Piezoelectric Earcanal Deformation Sensor

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Abstract—The earcanal shape is unique for each human being and temporarily changes when the jaw moves due to eating, chewing or speaking. The earcanal deformation can be studied by the geometrical analysis of a distorted earpiece custom fitted inside the earcanal, but the distortion of the earpiece is complex in nature and complicated to analyze. An earcanal deformation sensor consisting of a thin piezoelectric strip attached to a custom-fitted earpiece is presented in this paper. An analytical approach based on computing the geometrical parameters of distorted and undistorted earpieces is developed to model the electromechanical behavior of the piezoelectric strip for sensing the bending components of the earcanal deformation. The theoretical model is experimentally validated. The proposed approach provides a reliable tool to measure the bending of any curved body in general, and custom-fitted earpieces in particular. It, therefore, enables designing of versatile in-ear sensors capable of tracking jaw activity and evaluating the energy capacity of earcanal deformation for in-ear energy harvesting purposes.

Index Terms—Earcanal deformation, Piezoelectric sensor, Bending of curved surfaces

I. INTRODUCTION

The earcanal is mostly known as the outer part of the human auditory system, however it can offer a variety of sensory applications beside hearing [1]. Heart rate can be monitored by measuring the pressure variance of the surface of the earcanal using a piezoelectric film sensor [2]. Pulmonary monitoring can be done by using pulse oximetry sensors placed inside the earcanal [3]. Brain waves or electroencephalography (EEG) signals can be successfully recorded using either instrumented earpieces worn inside the earcanal [4] or an array of electrodes located around the earcanal [5]. Body temperature can be accurately measured through the earcanal using an infrared tympanic membrane thermometer [6]. In addition, certain tongue movements are detectable by measuring the airflow to or from the ear given the connection of the ear to the oral cavity via the Eustachian tube [7].

Some in-ear sensors are based on the earcanal deformation. Although the earcanal is often considered morphologically rigid, jaw movements change its shape when chewing, talking or even smiling [8]. An Outer Ear Interface (OEI) including some optical proximity sensors has been developed to measure the lower jaw location from the volume expansion in the earcanal [9]. More recently, an in-ear electric field sensing device has been proposed to measure the earcanal deformation based on the impedance measurement of the electrode-skin contact inside the earcanal to control consumer wearables [10]. Other applications are also conceivable for earcanal deformation sensors: jaw gesture detection [9], food intake monitoring [11] and silent speech recognition [12] are a few examples. Unfortunately, measuring the deformation of the earcanal is particularly challenging due to the non-uniform shape of the earcanal and the complex strains exhibited.

In addition, earcanal deformation and its associated dynamic movements are proven to be a promising source of kinetic energy readily available to power in-ear devices such as hearing aids, electronic hearing protections and Bluetooth communication earpieces [13]. A hydro-electromagnetic energy harvester has been developed to convert the earcanal dynamic movements into electricity [14]. Also, an earplug wrapped in a layer of piezoelectric material has been shown to generate an electric potential from the dynamic movements of the earcanal [15]. Given the variation of earcanal shape and deformation among individuals, earcanal deformation sensors can help to estimate the energy potentially available from these dynamic movements during daily activity.

All earcanal deformation sensors proposed so far are active and require an external source of power to operate. A passive earcanal deformation sensor consisting of a piezoelectric strip integrated into a custom-fitted earpiece is presented in this paper. Since any earcanal deformation can impose mechanical loads on an earpiece placed inside the earcanal, the strain resulting from the distortion of the earpiece can be converted into electricity by a piezoelectric sensor. The design of an appropriate earcanal deformation sensor requires a better understanding as to how the earcanal deforms and how the earpiece fitted inside the earcanal gets distorted. Any complex distortion in the shape of the earpiece can be characterized by a combination of three basic mechanical loadings: (1) compression, (2) torsion and (3) bending. It has been shown by the authors that the energy associated with the bending generally surpasses the energy of compression and torsion [16]. Therefore, this paper focuses on measuring the bending strain components of the earcanal deformations.

Piezoelectric devices are most commonly researched and used for strain sensor applications. Polyvinylidene fluoride (PVDF) is a polymer-based piezoelectric material that is widely used in sensors [17], transducers [18], surface acoustic wave devices [19] and energy harvesting systems [20]. The main advantages of PVDF are its ruggedness, flexibility, and chemical inertness. Moreover, PVDF is bio-compatible and therefore suitable for body-worn sensors. PVDF subjected to axial loading has been extensively investigated in the literature [21]. Moreover, PVDF under buckling has been used for sensory applications [22]. In addition, the ability of PVDF sensors array to measure the bending strain on the flat surface of the structure has been proven [23], however, the physics of the pure-bending piezoelectric response of a PVDF film is not well understood [24].

This paper presents an analytical approach to model the PVDF sensor subjected to the bending of curved surfaces in general and the bending of earpieces in particular. Since the earcanal exhibits a considerable bending range during its dynamic movements, the boundary conditions needed for
buckling or stretching are hardly applicable for earcanal deformation sensors. PVDF follows the constitutive equations of piezoelectricity [25] and its behavior can, in principle, be modeled by finite element methods (FEM) [15]. However, given the complex geometry and the poorly characterized deformation of the earcanal, FEM techniques cannot be easily adopted for this problem. Therefore, an analytical model based on the coupled analysis of 3D geometrical analysis and beam bending stress analysis is proposed to model the earcanal deformation sensor. The proposed model is experimentally validated using a PVDF bending sensor designed, fabricated, and tested in order to transform the bending distortion of the earpiece into detectable electric potential.

The rest of the paper is organized as follows: The analytical model of the in-ear bending sensor is developed in Section II. The experimental setup and procedure is elaborated in Section III. The results are discussed in Section IV followed by conclusion in Section V.

II. ANALYTICAL MODELING

The earcanal contains two distinct bends in two different planes separated by an inflection point. The proposed in-ear bending sensor consists of a PVDF strip attached to an earpiece extended over the second bend, as shown in Fig. 1. The PVDF strip covers both bends on the anterior side of the earcanal where maximum deformation occurs. By opening and closing the jaw, the condyle of the mandible is slightly displaced, changing the curvature of the bends, and resulting in bending of the PVDF strip. This bending can be estimated by computing the variation of the curvature of the earpieces. Therefore, the theoretical modeling of the PVDF earcanal deformation sensor comprises four sections: deformation of the earcanal is first investigated by geometrical analysis of custom earpieces fitted at the two extreme positions of the jaw, i.e. open-jaw and closed-jaw, to estimate the bending moment applied to the PVDF earpiece. Then, the mechanical model is developed to calculate stresses applied to the PVDF strip based on the estimated bending moment. Afterwards, the piezoelectric model is constructed to obtain the PVDF induced voltage. Finally, an electrical model is used to calculate the electric potential across a resistive measuring probe.

1) Geometrical analysis: A white light 3D scanning technology (Shining 3D®, Hangzhou, China) was employed to obtain 3D point clouds of 4 custom-fitted earpieces (2 closed-jaw and 2 open-jaw earpieces) obtained using the SonoFit™ custom fitting system (EERS, Montreal, Canada) as shown in Fig. 2. The obtained dense point clouds were then analyzed based on the work presented by Stinson [26] enabling the computation of diameter, curvature and torsion of the scanned earpieces. In this paper, the focus is on the curvature of the center axis and the diameter of the cross section slices, as these two parameters are later used to calculate bending.

According to Stinson’s previous works, the center axis of the earpiece can be obtained by an iterative approach based on the Serret-Frenet coordinate framework. Each coordinate framework is characterized by an orthonormal set of three basic vectors \((\hat{s}, \hat{n}, \hat{b})\) where the first is tangent to the center axis, the second is perpendicular to the center axis and directs to the apparent origin of curvature, and the third is perpendicular to both previous vectors. Typical point clouds representing the earpiece and a Serret-Frenet coordinate framework are shown in Figure 3.

![Earplug point cloud with Serret-Frenet framework](image)

Figure 4 illustrates the diameter and curvature variations along the center axis curve for open-jaw and closed-jaw earpieces obtained from 3D point cloud models. Each curvature plot has two maximums corresponding to two opposing bends and a minimum representing the inflection point after which the curvature changes its direction. The diameter and curvature plots shown in Fig. 4 have been aligned using the inflection point.

2) Mechanical modeling: Since the PVDF strip is initially deformed to comply with the curvature of the earpiece, and assuming that the displacements and strains are limited to small values during earcanal deformation, the Winkler-Bach curved beam theory is used to calculate the stress applied to the PVDF strip [27]. A schematic section of the earcanal bend in the two jaw positions is shown in Fig. 5. The closed
Fig. 4. Diameter and curvature of the earcanal vs. the center axis distance for 4 scanned custom-fitted earpieces

jaw position is defined as having an angle $\theta$ and a radius of curvature $R$; upon opening the jaw when applying a bending moment $M$, this transforms into an angle $\phi$ and a radius of curvature $R'$. Therefore, the strain ($\varepsilon$) at distance $y$ from the center axis can be calculated by [27]:

$$\varepsilon = \varepsilon_0 + \frac{(R' + y)\phi - (R + y)\theta}{(R + y)\theta} - 1$$

Similarly, the strain at the center axis ($\varepsilon_0$) where $y = 0$ equals

$$\varepsilon_0 = \frac{R'\phi}{R\theta} - 1$$

By removing $\phi/\theta$ from Eqs. 1 and 2, one can obtain the strain at an arbitrary distance $y$ as a function of the strain at the center axis by

$$\varepsilon = \varepsilon_0 + (1 + \varepsilon_0)\left(\frac{R' - R}{1 + \kappa y}\right)\frac{y}{1 + \kappa y}$$

where $\kappa$ and $\kappa'$ are the reciprocal of the radius of curvature or simply the curvature of the closed-jaw and open-jaw earpieces respectively. Knowing the strain at an arbitrary distance $y$, the corresponding stress $\sigma$ can be calculated using Hooke’s Law:

$$\sigma = E\varepsilon = E\left[\varepsilon_0 + (1 + \varepsilon_0)\left(\frac{y}{1 + \kappa y}\right)\right]$$

where $E$ is the earpiece’s Young’s modulus of elasticity. The bending moment can be obtained by integrating the moment of all forces around the center axis

$$M = \int \sigma dA$$

By substituting Eq. 4 in Eq. 5, knowing $\int ydA = 0$ and defining a new geometrical parameter, $p^2 = \frac{1}{A} \int \frac{y^2}{1 + \kappa y} dA$, the bending moment $M$ can be written as

$$M = E(1 + \varepsilon_0)(\kappa' - \kappa)p^2 A$$

This geometrical analysis does not provide information about the amount of strain at the center axis, $\varepsilon_0$. However, since the center axis is close to the neutral axis where the strain is zero, it is assumed that $\varepsilon_0$ is a very small quantity and can be neglected in comparison to unity. Therefore, the bending moment equation can be approximated by

$$M \approx E(\kappa' - \kappa)p^2 A$$

Also $p^2$ can be estimated by the following first two terms of the Taylor series expansion for the circular cross section of the earpiece in the closed-jaw position [27]

$$p^2 \approx \frac{d^2}{16} + \frac{d^4 \kappa^2}{128}$$

in which $d$ is the average diameter of the cross section.

Using Eq. 7 as well as the data provided in Fig. 4 and neglecting the stiffness of the PVDF strip, one can estimate how much bending was necessary to transform the earpiece from the closed-jaw to the open-jaw shape. The bending moment induces stress to the PVDF strip at the exterior surface where $y = c$ and $c$ is the earpiece cross section radius. By substituting Eq. 7 into Eq. 4 and simplifying, the axial stress applied to the PVDF strip is estimated by

$$\sigma = \frac{M\kappa}{A}\left[1 + \frac{c}{p^2\kappa(1 + \kappa c)}\right]$$

where $c$ is the average radius whose sign is determined according to the positive direction of the curvature in each section of the earpiece as shown in Fig. 6.

Since the curvature and diameter vary along the center axis, all variables and coefficients in Eq. 9 are functions of $x$, the center axis distance, and are computed using the data presented in Fig. 4. The mean axial stress $\bar{\sigma}$ in the PVDF strip can then be calculated by

$$\bar{\sigma} = \frac{1}{L} \int_0^L \sigma(x)dx$$

in which $L$ is the total length of the center axis.
Fig. 6. Two-dimensional modelisation of the in-ear energy harvester showing the sign of $c$

3) Piezoelectric modeling: According to the constitutive equations of piezoelectricity, the open-circuit voltage $V_{oc}$ of a piezoelectric material subjected to an axial stress can be calculated by [25]:

$$V_{oc} = g_{31} \sigma t$$

in which $t$ is the thickness of the piezoelectric film and $g_{31}$ represents the piezoelectric stress constant. Combining Eq. 7, 9 and 10 and substituting the result in Eq.11 yields:

$$V_{oc} = \frac{g_{31} t}{L} \int_{0}^{L} E(k' - k) \kappa \left[ 1 + \frac{c}{p^2 \kappa(1 - c \kappa)} \right] dx$$

4) Electrical modeling: The electrical equivalent circuit [28] of the piezoelectric earpiece and the measuring setup is illustrated in Fig. 7. The piezoelectric material is modeled by a voltage source in series with a capacitance $C_{PVDF}$ as depicted in the figure below. Also, $R_{\text{probe}}$ represents the resistance of the measuring probe. Under the periodic excitation with the frequency of $f$, the behavior of the piezoelectric thin film is well established [29].

$$V_{oc} = \frac{g_{31} t}{L} \int_{0}^{L} E(k' - k) \kappa \left[ 1 + \frac{c}{p^2 \kappa(1 - c \kappa)} \right] dx$$

III. EXPERIMENTAL SETUP

The in-ear bending sensor is composed of a custom-fitted earpiece as shown in Fig. 8(a). The fitting process of this custom earpiece is based on the proprietary process Sonofit$^\text{TM}$ developed by the authors industrial partners [30]. In this method, the ear impression is taken by injecting a medical grade silicone elastomer, type MED-4910 (NuSil Technology, USA) into an expandable earpiece. The PVDF sheet is cut into a 5 mm-wide strip that was attached to the anterior side of the filled earpiece, as illustrated in Fig. 8(b). Therefore, the initial curvature of the PVDF strip is the same as the curvature of the exterior surface of the closed-jaw earpiece. Since the PVDF strip is located on the exterior surface, it is quite a distance from the bending neutral axis of the earpiece and hence it is either in pure stretching or pure compression while the jaw is opening and closing. Finally, the two electrodes of the PVDF strip are connected to wires, as shown in Fig. 8(c).

The experimental setup consists of a data acquisition system, type NI PXI 1033 (National Instruments$^\text{TM}$, Austin, USA) and a passive probe with 10X attenuation, as shown in Fig. 9. The amplitude and frequency of the earcanal movement depends on jaw activity and varies among individuals. In this experiment, the wearer was asked to consecutively move his jaw between the wide open and relaxed closed positions at which the ear impressions had been taken. In addition, the wearer was requested to maintain the frequency of jaw movements as even as possible. Some intervals of interruption were also considered during the test to verify system noise level.

IV. RESULTS AND DISCUSSIONS

Table I lists the parameters used in the theoretical modeling and experimental validation of the PVDF earcanal deformation sensor subjected to earcanal bending. The results are presented and discussed in this section as to theoretical modeling, experimental measurements and their comparison.
Table I: Parameters of the earcanal deformation sensor implemented in its theoretical model and experimentally validated on one subject.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative permittivity of PVDF</td>
<td>$\epsilon$</td>
<td>12</td>
</tr>
<tr>
<td>Piezoelectric constant</td>
<td>$g_{31}$</td>
<td>0.216 Vm/N</td>
</tr>
<tr>
<td>PVDF Cross section area</td>
<td>$S$</td>
<td>100 cm$^2$</td>
</tr>
<tr>
<td>PVDF Thickness</td>
<td>$t$</td>
<td>110 µm</td>
</tr>
<tr>
<td>Silicone Young’s modulus</td>
<td>$E$</td>
<td>0.89 MPa</td>
</tr>
<tr>
<td>PVDF capacitance</td>
<td>$C_{PVDF}$</td>
<td>9.6 nF</td>
</tr>
<tr>
<td>Probe resistance</td>
<td>$R_{probe}$</td>
<td>10 MΩ</td>
</tr>
</tbody>
</table>

Theoretical model: Using the diameter and curvature plots illustrated in Fig. 4 as well as the parameters given in Table I, Eq. 12 is numerically evaluated for different pairs of open-jaw and closed-jaw earpiece models. The theoretical voltage output for four pairs (2 closed-jaw × 2 open-jaw) of earpieces are computed and demonstrated in Table II.

Table II: Theoretical PVDF voltage output ($V_{out}$) computed from the transformation of 2 closed-jaw and 2 open-jaw ear moldings. Variability in the earpiece molding influences results.

<table>
<thead>
<tr>
<th>Earplug pairs</th>
<th>Closed-jaw No</th>
<th>Open-jaw No</th>
<th>$V_{out}$ (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>1</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>118</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1</td>
<td>278</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>136</td>
</tr>
<tr>
<td>Standard deviation</td>
<td></td>
<td></td>
<td>85</td>
</tr>
</tbody>
</table>

According to Table II, the theoretical output voltage varies greatly among earpiece pairs. It was predictable by the relatively large differences between earpiece diameters and curvatures even at the same jaw position as observed in Fig. 4. There are many reasons why the geometrical parameters of the earpieces are not perfectly identical even if they are taken at the same jaw position and on the same test subject. Firstly, it is difficult to keep the jaw at exactly the same position during the entire earpiece fitting process. This, in particular, influenced the results for the open-jaw earpieces despite the use of a “bite block”, a piece placed between the teeth as visible in Fig. 2. Also, because of the variability of the earpiece molding, the amount of silicone injected for each ear impression is not necessarily the same and there is always a risk of over injection, which influences the earpiece shape [31]. Moreover, there are some errors associated with the scanning process, forming of the point clouds and creating of curved surfaces. Finally, some parameters are adjustable in Stinsons model and should be determined separately for each earpiece model, which could affect the results.

Experimental measurements: Figure 10 shows the measured output voltage of the earcanal deformation sensor. According to this measurement, the peak value of the output voltage is approximately 136 mV calculated by averaging all voltage peaks in the plot with an excitation frequency of $f = 0.5$ Hz.

Model validation: The theoretical and experimental output voltage ($V_{out}$) are compared in Table III. Overall, there is a good agreement between the theoretical and experimental results as demonstrated in Table III.

Some of the discrepancy between the theoretical prediction and experimental measurement can be explained by the uncertainties associated with the earpiece molding, 3D scanning and geometrical analysis, as discussed above. In addition, the theoretical values are larger than experimentally observed, implying that there is less than 100% real efficiency and that...
the PVDF earpiece may not completely follow the eardrum deformation predicted by the theoretical model. Moreover, the model is valid when all the stress is applied instantaneously, while in reality the jaw closing movement is completed in a second or so. Therefore, the more rapidly the jaw closes, the more voltage is produced by the PVDF earpiece and the closer the experimental measurements approach to the model predictions. This effect can be seen in Fig. 10 for the larger voltage peaks.

V. Conclusion

In this paper, an analytical approach was developed to predict the output voltage of a PVDF strip attached to a custom-molded earpiece capable of measuring the strain associated with the bending of the eardrum. The 3D scanning of earpieces fitted at two extreme jaw positions was used to compute the applied bending. The Winkler-Bach theory was then used to estimate the resulting stresses in the PVDF strip and finally the PVDF output voltage was calculated using the piezoelectric constitutive equation. A prototype of the device was designed, fabricated, and tested to investigate the accuracy of the developed theoretical model. The theoretical and experimental results are consistent, supporting the validity of the theoretical model. The main advantage of the analytical model is that it enables one to estimate the bending moment applied by eardrum deformation, which would otherwise be impossible to measure directly. In addition, it effectively converts a complicated 3D bending problem into a 2D mechanical model described by geometrical parameters. Therefore, the proposed theoretical model can be extended to predict any other stress fields developed within distorted piezoelectric layers even if the mechanical loads causing the deformations are unknown or are difficult to measure. The proposed eardrum deformation sensor can be used for the applications require jaw movement tracking and enables us to accurately evaluate the energy capacity of the eardrum dynamic movements to more efficiently design in-ear energy harvesting devices.

VI. Acknowledgements

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References


