

Biomedical Acoustics: Paper ICA2016-148**A study on the feasibility of MEMS piezoelectric accelerometer coupled to the middle ear as sensor for totally implantable hearing devices****Andre Gesing^(a), Diego Calero^(a), Bernardo Murta^(a), Stephan Paul^(a), Julio Cordioli^(a)**^(a)Federal University of Santa Catarina, Brazil, andre.gesing@lva.ufsc.br, julio.cordioli@ufsc.br**Abstract**

The presence of an external element is still a major limitation of current hearing devices such as hearing aids and cochlear implants. The main problems associated with the external element are discomfort, inconvenience and social stigma, which can be overcome by totally implantable hearing devices. A fundamental requirement of such systems is a totally implantable sensor. In this sense, an accelerometer coupled to the ossicular chain of the middle ear may be used as an alternative sensor to the traditional external microphone. Although micro machined accelerometers are used in a variety of applications, there are no commercially available accelerometers that fulfill the requirements. This paper presents a review on implantable sensors for hearing devices, and requirements for these transducers are summarized. The Finite Element Method (FEM) is used to verify the feasibility of an implantable piezoelectric accelerometer. Design was made considering limitations and characteristics of microelectromechanical systems (MEMS) fabrication techniques. Different designs for the accelerometer are considered, and the results for the sensor response at different points of the ossicular chain are presented and analyzed in view of the defined requirements.

Keywords: MEMS, piezoelectric accelerometer, cochlear implant, implantable hearing devices.

A study on the feasibility of MEMS piezoelectric accelerometer coupled to the middle ear as sensor for totally implantable hearing devices

1 Introduction

Sensorineural hearing loss is characterized by damage to the cochlear hair cells, cochlea injury or damage to the neural auditory system. In several cases its effects can be mitigated by the use of hearing aids (HA) which amplify the sound acquired by one or more microphones by means of vibro-acoustic systems (speakers). This approach is not effective if the inner ear is severely damaged, so that profound hearing loss is present. In these cases, the cochlear implant (CI) appears as an alternative. In conventional CIs sound is captured by one or more microphones, located near the external ear. Signal from the microphone is sent to a digital signal processor (DSP), and, once treated, it is sent via radio frequency (RF) to the receiver surgically implanted under the skin of the skull. An electrode array is the direct interface between the speech processor and the auditory neural tissue in the cochlea [1].

Visibility of parts of the device may cause prejudices to people with such type of hearing device. Also, most devices can not be used under water, during intense physical activities or even in sleep. There are also problems with body noise interference. To deal with part of these limitations, the development of a totally implantable CI (TICI) has been proposed [2]. The components of a TICI (sensor, processor, battery, electrical wires) must be replaceable, made of bio-compatible materials, present no risk of electric shock, and be long-lived.

The implantable sensor is one of the challenges for the TICI development. Available sensor technologies include subcutaneous microphones and different types of sensors implanted in the middle ear. The sensor size can be reduced to be implanted in the middle ear by using micro electromechanical systems (MEMS) technology with several operating mechanisms, including piezoresistive [5], capacitive [6, 7], or piezoelectric accelerometers [8, 9]. Piezoelectric MEMS accelerometers offer a larger bandwidth and lower power consumption than other types of transduction. This work presents a feasibility study of a MEMS piezoelectric accelerometer to be used as a sensor for a TICI. The Finite Element Method (FEM) is used to model the sensor and to extract the parameters for an equivalent circuit (EC) model. The EC model of the sensor is then coupled to a EC model of the middle ear in order to estimate the system sensibility to external sound pressure levels.

2 Implantable sensors

2.1 Sensor requirements

The main requirements for an implantable sensor are defined by the characteristics of the input sound, in this case, speech sound. Therefore, an acceptable sensor bandwidth has been defined as from 100 Hz to 5 kHz in, which covers the speech frequency range and some low frequency sounds [9].

Most CI devices employ an input range from 20 to 80 dB sound pressure level (SPL) to match the dynamic range of human speech [1]. For implantable sensors, an appropriate dynamic range has been assumed to be from 40 to 100 dB SPL [6]. Additionally, implantable sensor materials must be bio-compatible and hermetically sealed. In the case of a sensor coupled to the middle ear ossicles, its size must allow its handling and implantation in the limited space of the middle ear cavity, which is generally assumed to be a maximum dimension of 2 mm [10]. The sensor mass must also be less than 10% of the ossicle's mass to which it will be fixed, so that the sensor does not considerably affect the ossicular chain dynamics and allows the patient to retain residual hearing [6]. Another requirement is low energy consumption, what is generally assumed to be less than 1 mW [6].

2.2 Subcutaneous microphone

Microphone technology satisfies most of the requirements from hearing devices related to sensitivity, bandwidth and directivity, explaining why it is extensively used as external sensors in modern HAs and CIs. Microphones can also be used as implantable sensors, when placed under the skin. A totally implantable HA (TIHA) which used a subcutaneous microphone implanted under the skin of the ear canal was the *TICA* hearing device [13], while Carina is a commercial TIHA that also uses a subcutaneous microphone placed behind the ear pinna [3]. Although a good sensitivity can be achieved by a subcutaneous microphone, problems related to skin infections, presence of body noises and variable sensitivity have been reported in the literature [3, 14].

2.3 Sensors implanted in the middle ear

Sensors implanted in the middle ear capture the ossicles' vibrations produced by external sounds when impinging on the tympanic membrane. This approach avoids the interference of body sounds and preserves the directionality and auricular filtering of the external ear. Some of these sensors use MEMS technology, which allows a considerable reduction of sensor size. Park et al. tested a piezoresistive MEMS accelerometer prototype in temporal bones, achieving a good sensitivity from 900 Hz to 7 kHz [5], but power consumption was an inherent problem of the design (≈ 1 mW). A capacitive MEMS accelerometer attached to the umbo was proposed by Zurcher et al. [7], while Ko et al. presented a capacitive MEMS displacement sensor also coupled directly to the umbo [6]. The sensors performance was compared in [6] showing that the MEMS accelerometer had a limited sensitivity between 2 and 4 kHz, but the MEMS displacement sensor showed a high sensitivity (30 mV/Pa at 94 dB SPL at 1 kHz) mainly at higher frequencies (above 1 kHz). Both capacitive sensors consume about 4.5 mW.

Piezoelectric transducers do not need to be externally powered, so that it has been argued that they would have lower power consumption than the other types of sensor (some power may still need to be provided for amplification purposes). The *Esteem* device is the only commercial TIHA that uses a piezoelectric force sensor implanted in the middle ear [4]. The complexity of the surgery procedure and problems of repositioning and removal of sensor has been reported in the literature [4]. Furthermore, the fixing of the sensor considerably affects the stiffness of the ossicular chain system, modifying its response at low frequencies. The first piezoelectric

MEMS accelerometer to be used as CI sensor was proposed by Beker et al. in 2013 [8]. The study presented a FEM model, validated experimentally through a prototype fabricated with a silicon base and a PZT layer. More recently, Yip et al. mentioned a piezoelectric MEMS accelerometer as a CI sensor, but without specific details concerning the sensor design [9]. The sensor presented a larger bandwidth (300 Hz to 6 kHz) than other MEMS devices, and sensitivity equals to 10 mV/Pa for 90 dB SPL at 1 kHz. Due to the promising results recently reported in the literature concerning piezoelectric MEMS devices, the presented work proposes a further study of the design and analysis of these devices as sensors for totally implantable hearing devices.

3 Design of implantable MEMS piezoelectric accelerometers

The operating modes of piezoelectric accelerometers include shear, bending and compression modes, but piezoelectric MEMS accelerometers generally operate only in the bending mode [15]. In general, a MEMS piezoelectric accelerometer includes: a frame, a seismic mass, a set of beams and a piezoelectric material layer. In the present study, three designs of MEMS piezoelectric accelerometer are analysed as shown in Figure 1. Designs were defined con-

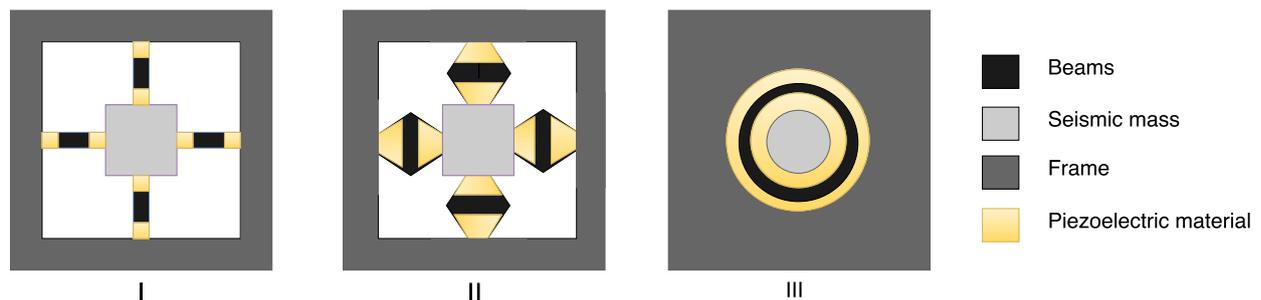


Figure 1: Top view of the different MEMS designs analysed. Design I: trampoline, design II: hexagonal beams with square seismic mass, design III: annular.

sidering MEMS fabrication restrictions imposed by Piezoelectric Multi-User MEMS Processes (PiezoMUMPSTM by MEMSCAP[®]). PiezoMUMPS processes start with a Silicon on Insulator (SOI) wafer which consists of stacks of handle wafers (400 μm), buried oxide (1 μm) and a SOI device layer (10 μm). A 0.5 μm aluminium nitride (AlN) layer is deposited and patterned on top of the SOI. Two metal layers and isolation oxide layers are also included in the process. Minimum feature size is 2 μm . The Finite Element Method has been used previously for simulating the behaviour of MEMS piezoelectric accelerometers and good agreement to experimental results was achieved [16, 17]. For the simulation presented in the present work, Comsol Multiphysics[®]FEM software is used in order to analyse the feasibility of a MEMS piezoelectric accelerometer as a sensor for totally implantable hearing devices.

In this study there are two sets of electrodes (inner and outer), hence differential charge is calculated. The electrodes cover the entire surface of the piezoelectric material, and electric losses at the electrodes are neglected. An optimization procedure based on Genetic Algorithms

(GA) has been applied to the problem with the aim of maximizing the charge sensitivity of each design. Maximum dimension equals to 2 mm and PiezoMUMPS fabrication restrictions are considered in the process.

4 Lumped parameter model of the middle ear and coupled model

In order to analyse the sensitivity of the different designs of piezoelectric MEMS accelerometers in the middle ear, a lumped parameter model was used to represent the coupled system formed by the accelerometer and the ossicles of middle ear. The one-dimensional EC model for the middle ear is shown in Fig. 2 [11], and it includes electrical elements representing mechanical and acoustical magnitudes: resistors for damping elements, capacitors for stiffness elements, and inductors for the masses. Voltage is analogous to pressure and force, current is analogous to volume velocity and velocity. Three transformers represent the tympanic membrane area, the malleus-incus lever ratio, and the stapes footplate area. The tympanic membrane is represented as a distributed-parameter transmission line to include the reflection effects. The parameters of the middle ear model are obtained from measurements of stapes velocity transfer functions and adjusted with a fitting procedure. The principal limitation of using this model is the assumption that the points selected for the sensor position on the ossicular chain have the same velocity vector direction as the piston like movement of the stapes, as shown in Fig. 2, ignoring the other movements of the ossicular chain.

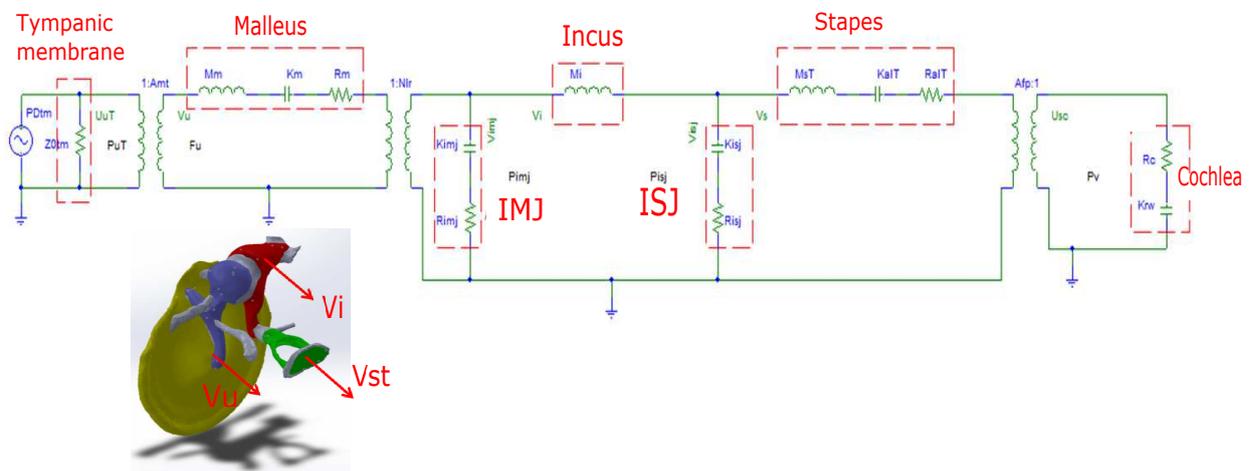


Figure 2: Equivalent circuit model of the middle ear and direction of velocities

A lumped parameter model of the accelerometer was coupled to the middle ear model as shown in Fig. 3. The pre-amplification circuit is also represented in the EC model by an equivalent resistance ($R = 100 \text{ k}\Omega$) in series with the piezoelectric capacitance. The operational amplifier gain will depend on the other circuit elements not considered in this work. The transformer represents the electromechanical coupling.

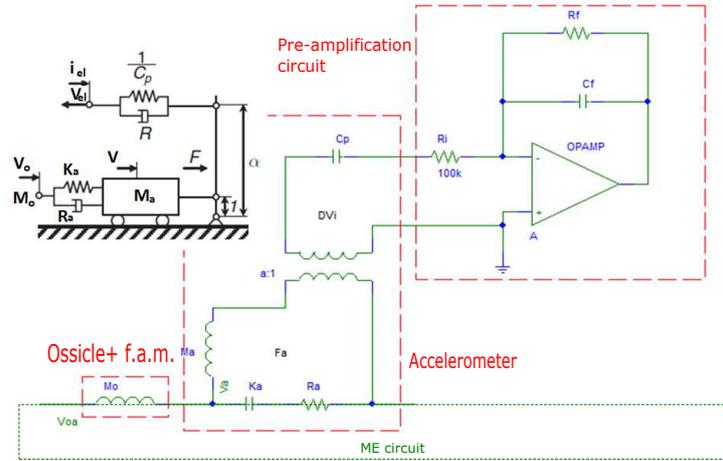


Figure 3: Equivalent circuit model of the accelerometer with its pre-amplification circuit coupled to the ossicular chain

The parameters of the accelerometer's EC model are obtained by means of an analysis of the electrical impedance obtained from measurement in a prototype or by the FE model. The equivalent resistance R_{eq} , inductance L_{eq} and capacitance are related to the electrical admittance (inverse of electrical impedance) Y_{el} by [19]

$$R_{eq} = \frac{1}{\max[\Re(Y_{el})]}; \quad L_{eq} = \frac{R_{eq}}{\omega[\min[\Im(Y_{el})]] - \omega[\max[\Im(Y_{el})]]}; \quad C_{eq} = \frac{1}{L_{eq}\omega_r^2}; \quad (1)$$

The piezoelectric capacitance C_p is obtained from the electrical admittance Y_{el} and the resonance frequency ω_r by [19]

$$C_p = \frac{\max[\Im(Y_{el})] - \min[\Im(Y_{el})]}{2\omega_r}. \quad (2)$$

The mechanical parameters, mass M_a , stiffness K_a and damping R_a are related to the electrical parameters by the electromechanical coupling factor α [19] so that

$$M_a = \frac{L_{eq}}{\alpha^2}; \quad R_a = \frac{R_{eq}}{\alpha^2}; \quad \frac{1}{K_a} = \frac{C_{eq}}{\alpha^2}. \quad (3)$$

Only the seismic mass is considered in the EC model, the remainder of the sensor mass is summed to the ossicle's mass to which the sensor is coupled. Electrical capacitances are measured on the inner and outer electrodes of sensors.

5 Results

The minimum charge sensitivity for the frequency range of interest and natural frequency of the optimized accelerometers are presented in Table 1. Note that the annular design (III) provides the highest charge sensitivity, although it has the highest natural frequency.

Table 1: Charge sensitivity and natural frequency of the different optimized MEMS accelerometers.

Design	Natural frequency [kHz]	Charge sensitivity [pC/g]
I	15.4	0.048
II	10.0	0.051
III	18.8	0.071

Electrical impedance obtained from FE model is compared to the electrical impedance obtained through Eqs (1), (2) and (3) for the CE in Figure 4. It can be noticed that the resonance frequencies from FEM model and EC model are very close, confirming that the EC model can represent this particular aspect of the accelerometers' behaviour in the middle ear model. Calculated values of the EC parameters are resumed in Table 2.

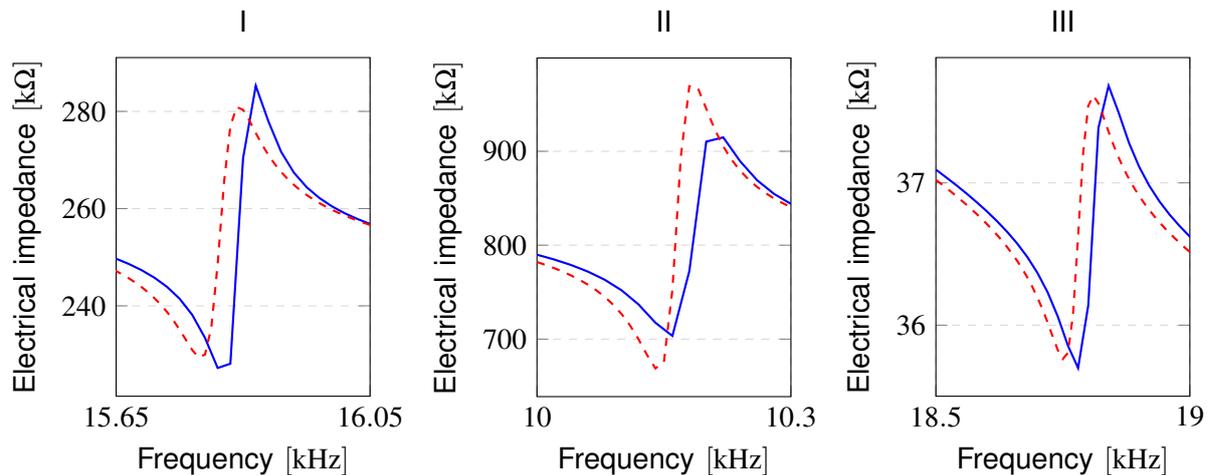


Figure 4: Electrical impedance calculated in the outer electrodes for the different designs. Impedance is obtained by FEM model (—), and then estimated by EC (---).

Table 2: Equivalent circuit parameters of the accelerometers.

Design	Seismic mass [mg]	Total mass [mg]	Stiffness [N/m]	Damping [N.s/m]	Capacitance [pF]
I	0.6	2.0	5883.4	$2.2 \cdot 10^{-4}$	39.6
II	0.8	2.2	2104.8	$1.3 \cdot 10^{-4}$	19.4
III	0.5	1.9	7191.3	$1.9 \cdot 10^{-4}$	231.1

Figure 5 presents the voltage response of the three different designs coupled to the malleus, in the frequency range from 100 Hz to 10 kHz. Note that, although design III (annular) has a higher charge sensitivity, design I (trampoline) has a higher voltage sensitivity when coupled to the the malleus in the middle ear model and an equivalent resistance is considered. This is

due to its lower electrical capacitance and lower mechanical stiffness.

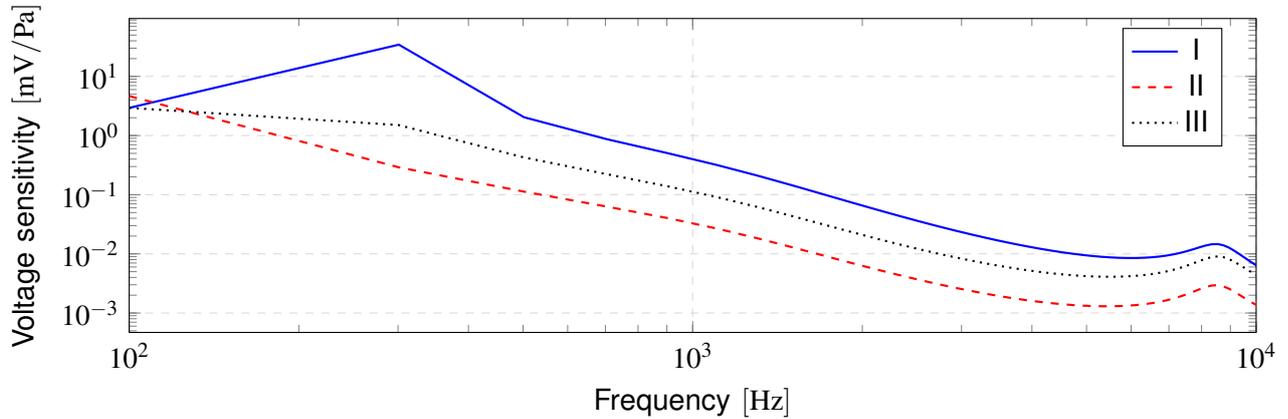


Figure 5: Voltage sensitivity of the different designs coupled to the malleus.

Figure 6 presents the voltage response of the design I accelerometer coupled to each one of the three ossicles of the middle ear. According to this simplified model, malleus and stapes are the best candidates to fix an accelerometer. Voltage responses reach a maximum of 30 mV/Pa at 300 Hz, decaying to 0.7 mV/Pa at 1 kHz. This is comparable to the accelerometer sensitivity of 10 mV/Pa at 90dB SPL at 1 kHz reported in [9] (measured with a charge amplifier circuit), and with the TICA subcutaneous microphone's sensitivity, which was reported to be 2 mV/Pa at 90 dB SPL at 1 kHz [13].

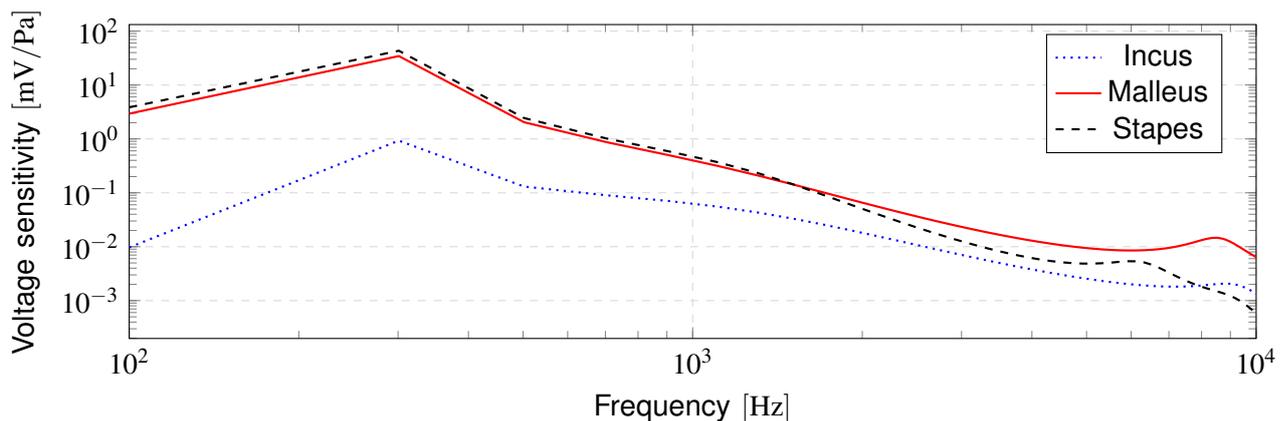


Figure 6: Voltage sensitivity of the design I (trampoline) accelerometer coupled to different ossicles of the middle ear.

6 Conclusions

An approach based on FEM and equivalent circuit (EC) models has been used to investigate the feasibility of MEMS piezoelectric accelerometers as sensors for totally implantable hearing. While the FEM model was used to investigate piezoelectric MEMS accelerometer designs, a CE model of the accelerometer coupled to a middle ear CE model was used to investigate the resulting sensitivity. Preliminary results show that the voltage sensitivities of the MEMS piezoelectric accelerometers coupled to the EC model of the middle ear is similar to other sensors currently being used. Mass of the designed accelerometers vary from 1.9 to 2.3 mg with a maximum dimension of 2 mm when encapsulation is not considered, satisfying part of requirements for an implantable sensor. Different designs incur in large differences in voltage and charge sensitivity. The trampoline design (I) coupled to the malleus achieved the best results so far (voltage sensitivity of 0.7 mV/Pa at 1 kHz), although further analysis are necessary in order to confirm this behaviour. Future works include the development of the charge amplifier circuit, Brownian and electrical noise analysis, and the development of a middle ear model which considers all translational and rotational movements of the ossicular chain.

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