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Modeling and experimental characterization of an active MEMS based force sensor

Jonathan Cailliez¹ · Mokrane Boudaoud¹ · Abdenbi Mohand-Ousaid² · Antoine Weill-Duflos³ · Sinan Haliyo¹ · Stéphane Régnier¹

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Abstract

Active force sensors are based on the principle of force balancing using a feedback control. They allow, unlike passive sensors, the static characterization of forces without interference of the sensor mechanical properties on the estimated stiffness of the object to be studied. This capability is fundamental when dealing with the mechanical characterization of samples having a wide range of stiffness. This paper deals with the modeling and the experimental characterization of a new active MEMS based force sensor. This sensor includes folded-flexure type suspensions and a differential comb drive actuation allowing a linear force/voltage relationship. A control oriented electromechanical model is proposed and validated experimentally in static and dynamic operating modes using a stroboscopic measurement system. This work is a first step towards new MEMS active force sensor with high resonant frequency ($>2\text{kHz}$) and high linear measurement force range ($50\ \mu\text{N}$). The advantage of this structure is to be able to change the sensor operating point without changing the sensor dynamics. Thus simplifying the control law. Modifying the operating point allows performing an accurate self positioning of the probe in close proximity to the surface to be studied.

Keywords

1 Introduction

Small and embeddable force sensing tools are essential in micro-robotics [1]. The need of size reduction has led to forgo traditional engineering techniques for sensors fabrication in favor of clean room fabrication processes. The clean room facilities have enabled the production of the Micro Electro Mechanical Systems (MEMS). MEMS engineering can provide systems with much smaller details [2] than conventional techniques and can perform batch manufacturing, efficiently reducing costs and production time per unit.

MEMS force sensing can be divided into two main categories, namely elastic sensing and zero displacement sensing. The first one is the most widely reported in the literature with piezoresistive sensors [3, 4], fluidic sensors [5], capacitive sensors [6–8], MOSFET sensors [9], vision tracked sensors [10] and so on. Elastic sensors are

based on a mechanical transformation of an external force into a displacement. The force measurement is deduced from the displacement measurement by the knowledge of mechanical suspensions stiffness. This method tends to provide smaller sensors with the need of little control electronic, leading to more integrated sensors. A trade-off between the measurement range and the resolution is often involved [11]. An increase of the sensor stiffness increases its measurement range at the cost of its resolution. In order to circumvent this drawback, a mechanical structure is used in [12] to change the sensor stiffness when the applied force exceeds a threshold value. One can also design an infinite stiffness sensor, called a zero displacement sensor.

The working principle of a zero displacement sensor, also referred here as an active sensor, is to hold the position of the probe at a fixed value despite of an external applied force. This is feasible thanks to a feedback control driving a set of actuators in order to compensate the applied external force. The force measurement is deduced from the actuator voltage or current. Active sensors have also the advantage of being able to provide quantitative force measurement without an accurate calibration of the suspensions. Some of zero displacement sensors have been reported in the literature. In

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40 [11] and [13], the sensor is composed of an electrothermal
 41 position sensor and an electrostatic comb drive actuator.
 42 However, the use of a traditional (i.e. not differential)
 43 comb drive configuration leads to a quadratic force/voltage
 44 relationship that involves control issues for the force
 45 measurement. In [14], the zero displacement force sensor
 46 includes a piezoresistive position sensor and an additional
 47 comb drive actuator, taking advantage of the equivalent
 48 'negative stiffness' behavior of some electrostatic actuators,
 49 to adjust in real time the resonance frequency of the sensor.
 50 Overall, passive force sensors allow for more integrated
 51 sensors and can perform adequately provided their stiffness
 52 is higher than the maximum gradient of measured forces.
 53 They are also able to perform up to 6 DOF measurements
 54 [15], while active force sensors are more fit to measure
 55 forces with a high range of gradients.

56 The goal of this work is to present the modeling
 57 and experimental characterization of a high bandwidth
 58 MEMS force sensor with linear force-voltage actuation,
 59 folded flexure suspensions, while being as compact as
 60 possible A knowledge model of the sensor is proposed.
 61 Knowledge models are useful to study the influence of
 62 electromechanical parameters on the sensors performance
 63 and to have some feedback on conception.

64 A description of the MEMS structure is presented in
 65 Section 2. Section 3 deals with the electromechanical mod-
 66 eling of the sensor. The model describes the relationship
 67 between the sensor probe position and the actuation volt-
 68 age of the comb drive actuator. The experimental protocol
 69 for the dynamic and the static characterization of the sen-
 70 sor is presented in Section 4. In Section 5 experimental data
 71 are analyzed and results are followed by several discussions.

72 The characterized model is used to perform some simula-
 73 tion as well as the synthesis on a controller for the sensor.
 74 A conclusion and future perspectives of the work finish the
 75 paper.

2 Description of the MEMS structure

76 The considered MEMS is presented in Fig. 1. A 2D plan and
 77 a picture of the MEMS with it's PCB are presented in Fig. 2.
 78

79 The sensor is composed of a differential comb drive
 80 actuator, folded-flexure suspensions, a probe and six contact
 81 pads for the electrical connections as shown in Fig. 1. The
 82 goal was the design of a force sensor with a high linear
 83 range and a bandwidth superior to 2kHz, to do so we made
 84 the choice of folded flexure suspensions. The choice of the
 85 actuator (number of comb drives and dimensions) was made
 86 so that it could be operated between -70V and 70V. The
 87 rest of the mechanical elements have been designed so that
 88 the mechanical resonant frequency fits our specifications.
 89 There are mainly 3 suspensions architectures used in MEMS
 90 devices: clamped clamped flexure, Crab-leg flexure and
 91 folded flexure design. If we consider the same flexure length
 92 and width and a force measurement in y direction, the
 93 clamped clamped suspensions have a high stiffness ratio
 94 k_x/k_y equal to the square of the ratio length/width, but the
 95 linear range of k_y is very low. The Crab-leg flexure design
 96 allows extending the linear range of k_y but significantly
 97 reduces the ratio k_x/k_y . The folded flexure design, however,
 98 increases the linear range of k_y compared to the clamped
 99 clamped design while it has the same ratio k_x/k_y as for
 100 the clamped clamped flexures. Therefore, among these

Fig. 1 3D CAD view of the MEMS based force sensor. The folded-flexure suspensions are highlighted in yellow

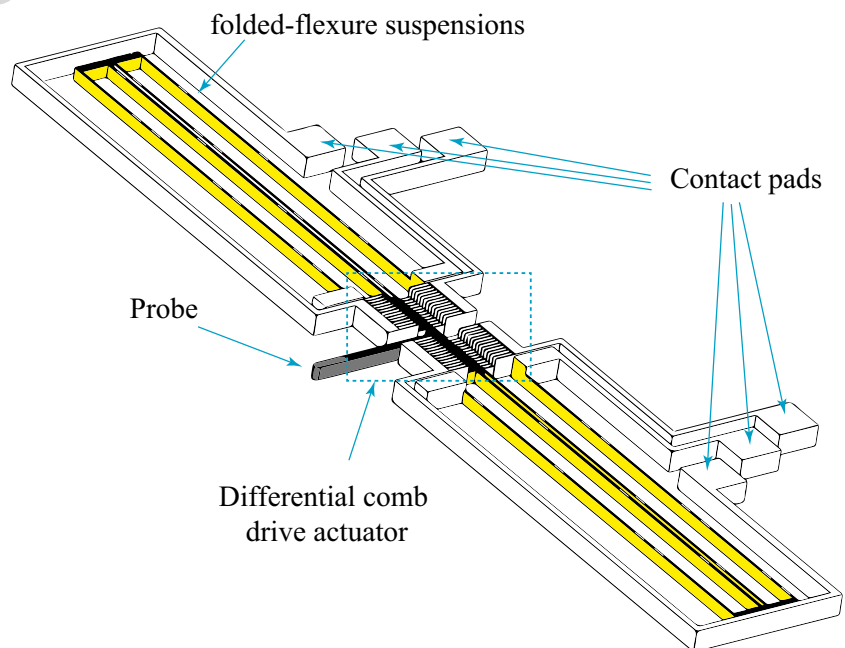
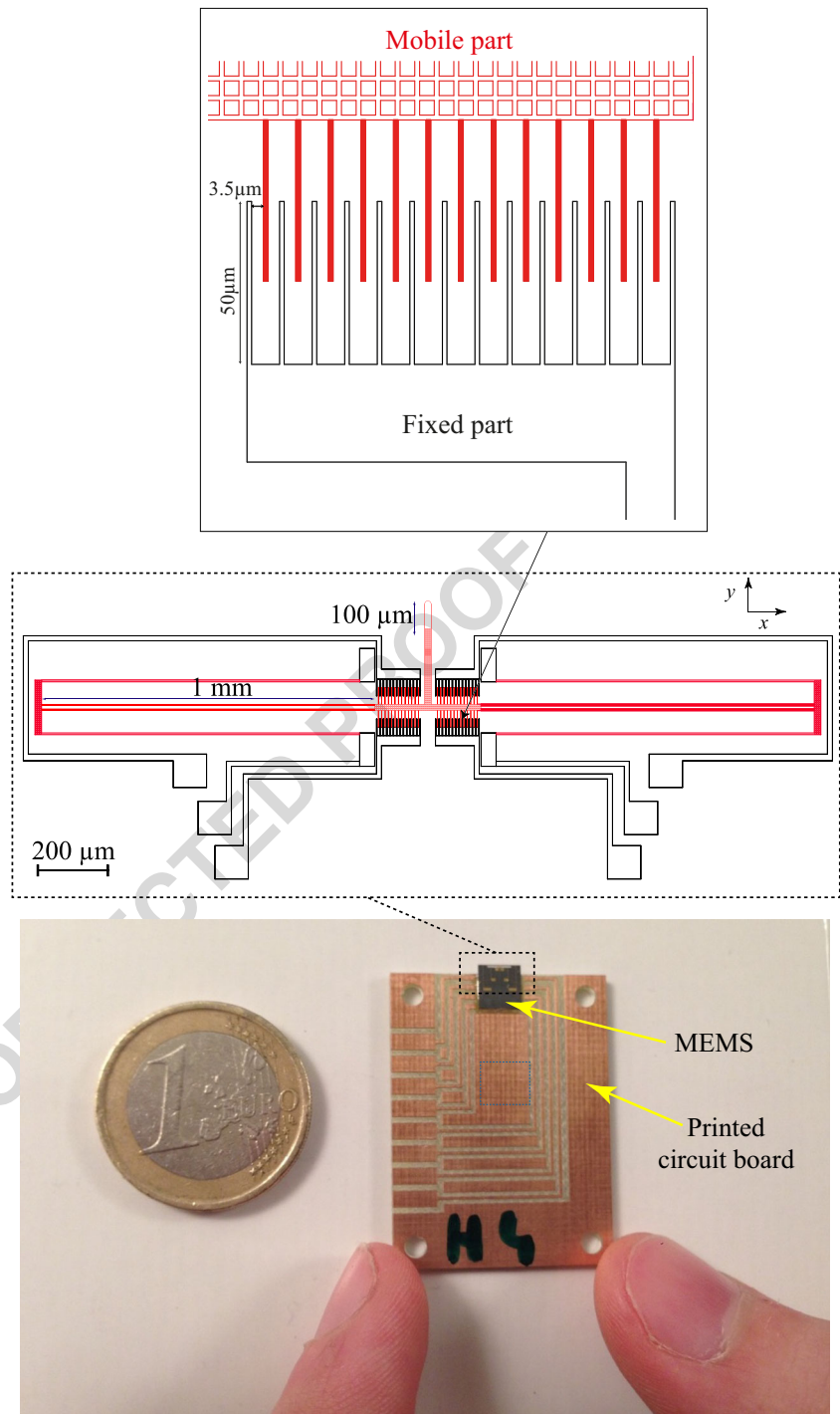


Fig. 2 MEMS based force sensor and enlarged view of the internal structure of the mechanical part. The movable structures are highlighted in red. Detail of one quarter of the comb drive actuator is presented above the global plan (the whole structure is 30 μm thick)



101 three design architectures, the folded flexure design is
 102 the best candidate when dealing with unidirectional force
 103 measurement in a wide linear operating range [16]. It has
 104 been monolithically fabricated on a silicon on insulator
 105 (SOI) wafer of 30 μm thickness. Wire bonding has been
 106 used to connect the contact pads of the MEMS to a printed
 107 circuit board (Fig. 2).

The conception has been performed in our lab using
 a CAD software. However, as no cleanroom facilities
 are available in the lab, the MEMS were realized thanks
 to the help of the RENATECH platform and the IEMN
 lab (Institut d'électronique de microélectronique et de
 nanotechnologie). RENATECH is a french platform of
 nanofabrication.

108
 109
 110
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 112
 113
 114

115 The nominal comb drive actuator includes 56 fixed
 116 fingers and 52 movable fingers, it can be seen in Fig. 2.
 117 The gap spacing between the fingers is $g = 3.5 \mu\text{m}$. The
 118 suspensions have 1 mm length and $3.5 \mu\text{m}$ width. The
 119 external part of the probe has a length of $100 \mu\text{m}$ as
 120 shown in Fig. 2. The maximum actuation voltages of the
 121 differential comb drive actuator is 70 Volts. The linear
 122 displacement range of the probe is about $50 \mu\text{m}$. The
 123 direction of motion of the probe is the y direction.

124 **3 Dynamic modeling of the MEMS actuator**

125 For control purposes, a dynamic model of the sensor
 126 is needed. This section deals with the electromechanical
 127 modeling of the transfer between the probe displacement
 128 and the input voltages of the differential actuator.

129 **3.1 Electrical modeling of the differential
 130 electrostatic comb drives**

131 Let's consider an elementary finger pair of the comb drive
 132 actuator as depicted in Fig. 3. The movable fingers are
 133 represented by the electrode (2). The fixed fingers are
 134 represented by the electrodes (1) and (3). When no voltage
 135 is applied, the MEMS is designed to have $y_1 = y_2 =$
 136 y_0 , where y_1 and y_2 are the overlapping lengths between
 137 the electrodes (2) and (1) and the electrodes (2) and (3)
 138 respectively.

139 Hence, one can write:

$$\begin{cases} y_1 = y_0 - y_e \\ y_2 = y_0 + y_e \end{cases} \quad (1)$$

140 y_0 is the overlapping length when no voltage is applied
 141 and y_e is the displacement of the movable finger in y
 142 direction.

143 The electrostatic force exerted on the movable finger, in
 144 y direction, in response to a voltage is equal to the gradient
 145 of the electrostatic energy stored by the system.

146 The stored energy can be expressed as follows :

$$E = \frac{1}{2} \left(C_{12}(V_1 - V_2)^2 + C_{23}(V_2 - V_3)^2 + C_{13}(V_1 - V_3)^2 \right) \quad (2)$$

147 C_{ij} is the capacitance between the electrodes (j) and (i).
 148 V_i is the voltage between an electrode (i) and the electrical
 149 ground. Here, C_{13} is considered equal to 0 (the electrical
 150 coupling between electrodes 1 and 3 is neglected).

151 By neglecting side effects, one can get:

$$\begin{cases} C_{12} = 2(y_0 - y_e) \frac{N\epsilon_0\epsilon_r t}{g} \\ C_{23} = 2(y_0 + y_e) \frac{N\epsilon_0\epsilon_r t}{g} \end{cases} \quad (3)$$

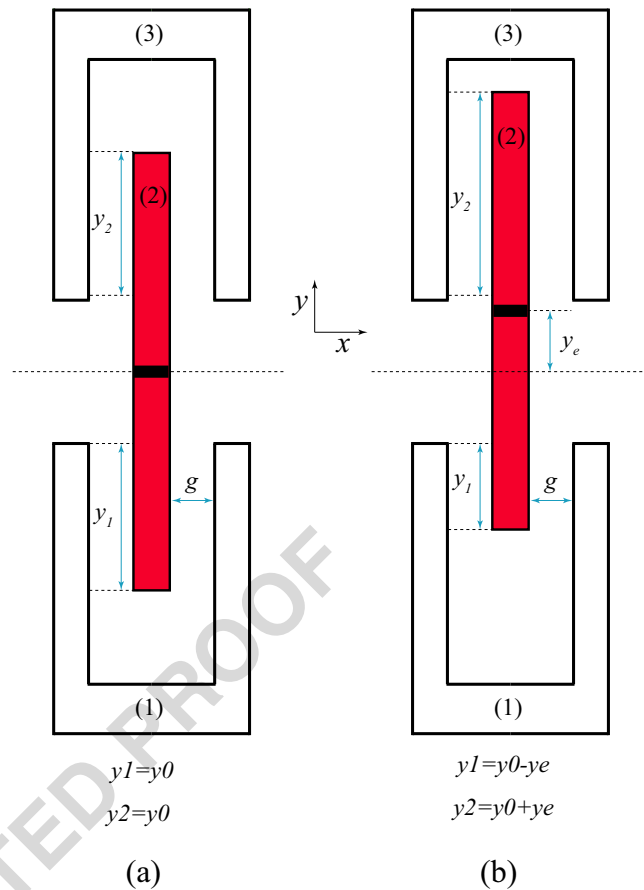


Fig. 3 Scheme of an elementary pair of fingers in the differential comb drive actuator when the movable fingers are at the initial position $y_e = 0$ (a) and at a position $y_e \neq 0$. The movable fingers are represented by the electrode (2). The fixed fingers are represented by the electrodes (1) and (3)

152 $N = 26$ is the total number of mobile fingers pairs, ϵ_0
 153 is the vacuum permittivity, ϵ_r the relative permittivity of air
 154 and $t = 30\mu\text{m}$ the thickness of the electrodes.

155 Let us now consider the following gain:

$$k_c = \frac{N\epsilon_0\epsilon_r t}{g} \quad (4)$$

156 The electrostatic force can then be expressed as follows:

$$F = -\frac{\partial E}{\partial y_e} = k_c((V_1 - V_2)^2 - (V_2 - V_3)^2) \quad (5)$$

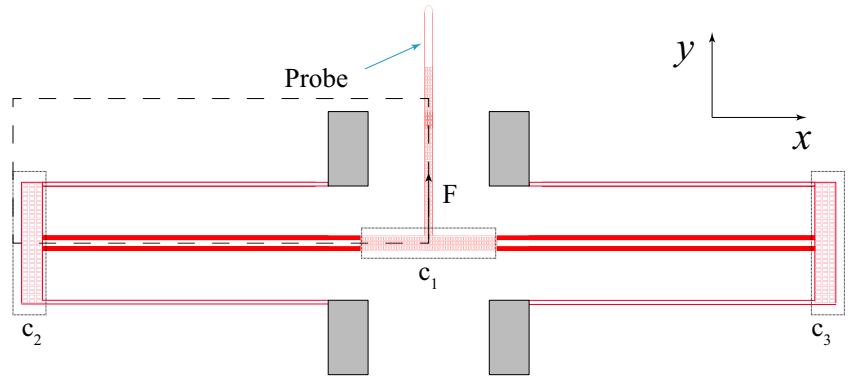
157 By setting $V_1 = -V_3$, which is thereafter used to operate
 158 the force sensor, the Eq. 5 can be simplified as follows:

$$F = 4k_c V_3 V_2 \quad (6)$$

159 Using the numerical value of each parameter of the
 160 electrical model, and choosing $V_3 = 40 \text{ V}$, the relationship
 161 between the electrostatic force F that drives the sensor
 162 probe and the voltage V_2 is:

$$|F| = 0.3157V_2 [\mu\text{N}] \quad (7)$$

Fig. 4 Schematic representation of the folded-flexure suspensions. The dashed rectangle shows the quarter model of the suspensions as shown in Fig. 5



163 V_1 will be set at -40V and V_3 at 40V for the
 164 experiments, V_2 becoming the only control signal. The
 165 linear force/voltage relationship which is one of the main
 166 advantages of the differential comb drive actuation is
 167 therefore demonstrated.

168 **3.2 Static mechanical modeling of the suspensions**

169 The aim of this section is to define a knowledge based
 170 model of the static force/deflection characteristic for the
 171 suspension structure. Let us recall that folded-flexure
 172 suspensions are designed for the MEMS sensor (Fig. 1). The
 173 bodies C1, C2, and C3 (Fig. 4) are supposed to be infinitely
 174 rigid and the flexible structures will be modeled with small
 175 displacement theory.

176 Due to the symmetry of the structure, the problem can be
 177 reduced by considering the quarter model of the suspensions
 178 as shown in Fig. 5. The dimensions of the beam 1 and that
 179 of the beam 2 are given in Table 1.

180 All the displacements are considered in y direction. The
 181 displacement of the rigid body C1 will be supposed equal to
 182 the displacement of the point A of the beam 1 relatively to
 183 the point B (y_a) plus the displacement of the point C of the

184 beam 2 (y_c). The beam 1 will be supposed clamped at both
 185 ends and the beam 2 will be treated as simply clamped. The
 186 distance between the points B and C is equal to $18 \mu\text{m}$.

187 Using Euler-Bernoulli beam theory, one is able to get the
 188 following Eqs. 8 and 9.

$$y_a = \frac{Fl_1^3}{48EI} \tag{8}$$

$$y_c = \frac{Fl_2^3}{12EI} - \frac{Fl_1l_2^2}{16EI} \tag{9}$$

189 With E the young modulus of silicon and I the area
 190 moment of inertia of the beam in the considered direction.

191 By combining Eqs. 8 and 9, the total displacement of the
 192 sensor probe is

$$y_p = \frac{F}{12EI} \left(\frac{l_1^3}{4} + l_2^3 - \frac{3}{4}l_1l_2^2 \right) \tag{10}$$

193 The total stiffness k of the suspension structure can then
 194 be deduced from the force/displacement relationship:

$$k = \frac{y_p}{F} = \frac{12EI}{\frac{l_1^3}{4} + l_2^3 - \frac{3}{4}l_1l_2^2} \tag{11}$$

Fig. 5 Quarter model of the suspensions (Dashed rectangle in Fig. 4)

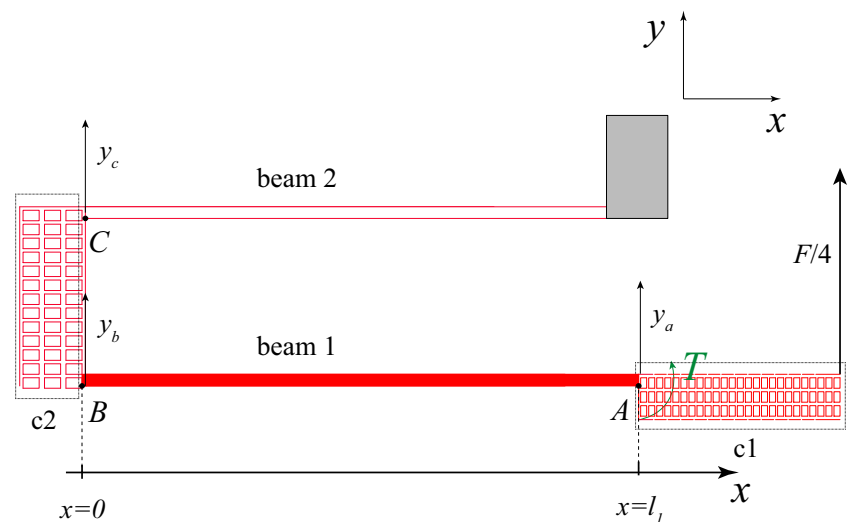


Table 1 Dimensions of the beam 1 and the beam 2 in the suspension structure

	width	thickness	length
beam1	$w = 4.5 \mu m$	$t = 30 \mu m$	$l_1 = 1 mm$
beam2	$w = 4.5 \mu m$	$t = 30 \mu m$	$l_2 = 0.965 mm$

195 Taking into account the dimensions of the MEMS
 196 structure and the silicon Young modulus $E = 127 \text{ GPa}$, the
 197 model (11) allows to compute $k = 1.37 \text{ N/m}$.

198 The static force/displacement characteristic of the sus-
 199 pensions has been also analyzed using a computer-aided
 200 design (CAD) software. Several finite element analysis with
 201 different forces exerted on the probe in y direction have
 202 been performed. The operating points have then been fitted
 203 to obtain the result of Fig. 6.

204 The finite element analysis leads to a stiffness $k=1.451$
 205 N/m . The difference between this result and the one
 206 obtained by the knowledge-based model is equal to 5.58
 207 %, hence validating the hypothesis of the knowledge based
 208 model. However, both of these models consider perfect
 209 geometries, which is not necessary the case here due to the
 210 dimensions of the structure.

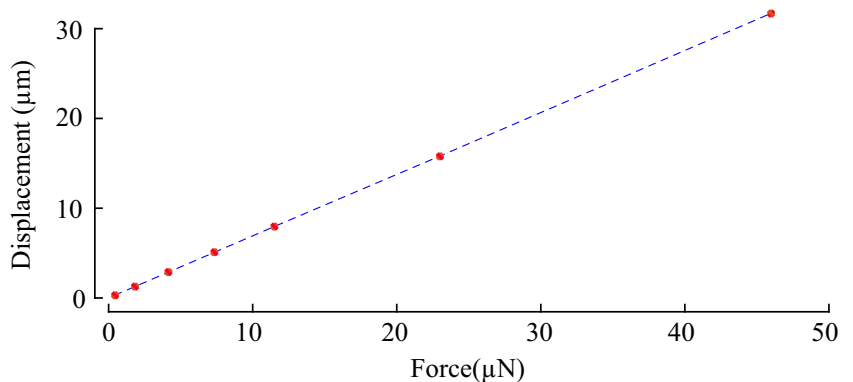
211 **3.3 Electro-mechanical dynamic model of the MEMS**

212 In the previous sections, the electrical force/voltage
 213 relationship and the static mechanical displacement/force
 214 model of the MEMS have been obtained leading to a
 215 static knowledge-based model. To extend the model into
 216 a dynamic formulation, the damping coefficient μ and the
 217 mass m of the movable structure are added here.

218 The dynamic equation of the movable part of the MEMS
 219 can be expressed as follows:

$$m\ddot{y}_p = -ky_p - \mu\dot{y}_p + 4k_c V_3 U \quad (12)$$

Fig. 6 Static force/displacement finite element characteristic of the suspensions



$U=V_2$ is the input of the system. 220

Using the Laplace transform of the Eq. 12, the transfer 221
 function $H(p)$ of the MEMS can be expressed as follows (p 222
 being the Laplace variable): 223

$$H(p) = \frac{y_p}{U} = \frac{4k_c V_3}{mp^2 + \mu p + k} \quad (13)$$

224 **4 Experimental characterization**

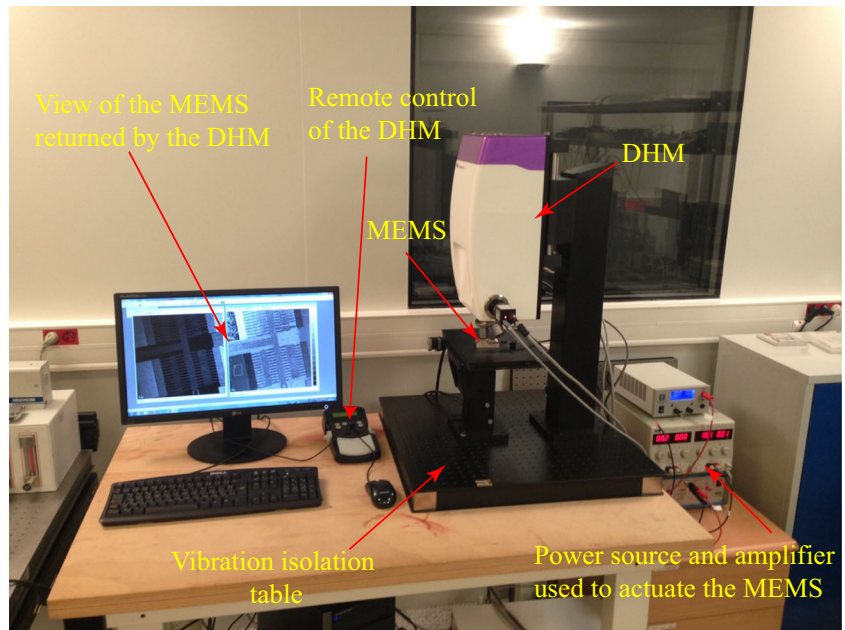
225 **4.1 Experimental setup**

226 As shown in Fig. 7, the experimental setup is composed
 227 of the MEMS sensor, voltage generators, a Digital
 228 Holographic Microscope (DHM) and a vibration isolation
 229 table. The DHM is used to measure the displacement of the
 230 mobile part of the MEMS in response to a voltage $U = V_2$.
 231 A beam of coherent light is emitted and focused on the
 232 MEMS. The intensity and phase of the reflected beam are
 233 recorded. The phase information is treated to get a 3D real
 234 time image of the observed structure.

235 **4.2 Dynamic characterization of the MEMS actuator**

236 Because of the high resonant frequency of the MEMS
 237 (relative to the DHM camera frequency), a stroboscopic
 238 unit has to be used to be able to track the position of the
 239 movable structure. For the experiment, a voltage of 40 V
 240 has been chosen for V_3 , and the actuator is driven by a
 241 square wave $U = V_2$ at 50 Hz. The stroboscope is set to
 242 get images at a frequency of 25 kHz. The first problem to
 243 solve is that the MEMS is not aligned with the microscope
 244 axes. The picture has to be rotated in order to align the
 245 movement direction with the image horizontal axis. To do
 246 so, the user selects 16 points in the image whose coordinates
 247 are known a priori. Then, 32 vectors are extracted from the
 248 16 points.

Fig. 7 Experimental setup for the characterization of the MEMS sensor. The stroboscopic unit is under the table



249 Let A be the matrix containing the vector of coordinates
 250 in the image and B the matrix containing the vector of the a
 251 priori coordinates such that $B = R \times A$:

$$A = \begin{bmatrix} x_{a_1} & y_{a_1} \\ x_{a_2} & y_{a_2} \\ \vdots & \vdots \\ x_{a_n} & y_{a_n} \end{bmatrix}, B = \begin{bmatrix} x_{b_1} & y_{b_1} \\ x_{b_2} & y_{b_2} \\ \vdots & \vdots \\ x_{b_n} & y_{b_n} \end{bmatrix}$$

252 The determination of R can be seen as an overdetermined
 253 system of equations. That means that no matrix R is solution
 254 of this equation. However several solutions exist to provide
 255 a matrix R that minimizes a cost function of $B - RA$. Here,
 256 the cost function will be quadratic. The chosen matrix R will
 257 be:

$$R = B \times pinv(A) \tag{14}$$

258 Where $pinv(.)$ is the Moore-Penrose pseudoinverse [17].

259 The rotation angle and scale ratio are extracted from R .
 260 The image is first rotated, missing pixels are recovered by a
 261 linear interpolation between neighboring points. The image
 262 is in grayscale, so pixels intensities range from 0 (black) to
 263 255 (white). Pixels intensities are summed along the rotated
 264 image vertical axis. Figure 8 represents the sum of pixels
 265 intensities for one position of the MEMS probe. Similarly,
 266 Fig. 9 shows the same sum for several positions of the probe.

267 Let's consider the red curve in ROI represented by the
 268 dashed rectangle of Fig. 8 for a fixed position of the
 269 MEMS. The horizontal axis represents a pixel number in the
 270 horizontal direction. The vertical axis represents the sum of
 271 the intensities of the pixels that have the same horizontal
 272 position. This shape is characteristic of the probe. Around
 273 this shape, the intensity is constant, hence the corresponding

offset can be removed, so the center of mass of the shape can
 274 be computed using Eq. 15 after removing the corresponding
 275 intensity offset. When the probe moves horizontally, the
 276 shape moves along with it by the same amount (with some
 277 distortion due to image blur). Therefore, the displacement of
 278 the probe can be estimated as the displacement of the center
 279 of mass of the ROI.
 280

$$y_0 = \frac{\sum_{ROI} y \times (I(y)^4)}{\sum_{ROI} (I(y)^4)} \tag{15}$$

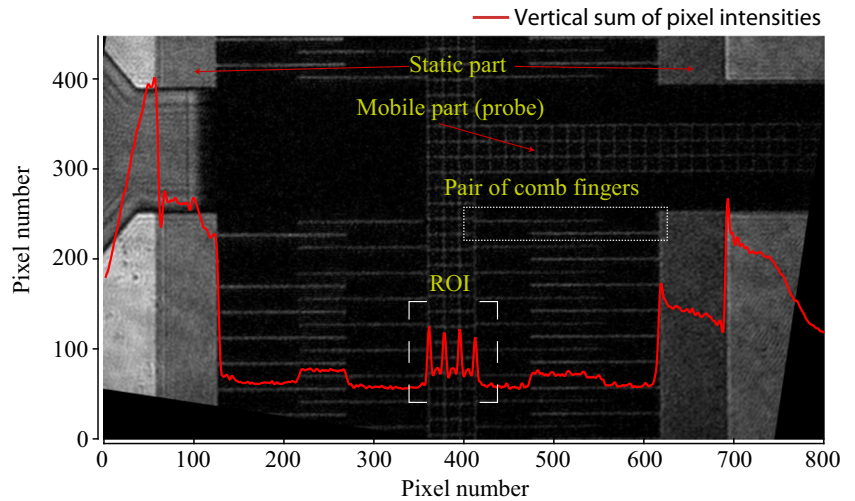
$I(y)$ is the sum of the intensities of all the pixels that
 281 share the coordinate y i.e. vertical sum of the intensities
 282 on y , it is taken at the power four to increase the detection
 283 accuracy. y can be expressed either as pixel number or
 284 converted to a position in microns using the scale ratio
 285 extracted from Eq. 14. Pattern tracking and data correlation
 286 are rendered impossible here due to high movement noise.
 287

288 This method has been used to measure the step response
 289 of the MEMS probe experimentally (Fig. 10). These signals
 290 resulted in the identification of a second order model $H_i(p)$
 291 describing the dynamic behavior of the MEMS. The step
 292 response of the model for a 4.5 Volts step input is also shown
 293 in Fig. 10.

294 The transfer function has been identified using MATLAB
 295 "system identification toolbox" on the system step response
 296 with $V_3 = 40V$. It was performed looking for a transfer
 297 function model of order 2 with no zeroes The identified
 298 transfer function $H_i(p)$ is:

$$H_i(p) = \frac{0.842 \times 10^8}{p^2 + 774.6p + 1.818 \times 10^8} \tag{16}$$

Fig. 8 Top view of the MEMS with the DHM and example of curve showing vertical sum of pixels for a fixed position of the probe



299 Its input and output are expressed in Volts and μm
 300 respectively. The resonant frequency of this model is 2.2
 301 kHz. This value is coherent with the one obtained through
 302 the finite element analysis of the MEMS. Bode plot of the
 303 identified transfer function is displayed in Fig. 11.

304 **4.3 Static characterization of the MEMS actuator**

305 The MEMS static characterization is essential to check the
 306 system linearity. To do so, the setup described in Section 4.2
 307 is used. The system input is chosen to be sine wave at 5 Hz.
 308 The position is recorded and plotted with respect to the input
 309 voltage. Result is shown in Fig. 12.

310 This curve can be modeled by first order polynomial.
 311 The experimental static gain of the MEMS is equal to
 312 $0.51 \mu\text{m}/\text{V}$. The static gain deduced from the fitted transfer
 313 function is $0.463 \mu\text{m}/\text{V}$. Figure 12 shows a characteristic
 314 that can be assimilated as hysteresis. However, as this
 315 nonlinearity is not described in the literature as being

specific to electrostatic MEMS, we assume that this 316
 phenomenon is not mainly due to a hysteresis and could 317
 be due to some motion blur. Even though, this behavior is 318
 not predominant and can be neglected in the modeling. The 319
 non linearity error is lower than $0.4 \mu\text{m}$ once measurement 320
 artifacts have been removed, this error can be due to image 321
 noise or outside vibrations. Experimental results differ by 322
 a factor 2 from the ones presented in [18] because of a 323
 faulty amplifier in the original setup which introduced an 324
 amplification 2 times higher than expected. 325

326 **5 Simulation and test of the sensor in closed loop**
 327

328 **5.1 Sensor simulation**

Now that the system transfer function has been character- 329
 ized, a controller has to be designed for the sensor to operate 330
 in active mode. For the test in simulation to be possible, the 331
 coefficients of Eq. 13 have to be identified. However Eq. 16 332
 only allows the identification of three of the four param- 333
 eters. Because of this one of the four parameters has to be 334

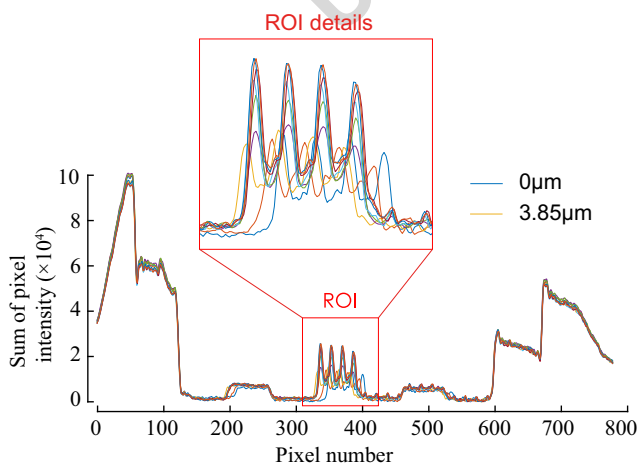


Fig. 9 Vertical sum of pixels for different values of displacements of the sensor probe (extreme values are shown with their legend)

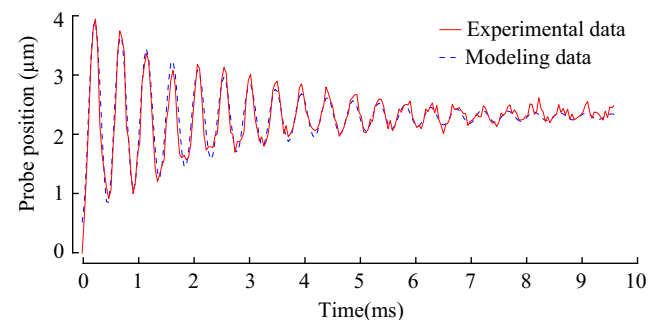


Fig. 10 Experimental and simulation step response of the MEMS sensor for a 4.5 Volts step input

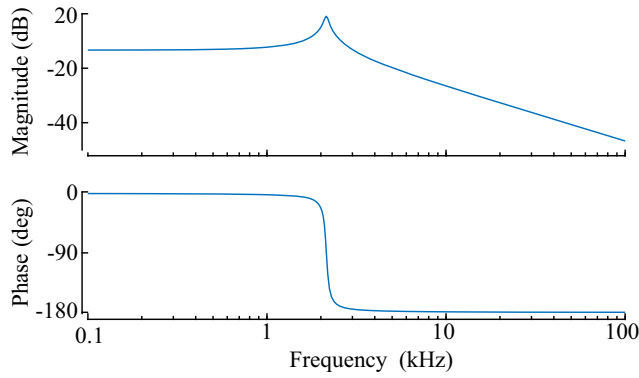


Fig. 11 Bode plot of the MEMS identified transfer function

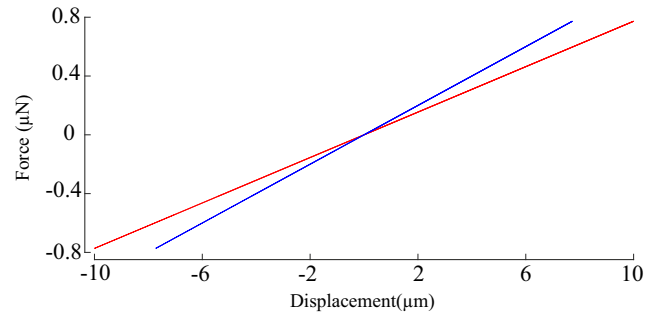


Fig. 13 Simulated force position characteristic of a $0.1N/m$ stiffness spring (blue) and estimated characteristic with the proposed sensor in passive mode (red)

335 identified by other means. There is little way to obtain m and
 336 ν with enough accuracy, so either k or $4k_c V_3$ has to be taken
 337 from the knowledge model. Between both $4k_c V_3$ is chosen.

$$4k_c V_3 = 0.316\mu N/V \quad (17)$$

338 This leads to :

$$\begin{aligned} m &= 3.7 \times 10^{-9} kg = 3.7\mu g \\ \nu &= 2.8 \times 10^{-6} N/m \times s \\ k &= 0.68 N/m \end{aligned} \quad (18)$$

339 The difference between finite element analysis result and
 340 the identified k can be explained by several causes :

- 341 – The value of $k_c V_3$ is highly sensitive to the mechanical
 342 parameters of the comb drive, and the manufacturing
 343 processes can lead to some dimensions inaccuracies.
 344 Moreover the side effects (such as the capacitance
 345 between the finger front end and the part of fixed
 346 electrode in front of it) were neglected when computing
 347 the values of C_{12} and C_{23} and these hypothesis can not
 348 be entirely true [19].
- 349 – Finite element analysis at these scales is prone to errors
 350 as the geometries are supposed to be perfect and the
 351 materials are supposed to be homogeneous. However
 352 Deep Reactive Ion Etching often creates defects that are
 353 far from negligible at these scales.

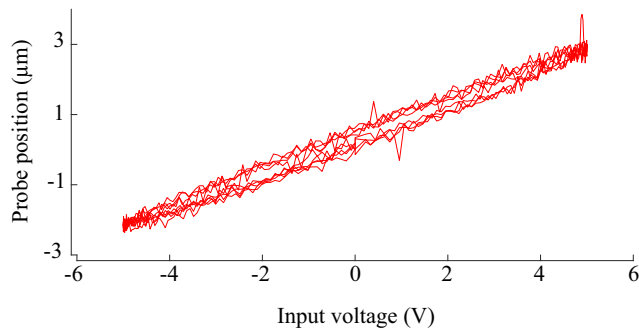


Fig. 12 Experimental static characteristic of the MEMS sensor

5.2 Differences between passive and active modes

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In passive mode, the sensor isn't actuated, any force applied
 on the sensor tip is translated into a displacement of the
 mobile part. In our case the displacement could be recorded
 thanks to a laser interferometer or by capacitive reading
 [20]. This mode only requires the identification of the
 flexures stiffness and is faster to implement than the active
 mode. However the sensor linearity depends on the flexure
 stiffness as well as the position measurement linearity.
 Furthermore, with this mode of operation, when trying
 to obtain force-position characteristics, the estimation is
 altered by the stiffness of the sensor flexures. In Fig. 13
 are displayed the simulated force position characteristic of
 a spring with $0.1N/m$ stiffness acquired with the proposed
 sensor in passive mode only knowing the sensor position, as
 well as the actual characteristic.

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One can notice a slight difference between the estimated
 and real force position characteristic. This is caused by
 the estimation of the characteristic of the spring in serial
 with the flexures equivalent spring. To compensate for this
 problem several solutions are possible :

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- use a stiffer force sensor,
- subtract probe displacement from the sensor position,
- use the sensor in active mode.

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Using the sensor in active mode can provide the
 advantage of having a virtually infinite stiffness and to
 measure far greater forces than would be allowed by the
 mobile part maximum displacement. First a controller has
 to be designed for the sensor, to do so, a PID controller
 has been implemented in simulation and fitted using Matlab
 PID tuner. During the design the constraints where a phase
 margin of 60° and a bandwidth of $5 \times 10^5 rad.s^{-1}$ for
 the system in closed loop. The chosen bandwidth is of the
 same order of magnitude as the system resonant frequency
 as increasing it further would not improve the sensing
 performance. Figure 14, shows the normalized step response
 of the sensor with and without the controller. Position of

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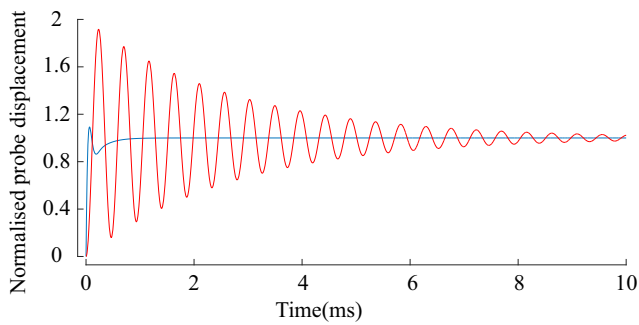


Fig. 14 Simulated normalized position of the sensor's probe in open loop (red) and in closed loop (blue)

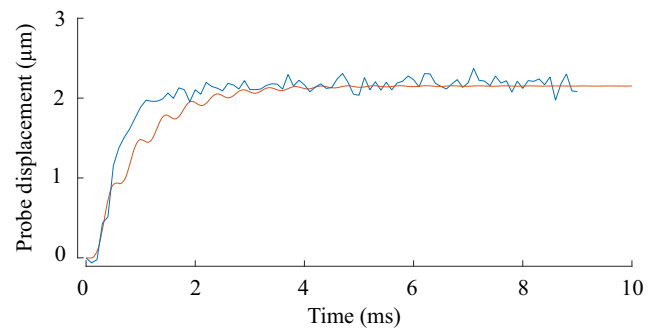


Fig. 16 Experimental probe displacement (blue) and simulation result (orange) for a step reference of $2\mu m$

391 the sensor's probe and PID output when a force of $10\mu N$
 392 is applied to the sensor are displayed in Fig. 15. On this
 393 curve one can notice a slight transient behavior of the
 394 sensor. However, this transient displacement is inferior to
 395 the sensor maximum displacement ($20\mu m$) thus allowing
 396 for the estimation of forces superior to the ones measurable
 397 in passive mode. furthermore, once steady state is reached
 398 the sensor mobile part is kept at its initial position.

399 5.3 Experimental test of the sensor

400 The actual experimental setup lacks the ability to measure
 401 the displacement of the sensor's probe in real time.
 402 Consequently, to validate the simulation results and the
 403 controller that has been synthesized, a simulation is run
 404 with the model of the sensor and the controller output
 405 is recorded. This record is played in a loop in order
 406 to be able to perform a stroboscopic analysis similar to
 407 the one performed in Section 4.2. However, the actual
 408 experimental setup lacks the capability to play the data
 409 at a sufficient speed. To be able to test the validity of
 410 the proposed MEMS model, a discrete time PID has been
 411 designed for the sensor with a 10kHz sampling frequency,
 412 with design requirements of a 2ms closed loop response
 413 and a 60° phase margin. The closed loop response time

is a compromise between system speed and the likeness
 of having undetectable oscillations between samples. The
 resulting sensor trajectory is displayed in Fig. 16, alongside
 with the predicted results. The results show the sensor's
 ability to reach a position of $2\mu m$, which corresponds, based
 on the value of k deduced from the transfer function, to a
 force of $1.36\mu N$.

The experimental results fit the simulation results
 reasonably well, the discrepancies can be explained by the
 measurement noise due to the image motion blur.

6 Conclusion

Based on a differential comb drive actuator and a folded-
 flexure suspension, a new MEMS force sensor is pro-
 posed in this paper. By design, its suspension is arranged
 to constrain the sensor probe within a single direction.
 Whilst, the differential actuator is chosen to provide a linear
 force/voltage relationship where force and probe position
 are independent. Furthermore, because of the suspension
 linearity, the sensor can be used as a force-sensing posi-
 tioner with $\pm 20\mu m$ displacement range, while retaining
 its mechanical performance independently from the operat-
 ing point. In view of using a zero displacement principle
 (balance principle), a control oriented electromechanical
 model is driven. Preliminary experimental characteriza-
 tion validates this model in static and dynamic operating
 modes using a stroboscopic measurement system. The sen-
 sor shows a promising potential with a high bandwidth and
 a great linear force measurement range, thus allowing for
 future work on the measurement of forces with great dynam-
 ics. Furthermore, because of the zero displacement sensing,
 this sensor is usable for the measure of forces with high gra-
 dients without compromises on its resolution or accuracy.
 The simulations results have shown the possibility to control
 the sensor in active mode.

Future work will focus on the sensor control in real
 time by the use of a laser interferometer and the sensor

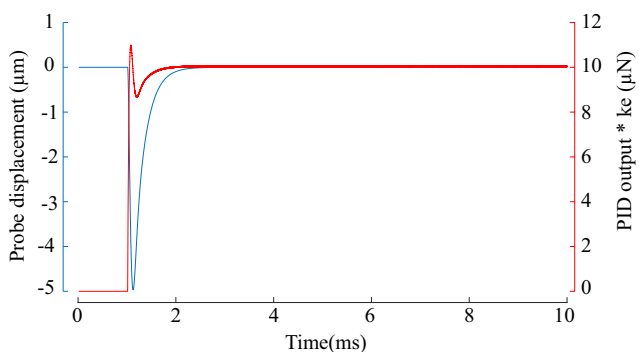


Fig. 15 Simulated probe displacement (blue) and active sensor reading (red) for an applied force of $10\mu N$

450 calibration, as well as the controller implementation with
 451 analog components. This sensor will be used for instance
 452 to measure the stiffness of muscular cells in order to
 453 differentiate cancerous cells from healthy ones.

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461 **References**

462 1. Chailliet N, Régnier S (2013) Microrobotics for micromanipulation, isbn: 9781848211865
 463
 464 2. Koch SJ, Thayer GE, Corwin AD, de Boer MP (2006) Micro-machined piconewton force sensor for biophysics investigations. Appl Phys Lett 89(17):173901
 465
 466 3. Kohyama S, Takahashi H, Yoshida S, Onoe H, Shoji KH, Tsukagoshi T, Takahata T, Shimoyama I (2017) Mems force and displacement sensor for measuring spring constant of hydrogel microparticles. In: International conference on micro electro mechanical systems (MEMS), pp 1040–1043
 467
 468 4. Mei T, Li WJ, Ge Y, Chen Y, Ni L, Chan MH (2000) An integrated mems three-dimensional tactile sensor with large force range. Sensors Actuators A Phys 80(2):155–162
 469
 470 5. Gutierrez CA, McCarty C, Kim B, Pahwa M, Meng E (2010) An implantable all-parylene liquid-impedance based mems force sensor. In: 2010 IEEE 23rd international conference on micro electro mechanical systems (MEMS), pp 600–603
 471
 472 6. Boudaoud M, Le Gorrec Y, Haddab Y, Lutz P (2015) Gain scheduling control of a nonlinear electrostatic microgripper: design by an eigenstructure assignment with an observer-based structure. IEEE Trans Control Syst Technol 23(4):1255–1267
 473
 474 7. Boudaoud M, Haddab Y, Le Gorrec Y (2013) Modeling and optimal force control of a nonlinear electrostatic microgripper. IEEE/ASME Trans Mechatronics 18(3):1130–1139
 475
 476 8. Boudaoud M, De Faria MG, Gorrec YL, Haddab Y, Lutz P (2014) An output feedback lpv control strategy of a nonlinear electrostatic microgripper through a singular implicit modeling. Control Eng Pract 28:97–111
 477
 478
 479
 480
 481
 482
 483
 484
 485
 486
 487
 488
 489

9. Gao W, Zhao L, Jiang Z, Xia Y, Guo X, Zhao Z, Zhao Y, Sun D (2017) A novel mems force sensor based on laterally movable gate array field effect transistor(lmgafet). In: International conference on nano/micro engineered and molecular systems (NEMS), pp 723–727
 490
 491
 492
 493
 494
 495 10. Guelpa V, Prax J, Vitry Y, Lehmann O, Dehaeck S, Sandoz P, Clévy C, Le Fort-Piat N, Lambert P, Laurent GJ (July 2017) 3d-printed vision-based micro-force sensor dedicated to in situ sem measurements. In: 2017 IEEE international conference on advanced intelligent mechatronics (AIM), pp 424–429
 496
 497
 498
 499
 500 11. Coskun MB, Moore S, Moheimani SR, Neild A, Alan T (2014) Zero displacement microelectromechanical force sensor using feedback control. Appl Phys Lett 104(15):153502
 501
 502
 503 12. Chen W, Jiang J, Liu J, Chen W (July 2013) A mems based sensor for large scale force measurement. In: 2013 IEEE/ASME international conference on advanced intelligent mechatronics, pp 1278–1283
 504
 505
 506
 507 13. Moore SI, Coskun MB, Alan T, Neild A, Moheimani SOR (2015) Feedback-controlled mems force sensor for characterization of microcantilevers. J Microelectromech Syst 24(4):1092–1101
 508
 509
 510 14. Maroufi M, Alemansour H, Moheimani SOR (2017) A closed-loop mems force sensor with adjustable stiffness. In: IEEE conference on control technology and applications (CCTA)
 511
 512
 513 15. Beyeler F, Muntwyler S, Nelson BJ (2009) Design and calibration of a microfabricated 6-axis force-torque sensor for microrobotic applications. In: 2009 IEEE international conference on robotics and automation, pp 520–525
 514
 515
 516
 517 16. Legtenberg R, Groeneveld AW, Elwenspoek M (1996) Comb-drive actuators for large displacements. J Micromech Microeng 6(3):320
 518
 519
 520 17. Courrieu P (2008) Fast computation of moore-penrose inverse matrices. CoRR arXiv:0804.4809
 521
 522 18. Cailliez J, Boudaoud M, Mohand-Ousaid A, Weill-Duflos A, Haliyo S, Régnier S (2018) Modeling and experimental characterization of an active mems based force sensor. In: International conference on manipulation, automation and robotics at small scales (MARSS), pp 91 (6), Nagoya, Japan, p 2018
 523
 524
 525
 526 19. Jaecklin VP, Linder C, de Rooij NF, Moret JM (1992) Micromechanical comb actuators with low driving voltage. J Micromech Microeng 2(4):250
 527
 528
 529
 530 20. Sun Y, Fry SN, Potasek DP, Bell DJ, Nelson BJ (2005) Characterizing fruit fly flight behavior using a microforce sensor with a new comb-drive configuration. J Microelectromech Syst 14(1):4–11
 531
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