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Abstract—This paper describes the design of a six-axis microelectromechanical systems (MEMS) force–torque sensor. A movable body is suspended by flexures that allow deflections and rotations along the x-, y-, and z-axes. The orientation of this movable body is sensed by seven capacitors. Transverse sensing is used for all capacitors, resulting in a high sensitivity. A batch fabrication process is described as capable of fabricating these multiaxis sensors with a high yield. The force sensor is experimentally investigated, and a multiaxis calibration method is described. Measurements show that the resolution is on the order of a micro-Newton and nano-Newtonmeter. This is the first six-axis MEMS force sensor that has been successfully developed.

Index Terms—Calibration, force measurement, microelectromechanical devices, microsensors, torque measurement.

I. INTRODUCTION

In the fields of biomaterial characterization, material science, and microsystems testing, reliable force sensing is an important objective [1]. Mechanical characterization and micromanipulation are usually performed using a precise positioning device under control of an optical microscope or a scanning electron microscope. Often, only position feedback is available, with no information about interaction forces between the end effector and the microcomponents. In order to avoid breaking or damaging objects during the manipulation process, force feedback is important for proper functionality. For handling and characterizing animal cells, plant cells, and embryos, force feedback is important [2]–[4]. The most common techniques used for force sensing in the microdomain are atomic force microscopy (AFM) or piezoresistive cantilevers. Recently, capacitive force sensing probes have become commercially available. With these force sensing systems, forces along a single axis can be measured. For some applications such as automated cell injection, multiaxis force feedback is advantageous, since a misalignment between the injection pipette and the cell can be detected [5]. Other applications in biological research such as the characterization of the flight mechanics of fruit flies can benefit from high-speed multiaxis force–torque sensing [6]. Other research areas such as material characterization [7] and microsurgery [8] also require multiaxis force–torque sensors.

The forces dominating micromanipulation are in the range of tens of nano-Newtons \( (10^{-9}\text{N}) \) up to hundreds of micro-Newtons \( (10^{-6}\text{N}) \) [1], [9]. Many microelectromechanical systems (MEMS) force sensing systems exist based on principles such as metal strain gauges, piezoresistive effect, piezoelectric effect, capacitive sensing, and optical methods and are limited to single-axis force sensing. In conventional robotics, six-axis force–torque sensors are highly preferred, providing complete force and torque information on the end effector. Conventional high-precision six-axis force–torque sensors, such as the ATI Nano17, feature a resolution of 3.1 mN and 15.6 mN·m. This is three orders of magnitude too high for the application fields mentioned earlier. A six-axis force–torque sensor operating in the range of micro-Newton can provide a valuable and versatile tool for many micromanipulation tasks.

A number of two-axis and three-axis MEMS sensors exist. The tilting of AFM cantilevers can be monitored to resolve a second force component for friction and topology measurements. In [6], a capacitive two-axis micro force sensor is presented. Recently, three-axis piezoresistive force sensors have been described [11]–[14]. These sensors are designed for measuring forces up to a single Newton, which is much larger than necessary for most micro- and nanorobotics applications. Some of these sensors require assembly, which must be performed at the single device level, making manufacturing expensive. In [2], a high-resolution three-axis force sensor for biomicromanipulation is described. Little work exists on MEMS torque measuring devices. A piezoresistive MEMS torque sensor has been presented in [15]. In [7], two force components and one torque component have been measured for the characterization of magnetic material properties.

This paper presents the design of the first microfabricated six-axis force–torque sensor. The sensing principle is based on the measurement of a deflection of the sensing element by a number of variable capacitors. A five-mask fabrication process is described that was used to manufacture sensor prototypes. Fabrication incorporates a probe onto the force sensor, which simplifies the application of the load to the sensor. The readout electronics used to transform the change of capacitance to a change of voltage are described. In addition, a method for calibrating the six-axis device is presented.

II. SENSOR DESIGN

A. Working Principle and Sensor Buildup

Fig. 1 shows a photograph of the six-axis force sensor. The schematics in Fig. 2 display the configuration of the device in a top view. The sensor consists of a silicon handle layer with...
an insulating SiO$_2$ layer. Gold electrodes have been patterned as shown in Fig. 2(b). Subsequently, a 6-μm spacer layer made of benzocyclobutene (BCB) is patterned on the handle wafer. Bonded on top of the spacer layer is a 100-μm silicon device layer as shown in Fig. 2(b). One part of the device layer is anchored on the spacer layer. The second part is suspended by four deformable flexures, which allow the movable part to translate and rotate along the x-, y-, and z-axes. The movable body has a probe 3 mm long that hangs over the rest of the device. When a force or a torque is applied to the probe, the movable body deflects. One capacitor pair for sensing deflections in the x-axis and two capacitor pairs for sensing deflections in the y-axis are included in the device layer. In addition, the device layer forms another four capacitors together with the lower electrodes to sense deflections in the z-axis. In the inset (a) of Fig. 1, two rectangular flexures, as well as one of the comb drives, are shown. The inset (b) in Fig. 1 shows a capacitor for sensing deflections along z-axis. The dimensions of the entire device including the probe are 10 mm × 9 mm × 0.5 mm.

By monitoring the capacitance of all seven capacitors, the force and torque components can be decomposed by the readout electronics and software. To increase the signal-to-noise ratio of the capacitive measurement, comb drives are used for the x- and y-capacitors. Capacitive position sensing can be performed by either of the following:

1) lateral sensing (changing the overlapping area of the capacitor);
2) transverse sensing (changing the gap between the capacitor plates).

The gap between the capacitor plates can be designed to be small, and transverse sensing can be used to obtain a high sensitivity [5]. In addition, making use of transverse capacitors enables the design of stiffer sensors with maintaining a high resolution. A high stiffness is desired for high-bandwidth measurements.

B. Force–Torque Decomposition Method

Fig. 3 shows the deflection of the movable body when a load component is applied to the sensor probe. The plus and minus signs indicate whether the deflection is positive or negative at the position of the capacitors due to a positive force or torque component. The deflections $\mathbf{w} = [w_1, \ldots, w_7]^T$ are measured at seven positions by the corresponding capacitors $C_1, \ldots, C_7$. The capacitor pair $C_1$, consisting of $C_{1a}$ and $C_{1b}$, is used to measure deflections along x-axis caused by $F_x$. By measuring the difference of two capacitors instead of absolute capacitance, it is possible to compensate for unwanted disturbances. The differential configuration also creates a linear relationship between deflection and the sensor output signals for small deflections [16]. Since the comb drive pair is only sensitive in the x-direction, this capacitor pair is also called the x-capacitor. For measuring deflections in the y-direction caused by $F_y$ and $M_z$, the two y-capacitors $C_2$ and $C_3$ are used. Again, $C_2$ and $C_3$ consist of $C_{2a}$, $C_{2b}$ and $C_{3a}$, $C_{3b}$, respectively, for differential measurements. The force component $F_y$ and the torque components $M_x$ and $M_y$ cause a deflection in the z-direction. This deflection is sensed at four positions using the z-capacitors $C_4$, $C_5$, $C_6$, and $C_7$.

In Fig. 3, a coupling between $F_y$ and $M_z$ can be seen. There is also a strong coupling between $F_z$, $M_x$, and $M_y$. However, the ratio of the signals is not identical for different load components, due to the placement of the flexures and capacitors. For example, a pure torque $M_z$ creates an equally large deflection in the capacitor pairs $C_2$ and $C_3$ with an opposite sign. For a force $F_y$, the deflection in $C_2$ is twice as large as the deflection in $C_3$ for the sensor design proposed in this paper. Similarly, a pure torque $M_y$ creates negative deflections in $C_4$ and $C_5$ and positive deflections in $C_6$ and $C_7$ with the same magnitude. For a pure force $F_z$, the deflection in $C_4$ and $C_5$ is twice as large as the deflection in $C_6$ and $C_7$.

Mathematically, the relationship between the measured deflections $\mathbf{w} = [w_1, \ldots, w_7]^T$ and the load applied to the probe of the sensor is given by the stiffness matrix $K$:

$$
\begin{bmatrix}
F_x \\
F_y \\
F_z \\
M_x \\
M_y \\
M_z
\end{bmatrix}
= \begin{bmatrix}
w_1 \\
w_2 \\
w_3 \\
w_4 \\
w_5 \\
w_6 \\
w_7
\end{bmatrix}
= K \cdot \begin{bmatrix}
w_1 \\
w_2 \\
w_3 \\
w_4 \\
w_5 \\
w_6 \\
w_7
\end{bmatrix}.
$$

This notation requires a linear relationship between the applied load and the deflection. For the given design, the deflections are in the range of a micrometer, which is on the order of 1% of the total flexure length. Therefore, a linear relationship can be assumed.
The calibration matrix $K$ includes the mechanical stiffness of the device and the mechanical crosstalk between the axes. To be able to decompose the force and torque components, $K$ must have full rank. The condition number of $K$ is a measure of the quality of the sensor design. A small numerical condition number results in a good decomposability.

A finite element simulation was performed with sensor designs featuring different flexure geometries, as well as different capacitor and flexure positions. The following design goals were defined:

1) equivalent sensitivity for forces in $x$-, $y$-, and $z$-directions;
2) equivalent sensitivity for torques along $x$-, $y$-, and $z$-directions;
3) maximum sensor dimensions of $10 \text{ mm} \times 10 \text{ mm} \times 0.5 \text{ mm}$;
4) optimal decomposability (minimal $K$ for the given boundaries).

The result of the simulation showed that the decomposability of forces in $z$-direction and torques along $x$- and $y$-directions is...
that the simulations could be capacitors that overlap area of the parallel plate capacitors changes. To are also sensitive to deflections in the z-axis best when the four z-axis capacitors C4,...,C7 are located as far away from each other as possible on the device. To improve the decomposability of forces in y-direction and torques in z-direction, C2 and C3 should also be placed at a maximum distance from each other. The sensor shown in Fig. 1 is the design with the lowest condition number K that the simulations produced. The simulation results showed that K could be further minimized when the forces and torques are not applied at the probe tip but in the middle of the device. However, experiments in [3],[6], and [7] have demonstrated that the probe greatly simplifies the application of the load to the sensor.

Simulations also show that the lowest resonance frequency that limits the bandwidth of the sensor is 2.2 kHz. The proposed design performs a deflection measurement at seven positions. For a full six-axis force sensor, six position measurements are sufficient; therefore, one of the z-axis measurements is redundant. Four z-axis capacitors are included in the design to improve decomposability.

C. Reduction of Nonlinear Effects and Crosstalk

A number of design optimizations were performed to reduce nonlinearities which induce errors in the readout signals. These design optimizations also reduce the crosstalk between the individual readout signals.

One possible undesired effect of the sensor configuration is that the x-capacitor pair C1 and y-capacitors C2 and C3 are also sensitive to deflections in the z-direction since the overlapping area of the parallel plate capacitors changes. To reduce this effect, a device layer of l = 100 μm thickness was chosen. The z deflections are as large as 2.5 μm over the full range of the force sensor. The ratio between the capacitance C without deflection in z-direction and the capacitance C2 with a maximum deflection of z = 2.5 μm is given by

$$\frac{C_z}{C} = \frac{n \varepsilon \ell (t - z)}{d} = \frac{t - z}{t} = 0.975$$  \hspace{1cm} (2)

where n is the number of comb drive fingers and l is the length of the comb fingers. It can be seen that the error due to deflections in the z-axis is less than 2.5%.

In addition, this effect is further reduced by the differential capacitance measurement of the comb drives. Similarly, a displacement in the x−y plane should not influence the z-axis capacitors (C4,...,C7). This has been realized by designing the lower capacitor electrode smaller than the upper one, as shown in Fig. 4(b).

To reduce the crosstalk between x-capacitors and y-capacitors, the comb drives have been designed such that a lateral deflection does not change the overlapping area of the parallel plate capacitors. This comb drive design is shown in Fig. 4(a).

Another source of error is that the flexures convert the force and torque applied to the sensor tip into a translation and a rotation of the movable body. The rotation also induces a rotation of the capacitor plates. For small angles, the capacitance of rotated capacitors Cr can be written as

$$dC_r = \varepsilon_0 \cdot \frac{l}{d(x)} \, dx \quad \text{with} \quad d(x) = d_{\text{ideal}} + \alpha x$$  \hspace{1cm} (3)

where d(x) is the nonconstant gap width, d_{ideal} is the gap width of the nonrotated capacitor plates, and \( \alpha \) is the rotation angle. By integrating the capacitance over the whole length of the capacitor, the capacitance is given by

$$C_r = \varepsilon_0 l \int_{-\frac{l}{2}}^{\frac{l}{2}} \frac{1}{d_{\text{ideal}} + \alpha x} \, dx$$

$$C_r = -\varepsilon_0 \left( \log(2d_{\text{ideal}} - l\alpha) - \log(2d_{\text{ideal}} + l\alpha) \right).$$  \hspace{1cm} (4)

To reduce this error, the device has been designed such that the maximum rotation angle is only \( \alpha = 0.07^\circ \). The maximum error occurs in the z-axis capacitors with a length of l = 1000 μm and a gap d_{ideal} = 2.5 μm (maximum deflection). When calculating the capacitance C_r of the rotated capacitors by (4), it can be seen that the change in capacitance is 2% for the maximum deflection.

Table I gives the numerical values for the geometry of the capacitors and for the zero-load capacitance. The device layer thickness of the wafer is t, n is the number of capacitor plate pairs of a comb drive, C_{xy} is the capacitance of the comb drives, and C_z is the capacitance of the z-capacitor.

III. Fabrication

One drawback of MEMS force sensors is their fragility. By using relatively cheap wafer-level fabrication processes, the costs for a force sensor can be reduced. Cost efficiency is a precondition for being able to replace force sensors as they become damaged during use.
 TABLE I
PROPERTIES OF THE CAPACITORS FOR DEFLECTION MEASUREMENTS

<table>
<thead>
<tr>
<th>xy-axis capacitor (comb drive)</th>
<th>z-axis capacitor</th>
</tr>
</thead>
<tbody>
<tr>
<td>d₁, d₂</td>
<td>d₃</td>
</tr>
<tr>
<td>5μm, 20μm</td>
<td>5μm</td>
</tr>
<tr>
<td>t</td>
<td>100μm</td>
</tr>
<tr>
<td>l₁</td>
<td>l₂</td>
</tr>
<tr>
<td>260μm</td>
<td>1000μm</td>
</tr>
<tr>
<td>n</td>
<td>30</td>
</tr>
<tr>
<td>Cₙₓᵧ</td>
<td>1.84pF</td>
</tr>
<tr>
<td>Cₙ</td>
<td>1.78pF</td>
</tr>
</tbody>
</table>

Fig. 5. Microfabrication sequence.

In [16], a bulk silicon fabrication process based on a silicon-on-insulator wafer is described. These fabrication processes are suitable for force sensor designs capable of measuring forces only in x- and y-directions, since all capacitors are perpendicular to the wafer plane. In [17], a fabrication process is described, which overcomes this problem by forming additional capacitors parallel to the wafer plane. For the multi-axis sensor presented in this paper, a combination of the processes in [16] and [17] is required, since deflections in all directions must be measured by a transverse capacitor configuration. In addition, overhanging structures (sensor probe) are required to allow a simple application of the force and torque to the sensor. Fig. 5 shows a cross section of the sensor for the individual fabrication steps.

1) As a substrate, a 100-mm-diameter silicon wafer is used with a layer of thermal oxide (SiO₂). The thickness of the wafer is 400 μm, and the thickness of the oxide layer is 1 μm.

2) The oxide is removed on the backside of the wafer using reactive ion etching (RIE). Alignment marks are etched into the wafer using deep reactive ion etching (DRIE). The following photolithographic steps in 3), 5), 7), 8), and 9) are aligned to these alignment marks by topside or backside alignment.

3) A 250-nm-thick layer of gold is evaporated onto the oxidized topside of the wafer. The metal is etched to form the lower electrodes and bonding pads.

4) BCB is dispensed onto the wafer for spin coating. For this process, the dry etch resin Cycolene 3022-57 is used. A substrate rotation speed of 4500 r/min results in a layer thickness of 5.8 μm. The BCB layer is used as adhesive material for low-temperature bonding and as a spacer between the device layer and the lower electrodes. The BCB is cured on a hotplate for 35 min at a temperature of 200 °C in a N₂ atmosphere. After this treatment, the BCB is about 60% cured and can resist further processing.

5) A 10-μm layer of photoresist is dispensed on the BCB. Subsequently, the BCB is patterned using dry etching. A mixture of O₂ and CF₄ is used for etching the BCB. The selectivity of BCB:Photoresist is about 1 : 1. After etching the BCB, the remaining photoresist is stripped in acetone.

6) A 100-μm-thick silicon wafer is bonded onto the lower wafer using adhesive bonding [18]. The wafer is highly doped such that the resistivity is lower than 0.01 Ω · cm. This bonding step is carried out at a low temperature of 250 °C, maximum. Since the top wafer has not been structured until this step, alignment is not required during the bonding process.
7) A border around the devices is etched into the lower wafer using DRIE. The SiO$_2$ acts as an etch stop. By leaving some space between the devices, the wafer is still robust enough for further processing. The SiO$_2$ is etched using RIE.

8) Pads for making electrical contact to the top wafer are evaporated and patterned as described in step 3).

9) The wafer is mounted on a carrier wafer, and the topside is etched using DRIE. This step creates the comb drives, the upper electrodes, and the springs. A high aspect ratio of 1 : 20 has been achieved. After etching through the 100-μm top wafer, the movable structures are automatically released. No wet etching is necessary. On the bottom wafer, a border is also etched around the device so that no dicing is required.

10) The MEMS sensor is directly glued and wire-bonded to the printed circuit board (PCB) of the readout electronics. Holes in the device layer allow bonding to the lower pads. The process has been repeated several times, resulting in a yield rate of 80%. Wafer cleanness is of great importance for wafer bonding to avoid unbonded areas on the wafer. Since the process allows for the fabrication of electrodes in the $x$-, $y$-, and $z$-directions, it is not limited to multiaxis force sensors. Other devices such as multiaxis inertial sensors or multiaxis actuators can also be fabricated using this process.

IV. READOUT ELECTRONICS

The capacitance is converted into an analog voltage signal by the MS3110 ASIC. Subsequently, the voltage signal is converted into a digital signal and saved on a PC using an NI USB-6009 I/O module. Ideally, the readout ASIC is placed as close as possible to the MEMS device for optimal performance. The output voltage $V$ is proportional to the capacitance difference of the capacitor pair $C_a$ and $C_b$. For small deflections, $V$ is proportional to the deflection of capacitor plates as described in detail in [16]. The transfer function for the capacitor pairs $C_1 - C_3$ is given by

$$ V_{C1} \propto \text{Gain} \frac{C_{1a} - C_{1b}}{C_F} $$

$$ V_{C2} \propto \text{Gain} \frac{C_{2a} - C_{2b}}{C_F} $$

$$ V_{C3} \propto \text{Gain} \frac{C_{3a} - C_{3b}}{C_F} $$

(5)

where $\text{Gain}$ and $C_F$ are programmable variables on the ASIC. For the $z$-axis capacitors $C_4 - C_7$, a reference capacitor $C_{ref}$ soldered onto the PCB of the readout electronics is used to enable a differential readout. The output voltage is given by

$$ V_{C4} \propto \text{Gain} \frac{C_{4} - C_{ref}}{C_F} $$

$$ V_{C5} \propto \text{Gain} \frac{C_{5} - C_{ref}}{C_F} $$

$$ V_{C6} \propto \text{Gain} \frac{C_{6} - C_{ref}}{C_F} $$

$$ V_{C7} \propto \text{Gain} \frac{C_{7} - C_{ref}}{C_F}. $$

(6)

V. CALIBRATION AND CHARACTERIZATION

Precise calibration of multiaxis MEMS force sensors is difficult for several reasons, including the need to apply known force vectors at precise positions and orientations which risk damaging the small and fragile microdevices [19], [20]. The $z$-capacitors do not create a linear relationship between deflection and output voltage. Therefore, the $z$-capacitor sensor signal is linearized by the PC after A/D conversion. The MS3110 capacitance-to-voltage converter can be used to measure only a single capacitor pair at one time. Multiplexing is applied to switch between the seven capacitor pairs as shown in the circuit diagram in Fig. 6. The common electrode of the capacitors (movable body of the sensor) is constantly connected to the MS3110 chip, while the other capacitor electrodes are switched pairwise. The proposed method enables relatively simple interfacing of multiple capacitors. A drawback is that the maximum readout frequency of the MS3110 is divided by the number of capacitors.
relationship between the seven analog sensor output signals $V = [V_{c1}, V_{c2}, \ldots, V_{c7}]^T$ and the loads $F = [F_x, F_y, F_z, M_x, M_y, M_z]^T$ applied to the sensor

$$
\begin{bmatrix}
F_x \\
F_y \\
F_z \\
M_x \\
M_y \\
M_z
\end{bmatrix} = A^{6 \times 7} \cdot \begin{bmatrix}
V_{c1} \\
V_{c2} \\
V_{c3} \\
V_{c4} \\
V_{c5} \\
V_{c6} \\
V_{c7}
\end{bmatrix}
$$

with

$$
A = \begin{bmatrix}
a_{11} & a_{12} & \cdots & a_{17} \\
a_{21} & a_{22} & \cdots & a_{27} \\
\vdots & \vdots & \ddots & \vdots \\
a_{61} & a_{62} & \cdots & a_{67}
\end{bmatrix}.
$$

(7)

For the calibration of the six-axis force–torque sensors, a commercial single-axis reference force sensor (FemtoTools FT-S270) is used. The six-axis sensor is mounted on a three-axis micromanipulator (Sutter MP285) and the reference sensor attached onto a three-axis rotation stage. This setup enables the accurate application of known reference force vectors at different locations and directions. Six reference forces at different orientations and positions are chosen, $F_1, \ldots, F_6$, as shown in Fig. 7. The output of all seven capacitors is stored.

No reference torques are applied to the sensor since this is difficult to do in a controlled way at the microscale. Depending on the location where the force is applied on the movable body of the sensor, the resulting deflection changes. A force applied on the probe tip can be replaced by a superposition of a force and a torque applied at a different location on the movable body. This correlation between the position, force, and torque can be used for calibrating force–torque sensors.
as demonstrated in [7]. For calculating the calibration matrix $A$, the following matrices $F_1, \ldots, F_6$ and the corresponding output signals are used:

$$
F_1 = \begin{bmatrix}
F_{x1} & F_{x2} & \cdots & F_{xn} \\
0 & 0 & \cdots & 0 \\
0 & 0 & \cdots & 0 \\
0 & 0 & \cdots & 0 \\
0 & 0 & \cdots & 0 \\
0 & 0 & \cdots & 0 \\
\end{bmatrix}
$$

$$
F_2 = \begin{bmatrix}
0 & 0 & \cdots & 0 \\
0 & 0 & \cdots & 0 \\
0 & 0 & \cdots & 0 \\
0 & 0 & \cdots & 0 \\
0 & 0 & \cdots & 0 \\
0 & 0 & \cdots & 0 \\
\end{bmatrix}
$$

$$
F_3 = \begin{bmatrix}
-2F_{y1} & -F_{y2} & \cdots & -F_{yn} \\
0 & 0 & \cdots & 0 \\
0 & 0 & \cdots & 0 \\
0 & 0 & \cdots & 0 \\
0 & 0 & \cdots & 0 \\
0 & 0 & \cdots & 0 \\
\end{bmatrix}
$$

$$
F_4 = \begin{bmatrix}
0 & 0 & \cdots & 0 \\
-2F_{y1} & -F_{y2} & \cdots & -F_{yn} \\
0 & 0 & \cdots & 0 \\
0 & 0 & \cdots & 0 \\
0 & 0 & \cdots & 0 \\
0 & 0 & \cdots & 0 \\
\end{bmatrix}
$$

$$
F_5 = \begin{bmatrix}
F_{y1} \cdot l_1 & F_{y2} \cdot l_1 & \cdots & F_{yn} \cdot l_1 \\
0 & 0 & \cdots & 0 \\
0 & 0 & \cdots & 0 \\
-F_{z1} \cdot l_1 & -F_{z2} \cdot l_1 & \cdots & -F_{zn} \cdot l_1 \\
0 & 0 & \cdots & 0 \\
0 & 0 & \cdots & 0 \\
\end{bmatrix}
$$

$$
F_6 = \begin{bmatrix}
0 & 0 & \cdots & 0 \\
-F_{z1} & -F_{z2} & \cdots & -F_{zn} \\
-F_{z1} \cdot l_3 & -F_{z2} \cdot l_3 & \cdots & -F_{zn} \cdot l_3 \\
0 & 0 & \cdots & 0 \\
0 & 0 & \cdots & 0 \\
\end{bmatrix}
$$

The numerical values for the offset location are $l_1 = 2100 \ \mu m$ and $l_2 = l_3 = 3500 \ \mu m$. Fig. 8 shows the slopes of the seven output signals for the calibration vectors $F_1, \ldots, F_6$. It can be seen that the two $y$-capacitors $C_2$ and $C_3$ show the largest signal change $V_{C2}$, $V_{C3}$ and that the $x$-capacitors and the $z$-capacitors feature a low sensitivity for forces in the $y$-direction. The sensor has been calibrated for forces up to 1000 $\mu N$ and torques up to 2600 $nN \cdot m$. The standard deviation of the noise level of the capacitive readout corresponds to 1.4 $\mu N$ and 3.6 $mN \cdot m$, respectively, at a readout frequency of 30 Hz.

After collecting the seven output signals for all six calibration vectors, the components of the calibration matrix are calculated using a least squares optimization method by MATLAB software. For the given design, a typical calibration matrix $A$ is given by (9), shown at the top of the page, for forces given in micro-Newton and torques in nano-Newtonmeter. The matrix has full rank, indicating that decomposition of the force and torque components can be performed. The condition number of $A$ is 19.34.

VI. CONCLUSION

A capacitive six-axis force sensor intended for applications in biological research, material science, and microsystems characterization was presented. This is the first time that a six-axis MEMS force–torque sensor has been successfully designed and fabricated. The wafer-level manufacturing process is not limited to force sensors and may be used for other transducers such as multiaxis inertial sensors or multiaxis actuators. The six-axis force sensor was calibrated, and the calibration matrix was computed based on experimental data. The evaluation of the noise level shows that a resolution in the range of a single micro-Newton and nano-Newtonmeter was achieved, which is three orders of magnitude better than for existing six-axis force sensors.

REFERENCES


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