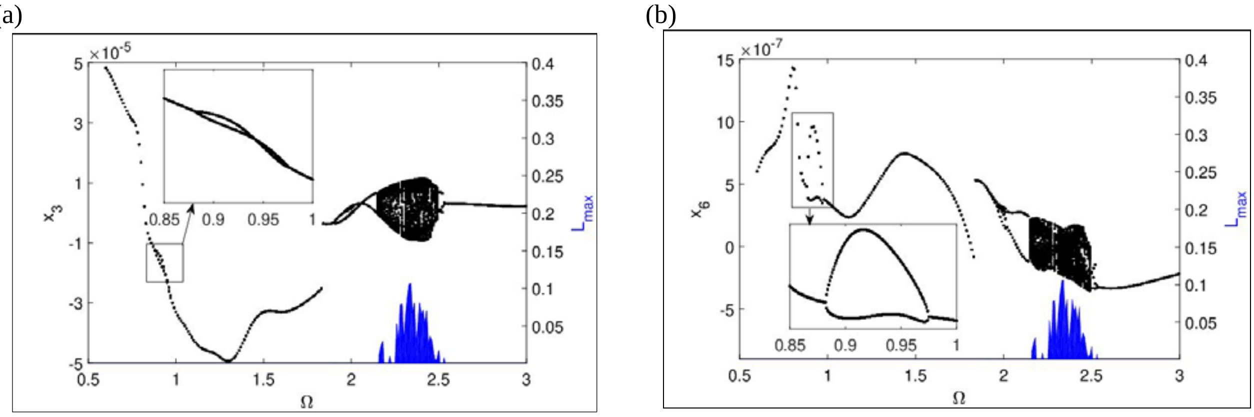

Figure 2: Bifurcation diagrams of stapes motion (a), magnet motion (b) with positive value of maximal Lyapunov exponent (blue).

The results of numerical simulation are presented in Figure 2 as bifurcation diagrams, where Figure 2a presents stapes motion while Figure 2b – motion of the magnet. Both, the stapes and the magnet exhibit regular and chaotic vibrations depending on excitation frequency.

Concluding Remarks

Electromechanical coupling between the electrical circuit and the mechanical part of the implanted middle ear strongly influences system dynamics causing harmonic, subharmonic and even chaotic vibrations for chosen range of excitation frequency.

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