A magnetic probe to study the vibration of the tympanic membrane: Experimental aspects

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1 Introduction

The study of the dynamics of the human tympanic membrane is important for better understanding of the hearing mechanism of the normal and reconstructed middle ear. A middle ear implant, for instance, needs to have the same transmission properties as a normal human middle ear. The transmission properties are determined by evaluating the transfer function of the middle ear, which is determined by measuring the displacement amplitude at both the input (tympanic membrane) and the output (stapes footplate) of the system.

On the other hand, in general any pathology that affects the middle ear results in changes in the vibration amplitude of the tympanic membrane. An otosclerosis, that is a fixation of the ossicular chain of the middle ear results in a stiffening of the tympanic membrane, and therefore in a decreasing of the displacement amplitude. On the contrary, a disarticulation of the ossicular joints results in an increasing of the compliance at the tympanic membrane.

In this paper a new magnetic probe based on a magnetoresisitve sensor is proposed to study the vibrations of the human tympanic membrane. The probe was evaluated with respect to its applicability to detect displacement amplitudes in the tympanum by measurements performed in an excised temporal bone. A sensitivity sufficient to detect vibrations of the order of 50 nm was observed.

2 Methods

Several methods have been proposed to measure the tympanic membrane vibrations, such as: Capacitive probe [1], holography [2], laser interferometer [3] and Mössbauer technique [4]. However most of them are so sophisticated and other are so invasive, that make difficult their wide use. Most of these methods have been used in animals, such as guinea pigs and cats. As an alternative, more recently it has been proposed a magnetic method [5] based on the measurements of the flux changes produced by the vibrations of a small permanent magnet attached to the tympanic membrane. This method uses a SQUID as magnetic sensor and it has been used to measure tympanic membrane vibrations in human cadavers [6].

In this work a magnetic probe using a magnetoresistive sensor is proposed. Although the sensitivity of a magnetoresistive sensor is on the order of 10^{-9} T, which is much less than the sensitivity of a typical SQUID, which is of the order of 10^{-15} T. The fact that the magnetic field for a dipole decreases as r^{-3} and that the small size of the probe allow the possibility of inserting it close to the tympanic membrane, could compensate for this lack of sensitivity.

On the other hand, the size of the probe suggests significant potential for possible measurements in vivo.

The probe developed consisted of a cylinder 9.0 mm diameter and 16.0 mm length, with the magnetoresistive sensor attached in one end. Sinusoidal acoustic stimulation was produced by a loudspeaker located at 1 m from the tympanic membrane. The loudspeaker was inserted in one end of a 50 mm PVC tube focused directly to the tympanic membrane. Measurements of the sound pressure level were performed using a digital decibelimeter located at 1 cm from the tympanum. The magnetoresistive sensor was positioned at 0.5 cm from a small rare earth magnet glued to the tympanic membrane. The direction of maximum sensitivity of the sensor was aligned to the axis of the magnetic moment of the magnet. The piece of permanent magnet used consisted of a 15 mg cube of 1.2 mm sides, which produces a magnetic field of 5 μT at 1 cm. The magnet was glued to the sample by using an organic cement. In Figure 1 a schematic diagram of the experimental system is shown. Using this experimental array measurements were first performed in a phantom consisting of a latex membrane of 65 mm^2 of area, which coincides with the average vibrating area of the human tympanic membrane, and then in a sample consisting of a human temporal bone excised from a male adult 56 years old, which was

preserved in formaldehyde in order to maintain the acoustic characteristics of the tympanum. The sample was prepared by exposing the tympanic membrane by a transversal cut through the external auditory meatus at 3 mm from the tympanum. The middle ear was intact.

The temporal bone was firmly fixed on a heavy non-magnetic base positioned on modelling clay to absorb possible vibrations of the system. The loudspeaker and the sensor were placed separately and isolated from the sample.

Signals from the sensor were sent directly to a lock-in preamplifier and then processed in a PC computer.

To calibrate the probe a PZT transducer was connected to a DC variable power source and glued to one side of a diffraction system. A He-Ne laser of 632.2 nm was used to illuminate the slit. The diffraction pattern was observed in a viewing screen located 3.80 m. Figure 2 shows the results of this calibration. A PZT calibration factor of 60 nm/V was obtained.

With the magnet glued to the PZT and the experimental system in the standard conditions, a calibration of the probe was determined at 200 Hz. A probe calibration factor was determined to be equal to 1 nm/nV.

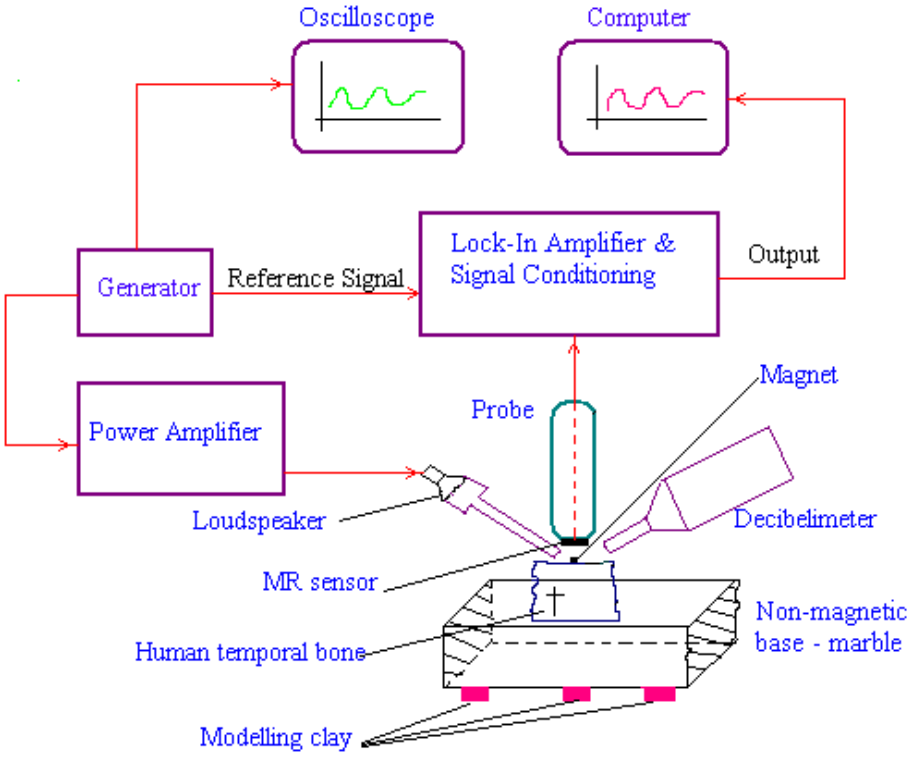

Figure 1: *Schematic diagram of the experimental set up*

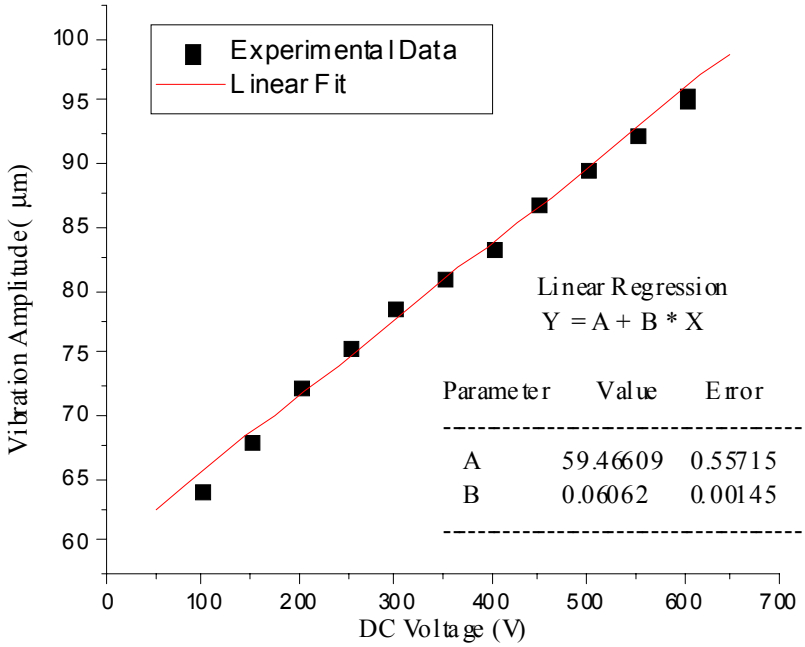

Figure 2: *Results of the calibration of the PZT transducer used to calibrate the MR probe. In this case lower voltages were employed.*

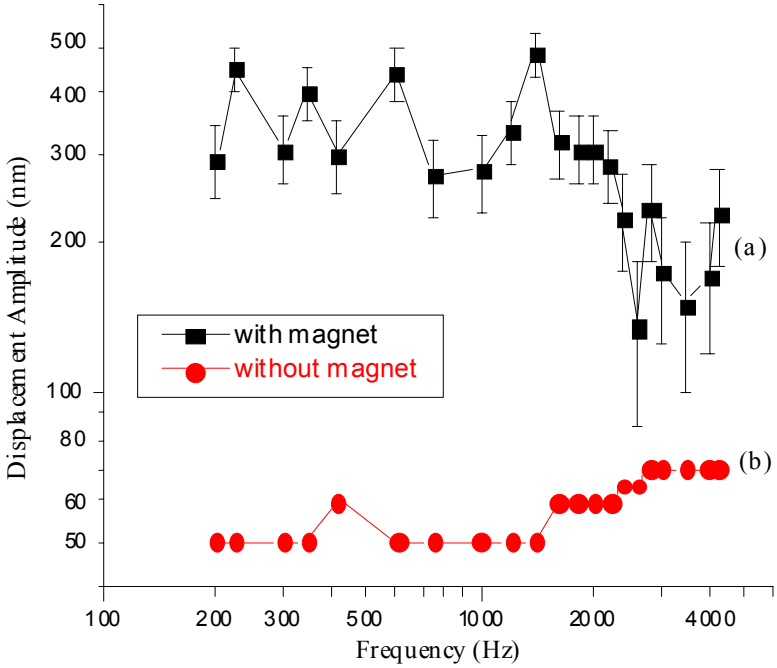

Figure 3: *Tympanic membrane vibration. Uncertainties are systematic only.*

3 Results

Measurements were performed in an excised human temporal bone. The acoustic field was swept from 200 Hz to 5.0 kHz, at frequency values that produces the maximum detected signals, in order to avoid destructive acoustical interference. Figure 3 shown the results of a measurement performed at 100 db SPL. Figure 3a shows the displacement amplitude of the tympanum as a function of the acoustic frequency, showing displacement amplitudes on the order of 300 nm, while in Figure 3b is shown a similar measurement performed on the tympanic membrane after removing the magnet. From these figures a suitable signal to noise ratio is observed. In order to detect parasitic vibrations of the system, measurements were also performed gluing the magnet to the structure on which the temporal bone was fixed and on the temporal bone itself. No signal was observed in any of these cases. On the other hand, measurements were also performed at different SPL for several frequencies (results not shown) demonstrating that the displacement amplitude varies linearly with SPL, as expected. This result agrees with previous experimental findings reported in the literature.

4 Conclusions

A simple new magnetic probe based in a magnetoresistive sensor has been constructed and evaluated with respect to its applicability to detect vibrations of the human tympanic membrane. The probe is shown to have enough sensitivity to measure displacement amplitudes of the order of 50 nm.

Measurements were performed on a human tympanic membrane for frequencies in the range of 200 Hz to 5.0 kHz at SPL = 100 db. Displacement amplitudes on the order of 300 nm were observed for frequencies up to 1.0 kHz and then starts to decrease at higher frequencies. This behavior is in agreement with the Onchi's model [7] of the middle ear, which predicts that the displacement amplitude of the tympanic membrane must increases at low frequencies and decreases at high frequencies when a magnet is attached to it.

Our results are in general agreement with previous results reported in the literature.

Efforts are underway to reduce the size of the probe and to increase its sensitivity in order to allow measurements in vivo and at lower SPL intensities.

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