Robust H-infinity control of two novel MEMS force sensors

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Abstract
This paper presents the design and implementation of a robust H-infinity controller on two novel MEMS force sensors. The novel microelectromechanical system (MEMS) sensors incorporated a mechanism that permits tuning of the device’s mechanical stiffness and has been used for the characterization of micro-cantilever and biological tissues. To ensure stability and guaranteed performances, certain specifications such as error tracking, command moderation, disturbance rejection, and robustness in presence of uncertainties, were made and the H-infinity control technique was employed to synthesize robust controllers for the two force sensors. Finally, this robust controller, integral, and PID controllers were implemented on the real systems and their performance in closed-loop were compared.

1. Introduction

Microelectromechanical systems (MEMS) are important in diverse applications. This high-precision mechatronic system has been utilized in the realization of force sensors [1], sophisticated mechanical and biomedical systems, artificial intelligence, etc.

A MEMS force sensor consists of mechanical sensory parts that move under applied forces and the corresponding circuitry transducing this mechanical displacement into an electrical signal [2, 3]. The mechanical stiffness is an essential property considered in several applications. Characterization of biological tissues using force sensors and other MEMS devices is vital in basic physiology, biomechanics, tissue engineering, and dermatology, etc and has been the focus of many researchers. A myriad of force sensors are proposed for different microcantilever in [4], and [5] presented a structure made up of an on-chip sensor and actuator. The study of mechanical properties of micro and nano-sized structures and samples was reported in [6]. Also, force sensors have been evaluated as an integral part of MEMS devices [7], where they were incorporated with micromanipulators for characterizing biological cells.

According to [1], a MEMS force sensor transduces an input force to displacement/deflection using a mechanical flexure, and this resulting displacement can be measured in open or closed-loop sensing conditions. To eliminate the effect of nonlinearities which characterized the displacement of the mechanical flexure in open loop, a closed-loop mechanism is employed for the sensors, since the stiffness of the flexure can directly affect the operations of the sensors, [8] incorporated a mechanism known as stiffness adjustment mechanism that allowed on-line tuning of the sensor properties. A similar mechanism has been investigated on an atomic force microscope (AFM) probe [9].

It was reported in [10] that the design of sensors for displacement measurement involves some trade-offs between qualities such as sensor linearity, sensitivity, power consumption, and dynamic performance. Although, these sensors can offer high bandwidths and high precisions that are characterized by badly damped vibration. Consequently, they lose their performances: an increase in settling time and loss of accuracy of the sensing probe [11]. Therefore, the control of the probe of the sensors has attracted the attention of researchers in recent times. In other words, Research on MEMS force sensors has achieved invaluable results in calibration, characterization, and control using conventional strategy, which hinders the real-time implementation since robust stability and optimal performance are not guaranteed with these methods. Conventionally, integral
controller and internal model control have been designed and implemented on the MEMS piezoresistive sensor [12]. Different closed-loop control has been surveyed in [13] and it highlighted that one of the efficient control techniques that guarantee stability and performance is the H-infinity control.

The H-infinity control is a known optimal algorithm for eliminating uncertainties in sensors and actuators. This technique has been widely implemented in actuators [14] presented the robust H-infinity control of the displacement of a two degrees of freedom bimorph piezoelectric actuator and this was extended to multimorph cantilevered piezoelectric actuated in [15]. Adaptive and H-infinity control of the MEMS electro-thermal force sensor has been studied in [16]. To use this technique, a control designer first expresses the control problem as a mathematical optimization problem and then finds the controller that solves this problem. The H-infinity control technique is readily applicable to solve problems involving multivariable systems [17]. The non-linear methods namely, sliding mode, artificial neural network (ANN), fuzzy logic and gain tuning Proportional Integral (PI) controllers are often utilized for force sensing control, these traditional control techniques are incompetent in providing superior damping performance [18]. This control scheme makes it possible to apply multivariable control with the frequency domain design technique and to obtain efficient stable control systems [19]. It is suitable for reference tracking applications, especially in the control of process elements such as the position of a control valve, damper [20, 21], and sensor’s probe, etc.

While the design and calibration of these MEMS force sensors with on-chip electro-thermal sensing mechanisms are not the focus of the paper, the calculation and implementation of robust controllers for the sensors (electro-thermal and Piezo-resistive) are the main interest of this work as recommended in [1, 22]. As compared to conventional controllers, the robust controller (H-infinity) is known to guarantee stability and optimal performance. This would enable the device to be used in high-precision applications.

2. Presentation of the MEMS force sensors

Two microelectromechanical (MEMS) force sensors were considered in this study. The main features of these sensors are highlighted in the following sections. It is important to note that the cleanroom fabrication of these sensors is not included in the scope of this work. The sensors developed at the LDCN (Laboratory for Dynamic and Control of Nanosystems), the University of Texas at Dallas, USA, are presented in [4], while the piezoresistive sensor which is made up of a probe and a shuttle at the center which displaces directionally using the electrostatic actuator is detailed [1].

3. Characterization

The characterization steps of the two sensors are the same. The setup used is depicted in figure 1. It comprises of the following:

(a) The two MEMS force sensors.
(b) Polytec Micro System Analyzer.
(c) A computer and a Dspace-board
(d) An oscilloscope

The performance of the MEMS force sensor with adjustable stiffness mechanism was experimentally determined. The step responses of the two sensors are plotted in figure 2. The displacement of this sensor was measured as a function of the actuation voltage (Va) as shown in figure 3.

3.1. System identification

The nominal system was identified using the Ident optimal toolbox in Matlab. Best fits prediction above 70% were obtained using the ARMAX (Auto-Regressive Moving Average with external inputs) technique for all the systems identified.

The dynamics of the two MEMS sensors $D_p(s)$ and $D_q(s)$ are identified from the step response in figures 3(a) and (b) respectively. For this dynamics to be normalized, $D_p(s = 0) = 1$ and $D_q(s = 0) = 1$.

The AutoRegressive Moving Average with eXternal inputs (ARMAX) of the Matlab software was applied to the experimental data of figures 3(a) and (b) to perform the identification. Different orders of the models were used.
Figure 1. The characterization set-up.

Figure 2. Step responses (a): response for the electro-thermal sensor (b): response for piezoresistive.

Figure 3. System identification of the sensors at 0 V adjustment voltages.

\[
\begin{align*}
D_c^{\text{ident}}(s) &= \frac{-1.671 \times 10^{-5}s + 0.7524}{9.851 \times 10^{-13}s^3 + 3.304 \times 10^{-8}s^2 + 3.705 \times 10^{-5} + 1} \\
D_p^{\text{ident}}(s) &= \frac{1.257 \times 10^{-5}s + 0.6133}{8.527 \times 10^{-13}s^3 + 2.669 \times 10^{-8}s^2 + 3.783 \times 10^{-5} + 1}
\end{align*}
\]
The dynamics are given in equations (1) and (2), when \( D^\text{ident}(0) \) and \( D^\text{ident}(0) \) are the dynamics of the systems at \( s = 0 \). To normalize these dynamics (i.e. \( D^\text{ident}(s) \) and \( D^\text{ident}(s) \)), the expressions in equation (3) was used. The normalized dynamics are given in equation (4):

\[
\begin{align*}
D_i(s) &= \frac{D^\text{ident}(s)}{D^\text{ident}(0)} \\
D_p(s) &= \frac{D^\text{ident}(s)}{D^\text{ident}(0)}
\end{align*}
\]

According to \([12]\), the model for nonlinearity and output disturbance compensation can be expressed as equation (5):

\[
\begin{align*}
\gamma = (1 + \Delta_s W_e \Delta ) k_e D_i(s) U_e + b_e \\
\gamma_p = (1 + \Delta_p W_p \Delta ) k_p D_p(s) U_p + b_p
\end{align*}
\]

\[-1 \leq \Delta_e \leq 1 \quad \text{and} \quad -1 \leq \Delta_p \leq 1 \]

\[
W_e = \frac{k_e}{2}, \quad \text{where } k_e = \text{slope of the measured output of figure 3a}
\]

\[
W_p = \frac{k_p}{2}, \quad \text{where } k_p = \text{slope of the measured output of figure 3b}
\]

The slopes \( k_e \) and \( k_p \) were estimated following the steps highlighted in \([12]\). From equation (5), indicating \( G_e(s) = k_e D_i(s) \) and \( G_p(s) = k_p D_p(s) \), the model can be rewritten as equation (6).

\[
\begin{align*}
\gamma = (1 + \Delta_s W_e \Delta ) G_e(s) U_e + b_e \\
\gamma_p = (1 + \Delta_p W_p \Delta ) G_p(s) U_p + b_p
\end{align*}
\]

Models represented in equation (6) are the models of the systems to be controlled. The block diagram of this final model is shown in figure 4. The models are used to find the controllers that enhanced the performances of the two MEMS force sensor.

4. Design and implementation the controllers

The improvement of the sensors’ performance in terms of sensitivity, linearity, and range can be achieved by using control techniques. In this section, Integral controller, Proportional-Integral-Derivative (PID), and H-infinity controllers.

4.1. Integral and PID controllers

An integral controller \((I_c)\) is used in reference tracking applications, and the transfer function of this controller in a feedback loop can be represented as:

\[
I_c = \frac{K_i}{s}
\]

Where \( K_i \) is known as integral gain, which is tuned in closed-loop with the systems.

This controller was first synthesized and implemented in closed-loop with the electro-thermal sensor (see figure 5), which has earlier been applied to the piezo-resistive sensor in \([2]\). In both cases, the steady-state errors of the devices were decreased. To improve the rise time, reduce the overshoot and steady-state, a PID controller was calculated and implemented separately on the two force sensors. This controller is widely employed in control theory, and can be defined as:
Where $K_d$ and $K_p$ are the proportional and derivative gain respectively.

The closed-loop transfer function with controllers ($T_{e,p}$) for the two sensors can be expressed as:

$$T_{e,p} = \frac{G_{e}(s)K_p(s)K_{ep}}{1 + G_{e}(s)K_{ep}}$$

Figure 4. The systems to be controlled: (a) Electro-thermal, (b) Piezo-resistive.

Figure 5. The step response of the Electro-thermal sensor in open-loop and closed-loop conditions with Integral controller.

$$PID_t = \frac{K_ds + K_ps + K_i}{s}$$

With the PID controller, the settling time was reduced from 40 ms in uncontrolled (open-loop) to about 1 ms in closed loop for electro-thermal sensor (figure 6), and 2 ms for piezo-resistive (figure 7).

The displacement measurement bandwidths at ±3 dB of $T_{e,p}$ are approximately 2.3 kHz and 4.0 kHz at the zero stiffness adjustment voltage for Electro-thermal and Piezo-resistive sensors respectively.

4.2. H-infinity (∞) controller

H-Infinity is a well-known robust control technique, used to achieve robust performance of sensors and actuators. Although the integral and PID controllers exhibited good performance, the robustness of the device in the presence of uncertainties, and input disturbance rejection are not guaranteed. Robust H-infinity provides the optimal dynamic response of a closed-loop using design specifications. Such requirements include error tracking, disturbance rejection, command moderation, and robustness in the presence of uncertainties.
4.3. Principle specifications

Tracking performance.

- The static error should be less than 1%.
- No overshoot
- The settling time should not exceed 15 ms.

**Input voltage limitation**

The maximum ratio is imposed as;

\[
\frac{U_{\text{max}}}{V_{\text{max}}} = \frac{10 \, \text{V}}{25 \, \mu\text{m}} = 0.4 \left( \frac{V}{\mu\text{m}} \right)
\]  

**Disturbance \( (b_\epsilon) \) rejection - :**

- No overshoot
- A disturbance of 2.2 \( \mu\text{m} \).
- The maximum settling time of 10 ms.

**Robustness in presence of the uncertainty \( \Delta_\epsilon W_{\epsilon\Delta} \)**

- The specifications above should be ensured for any uncertainty present in \( \Delta_\epsilon W_{\epsilon\Delta} \)
In $H_\infty$ control technique, these desired specifications can be achieved by employing weighting functions \cite{9}. The standard scheme derived from the augmented closed-loop is shown in figure 10. The uncertainty in the system is a direct multiplicative structure of $\| \Delta \|_\infty \leq 1$ weighted by $W_\Delta$, as illustrated in figure 8 the condition of stability of the closed-loop is as equation (11).

\[
\| S \mathcal{G}_K W \Delta \|_\infty \leq 1
\]  

(11)

Where $S$ is the sensitivity function and is given by:

\[
S = \frac{e}{1 + \mathcal{G}_K e} = \frac{1}{1 + \mathcal{G}_K e}
\]  

(12)

And $S, K, G_e = T_c$ is called the complementary sensitivity function which links the output $y$ and the input $Y_{\text{ref}}$. It is expressed as:

\[
T_c = 1 - S_c = S_c K_c G_e = \frac{y}{Y_{\text{ref}}} = \frac{1}{1 + \mathcal{G}_e}
\]  

(13)

The standard form of $H_\infty$ control design connects the augmented system $P(s)$ to the controller $K_c(s)$ are depicted in figure 10(a). This augmented system is composed of the nominal system $G_e(s)$ and weighting functions. The details of the standard interconnection from the weighted closed in figure 9 is highlighted in figure 10(b).

The objective is to determine the controller $K(s)$ such that:

- The interconnection of the figure [7] is stable.
- The lower linear fractional transformation (LFT) $F_l(P(s)K(s))$, which is defined as the transfer function between the exogenous signals $e_1, e_2, e_3$ and $Y_{\text{ref}}, b$ in presence of the interconnection with $K(s)$ \cite{16}.

\[
\| F_l(P(s), K(s)) \|_\infty < \gamma
\]  

(14)

In this case, the LFT function $F_l(P(s), K(s))$ can be represented in matrices function as:

\[
\begin{bmatrix}
e_1 \\
e_2 \\
e_3
\end{bmatrix} = F_l(P(s), K(s))
\begin{bmatrix}
Y_{\text{ref}} \\
b
\end{bmatrix}
\]  

(15)

From the standard $H$-infinity approach;

\[
\begin{bmatrix}
W_1 S - W_1 S W_3 \\
W_2 K S - W_2 K S W_3 \\
G_e K S W_1 - W_1 S W_3
\end{bmatrix} < \gamma
\]  

(16)
Applying Cauchy–Schwartz inequality,
\[
\begin{align*}
|S| < \gamma | \frac{1}{W_1} |, \quad |S| < \gamma | \frac{1}{W_1 W_3} | \\
|KS| < \gamma | \frac{1}{W_2} |, \quad |S| < \gamma | \frac{1}{W_2 W_3} | \\
|G_3 KS| < \gamma | \frac{1}{W_3} |, \quad |S| < \gamma | \frac{1}{W_3} |
\end{align*}
\]

In the above inequalities, \( \frac{1}{W_1} \) is called the gabarit (performance frequency) for the tracking performance specification since it is used to impose bound and shape for \( S(s) \) in its frequency domain. Similarly, \( \frac{1}{W_2} \) is for the command moderation specification and \( \frac{1}{W_3} \) is the gabarit for the disturbance rejection specification. The weighting functions \( W_1, W_2, \) and \( W_3 \) are derived by matching these Gabarits with the specifications.

\[
\frac{1}{W_1} = \frac{K_0 S + \left( \frac{3 \epsilon_s}{tr} \right)}{s + \left( \frac{3 \epsilon_s}{tr} \right)} = \frac{s + 3}{s + 300}
\]

For the command moderation specification, a simple gain can be used as bound:

\[
\frac{1}{W_2} = 0.269 \begin{bmatrix} V \\ \mu m \end{bmatrix}
\]

Finally, for the disturbance rejection, assuming input error of 0.3 nm and the estimated noise was converted to displacement using the electro-thermal sensor’s calibration factor of 1.43 nm.

\[
\frac{1}{W_1 W_3} = \frac{0.3}{1.43}
\]

From the previously calculated value of the weighting on the tracking performance \( W_1 \), the weighting function \( W_3 \) can be evaluated as,

\[
W_3 = \frac{1}{W_3} \left( \frac{1}{W_1 W_3} \right) = \frac{1.43s + 4.29}{0.3s + 90}
\]

In order to determine the robust controller that will solve the problem stated in approach 1 and to find the controller that satisfies the inequalities given above, a very useful and powerful algorithm known as the
Glover–Doyle (DGKF) algorithm will be applied. The resolution in this algorithm is based on the Riccati equations and it uses the dichotomy technique to find the optimal value of the performance level $\gamma$ [17].

According to [23], the H-infinity controllers are of higher order which may result in large control effort. Other design approaches and applications of this controller are given in [24–26].
Equation (22) gives the controller $K_c(s)$ and the performance level $\gamma$ obtained for this system.

$$
K_c(s) = \frac{1.076 \times 10^5 s^4 + 4.205 \times 10^9 s^3 + 2.317 \times 10^{12} s^2 + 5.28 \times 10^{16} s + 7.725 \times 10^{17}}{s^3 + 1.585 \times 10^5 s^4 + 1.148 \times 10^{10} s^3 + 4.972 \times 10^{13} s^2 + 1.491 \times 10^{16} s + 2.981 \times 10^{17}}
$$

$$
\gamma = 0.502777
$$

(22)
The procedure stated above was repeated in synthesizing the controller for the Piezoresistive MEMS force sensor. Equation (23) gives the controller $K_p(s)$ and the performance level $\gamma$ obtained for the Piezo-resistive system.

$$K_p(s) = \frac{5437 s^4 + 1.703 \times 10^8 s^3 + 2.446 \times 10^{11} s^2 + 6.381 \times 10^{14} s + 1.275 \times 10^{17}}{s^5 + 1.549 \times 10^5 s^4 + 1.156 \times 10^{10} s^3 + 3.186 \times 10^{14} s^2 + 6.385 \times 10^{17} s + 3.82 \times 10^{18}}$$

$$\gamma_p = 1.127792 \tag{23}$$

The performance levels of the two systems, $\gamma_e$ and $\gamma_p$, were obtained as 0.502777 and 1.127792 respectively. In figures 11 and 12, the overshoots of $|S_j|$, $|K_j S_j|$, and $|G_j K_j S_j|$ relative to the magnitudes $\left|\frac{1}{w_{j1}}\right|$, $\left|\frac{1}{w_{j2} w_{j3}}\right|$, and $\left|\frac{1}{w_{j4}}\right|$, where $j = \{e, p\}$ are negligible. Hence, the calculated controllers are acceptable for these systems.

The synthesized $H_\infty$ robust controllers were implemented for these devices, using a dSPACE MicroLabBox with a sampling rate of 100 kHz. A simple closed-loop diagram for this implementation is shown in figure 13. The closed-loop is made up of the controller and the force sensor to be controlled. First, the controller $K_e(s)$ was implemented on the electro-thermal sensor. A serial of signal $y_{ef}$ was experimentally applied to the closed-loop.

Figure 15. The output response and the reference of the feedback model of Piezo-resistive system: (a) Rectangular pulse, and its error function, (b) Step response.
Figures 14 and 15 depict the responses and their deviation (tracking error) of the step function of 25 $\mu$m. Also, a rectangular pulse function was applied to the real-time setup and the result is shown in figure 14(b). In both cases, the output response track theses references without vibrations and overshoot, and the input disturbance has a quick settling time. Similarly, the controller $K_p(s)$ was implemented on the piezo-resistive sensor, and the observed result is highlighted in figure 15(b). Also with these controllers, the highest tracking errors of the rectangular pulse function were about 15 nm and 10 nm for electro-thermal and piezo-resistive sensors respectively.

5. Discussion

A step reference was applied to analyze the performance of the two different MEMS force sensors (Electrothermal and Piezo-resistive). The results show that the design specifications were maintained for both. The response time was reduced while overshoots in figure 2 were eliminated. Thereafter the performances of the systems were analyzed in frequency domain. This domain is more concise than the time domain [13]. In this case, a rectangular pulse signal was applied to the systems, and the output displacement was measured. Bode plots are presented in figures 16–20. In [1] integral controller and Internal Model Control (IMC) were implemented on the piezo-resistive sensor, and their sensing bandwidths were 3.6 kHz and 800 Hz respectively. Similarly, an integral controller of low bandwidth (10 Hz) was observed in a closed-loop with the electro-thermal sensor as depicted in figure 16. With this closed-loop behavior, the required performance is not guaranteed. To improve the dynamic characteristics of these sensors, a
PID controller was also synthesized and implemented on each device. Their frequency responses are highlighted in figures 17–18, and the closed-loop bandwidth obtained were 2.3 kHz and 4.0 kHz for the electro-thermal and piezo-resistive. These are good sensing bandwidth for high-frequency measurement. Despite satisfactory transient
behavior of the closed-loop force sensors (with PID/integral controller), the systems become unstable after a short period during interaction with a sample. To solve this problem of instability, the $H_{\infty}$-infinity controller was employed. With closed-loop bandwidth of 5.88 kHz and 6.28 kHz for electro-thermal and Piezo-resistive respectively, it was observed that this controller in closed-loop with the sensors (figures 19–20) showed high robustness irrespective of the characteristics of the sensor.

With Infinite gain margins, and phase shifts of 109 and 143 degrees (electro-thermal and piezo-resistive respectively), the PID controller was able to suppress the resonant peak of the uncontrolled systems (see figures 17 and 18). This suppression was also achieved by the robust $H_{\infty}$ controller having magnitudes of 12.34 dB and 31.82 dB in closed-loop with electro-thermal and piezo-resistive sensor respectively (figures 19 and 20). Also, the phase shifts indicate that external disturbance will be rejected by the controllers’ output in wide-ranging frequencies.

6. Conclusion

This report presented the robust $H_{\infty}$-infinity control of two force sensors. The sensors are novel electromechanical devices with an in-built stiffness adjustment mechanism. The operations of the sensors are limited due to inherent nonlinearity and uncertainties. These effects generally contribute to the accuracy, settling time, and other performances of the sensors, and could lead to loss of their high bandwidths and resolutions. Integral and PID controllers were tuned and implemented on these systems. Also, the robust $H_{\infty}$ controller was synthesized and implemented in closed-loop with the sensors. The $H_{\infty}$ controllers achieved better performance and optimal robustness margin with multiplicative uncertainties, when compared with both the integral and PID controllers.

Future work will utilize more robust controllers to improve the dynamic resolution and measurement range of these sensors at different stiffness adjustment voltage.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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