PZT AND MEMS APPLICATIONS FOR THE VESTIBULAR SYSTEMS

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Abstract

The paper presents a research in the area of PZT and MEMS uses for the vestibular systems. The following will introduce the anatomy and physiology of the inner ear and more specifically, the vestibular system. And some of the modern developments in the field of PZT and MEMS uses for the vestibular systems. It is important to note that holds medical devices more and compact and and that the interest in the field still continues to grow with the development of new devices and new methods for the PZT and MEMS uses in the field of the vestibular systems. Lead zirconium titanate is an intermetallic inorganic compound with the chemical formula $Pb[Zr_xTi_{1-x}]O_3$ *(*$0 \le x \le 1$*). Also called PZT, it is a ceramic perovskite material that shows a marked piezoelectric effect, which finds practical applications in the area of electroceramics. It is a white solid that is insoluble in all solvents. Microelectromechanical systems (MEMS)*

1. INTRODUCTION

The following will introduce the anatomy and physiology of the inner ear and more specifically, the vestibular system, Figure 1 [1].

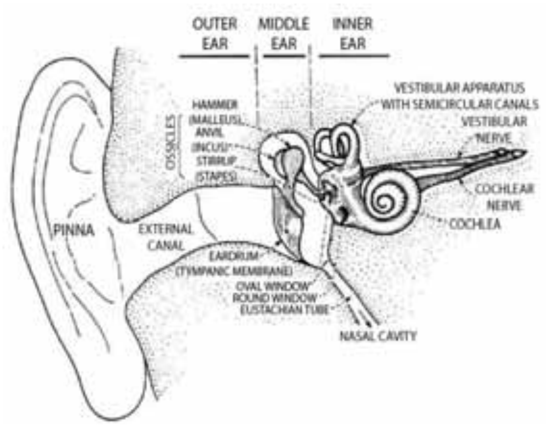

Fig. 1. Anatomy of the human ear [1]

The vestibular system, located in the inner ear, is used to maintain equilibrium bycoordinating motor responses, eye movements, and posture. Bycoordinating head and eye movements, the vestibular system allow for the eyes to remain fixed on a point when the head is in motion [4]. The vestibular organs include the otolith organs, the utricle and saccule, and the semicircular canals (Figure 2). Located within each of these organs are sensory mechanoreceptors in the form of hair cells. The vestibular hair cells respond to accelerations of the head or accelerations due to gravity. [3]

The human vestibular organs consist of the utricle, the saccule, and the three orthogonal semicircular canals. The human semicircular ducts, housed within the semicircular canals, are important in the detection of angular motion and in measuring the head's angular velocity. Three different semicircular ducts are located in different planes. The anterior and posterior ducts are located in the vertical plane at approximately right angles to each other. The lateral duct is in the horizontal plane when the head is tilted down □0□ (Figure 3).

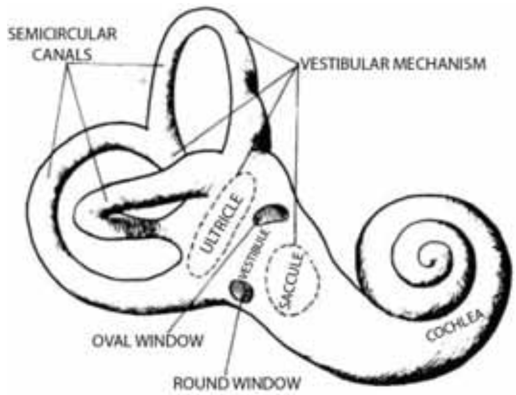

Fig. 2. Human vestibular organs [2]

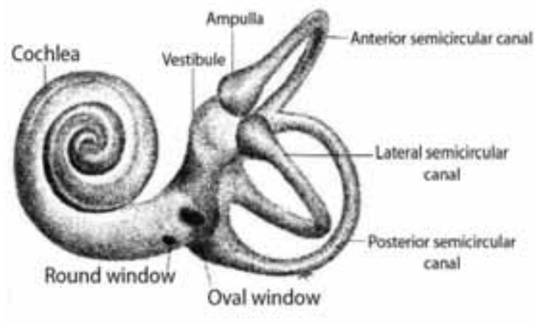

Fig. 3. Orientation of the human semicircular canals in the vestibular system [3]

Each duct forms two thirds of a circle and is ampullated at one end. The ampulla contains the sensory hair cells in a region referred to as the ampullary crest or crista (Figure 4).The ampullary crest contains the hair bundles embedded in a gelatinous mass, the cupula. When the head undergoes angular accelerations, the viscous endolymph in the semicircular ducts lags behind due to inertia and initiates fluid flow in the duct that results in pressure on the cupula (Figure 5). The motion of the cupula elicits a response in the hair cells (Kelly, 1981) [4].

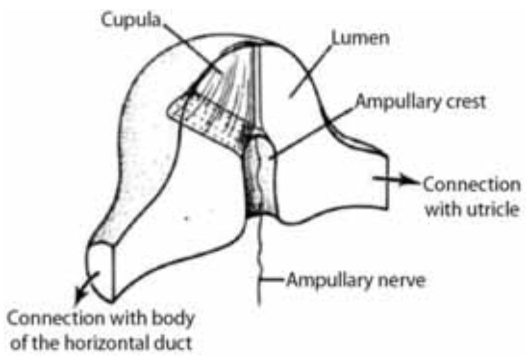

Fig. 4. The ampulla of the semicircular ducts. The ampullary crest contains hair cells embedded in a gelatinous layer, the cupula [4]

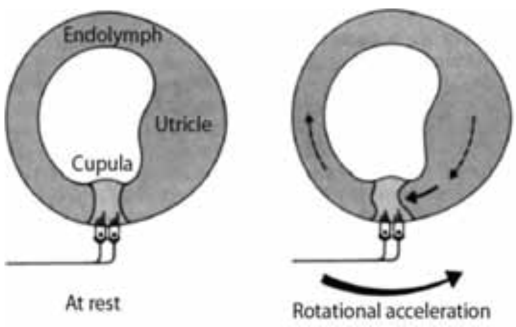

Fig. 5. Positioning of the cupula during angular accelerations [2]

During angular accelerations, the endolymph causes a force on the cupula resulting in a displacement of the cupula and the hair cells embedded in it the entire substance and its contents are referred to as the otolith membrane. The epithelium is connected to the otolithic membrane by a 5-8 μm thick column filament layer [5]. When the head is tilted, gravity will displace the otoconia, causing a disturbance in the gelatinous layer (Figure 6)

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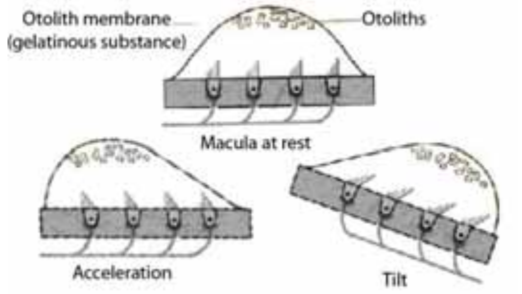

Fig. 6. Displacement of the macula during motion [2]

There is very limited research in the area of inner ear hair cell mechanics. Different techniques have been used to determine the mechanical stiffness of hair bundles. Glass whiskers are used to deflect hair bundles and the deflection is measured with video microscopy or with photodiodes [9].

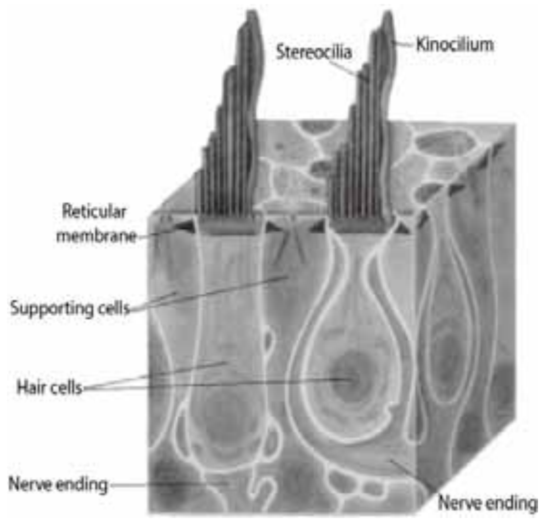

Fig. 8. Hair cells are separated by supporting cells [7]

Another method used to deflect the bundles involves using the stream from a water jet. The resulting stiffness values from previous works are shown in Table 1. These average stiffness values are for different animals and are from different parts of the vestibular and auditory systems. One study showed the relationship between different types of hair bundles in the utricle and their stiffness values. It was found that the striolar hair bundles (stiffness of $2.83\text{-}27.1\times10^{-5}$ N/m) [10]. There has been no research to date comparing the measured location of the hair bundle within the utricle to its stiffness.

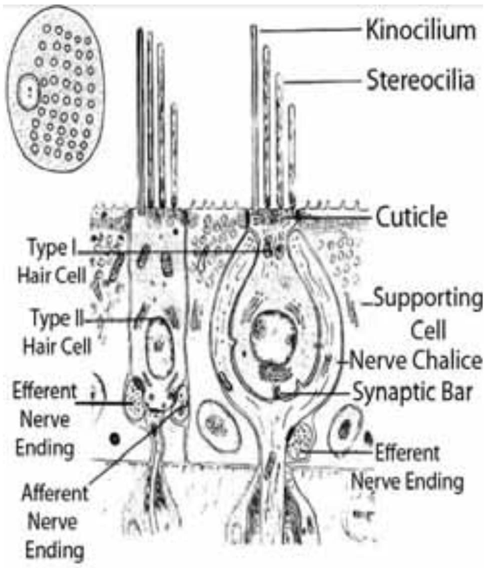

Fig. 9. Hair cell types [8]

Table 1. Experimental stiffness values [11]

INVESTIGATOR	STIFF-NESS ($\times 10^{-4}$ N/m)	HAIR CELL ORGAN
Ashmore (1984)	1.32	frog sacculus
Flock and streiloff(1984)	7.8 to 34.7	guinea pig cochlea
Streiloff and Flock (1984)	1 to 97.2	guinea pig cochlea
Crawford and fettiplace(1985)	6	turtle cochlea
Howard and Ashmore(1986)	2.56	frog sacculus
Howard and Hudspeth(1988)	6.3	bullfrog sacculus
Denk. Webb. And Hudspeth(1989)	3.41	frog sacculus
Russell. Richardson and Kossl(1989)	16 to 35	mouse cochlea
Szymko, Dmitri and saunders (1992)	5.4	chick cochlea

2. EXPERIMENTAL SETUP AND THE EQUIPMENT USED TO LOCATE AND MEASURE A HAIR BUNDLE'S STIFFNESS

A solution was developed to preserve the viability of the hair cells during testing. After measuring the extracellular fluid, or perilymph, in the inner ear of the turtle, it was determined that the fluid had a solute concentration of approximately 300 mOsm. Osmolality measurements were conducted using a VAPRO Vapor Pressure Osmometer 5520. An artificial perilymph (AP) solution was then developed to contain the same osmolality as the actual biological fluid. The solutes in Table 2 were added to one litter of deionized water. Also added were 10 mL of vitamins and 20 mL of amino acids. Once the AP solution was properly mixed, the pH was then measured. In order to get the pH close to the normal pH of blood and most extracellular fluids, the AP solution was titrated with hydrochloric acid until the pH was approximately 7.3-7.4. The AP solutions were stored in 100-mL aliquots, then frozen and thawed upon use.

Table 2. Solute concentrations mixed into a solution to be used during dissection and testing

Solute	milliMolar values (mM)	Mass (grams)
NaCl	144.0	8.415
NaH_2PO_4	0.7	0.084
KCl	5.8	0.432
$CaCl_2$	1.3	0.144
$MgCl_2$	0.9	0.086
HEPES	10.0	2.383
D-Glucose	5.6	1.001

The whiskers are made in a two step process from borosilicate glass rods pulled with a micropipette puller and microforge (Steolting Co.) to a tip diameter of 1-2 μm. Glass whiskers were used because of they were simple to manufacture with the equipment available and it was possible to produce whiskers with a very small stiffness value. The whisker is designed to be less stiff than the bundle so the pipette displacement is greater than the bundle displacement. The glass rods are first placed in the micropipette puller and a piece of clay is placed on the end of the rod. The coils are heated until the pipette begins to elongate due to the weight of the clay. Once the pipette is drawn to approximately 4 μm, the heat is turned off. The rod is then placed in a microforge (Steolting Co.) where it is heated again by a nickel-chromium filament. Another weight is attached to the bottom of the pipette and it is again drawn until the diameter is now 1-3 μm. Another pipette that has already been pulled to approximately 25 μm by the micropipette puller and shaped by the microforge to fit the contour of the slides is aligned perpendicular to the smaller pipette. Using a light sensitive adhesive, the smaller pipette is bonded to the tip of the larger pipette. The smaller pipette is then trimmed to a length of 600-900 μm. The smaller pipette is now referred to as the glass whisker (Figure 10) [10].

The (micromanipulator) Burleigh PCS-5100 was used in "Experimental Measurements of Vestibular

Hair Bundle Stiffness in the Red Ear Slider Turtle Utricle" to hold and manipulate the motion of the pipette. The micromanipulator (Figure 11) [12] utilizes piezoelectric (PZT) actuators to make very small, precise movements.

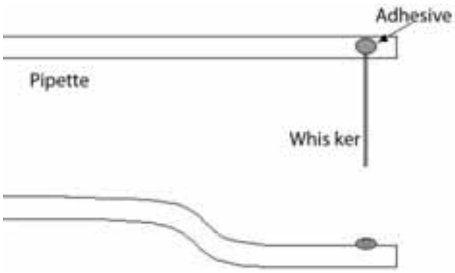

Fig. 10. Pipette with attached whisker [10]. The glass pipette is shaped to fit the contour of the slides on which the utricle is mounted

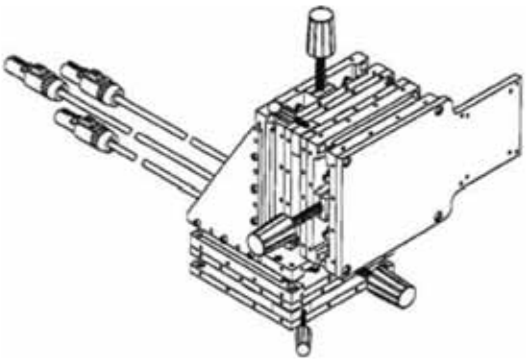

Fig. 11. Micromanipulator (Burleigh manual). The three large knobs on the micromanipulator are used to □ □□□□□□□the pipette in three orthogonal directions [12]

Three actuators allow for motion in three orthogonal directions, up and down, left and right, and forward and backward. An Axis Control Unit (ACU) controls the actual movement. Three knobs on the ACU correspond to the three different directions and are used to move the pipette in those directions (Burleigh manual). The PZT actuators and the ACU are used to position the whisker on the bundle and to produce a force on the bundle. In order to position the whisker in the vicinity of the bundle, screws located on the side of the stage are turned. The screws allow for greater movement, while the actuators and the ACU allow for smaller movements of up to 300 mm. The pipette is held by placing it in a groove on the micromanipulator and another plate is screwed on top to clamp it down, Figure 12.

The groove in the large aluminium plate holds the pipette when the smaller aluminium plate is screwed in to clamp down on the pipette. MEMS and PZT are being used in a device for diagnosing and treating hearing disorders [13]. Figure 13 illustrates a supersonic hearing assist device which includes a transducer 20, a cable 21, and a tuning circuit 22 which is mounted within an electronic housing 23. The transducer is held up against the mastoid process of the temporal bone. The transducer can also be applied to other surfaces of the human body, for example, the Wall of the ear canal, the middle of the human forehead, the human tooth, human clavicle, human spine, or other bones. In general the housing 23 includes a microphone for receiving sounds in the auditory frequency range and a device for amplifying and converting the frequencies to the supersonic range and for applying electrical signals to the transducer.

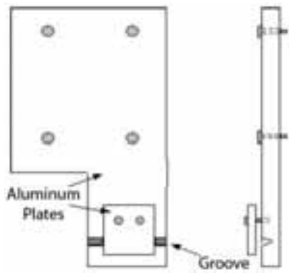

Fig. 12. Pipette holder [10]

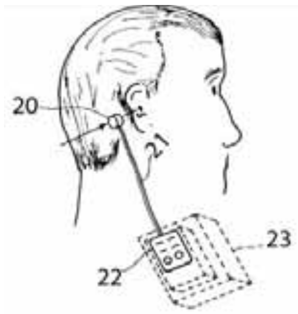

Fig. 13. Supersonic transducer formed in accordance with the invention being used as a hearing assist device

In figure 14, the transducer 20 is best described as a piezoelectric longitudinal vibrator and includes a central piezoelectric ceramic tube 25, a radiating surface or head mass 26, and an inertial or tail mass 27. The radiating surface and inertial mass are tied together by a tensioning rod 28 to keep the assembly from self destructing as a result of large displacements of the radiating surface.

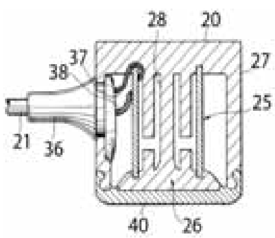

Fig. 14. Enlarged sectional view of the transducer [13]

According to Figure 15, the inertial mass 27 can be formed from separate components which include a generally cylindrical housing 30, a back plate 31, and a nut 32.

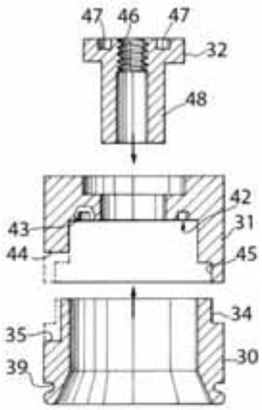

Fig. 15. Exploded sectional view of the tail mass assembly of the transducer [13]

3. CONCLUSION

Of the following, it can be concluded that PZT and MEMS are widely used in the field of research related to the vestibular system, and part of the modern and active developments in the field.

Both electrodes are etched back on both ends of the ceramic a small distance to allow for capture of the ceramic in the ceramic capture ring 42 of the back plate 31 and head mass 26 without resulting in a short circuit. When a voltage is applied across the electrodes of the ceramic, the ceramic either expands or contracts in thickness. This motion is inconsequential to the operation of the device. At the same time, the ceramic also contracts or expands in length and circumference. The expansion and contraction in length is what drives the head mass in a longitudinal vibration.

The ceramic material is selected from the family of lead zirconate titanate (PZT), more specifically from the PZT-4 and PZT-8 ceramics. These particular ceramic materials are selected for their especially low value of dissipation factor or loss tangent, the parameter which relates to the tendency of the ceramic to generate heat as a result of large applied electric fields. The low heat abilities of these materials markedly overshadow the attendant reduced displacement. The static "DC" longitudinal zero to peak displacement D of the cylindrical tube ceramic is given by the expression:

$$D = d_{31} \cdot V \cdot \frac{L}{thk} \qquad (1)$$

where

d_{31} is the piezoelectric charge constant, typically in the range from 97 to 122×10^{-12} m/V for the PZT-8 and PZT-4, respectively,

V is the applied zero to peak voltage,

L is the length of the ceramic tube.

thk is the thickness of the ceramic tube Wall.

The displacements predicted by the above expression are modest, below the levels required for the hearing assist device. The resonant frequency emission typically increases by 35 to 40 dB.

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