CHAPTER 4

DESIGN AND MODELING OF CANTILEVER BASED ELECTROSTATICALLY ACTUATED MICROGRIPPER WITH IMPROVED PERFORMANCE

4.1 INTRODUCTION

Bio-manipulation techniques and tools including optical tweezers, acoustic traps, magnetic tweezers, hydrodynamic flows and pipettes are powerful for specific micro-applications; however, these techniques require expensive experimental set-ups. The picking, handling and releasing of micron sized objects in the field of robotics, and the bio-manipulation and assembling of micro parts, are challenging concepts, which require proper design and analysis of the devices (Khan et al 2010) like microgrippers. The micromanipulation of devices is based on the principle of micro tweezers, which will grasp the objects using the force created by the microgripper. In recent years, microgrippers developed for the micromanipulation of biological samples are very effective. They are operated, based on different actuation mechanisms.

The electrostatically driven microgripper with an inter-digitated comb drive is one of the widely used microgrippers. These microgrippers possess the cantilever structure, and the design of the same with improved displacement is considered in the present work. Here, non-rectangular finger shapes are investigated for increasing the displacement of a given voltage excitation. The objective of this work is to design a simple microgripper
based on the cantilever structure which is of good displacement, which operates on lower voltage, as compared to the existing electrostatically actuated microgripper. Here performances of different finger shapes have to be analysed and best performing finger shape has to be identified. In order to meet the objective, different finger shapes are chosen, as discussed in Chapter 3, which have either a constant or a linear force profile. The linear force profile is required for effective actuation and control of microgrippers. The linear force profile simplifies the control system required for the microgripper (Jensen et al 2003). Amongst the shaped fingers, the optimal finger shape proposed by Ye et al (1998) is also considered for analysis, to compare the performances of the previous work. As reported in chapter 3, best performing finger shape has been identified based on the optimization code by the author Ye et al (1998). But, the analytical modeling is not done to found the best performing finger shape. But, in this work the best performing finger shape is to be identified using analytical modeling. On incorporating the proposed designs of shaped fingers, it is found that the displacement of the microgripper is improved. In order to validate the simulation results analytical calculations are done, and it is found that both the results are in good agreement.

In this work, the load analysis of gripper is also done, to verify the load carrying capability of the proposed gripper. This is done to determine whether the displacement of the shaped finger gripper is affected by the load.

In the design of the microgripper, the pull-in analysis is also done, using the closed form models derived in Chapter 2. This is done to determine the safe operating voltage so as to actuate the microgripper. The designed microgripper with different finger shapes is finally fabricated, tested and its performance is validated.
4.2 MICROGRIPPER MODELING

4.2.a Displacement Analysis

An electrostatic gripper is one of the simplest actuation based grippers. The main part of this type of actuators is the comb drive. Comb drives are made of two combs, a movable one and a fixed one. When voltage is applied between two combs, it generates a force, moving the movable comb.

![Comb Drive Diagram](image)

**Figure 4.1 Lateral and transverse comb-drive**

In comb-drives, the electrostatic force can be controlled by controlling the applied voltage (Khan et al 2010). Figure 4.1 shows the typical design layout of a combdrive. It has two types of movement configuration. 1. Lateral and 2. Transverse. The lateral comb-drive is used for microgripper applications (Khan et al 2010).

In a microgripper, the magnitude of the force depends on the applied voltage and the geometry of the fingers. For rectangular fingers, the force generated is constant as the gap between the fixed and moving fingers is
constant. But in the shaped fingers, the gap between the fingers is varied, as they engage. Hence, the force is also varied. In this work, three new finger shapes, which were proposed in Chapter 3, are used. The optimal finger shaped gripper is also designed and analyzed. Further, the microgripper and its displacement is verified with FEM simulations, and the simulation results are compared with the analytical results. The microgripper with the rectangular finger has been simulated in IntelliSuite, which is shown in figure 4.2. The parts of the gripper are shown in Table 4.1, and its dimensions are given in Table 4.2. In the previous chapter the considered gap distance between the fingers is 2 µm, but it is increased to 10 µm in the design of microgripper because of the limitation in fabrication facility. Minimum feature size which can be fabricated was limited to 5 µm, therefore the finger size is increased, and hence the gap between the fingers had to be increased to 10 µm. Microgripper with the regular rectangular finger shape has been replaced with the proposed finger shapes as shown in figure 3.1. New microgripper models with the proposed finger shapes, and microgripper with the optimal finger shape has been simulated. Then the microgripper is fabricated and its performance is tested and validated.

![Figure 4.2 Model of a microgripper with a rectangular finger in IntelliSuite](image-url)

*Figure 4.2 Model of a microgripper with a rectangular finger in IntelliSuite*
Table 4.1 Description of the parts of the microgripper

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Extension arm</td>
</tr>
<tr>
<td>2</td>
<td>Jaw</td>
</tr>
<tr>
<td>3</td>
<td>Movable Comb</td>
</tr>
<tr>
<td>4</td>
<td>Stationary Comb</td>
</tr>
<tr>
<td>5</td>
<td>Actuator pad</td>
</tr>
<tr>
<td>6</td>
<td>Outer beam</td>
</tr>
<tr>
<td>7</td>
<td>Central beam</td>
</tr>
</tbody>
</table>

Table 4.2 Dimensions of the microgripper

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Length of the Finger</th>
<th>Width of the Finger</th>
<th>Height of the Finger</th>
<th>No. of Fingers</th>
<th>Length of the Extension Arm</th>
<th>Gap Between Fingers</th>
<th>Over Lap</th>
<th>Width of the Beam</th>
<th>Gap Between Jaws</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values (µm)</td>
<td>15</td>
<td>1</td>
<td>1.2</td>
<td>28</td>
<td>101</td>
<td>10</td>
<td>5.6</td>
<td>1.2</td>
<td>10</td>
</tr>
</tbody>
</table>

4.2.b Load Analysis of Microgripper

A microgripper force model is developed to estimate the force exerted by grippers when grasping an object. The input for the model is the weight of the object being lifted and the output is the amount of force that needs to be exerted by the gripper to grasp that object securely.

Analysis of the gripper with load is carried out using the following procedure.

Input for the model = Weight of the object being lifted.

Output is the amount of force that needs to be exerted by the finger to grasp that object securely. Here the object assumed is spherical in shape for example, a Dried red blood cell. Force exerted by the gripper is given in Equation (4.1) with reference to [99]

\[
F = \frac{mg_1}{2\mu_1\cos \theta - 2\sin \theta}
\] (4.1)
where $m$ – mass of the load in kg

$g_1$ – Gravitational constant 9.8 m/s²

$\mu_1$ - frictional coefficient between gripper and load

$\theta$ – Angle between the load and gripper.

Calculation of force/contact area (Pressure) is described below.

Load or objects aimed to grip: Dried red blood cell.

Diameter of one red blood cell = 8 µm.

Mass of one red blood cell = 27 picogram

$\mu_1 = 0.38$

Angle between the load and jaw = 35°

Using Equation (4.1), Force exerted = 2 x 10⁻⁶ N

Surface area of gripper jaw = 50 µm

Pressure = Force exerted /Surface Area = 0.0312 Pa.

Simulation is done using IntelliSuite software (IntelliSuite 2007) with this value of pressure applied on the jaws of the gripper.

4.3 FEM SIMULATION OF MICROGRIPPER USING INTELLISUITE

IntelliSuite is a FEM based software, which simulates the fabrication process as well as the performance of the MEMS device. It is IntelliSense’s tool for MEMS, and it has been utilized to efficiently design the process specifications and performance of devices, such as gyros, accelerometers, pressure sensors, microphones and optical sensing devices.
IntelliMask is used to create 2D masks for the microfabrication process. Masks can be imported in GDSII and DXF formats. All the basic shapes are available to draw the required mask files. From the mask file, the designed layouts can be imported either to a 3-D builder to add the height information, or to IntelliFab to visualize the virtual fabrication process.

The 3D Builder is an IntelliSuite module for building and meshing the three-dimensional geometry of MEMS structures. The mask layout form IntelliMask may be imported here, and the 3-D structure can be drawn. The required model can be directly built, as a set of layers in a 3-D builder. The elements are the basic building blocks that make the mesh. The mesh must be compatible; otherwise, the analysis cannot be done.

Meshing is done automatically by IntelliSuite. This automatic meshing will refine the mesh globally. But this is undesirable, since both the areas of mechanical importance as well as those of non-mechanical importance will be refined. So, local meshing is preferred. Mechanical and electrostatic meshing are the two available local meshes. The mechanical mesh uses a 3-D brick solid element. But the electrostatic mesh uses the triangular surface element. A Mesh convergence study has to be done, by performing a series of analyse and refining the mesh.

ThermoElectroMechanical is the coupled electromechanical analysis, which is used to find the displacement for the applied voltage. It couples both the finite element and boundary element techniques.

4.4 ANALYTICAL MODELING OF THE MICROGRIPPER

Electrostatic force is calculated using the force equation given in Equation (4.2).


\[ F = \frac{\varepsilon_0 n t V^2}{g} \]  

(4.2)

where, \( \varepsilon_0 \) – the permittivity, \( n \) – number of fingers, \( t \) – thickness of finger, \( g \) – gap distance between fingers, \( V \) – applied voltage. The spring constant \( (k) \) is given by Equation (4.3).

\[ k = \frac{E w t^3}{4 l^3} \]  

(4.3)

where, \( w \) – width of the beam and \( l \) – length of the beam. Then, the displacement \((x)\) is calculated using the Equation (4.4)

\[ F = kx \]  

(4.4)

The displacement results that are calculated using simulation, are compared with the analytically computed displacements. It is found that both the results are in good agreement, with a maximum percentage error of 1.2%, which is discussed in the next section.

4.5 RESULTS AND DISCUSSION

4.5.1 Pull-in Analysis of Microgripper

The closed form models proposed in chapter 2, are also applied to find the pull-in voltage of the electrostatically actuated microgripper. Figure 4.8 shows the FEM model of the rectangular microgripper. Similar to the cantilever beam simulation described in Chapter 2, here also the CoSolve (coupled analysis of MemMech and MemElectro) of CoventorWare is used to detect the pull-in voltage of microgripper. The pull-in voltage comparison for the rectangular microgripper is given in Table 4.3.
Figure 4.3 FEM simulation of the pull-in analysis in CoventorWare

Table 4.3 Pull-in voltage and % Error comparison for the microgripper

<table>
<thead>
<tr>
<th>Models</th>
<th>$V_{PI,1}$</th>
<th>$V_{PI,3}$</th>
<th>$V_{PI,4}$</th>
<th>$V_{PI,5}$</th>
<th>Coventor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pull-in voltage</td>
<td>29.331</td>
<td>38.898</td>
<td>24.612</td>
<td>27.346</td>
<td>29.688</td>
</tr>
<tr>
<td>%Error</td>
<td>1.202</td>
<td>7.886</td>
<td>31.032</td>
<td>17.097</td>
<td>-</td>
</tr>
</tbody>
</table>

With reference to the results presented in Chapter 2 on the pull-in voltage analysis, for a dimension range of $w/d_0 \leq 2$, $V_{PI,1}$ was found to be the better suited model with less error. It may be noted that as per the conclusions in Chapter 2, in Table 4.3 also, with the dimension range being $w/d_0 \leq 2$, the $V_{PI,1}$ shows an error of 1.202%, which is less compared to that of the other models. Hence, the closed form model approach discussed in Chapter 2 is once again validated by the pull-in voltage analysis of the microgripper.
4.5.2 Displacement Analysis of Microgripper

The microgripper with the proposed finger shapes, as given in Figures 3.1 (a) to (e) in Chapter 3, is simulated in IntelliSuite. To verify the constant displacement behavior of the rectangular finger microgripper, it is also simulated. The simulation results showing the displacements of microgrippers for all shapes, has been shown in figures 4.3 through 4.7.

Figure 4.4 Simulation model of the microgripper with the rectangular finger

Figure 4.5 Simulation model of the microgripper with the tapered 1 finger
Figure 4.6 Simulation model of the microgripper with tapered 2 finger

Figure 4.7 Simulation model of the microgripper with stepped finger

Figure 4.8 Simulation model of the microgripper with optimal finger
Table 4.4 provides the comparison of the simulation and analytical results of the microgripper with different shapes. It is found that both the results are in good agreement, with a maximum percentage error of 1.9%. From the results it could be seen, that for the same voltage the displacement has been increased by modifying the finger shapes, and it also provides a linear force profile. For the rectangular finger, a displacement of about 1.9 µm has been obtained at a voltage of 14 volts. On the other hand, a displacement of 3 µm and 4.44 µm has been obtained at 14 volts for microgrippers, with finger Tapered 1 and Tapered 2 shapes. A displacement of about 6.66 µm has been obtained for the microgripper with a stepped finger shape. The microgripper with the optimized finger shape (Ye et al, 1998) gives a displacement of 9 µm. Therefore among all the shapes, a better displacement is achieved by the optimized finger shape based design, as could be seen from the results presented in Table 4.4.

Table 4.4 Comparison of the displacement of the microgrippers

<table>
<thead>
<tr>
<th>Microgripper - Finger shape</th>
<th>Voltage (Volts)</th>
<th>Displacement (µm)</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FEM</td>
<td>Analytical</td>
<td></td>
</tr>
<tr>
<td>Rectangular</td>
<td>14</td>
<td>1.92</td>
<td>1.885</td>
</tr>
<tr>
<td>Tapered 1</td>
<td>14</td>
<td>3.04</td>
<td>2.99</td>
</tr>
<tr>
<td>Tapered 2</td>
<td>14</td>
<td>4.44</td>
<td>4.3835</td>
</tr>
<tr>
<td>Stepped</td>
<td>14</td>
<td>6.66</td>
<td>6.7318</td>
</tr>
<tr>
<td>Optimal</td>
<td>14</td>
<td>9.09</td>
<td>8.9758</td>
</tr>
</tbody>
</table>

4.5.3 Analysis of Microgripper with Load

Table 4.5 gives the simulation results of microgripper with load. The force exerted by the microgripper while carrying the load is calculated using the procedure is described in section 4.2.b. amount of load applied on the gripper is 0.0312 Pa.
Table 4.5 Comparison of the displacement of microgrippers with load

<table>
<thead>
<tr>
<th>Microgripper (Finger shape)</th>
<th>Displacement (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Rectangular</td>
<td>0.027</td>
</tr>
<tr>
<td>Tapered 1</td>
<td>0.003</td>
</tr>
<tr>
<td>Tapered 2</td>
<td>0.2458</td>
</tr>
<tr>
<td>Stepped</td>
<td>0.2</td>
</tr>
<tr>
<td>Optimal</td>
<td>0.327</td>
</tr>
</tbody>
</table>

Comparing the displacement results of microgripper with and without load shows that the in-plane displacement (y) is slightly reduced with the application of load. The result also shows that the out of plane displacement (z) is appreciably increased due to the load which is exerting a force on the gripper. With this analysis it is clear that the proposed gripper is showing a good performance even with load.

4.5.4 V-I Characteristics of Microgripper

The microgrippers are fabricated, using the bulk micromachining technique on an N type SOI wafer. Microgrippers and cantilever beams are fabricated in the same sample. The fabrication details and fabrication steps are discussed in detail in section 2.5 of Chapter 2.

Though all the devices were successfully fabricated, the dimensions of the device were such, that it developed a force in the order of pico-newtons as obtained from the analytical calculation. This could not be measured due to the limitation of the characterization facility.

A voltage upto 100 V is applied across the microgripper for which no appreciable displacement could be observed, because the grippers developed a force in the order of pico-newtons. So in order to measure such a small force and displacement it was required to apply higher voltage
excitation. Analytical calculation showed that a voltage excitation of 2500 volts needs to be applied to get a displacement $2.6 \times 10^{-4}$ µm. Indeed the device characterisation facility did not support a voltage sweep above 100 volts. Therefore, the displacement in the designed microgripper could not be observed. Therefore to analyse the performance of microgripper, the current which is the cause of force and displacement is measured.

This study shows that amongst microgripper made of different finger shapes the optimized finger shaped microgripper performs better as it develops higher force for a given current. Therefore, from this study, though the displacement cannot be physically measured, it is concluded that the optimized finger shape would result in a higher displacement as it develops higher force amongst all the considered finger shapes. This optimized finger shape provides the best performance whose analytical study is done in the previous chapter of this thesis.

The SEM image of fabricated microgripper is shown in Figure 4.9. A closer look of the fabricated microgripper is shown in Figure 4.10. Using the characterisation facility at CeNSE Laboratory, IISc the Voltage Vs. Current (V-I) characteristics are obtained for the device.

![Figure 4.9 SEM Image of the fabricated microgripper with tapered 1 finger (CeNSE Laboratory, IISc)](image_url)
Figure 4.10 A closer look of the SEM Image of fabricated microgripper tapered 1 (CeNSE Laboratory, IISc)

The experimental setup of the 4-point probe station using which the V-I characteristics are obtained is shown in Figure 4.11. Figure 4.12 shows the simulation results of V-I characteristics of microgripper with different finger shapes. The comparison of the V-I characteristics obtained from the simulation and experimental results of the device of tapered 1 shaped microgripper is shown in Figure 4.13. The results fairly match each other.

From the figure 4.12, it could be seen that the current increases several hundreds of times from rectangular shape to tapered case and highest in the optimal case. This is due to the fact that the average current density (Current density = Current/Area) of the device is increasing manifold from rectangular to the optimal case as shown in Table 4.6.
### Table 4.6 Microgripper and its current density

<table>
<thead>
<tr>
<th>Type of Microgripper</th>
<th>Average Current Density (A/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectangular</td>
<td>4.63403E-07</td>
</tr>
<tr>
<td>Tapered 1</td>
<td>1.97E-05</td>
</tr>
<tr>
<td>Tapered 2</td>
<td>5.93E-06</td>
</tr>
<tr>
<td>Stepped</td>
<td>8.78E-06</td>
</tr>
<tr>
<td>Optimal</td>
<td>1.18E-04</td>
</tr>
</tbody>
</table>

The area of cross-section of different types of fingers is changing and hence current density is also changing for the same applied voltage. For rectangular finger the area of cross section remains same. Hence the change in current density is same and hence current of rectangular microgripper is lower compared to the other types of microgripper. The cross sectional area of optimal finger is the lowest amoung all and therefore the average current density is highest in that case. Since the average cross sectional area is decreasing it resulted in the increase of the respective current density and hence the current values. This feature is expressed through the simulation results shown in Figure 4.12.

Experimental and simulation study is performed on the microgripper made of parallel plate model. A D.C. voltage sweep from 0 to 100 volts is applied across the parallel plate and the corresponding current values have been noted using 4 point probe station. The charging current was initially rising and got saturated once it reached the steady state, as the applied voltage is D.C. in nature, in all the cases. Since the displacement was very small and could not be measured, the V-I characteristics study helped in analysing the trend of developed force with respect to the increase in current, as force is proportional to the square of the current.
Figure 4.11 Four point probe station to obtain V-I characteristics (CeNSE Laboratory, IISc)

Figure 4.12 Simulated V-I characteristics of the various types of microgrippers

Figure 4.13 shows the comparison of the simulation and experimental results of V-I characteristics of the one of the microgrippers, that is the type, tapered 1 finger. The deviation in results may be due to the
residual stress and also due to the various fabrication issues present in the fabricated microgripper.

![V-I Characteristics of Microgripper](image)

**Figure 4.13 V-I characteristics of fabricated and simulated microgripper**

Current density and velocity of the charges are as in Equation (4.5)

\[ J = nqU \]  

(4.5)

where,

- \( J \) – Current density in A/m²
- \( n \) – Number of charges
- \( q \) – Charge in coulombs
- \( U \) – Velocity of the charge, m/sec

Here, the increase in current is due to the increase in current density. The increase in current density also means that the charge velocity is
increasing. If charge velocity is increasing then the number of charges moving across an unit cross-sectional area, in unit time is also increasing. This will only result in the development of higher force in the microgripper and therefore results in a higher displacement. The increase in displacement is already found using optimization technique by Ye (Ye et al 1998). The same was confirmed in the Chapter 3, using analytical modeling of the fingers. Therefore, this feature of increasing displacement is already observed through analytical and FEM studies as shown in Table 4.4.

Thus, the different fingers shapes and their respective analytical models is developed the one with better performance is identified. Rectilinear microactuator with two jaws is considered for the development of analytical models of different finger shapes. The microactuator performance with load is also simulated and the performance is found satisfactory. Now through studies on V-I characteristics of different microgrippers the cause for increase in displacement is also confirmed. The optimal finger shaped microgripper yielding the higher displacement, is also validated using the developed analytical model.

4.5. CONCLUSION

In this work, the finger shapes proposed in Chapter 3, are used in the comb drive of a simple cantilever structured microgripper, which has only 28 fingers. It is found that a displacement of 6.66 µm has been obtained, at an actuation voltage of 14 volts for a particular shape, with linear force-engagement behavior. But 25 volts is required for a rectangular comb drive to develop the same displacement with constant force. Further, the design of a microgripper with the optimized finger shape, provides a displacement of 9.09 µm with just 14 volts as the input voltage. Therefore, the adoption of a linear force profile with optimized finger shape is suggested, for the electrostatic microgripper design. In this work, it is shown that the performance of the
microgripper can be improved, by using the non-rectangular finger shapes, and particularly the optimized shape. The force and the displacement values are increased for a given voltage. The microgripper with load is also simulated and the displacement is found to be almost the same with a very less value of out of plane displacement. The microgripper device is fabricated and tested for its V-I characteristics. Since the displacement was very small and could not be measured, so, the V-I characteristics study is carried out for analysing the trend of developed force with respect to the increase in current. Therefore it is concluded that the optimised finger shaped gripper is developing higher displacement, through the simulation and fabrication results.

Earlier, the pull-in analysis of microgripper is also done, using the closed form models derived in Chapter 2. The results again confirm that for a given range of dimensions only a particular model evaluates the pull-in voltage with less error.

Electrostatic actuation may give good displacement, but it requires high voltage for operation when compared to electro thermal actuators. The use of electro thermal actuators is appreciated much in the field of MEMS actuators. Therefore, the next chapter will discuss the design, analytical modeling and performance improvement of cantilever based electro thermal actuators in detail.