CHAPTER 7

FORCE ANALYSIS

In this chapter, the force that exerted on the microgripper jaws is measured, as the high force could affect the manipulating objects. This force can be measured either by incorporating the sensing device with the gripper device, or by sensing externally without incorporation. Here, the piezoelectric based sensing mechanism is proposed, which comes under external force measurement. This chapter deals with designing the piezoelectric bar and analysing the force in the microgripper jaws.

7.1 INTRODUCTION

The measurement of the amount of deformation suffered by a structure when subjected to external load is called as a force sensing. In general, the force sensing techniques are classified into two broad categories. Piezoelectric sensors, Strain gauges are widely used in contact, based method, whereas optics-based, hall effect based and capacitive based are familiar with the non-contact type sensing mechanism.

Velosa Moncada et al. (2018) designed MEMS microgripper with rotary electrostatic comb drive microgripper with integrated force sensor for analysing the mechanical characteristics of the circulating tumour cells (CTC). Analytical models were also developed to measure the damping force, resonant frequency, stiffness, etc. when actuated and weighed against with the results acquired from the FEA analysis. This gripper could analyse the
mechanical properties of cells with maximum force of 1.21 N with a large elastic modulus of E = 9.7 KPa. Beyeler et al. (2007) proposed electrostatic microgripper based on a micro electromechanical system with integrated capacitive force sensor. The proposed microgripper provides the force sensitivity higher than the previous monolithic models with gripper jaws opening up to 100 μm. The MEMS ultrasonic device is used to align the objects under the liquid medium using the ultrasonic field. The proposed gripper demonstrated to grip the hela cancer cells with high gripping force of 100 μN for the input driving voltage of 140 V. Piriyanont et al. (2013) developed the MEMS microgripper with integrated electro-thermal force sensor. The proposed device is demonstrated with the 85 μm glass ball which results in the gripping force of 15 μN. For a driving voltage of 100 V, the gripper can accomplish a gripping stroke of 60 μm. Typically, the electrostatic capacitive and electrothermal force sensing technique requires very high voltage in the region of 10 - 150 V which is the main limitation of using this technique, as this could affect the viability of the cells.

To overcome this problem, the contact technique like piezoelectric method can be used because this method does not require any input voltage to sense. In the cell microinjection application, probe type microinjection force sensor have been and it has some real time sensing limitation thus making the integration of force sensor in microinjection operation impossible. Xie et al. (2016) presented the supported-beam based force sensor with piezoelectric polyvinylidene fluoride (PVDF) thin film as the sensing element with the motive to resolve the real time force sensing problems. The corresponding theoretical mechanical and electrical model has been derived and tested the sensing device with zebra fish embryo microinjection. The force experiences by the proposed sensing device for 20, 40 and 80 μm diameter sized molecules are 7.3, 12.1 and 17.9 mN respectively. Mackay et al. (2013) presented the SU-8 electrothermal microgripper with the
tensile force sensor that characterize the operation over the biological samples such as fibrils. The microgripper is actuated using the electrothermal technique, which results in the expansion of the material and ends with gripping action. The resulting force is calibrated with the piezoelectric material. The gripper is demonstrated to handle the three different biological sample of sizes 30, 38 and 45 μm and measured the force using the piezoelectric force sensor, which results in 1.31, 1.67 and 2.04 mN respectively.

In this chapter, the contact force measurement, piezoelectric force measurement technique is proposed, as this method does not require any input voltage to operate which indeed will not affect the viability of the cells. Force exerted on the end effector and in the actuator shuttle measured by this proposed method is presented in this chapter.

7.2 FORCE SENSOR

Monitoring of force that act on the target object is very crucial in many gripping applications, as large force could damage the target. Over the past several decades, researchers developed many kinds of the force sensor. In general, there exist three ways in sensing force, namely, capacitive, piezoelectric and piezoresistive. The capacitive sensor utilizes a diaphragm-cavity construction as a capacitor to measure change occurs in the air gap that is resulted by gripping movement, thus the magnitude of the force is represented by the capacitance difference. This simple design and highly sensitive force sensing mechanism is efficient for lower order force sensing and requires more amount of operating voltage. The most common and a general purpose sensing mechanism is the piezoresistive sensor capable of detecting the force by measuring the strain experienced. However, there exists the factors like slower response for dynamic variations, the dependence over temperature and larger power requirement limits the usage of piezoresistive mechanism. The force experienced is detected in the form of electrical
response in piezoelectric mechanism. The benefits of this mechanism include the quickest response, dynamic load, simple detection circuitry and self powering which makes it superior to the other sensing mechanisms.

### 7.2.1 Piezoelectric Force Sensor

Piezoelectricity discovered by Curie brothers in 1880, discovered the production of surface electric charge in some materials like zincblende, topaz, and quartz, when mechanically stressed. In the following year, Lippmann predicted the inverse piezoelectric effect, i.e. the input voltage produces the mechanical deformation or strain in the material. Piezoelectric are the class of dielectric material, which can be polarized by electric field or by applying the mechanical stress and this, is named as piezoelectricity. The material model exhibiting the piezoelectric effect is shown in Figure 7.1.

In the ideal condition (in the absence of force over the piezoelectric material), the positive and negative charges at the centre coincide and this results in the electrically neutral molecule as depicted in Figure 7.1(a). Later, when the force is acting over the piezoelectric material surface, the internal reticular gets deformed. This action separates the positive and negative charges at the centre and form dipole there as depicted in Figure 7.1(b) and as a result, the fixed charges appear on the surface, as shown in Figure 7.1(c). When the electrode is externally connected to voltmeter in between them and when the force is applied to the piezoelectric material, the fixed charge density emerges at the material’s surface in touch with the electrode as shown in Figure 7.1(d). This polarization produces an electric field, which results in a free surge of charges. This free surge of charges continues until the free charge neutralizes the polarization effect. This indicates that no charges will flow into the steady state or in the unperturbed state.
Figure 7.1  Piezoelectricity (a) Force over the surface, (b) separation of charges and formation of dipole, (c) Appearance of fixed charges and (d) surge of charges due to electric field

In addition, to bring the material to the initial condition, the force is to be removed thereby reversing the flow of charges resulting in the disappearance of polarization. This phenomenon is said to be the “Direct piezoelectric effect” and this is the way the piezoelectric material will act as sensors. The reverse process is the “Indirect piezoelectric effect” where the voltage applied to the piezoelectric material results in the mechanical deformation and this nature will be used when the piezoelectric material will be used as actuators. The constitutive equation describing the piezoelectric property is
\[ \varepsilon_i = S_{ij}^E + d_{mi}^E E_m \]
\[ D_m = d_{mi}^E \sigma_i + \xi_{ik} \varepsilon_k \]

(7.1)

where the i,j=1,2,..,6 and m,k=1,2,3 refers to the direction within the material coordinate system. If the piezoelectric sensor experiences any load, based on the assumption of the applied electric field being zero, the resulting displacement vector is:

\[
\begin{pmatrix}
D_1 \\
D_2 \\
D_3 \\
\end{pmatrix} =
\begin{bmatrix}
0 & 0 & 0 & 0 & d_{15} & 0 \\
0 & 0 & 0 & d_{15} & 0 & 0 \\
d_{31} & d_{31} & d_{33} & 0 & 0 & 0 \\
\end{bmatrix}
\begin{pmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3 \\
\tau_{23} \\
\tau_{31} \\
\tau_{12} \\
\end{pmatrix}
\]

(7.2)

The charge, thus produced can be quantified from

\[ q = \int \int [D_1 \, D_2 \, D_3] \begin{bmatrix} dA_1 \\ dA_2 \\ dA_3 \end{bmatrix} \]

(7.3)

where dA_1, dA_2 and dA_3 represents the differential electrode area in the 2-3, 1-3 and 1-2 planes respectively. The induced voltage \( V_p \) is related to the charge via

\[ V_p = \frac{q}{C_p} \]

(7.4)

where \( C_p \) is the capacitance of the piezoelectric sensor. By measuring the \( V_p \) value, the strain can be calculated by
\[ \varepsilon_i = \frac{C_p V_s}{(1-v)d_{31}E_p l_w} \quad (7.5) \]

where, \( v \) is the poisson’s ratio.

### 7.3 FORCE SENSING MECHANISM

The proposed microgripper is actuated by electrothermal mechanism and this kind of actuation results in high force at the end effector (gripper jaws). As the objective of the proposed gripper is to manipulate the biological cells, the force at the end effector should be in such a way that it should not affect the physiological and morphological characteristics of the targeted cells in order to assist further assays that may be carried out with the manipulated cells. Hence, the force exerted at the end effector of the microgripper should be optimum and it should be measured frequently during the real-time manipulation. Though many researchers attempted to measure the real-time force exerted from the gripper using different sensing mechanism, they failed to effectively sense under the ionic solution condition. This is because of several reasons like: high voltage could affect the viability of the targeted cell in the case of electrostatic sensing mechanism, high temperature could lead to bubble formation and thus affecting the physiology of the cell. Whereas in the case of electrothermal mechanism, low force sensing efficiency in the case of mechanical sensing mechanism, high voltage problem in piezoelectric sensing mechanism, etc. Hence, a highly efficient force sensing mechanism is in demand, as force is being a very important parameter to be measured in manipulating the biological cells.

Here, the predetermined force sensing mechanism is adopted, as this will not affect the biological cell in any manner. The proposed sensing method will measure the force exerted in the gripper jaws in prior, way before it is used in manipulation applications. This method utilizes the piezoelectric
material capable of measuring forces in the range of μN level, which eventually could increase the sensing efficiency. The force sensing methodology is pictorially represented in the following Figure 7.2.

Figure 7.2 Pre-force measurement of the microgripper using piezoelectric bar

In this proposed work, the force is measured in prior because of the advantages exerting high efficiency by using the piezoelectric measurement, it does not affect the biological cells as the force is not going to be measured during manipulation as mentioned earlier. The piezoelectric material lead zirconate titanate (PZT), is placed between the gripper jaws. This PZT is being used for various reasons: it is physically strong, chemically inert and relatively inexpensive in manufacturing. Also, they can be easily tailored according to our requirement. It even has greater sensitivity and high operating temperature when compared with other piezoelectric materials.

The contact pads present in the actuating arms accept the actuating voltage. Due to joule heating principle and thermal expansion property based on the applied voltage, the actuating arm expands which pushes the gripping
arm to actuate in-plane but in an outward direction. Both the actuators exhibit the same motion, the movement of the gripping arms produces the closing action in the gripper jaws that can grip or hold the objects with size of interest. Because of the closing action, the gripper jaw holds the piezoelectric material, which induces the surface stress to the piezoelectric material. This induced stress polarizes the material and this creates the surface charge that can be extracted away with the conducting electrode. The extracted charge is fed to the measurement unit where the charge is converted to equivalent voltage and displayed therein, and then the force equivalent to the obtained voltage is calculated. This calculated force is equivalent to the force that exerted in the gripper jaws. This procedure is repeated for various input voltages, the corresponding force is calculated by the defined methodology, and all the obtained values are noted down as the predetermined force values. At the same time, the displacement of the gripper jaws equivalent to the input voltages are measured, which can be used during the manipulation of biological cells.

During the real-time manipulation, when the gripper is used to manipulate any biological cell of a particular cell, the corresponding input voltage needed to hold is observed from the predetermined displacement value and that specific voltage is applied to the actuating arms. This will result in the manipulation of biological cells and the relative force exerted is obtained from the predetermined force value. This way of measuring the force does not require any sensing mechanisms like electrostatic, mechanical, piezoelectric, electrothermal, piezoresistive, etc. during the real-time manipulation. This greatly reduces the adverse effects caused in the physiology and viability of cells and bubble formation. On the other hand, this reduces the fabrication complexity, reduction in power consumption during external force sensing mechanism, precision in force measurement, effective source utilization and more.
7.3.1 Computational analysis of force measurement

The predetermined force measurement methodology is implemented using the software based computational analysis for the designed microgripper. The PZT ceramic material, which is the piezoelectric material chosen for sensor design, is designed in a square shape as depicted in Figure 7.3, in which the direction of force applied is indicated with the help of arrow marks (gripping action). The dimension of the designed PZT ceramic is 40 μm x 40 μm. Some of the properties of PZT ceramic such as density, elasticity modulus, poisson’s ratio (v), direct charge coefficient (d33), transverse charge coefficient (d13), curie point, etc. are specified in below table 7.1. This piezoelectric material is designed to be placed between the gripper jaws (as specified in Figure 7.2).

<table>
<thead>
<tr>
<th>Table 7.1 Properties of PZT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parameter</strong></td>
</tr>
<tr>
<td>Density</td>
</tr>
<tr>
<td>Elasticity modulus (N/m²)</td>
</tr>
<tr>
<td>v</td>
</tr>
<tr>
<td>d13 (m/V)</td>
</tr>
<tr>
<td>d33 (m/V)</td>
</tr>
<tr>
<td>d15 (m/V)</td>
</tr>
<tr>
<td>Curie point (°C)</td>
</tr>
</tbody>
</table>

Electric current module and solid mechanics module are used to model the piezoelectric behaviour. Initially, the electric current and input force is set to zero. The electric voltage is applied to the actuating arm of the microgripper. Due to joule heat and thermal expansion property of aluminium metal, the material gets expanded and pushes the centre shuttle outwards in in-plane direction. This process is carried out in both the actuating arm in
order to get the gripping action. This subsequently pushes the gripping arm and thus the gripper jaws get actuated and moves close to each other in in-plane rather than out-of-plane direction. This ends up with the gripping action.

![Diagram of PZT bar dimension for gripper jaw opening](attachment:image.png)

**Figure 7.3 PZT bar dimension for gripper jaw opening**

As the PZT bar is positioned in between the gripper jaws, the closing action results in gripping of the PZT bar, which induces the stress in the piezoelectric material. This induced stress ultimately leads to the surface charge creation and this can be extracted by connecting the electrode to it, which will be measured with a voltmeter. This output of the voltmeter corresponds to the amount of force applied to the PZT material, which corresponds to the input potential applied. The simulation is carried out for the input voltages ranging from 0 to 0.12 V. For applied potential, the force is needed to be calculated in two areas,

(i) Force on the actuating arm

(ii) Force on the gripper jaw

### 7.3.2 Force on the Actuating Arm

The input potential is applied to the contact pads of the developed gripper and it is varied from 0 to 0.12 V. This expands the material based on
joule heating and thermal expansion property and pulls the centre shuttle outwards in in-plane direction. This action pushes the gripping arms with a certain force and this force should be in a such a way that it should not affect the gripper arm (should not break or affect in any manner) in order to have a reliable gripper. Hence, the force of the actuating arm should be measured. This force is measured by placing the piezoelectric bar near to the actuating arm first. Once the input voltage is applied to the contact pads, this actuates the centre shuttle which in turn induces stress in the piezoelectric material. This creates the surface charge and this is measured by defining terminal to the material surface in the electric current module. This induced voltage is measured for various input voltages and listed out in table 7.2. Then, the force equivalent to the output voltage is calculated and listed in the same table 7.2. As the maximum required input voltage to the gripper is limited to 0.125 V, the corresponding output voltage attained is 2.63 V, as shown in Figure 7.4, and the equivalent force that is exerted in the actuator arm is calculated to be 55 mN.

Table 7.2 Force in the actuator arm for 0 to 0.125 V input voltages

<table>
<thead>
<tr>
<th>Input voltage (V)</th>
<th>Displacement (μm)</th>
<th>Output voltage (V)</th>
<th>Force (mN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.025</td>
<td>0.34</td>
<td>0.08</td>
<td>2.2</td>
</tr>
<tr>
<td>0.05</td>
<td>1.36</td>
<td>0.362</td>
<td>8.76</td>
</tr>
<tr>
<td>0.075</td>
<td>3.04</td>
<td>0.81</td>
<td>19.5</td>
</tr>
<tr>
<td>0.1</td>
<td>5.41</td>
<td>1.4119</td>
<td>33.9</td>
</tr>
<tr>
<td>0.125</td>
<td>8.5</td>
<td>2.63</td>
<td>55</td>
</tr>
</tbody>
</table>

7.3.3 Force on the gripper jaws

The force that is exerted in the actuator arm pushes the gripping arm and this ends up with the closing action of the gripper jaws. Indeed, the force in the actuator arms gets transported to the gripper jaws and this force
enables the gripper jaws to hold the targeted cells effectively. Now, the PZT bar is positioned in between the gripper jaws and the same procedure (as in previous actuator arms force calculation section) is repeated. Now, the output voltage from the PZT bar relative to the input voltage is noted down for various input voltages and listed out in Table 7.3. The corresponding force that exerted on the PZT bar in the gripper jaws is calculated and tabulated in Table 7.3. The output voltage attained for a maximum of 0.125 V is 10.26 mV, as shown in Figure. 7.5, and the equivalent force exerted in the gripper jaws is 245 μN.

![Figure 7.4 Electric potential from PZT for 0.125 V at the actuating arm](image)

**Table 7.3 Force in the gripper jaws for 0 to 0.125 V input voltages**

<table>
<thead>
<tr>
<th>Input voltage (V)</th>
<th>Displacement (μm)</th>
<th>Output voltage (mV)</th>
<th>Force (μN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.025</td>
<td>1.02</td>
<td>0.4</td>
<td>9.9</td>
</tr>
<tr>
<td>0.05</td>
<td>4.08</td>
<td>1.5</td>
<td>38</td>
</tr>
<tr>
<td>0.075</td>
<td>9.15</td>
<td>3.7</td>
<td>86.5</td>
</tr>
<tr>
<td>0.1</td>
<td>16.3</td>
<td>6.45</td>
<td>154</td>
</tr>
<tr>
<td>0.125</td>
<td>25.5</td>
<td>11.7</td>
<td>245</td>
</tr>
</tbody>
</table>

The force in both the gripper jaws and near the actuator arm is calculated for the input voltages 0 to 0.125 V and their corresponding forces are represented graphically in Figure. 7.6. For 0.125 V, the forces in the
gripper arm and in the actuator arm were 245 μN and 55 mN respectively. It is made clear that the force transported from the actuator arm to the gripper jaws gets drastically reduced in the order from mN range to μN range. This means, though the actuator arm produces higher force, the force is getting reduced in the gripper jaws thereby enabling the safe handling of the micro objects or biological cells without affecting its physiological properties. Hence, this gripper produces gripping movement with forces in the μN range, which ultimately extends its applications towards biological manipulation.

![Figure 7.5 Electric potential from PZT for 0.125 V at the gripper jaws](image1)

![Figure 7.6 Voltage vs Force (with and without beams near the jaws)](image2)
7.4 SUMMARY

In this chapter, the piezoelectric force sensing methodology and its advantages over other methodologies is discussed extensively. Then, the force measurement that exerted in the proposed electrothermal microgripper is analysed computations in COMSOL software by developing the piezoelectric bar made of PZT (lead zirconate titanate) material. The force, both in the actuating arm and in the gripper jaws, were measured with the developed PZT bar. For 0.125 V, the force of the actuating arms is computed to be 55 mN and in the gripper jaw, it is computed to be 245 μN. This shows that, though the actuator arm produces higher force, the force gets reduced in the gripper jaws, thereby enabling the safe handling of the micro objects or biological cells without affecting its physiological properties.