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Model-based design of artificial zero power cochlear implant

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ABSTRACT

This paper deals with a model-based design of an autonomous biomechatronic device for sensing and analog signal processing of acoustic signals. The aim is to develop a biomechatronic artificial cochlear implant for people with hearing loss due to damage or disease of their cochlea. The unique artificial electronic cochlear implant is based on an array of microelectromechanical piezoelectric membranes. Oscillations of membranes detect and filter acoustic signals in individual acoustic frequencies. The proposed biomechatronic device of the artificial cochlear implant consists of an active filters array, signal processing electronics, stimulation nerves electrodes and energy harvesting system for autonomous powering of the device. This solution differs from current cochlear implants solutions, which are bulky electronic systems limited by their high power consumption. The multidisciplinary models of the artificial cochlea implant concept are presented. The mechatronic approach based on model seems to be very useful for development of the full implantable cochlear implant which is designed for the sensing and processing of acoustic signals without external energy source.

1. Introduction

The cochlea is a part of human ear, where acoustic signals from outer air space are transferred to electrical signals and then processed by the brain. The loss of hearing is frequently caused due to damage or disease of cochlea [1–5] and in this cases a cochlear implant is the only possibility to recover hearing, at least partially. The current cochlear implants are complex electronic systems which are composed of outer and inner parts. The outer part is placed outside the head and it consists of the following subsystems:

- A microphone to receive the acoustic waves from environment and transfer them into electrical signals.
- A speech processor to decompose the signals into simple frequency components.
- A transmitter to transmit the electrical signals from the outer part into the inner part of cochlear implant.
- A battery for power supplying the cochlear implant.

The inner part is permanently implanted inside of the head and consists of following subsystems:

- A receiver to receive the signals from the outer part of the cochlear implant.
- Stimulation electrodes to connect to the hearing nerve of brain.

Biomechatronic devices such as artificial cochlear implants are developed using modern microelectronic techniques, although there are still some technical issues which need to be solved. For instance, non-full implantability of common cochlear implants is limiting for patients (nowadays, there are only few prototypes of full implantable cochlear implants in the literature [6]) and low number of electrodes are used to reduce energy consumption. Average total power consumption of the implants is around 10 mW and batteries have to be recharged every 12–24 h of operation (depending on stimulation strategies) [7].

Our research presents a unique concept of artificial cochlear implant, which solves the problem of full implantability of this device and power consumption. The proposed artificial cochlear implant is based on a microelectromechanical system (MEMS), which can be fully implantable and has very low power consumption. The main aim of this work is to develop an energy autonomous device, which uses ambient energy in the head area for

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self-powering and without the use of external power supply. Several potential sources of ambient energy are analyzed and evaluated in this paper in order to obtain the self-powered cochlear implant. The use of ultra-low power electronics, an active MEMS sensing and a signal processing is required in case that the energy harvesting system have to supply the whole artificial cochlear implant. The cochlear biomechatronic device employing the active MEMS sensing, ultra-low power signal processing and energy harvesting power supply is presented and evaluated in this paper.

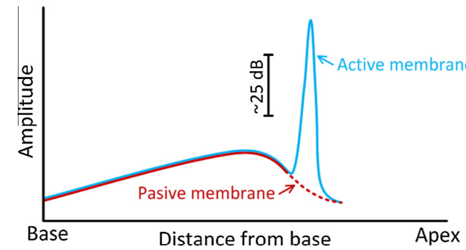

Fig. 1. Comparison between passive and active basilar membrane.

2. State of art

2.1. Cochlear implant

Nowadays cochlear implants use the standard microphones in combination with digital speech processors [8,9]. The disadvantage of standard microphones is their unselectivity for particular frequencies needed for particular nerves stimulation. Therefore the high performance speech processors have to select a desired frequency spectrum. The physical dimensions of the common microphones and their power consumption is not suitable for full implantation. Nowadays, dimensions reduction can be achieved by modern biomedical devices. The miniaturized MEMS microphones have been already developed but the frequency selectivity cannot be achieved yet and for this reason the speech processing is employed. The speech processor decomposes audio signal to the frequency spectrum and each frequencies are processed separately. The total decomposed signal is cumulated until the threshold value of signal power is reached and the nerve is excited by an electric pulse generated by processor. The processor has to prevent interferences between electrodes in the inner ear in case that more signals reaches the threshold value in the same time [10]. Excited signals can be generated synchronously with the defined timing or asynchronously with the priority of the signal with the higher signal power amplitude.

A bank of selective filters created by a MEMS acoustic sensor provides solution without the speech processor usage. Some of current MEMS devices are designed as an array of microcantilevers [11,12] which are not suitable for sensing ambient acoustic pressure like the human cochlea. The micro-membrane represents a much more promising shape of resonator for this purpose. The trapezoidal shapes of membranes are developed by other scientific groups involved in artificial cochlear implants development [13–15]. The trapezoidal shape of the membrane is similar to a basilar membrane which is placed inside the inner ear. The basilar membrane operates as natural mechanical filter where high frequencies excite the membrane on its basal end and low frequencies excite the membrane on its apical end [16]. The real basilar membrane is a highly nonlinear active system [17] which is impossible to be imitated by current MEMS technologies. The comparison between the passive and active basilar membrane vibration is shown in Fig. 1. There is a clearly visible peak in the case of using the active basilar membrane which enables much more accurate resolution in desired frequency range.

The aim of our research group is design, develop and fabricate the complex biomechatronic device which respects all patient aspects and allows miniaturization and integration of the cochlear implant into the autonomous MEMS device, which can be fully implantable in the head. In comparison with the trapezoidal membrane an array of micro-membranes as frequency filters with different dimensions provides the appropriate signal decomposition [18].

The basic principle of the signal decomposition by the array of membrane resonators is shown in Fig. 2. The basilar membrane was simulated as the array of connected resonators by springs with stiffness K_s. A model without connections between resonators achieves better results. The connected springs cause the vibrations of neighbor resonators which are visible in spectrogram as additional false lines.

A low mechanical damping of the resonators is inapplicable for the decomposition of non-stationary signals like speech or common ambient sounds because the spectrogram in this case is smudged due to long transient vibrations of resonators.

2.2. Energy harvesting system for biomedical devices

Several types of energy harvesting systems are currently developed as energy source for biomedical applications [19–22]. Based on the initial analyses and experience with energy harvesting systems, three fundamental types of energy converters in the head area can be considered: thermal gradient, mechanical movement (shocks) and bending movement of neck muscles or arteries in the head area.

2.2.1. Thermoelectric energy conversion

A human body produces waste heat as a result of basal metabolism. This waste heat might be converted into useful electric power by thermoelectric energy conversion based on the Seebeck effect. Temperature difference at the junction of two dissimilar materials produces the electromotive force [23]. Conversion of the small amounts of thermal energy into electricity is called thermoelectric energy harvesting. The common thermoelectric energy harvester consists of thermoelectric module (TEM), power management electronics and thermomechanical integration components. The main thermomechanical integration is usually ensured using the heat sink and heat source with heat spreader. Electric energy generated by the thermoelectric generator is significantly dependent on properties of the materials used in the thermoelectric module. An overview of the physics behind thermoelectric energy harvesting was described in detail previously [23].

Utilization of thermoelectric conversion for the powering of autonomous biomedical implants is a subject of several studies [24–27]. An example of recent effort in the field of bio-implantable thermoelectric generators can be found in the power supply for artificial accommodation system. The proposed device forms a part of the more complex micro-mechatronic system based on adaptive artificial lens. The power consumption of such complex system varies from 5 μW during standby mode up to several mW during the lens actuator operation [26]. A significant development is observed in the field of wearable thermoelectric devices [25]. Measurements performed with 200 mV output using the off-the-shelf TEMs showed the harvested electric power levels of 100–200 μW. Nevertheless, these devices are bulky [27] and generally not applicable for the biomedical implants. Miniaturization of TEMs to the MEMS scale is an issue of contemporary development.