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Pyroelectrically Charged Flexible Ferroelectret-Based Tactile Sensor for Surface Texture Detection

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Abstract: Texture detection is one of the essential features requested for artificial tactile sensing to push the demand for flexible low-cost tactile sensors in the robotics sector. In this manuscript, we demonstrate the ability of a ferroelectret-based pressure sensor together with a patterned elastomer layer to detect surface textures. The ferroelectret sensor was fabricated using fluorinated ethylene propylene (FEP) sheets bonded with a patterned adhesive layer to create cavities, integrated with the elastomer bumped surface, and finally charged using a pyroelectric method developed by our group. The ferroelectret-based sensor showed a linear response to the applied force in the range of 0.5 to 2 N, a piezoelectric coefficient of $150.1 ± 3.2$ pC/N in the range of 10–80 Hz, and a flat dynamic response in the range of 10–1000 Hz. The tactile sensing characterization of the sensor, performed at different scanning speeds (10 to 30 mm/s) and gratings with different periodicities (0 to 0.8 mm), showed that the fundamental frequencies observed ranged from 12 Hz to 75 Hz, as expected from the model. These results lay the foundation for the adoption of such sensors in different applications that need fine tactile information, such as an autonomous or teleoperated robotic hand, prostheses, and wearable devices.

Keywords: fluorinated ethylene propylene (FEP); electret; ferroelectret; tactile sensor; biomimetic

1. Introduction

The ability of texture discrimination is an essential feature of artificial tactile sensing for robotic applications in minimally invasive surgery, skin prosthetics, the manufacturing industry, and wearable devices. Several technologies were investigated for developing artificial tactile sensors, based on piezoresistive [1,2], capacitive [3,4], and piezoelectric [5,6] effects. Even if each of the sensing methodologies presents advantages and disadvantages in tactile sensing [7,8], piezoelectric-based tactile sensors provide the highest sensitivity, widest dynamic range, and a high-frequency response [9,10]. However, this type of sensor is not able to detect static stimuli due to the fast decay of a generated charge under a constant external force.

Ferroelectrets are voided dielectrics that present a piezoelectric response due to the interfacial polarization of the internal void surfaces [11,12]. The charge polarization takes place when a high electric field exceeding the breakdown voltage of the air contained in the voids is applied, leading to ionization and orientation of the generated charges on the internal surfaces of the voids. Recently, our group has reported electret and ferroelectret concepts for application in force sensing, invisible digital coding, and energy harvesting [13–16].

The study of the human sense of touch has always attracted the interest of the researchers involved in the field of haptic devices and tactile sensors [17] for robotic applications. Human skin, particularly the fingertips, is provided with a complex com-
bination of different types of mechanoreceptors, which are sensitive to static pressure and time-varying stimuli, such as the vibration occurring at the fingertips when stroking a surface texture [18].

In this paper, we demonstrate the ability of ferroelectret-based tactile sensors in differentiating surface texture profiles. Section 2 reports the tactile sensing model. In the same section, we describe the fabrication process for a ferroelectret-based tactile sensor with FEP and poly(dimethylsiloxane) (PDMS) bump structures, the method for the sensor characterization, and the experimental setup for the tactile ability characterization. Then, the experimental results and their discussion are presented in Section 3, followed by conclusions in Section 4.

2. Materials and Methods

2.1. Tactile Sensing

An established finding in the literature on the neural mechanisms underlying texture perception is the enhanced discrimination sensitivity obtained when a finger explores a surface. The light interaction (contact force in the range of 0.5 to 2 N) between the skin and the surface roughness elicits vibratory mechanical waveforms which propagate into the finger skin and induce the response of the mechanoreceptors. Among the different types of mechanoreceptors, the fast-adapting (FA) mechanoreceptors (Pacinian corpuscles) work as a high-pass filter for vibrational stimuli in a range of 40–500 Hz, with the highest sensitivity around 250 Hz [18,19].

Indeed, the vibration induced by the fingerprint scanning of a largely spaced texture has been proved to correlate with the periodicity of the surface sample [20]. In agreement with those studies, the fundamental frequency is correlated with the spatial frequency of the gratings,

\[ f = \frac{v}{\lambda} \]

which is determined by the scanning speed \( (v) \) and grating spatial wavelength \( (\lambda) \) [20,21].

Imitating the FA mechanoreceptors, the concept is to take advantage of the rapidly adaptive response of a charged FEP ferroelectret sensor to enable the temporal encoding of mechanical vibration cues elicited from the dynamic contact, which facilitates the perception of surface textures. In this preliminary study, the mimicking of patterns on human fingerprints was performed using an array of hemispherical bumps to amplify the texture-induced vibrations [22].

2.2. Sensor Fabrication

The preparation of the sensor, as schematically depicted in Figure 1, divided in two parts: (1) preparation of the ferroelectret sensor and (2) preparation of the PDMS bump structure. At the end of the process, both structures were bonded, and the sensor was charged and characterized.

The ferroelectret sensor was prepared following the protocol previously used in our laboratory [23]. A 25-µm-thick fluorinated ethylene propylene (FEP) sheet was coated with TiW (100 nm) and bonded with another 25-µm-thick FEP sheet using a laser-patterned PVC-film backing double-sided adhesive (170 µm thick) The patterns created on the double-sided acrylic film consisted of 600 µm by 600 µm squares arranged in an array (15 × 17) with a pitch of 1.2 mm, thus creating the cavities between the two FEP layers. The total thickness of the sensor was 220 µm.

The PDMS film, with a 5:1 weight ratio, was fabricated by the micro-molding of an aluminum alloy substrate with micro-dome patterns (350 µm in diameter, 1200 µm in pitch, and 200 µm in height). The PDMS pre-polymer was then spin-coated onto the mold at 400 rpm to reach a thickness of 120 µm, after which it was fully cured at 75 °C for 5 h. Finally, the PDMS replica was carefully peeled off from the mold.

After preparing the FEP ferroelectret, the PDMS pattern was bonded on top of the sensor (Figure 1). For this, as reported in [24], a treatment with an aqueous solution of
(3-Aminopropyl) triethoxysilane (3-APTES) (5% v/v) and plasma oxygen surface treatment were used to improve the adhesion between the metal electrode and the top PDMS layer.

Figure 1. Schematic view of the flexible tactile sensor using FEP and PDMS with an array of bumps on top.

2.3. Charging and Characterization of the Ferroelectret Sensor

After bonding the FEP ferroelectret and the PDMS film, the sample was charged using a pyroelectric method described in previous publications [23]. The charging process takes advantage of the pyroelectric properties of lithium niobate (LiNbO₃) to generate high voltage when subjected to a temperature gradient [25,26]. Thus, a custom-made charging setup, consisting of a thermoelectric cooler and a temperature controller, cycles the temperature of a LiNbO₃ crystal (25 mm diameter, 5 mm thickness) from 10 °C to 80 °C. The ferroelectret sensor, placed on top of the crystal, is subjected to the high electric field that breaks down the air molecules contained in the polymer voids and polarizes the internal surfaces.

The characterization was performed using the direct piezoelectric effect and a custom-made setup. For this, an out-of-plane sinusoidal excitation force \( F \) was applied to the sample under test. In order to characterize the sample over a wide range of frequencies (from 0.5 Hz to 1 kHz) two different types of sensors were employed. For low frequencies (<100 Hz), a load cell (FSAGPNXX010WC2C3, Honeywell, Fort Mill, SC, USA) with a force range of 10 N and a response time of 0.4 ms was used to measure the applied force. At higher frequencies (>100 Hz), a PVDF commercial sensor (Model DT1-052K, TE Connectivity, USA) was employed. Further details about this system can be found in [15]. Using this system, the response of the sensor to different forces and different frequencies was characterized.

As shown in Figure 2, the output voltage of the sensor \( V_{DUT} \) is linear (over the range of frequencies of interest (10 Hz to 80 Hz)) with the force in the range between 0.5 N and 2 N. The sensor was characterized in this narrow range of force to imitate how human touch works. Taking this curve into consideration, and knowing that the total capacitance of the measurement setup \( C \) is 10.5 nF, the piezoelectric coefficient \( d_{33} \) can be extracted using the following equation:

\[
d_{33} = \frac{Q}{F} = \frac{C V_{DUT}}{F}. \tag{2}
\]

Thus, the average value of the \( d_{33} \) over the aforementioned range of forces is 150.1 ± 3.2 pC/N in the range of 10 to 80 Hz.

The frequency response of the sensor (in Figure 3) shows a flat region from 10 up to 1000 Hz, which allows it to cover the typical spectrum of tactile cues.
Thus, the average value of the $d_{33}$ over the aforementioned range of forces is 150.1 ± 3.2 pC/N in the range of 10 to 80 Hz.

Figure 2. The average response of the ferroelectret sensor over the range of frequencies of interest (10 Hz to 80 Hz) for different applied forces (error bars: standard deviations over frequencies).

The frequency response of the sensor (in Figure 3) shows a flat region from 10 up to 1000 Hz, which allows it to cover the typical spectrum of tactile cues.

Figure 3. Characterization of the normalized dynamic response of the charged ferroelectret sensor in the range of 0.4–1000 Hz for different applied forces (error bars: standard deviation over applied force).

2.4. Experimental Setup for Tactile Sensing Characterization

To test the ability of the sensor in detecting texture spatial wavelength, several gratings varying in spatial periodicity were fabricated using a rapid prototyping SLA printer (FORM2 from Formlabs, Somerville, MA, USA). The height and width of the ridges were kept constant at 200 µm and 400 µm, respectively, while the width of grooves was varied from 400 to 800 µm.

The signals from the sensor were pre-amplified/buffered (1 x) and filtered (SR560 from Stanford Research Systems, Sunnyvale, CA, USA) through a first-order band-pass filter with the lower and higher cut-off frequencies at 3 Hz and 1 kHz, respectively, and then acquired through a data acquisition board (T7 pro from Labjack, Lakewood, CO, USA) at 5 kHz. In order to receive feedback about the level of the contact force when the grating touched the sensor, the tactile sensor was attached to a 3-axis load cell (LAN X1 20N from LCT, Xiamen China), while the surface textures with different gratings were fixed to a 3-axis CNC (S-400T from CNC-Step, Geldern, Germany) and scanned at different speeds in the direction perpendicular to the ridges (Figure 4a). Each axis of the load cell was connected to its dedicated 24-bit ADC (HX-711 from Sparkfun, Niwot, CO, USA) through a shielded cable and sampled at 80 Hz. A microcontroller (Teensy v.3.5 from Sparkfun,
Figure 3. Characterization of the normalized dynamic response of the charged ferroelectret sensor (FORM2 from Formlabs, Somerville, MA, USA). The height and width of the ridges were varied in spatial periodicity varying from 400 to 800 μm. The normal force of 1 N. For the spectral analysis, only the signals acquired during a constant velocity phase of the stroke were considered. The acceleration and deceleration phases were excluded. Initial manual control of the applied force was performed at the beginning of each grating. Each sample underwent 6 repetitions at the same speed.

Figure 4. Experimental setup: (a) picture and block diagram of the experimental setup with data acquisition equipment and (b) tactile sensor fixed on top of the load cell.

The signals of the tactile sensor underwent filtering (band pass filter with low and high cut-off frequencies of 8 and 100 Hz) and Fast Fourier Transform (FFT) spectral analysis in Matlab® 2021b. The test was performed by tangentially displacing the gratings over the sensor at velocities ranging from 10 mm/s to 30 mm/s over a length of 30 mm and an average normal force of 1 N. For the spectral analysis, only the signals acquired during a constant velocity phase of the stroke were considered. The acceleration and deceleration phases were excluded. Initial manual control of the applied force was performed at the beginning of each grating. Each sample underwent 6 repetitions at the same speed.

3. Results and Discussions

In this experiment, we validated the ability of the tactile sensor to measure the vibration frequency as it increased with the periodicity of each grating and the scanning speed. We assessed the temporal and spectral domains of the sensor signal in response to the different gratings’ periodicity scanned at the same speed (Figure 5), and to the same grating at different scanning speeds (Figure 6).

According to the spectral range calculated for each segment, the first harmonic appears to be inversely proportional to the periodicity and directly proportional to the velocity, as shown in Figures 5 and 6, respectively.

For each grating, linear regression was used to predict the wave number (inverse of the periodicity) in relation to the fundamental frequency, $f_I$. A significant regression equation was found ($p < 0.05$, $R^2 = 0.99$ for the three gratings). The estimated slope of each curve was 2.5586, 1.7159, and 1.2263 mm$^{-1}$, corresponding to the spatial wavelengths of 0.3908, 0.5828, and 0.8154 mm, respectively, which confirmed how the fittings of the experimental data are in agreement with the model defined in Equation (1).

Based on what is reported in the literature [19–22] and according to the model, the results (Figure 7) showed that the sensor was able to distinguish between all the gratings, and a good correlation was found between the expected and measured frequencies.
Additionally, the sensor’s long-term stability and robustness have not been thoroughly studied over the pattern surface of 0.6 mm periodicity at different scanning speeds.

Data are in agreement with the model defined in Equation (1). The estimated slope of each curve was 2.5586, 1.7159, and 1.2263 mm per harmonic, respectively, which confirmed how the fittings of the experimental data were inversely proportional to the periodicity and directly proportional to the vibration frequency as it increased with the periodicity of each grating and the scanning speed.

### Figure 5.
Temporal (top) and spectral (bottom) of the signal when the sensor is scanned over the smooth and patterned surfaces with different spatial wavelengths (0.4, 0.6, 0.8 mm) including the flat one (0 mm), at the same scanning speeds of 20 mm/s.

### Figure 6.
Temporal (top) and spectral (bottom) variation of the signal when the sensor is scanned over the pattern surface of 0.6 mm periodicity at different scanning speeds.

As mentioned in the introduction, many tactile sensors based on piezoelectric or triboelectric sensing mechanisms have been developed, as in [5,6,27–30]. Several studies ([5,28]) showed the ability to detect time-varying contact stress in the range of low frequencies, up to 30 Hz. In [29], a bandwidth of 10–140 Hz was reported, where only a qualitative tactile ability of texture discrimination was mentioned. The capacity of a tactile sensor to detect vibrating pressure up to 330 Hz was reported in [30]. In our work, the wide bandwidth of the sensor (10–1000 Hz) serves to potentially identify a broad spectrum of spatial wavelength components in surface textures.

Despite the tactile sensor’s demonstrated capacity to identify periodic gratings, this study has certain limitations. First, there was a lack of testing for various contact force levels, including an extensive test on various materials and textures (either regular or random). Additionally, the sensor’s long-term stability and robustness have not been thoroughly verified yet. The sensor’s inherent filtering of spectral components below 10 Hz is another issue, which inhibits the detection of slowly changing touch events. Additionally, more research is needed to validate this strategy utilizing other PDMS pattern geometries and develop a better method for aligning and bonding the PDMS layer to the metal electrode.
Based on what is reported in the literature [19–22] and according to the model, the... be tested. Additionally, the effect of the applied normal force on the piezoelectric coefficient will be evaluated.

4. Conclusions

This work introduced the fabrication and characterization of a pyroelectrically charged ferroelectret-type sensor for surface texture detection. The preparation of the sensor including the ferroelectret structure as well as the PDMS textured surface was presented. The sensor was then charged and characterized, showing a linear response to the applied force in the range of 0.5 to 2 N, and a $d_{33}$ of 150.1 ± 3.2 pC/N in the range of 10 to 80 Hz. Moreover, the dynamic response of the sensor was constant in the range of 10–1000 Hz.

The reported study showed promising results on the ferroelectret-based sensor’s ability to discriminate tactile features. Moreover, a wider range of textures and materials will be tested. Additionally, the effect of the applied normal force on the piezoelectric coefficient will be evaluated.

Despite their inability to detect static stimuli, ferroelectrets demonstrate a high potential to be exploited for tactile sensing in many applications, including autonomous robots, minimally invasive surgery, and wearable devices for rehabilitation, thanks to their low-cost fabrication, self-powering ability, and mechanical flexibility.

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