An Influence of Nonlinearity and Discontinuity on Sound Transfer in Reconstructed Middle Ear

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Summary. Biomechanical system of the middle ear can be damaged by various diseases. In this case middle ear prostheses is applied to reconstruct a connection between the stapes and the malleus or the tympanic membrane. Here, a new concept of the prosthesis made of shape memory alloy is proposed to improve the hearing process however behavior of reconstructed middle ear depends on different factors. Therefore, the problem of prosthesis length and proper fixation is analysed here on the basis of continuous and discontinuous model with soft impact. The obtained results show a possibility of different vibrations, regular and irregular.

Introduction

The three ossicles: the malleus, the incus and the stapes create the human middle ear. The ossicles form a sound conduction system which transmits a signal 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 the 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]. 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 also developed where ossicles are represented by lumped masses, connected with springs and dashpots. In the literature, one can find three or four and sometimes even six degrees of freedom model but the most often they are simplified to linear case.

Scientific Problem

In medicine practice middle ear dysfunction happens. It can be caused by chronic otitis media. In this case usually middle ear prostheses is applied to reconstruct connection between the stapes and the malleus or the tympanic membrane. Therefore, a new concept of the prosthesis made of shape memory alloy is proposed here to improve the hearing process [3]. The shape memory prosthesis can adjust its size to individual properties of the patient.
To model a behaviour of the reconstructed middle ear a nonlinear two degrees of freedom system is proposed (Fig.1a) where a polynomial function is used to describe properties of the shape memory prosthesis [4]. Moreover, the model is discontinuous (Fig.1b) to characterize the problem of a proper prosthesis fixation to the stapes. The middle ear system with shape memory prosthesis can have interesting dynamical behaviour depending on temperature, excitation and an initial tension of the prosthesis. Therefore, an analytical and a numerical results of the presented system, described by Eq.1 are shown in this paper.

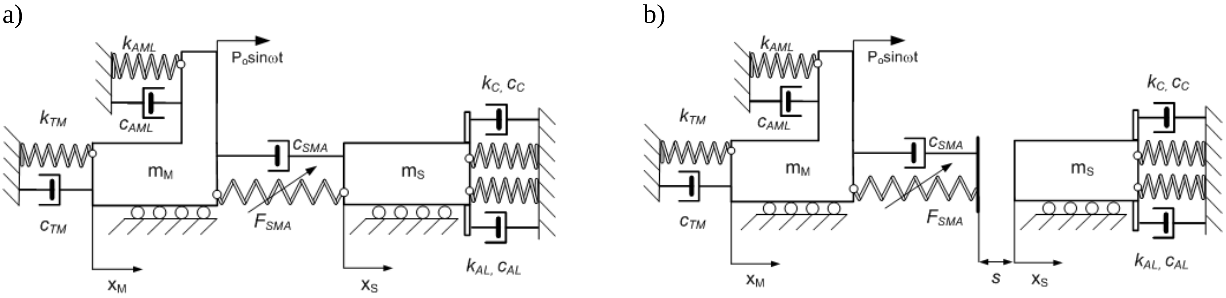

Fig.1 Model with connected (a) and disconnected (b) oscicles of the reconstructed middle ear

$$\begin{aligned} m_M \ddot{x}_M + (c_{TM} + c_{AML})\dot{x}_M + (k_T + k_{AML})x_M + F_{SMA}H(x_M - x_S) = P_0 \sin \omega t \\ m_S \ddot{x}_S + (c_C + c_{AL})\dot{x}_S + (k_{AL} + k_C)x_S - F_{SMA}H(x_M - x_S) = 0 \end{aligned} \tag{1}$$

The force of shape memory prosthesis F_{SMA} in the form of a helical spring is defined as follows:

$$F_{SMA} = c_{SMA}(\dot{x}_M - \dot{x}_S) + \frac{4\pi d^3}{D}\left(\frac{ad(T-T_M)X}{32D^2N\pi} - \frac{bd^3X^3}{48D^6N^3\pi^3} + \frac{b^2d^5X^5}{256aD^{10}N^5\pi^5(T_A-T_M)}\right) \quad (2)$$

Two variants are analysed here. In the first case with fully connected model (without impact) the prosthesis is bounded to the ossicular chain and then the step function H()=1. In the second case, the prosthesis is not fixed to the stapes, then a value of the step function depends on the distance *s*.

Results and Conclusions

Dynamics of the reconstructed middle ear with the help of the shape memory prosthesis, presented in the form bifurcation diagrams in Fig.2, shows a possibility of various kind of motion starting from regular and finishing on chaotic one.

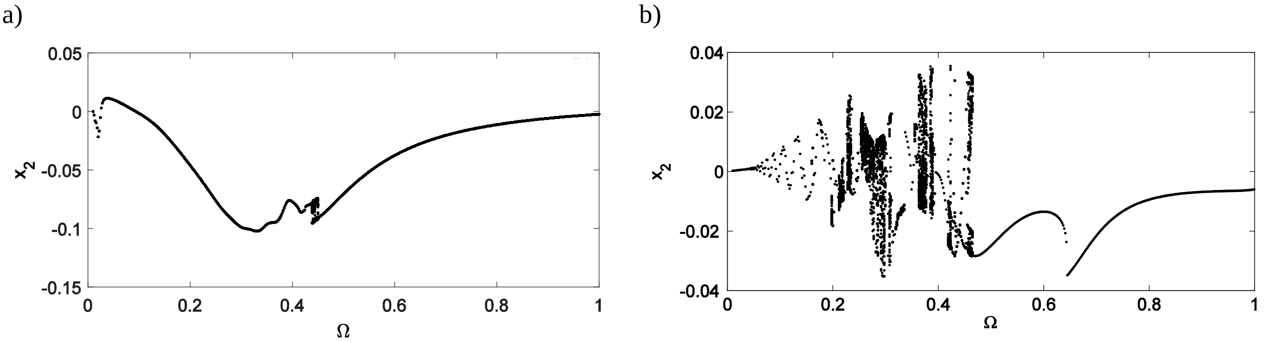

Fig.2 Bifurcation diagrams of stapes motion for fully connected (a) and disconnectedossicular chain (b)

An impact phenomenon and nonlinearities which describe properties of the shape memory element have strong influence on ossicular chain dynamics. More complex analysis of prosthesis length let us choose the best solutions for the patient and understand the mechanism of sound transfer throught the middle ear with shape memory element.

Acknowledgments:

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