Talk 1: Observer techniques appied to the control of piezoelectric microactuators

Micky RAKOTONDRABE, Cédric Clévy, Ioan Alexandru Ivan
and Nicolas Chaillet, FEMTO-ST (Besançon, France)

- *1 –* FEMTO-ST and SAMMI group activities

- *2 –* Observer techniques applied to piezocantilevers

- *3 –* Self sensing of piezocantilevers

microPAdS - FP7-PEOPLE-2007-2-1-IEF

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About FEMTO-ST Institute …

The roots of our activity comes from **Watchmakers** industry in Besançon area & **Automotive** industry in Belfort area.

- **A wide range of technical competencies in ENGINEERING SCIENCES**
- **A MULTIDISCIPLINARY research institute**
- **A high level MICROFABRICATION TECHNOLOGY facility**
- **A culture of INNOVATION : from basic research to industrial partnership**

. 500 staff people

. 28 M€ annual overall budget including 10 M€ operational budget

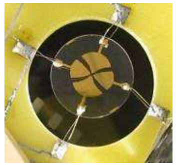
. About 250 running research contracts

6 research departments
6 main application fields
1 microfabrication center

→

Research Departments

TIME & FREQUENCY



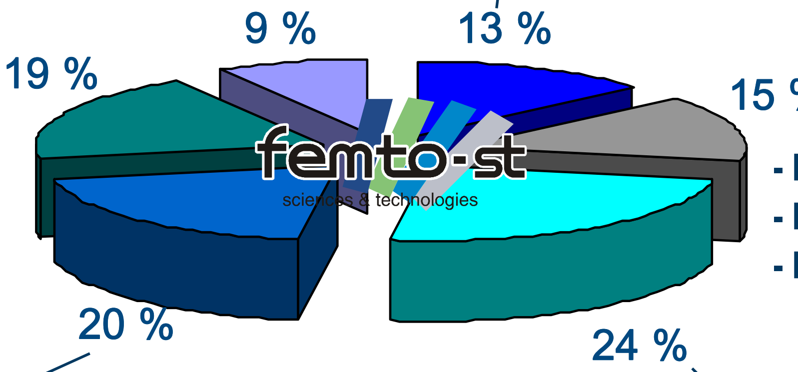
- High-stability oscillators
- Acousto-electronics and piezoelectricity
- Time-frequency metrology

AUTOMATIC CONTROL & MICRO-MECHATRONIC SYSTEMS (AS2M)

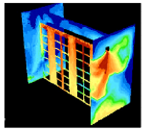
- Automatic control
- Microrobotics
- Micromechatronics
- Micromanipulation and micro-assembly
- E-maintenance and design activity guidance

OPTICS

- Photonics and telecommunications
- Nano-optics
- Optoelectronics
- Non-linear optics
- Biophotonics



ENERGY & MULTIPHYSICAL SYSTEMS



- Energy metrology and modelling
- Energy system design
- Radio protection and medical physics

MICRO NANO SCIENCES & SYSTEMS

- Micro and nano-instrumentation
- Nanosciences
- Micro & Nano-acoustics
- Multiphysical Microsystems
- Micro, Nanomaterials and surfaces

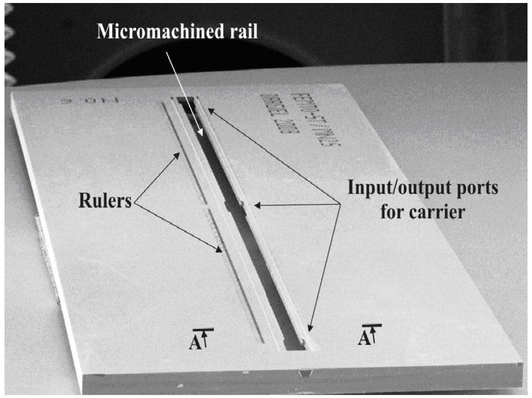
APPLIED MECHANICS

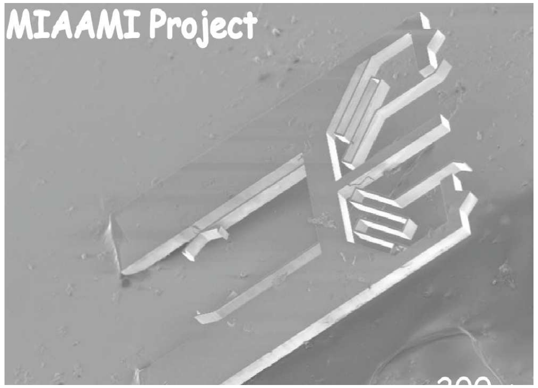
- Mechanical properties of materials
- Structural dynamics
- Material forming and microfabrication
- Surface microanalysis

SAMMI Group

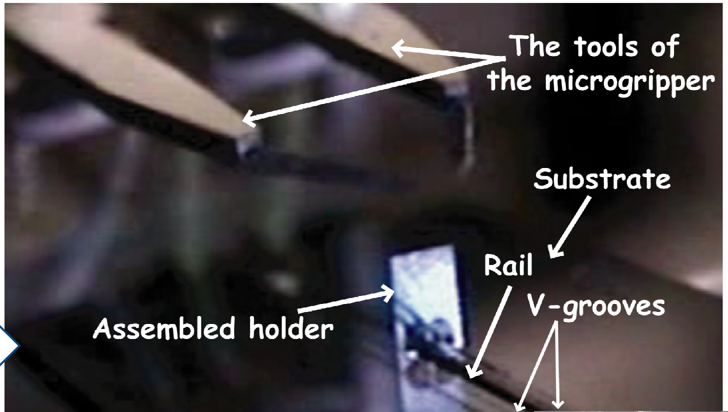
Automated Systems for Micromanipulation and Microassembly

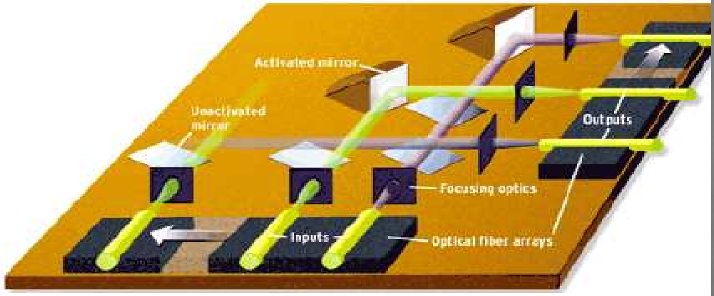
- **General objectives (1)**
  - **Create microrobots and microrobotic cells for flexible micromanipulation and microassembly**
    Because of the growing number of microproducts to assemble, efficient and reliable micromanipulation systems are required

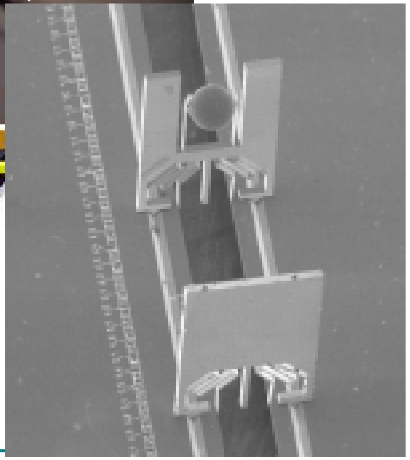




Micro-assembly





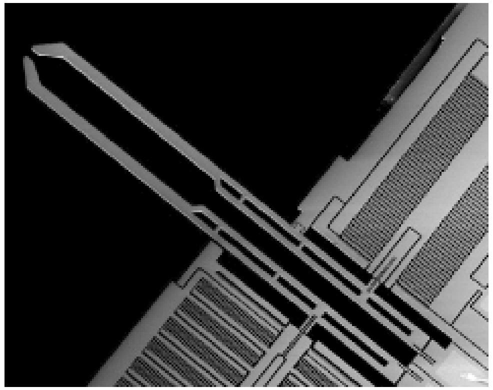


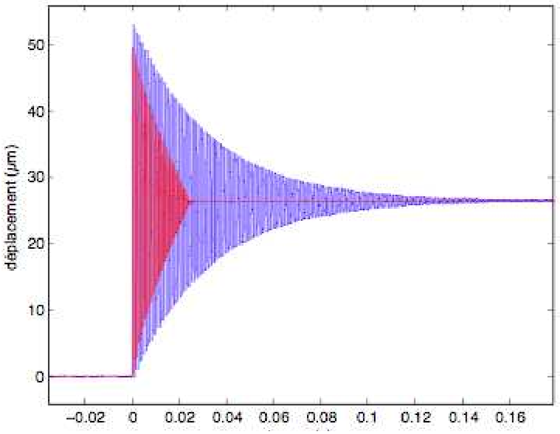
General objectives (2)

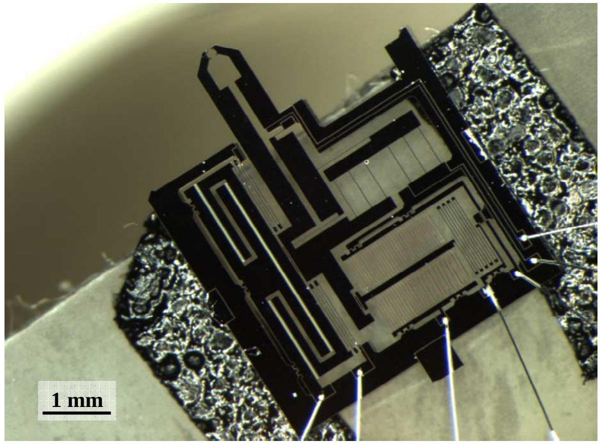
– Control complex microsystems

MEMS = specific paradigms for control science

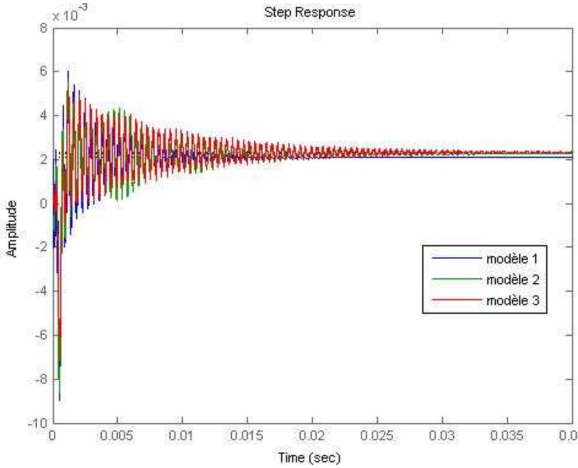
Microgripper from Femto-tools (FT G100)







Nanotweezer
from LIMMS



Main addressed scientific issues on control in the SAMMI group/ FEMTO-ST

Modelling and control of:

- **micro-actuators: SMA, MSMA, piezo, thermal…**
- **microrobots: stick slip actuation, digital MEMS,…**
- **discrete distributed systems: smart surface**
- **continuous distributed systems**
- **assembly microfactories: calibration, information data modelling and management**

⇒ **Need of measurement (sensors, observers)**

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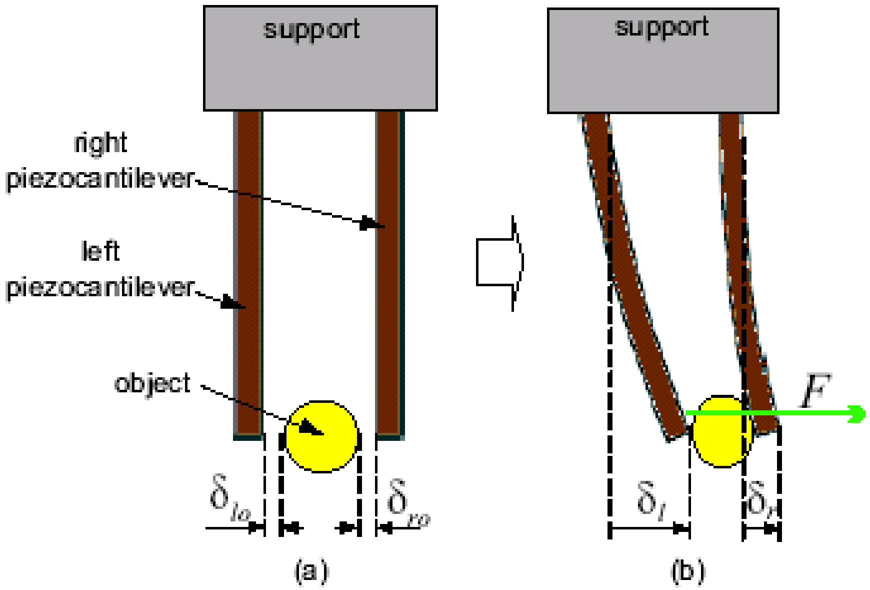
- 3 – Self sensing of piezocantilevers

2 – Observer techniques applied to piezocantilevers

A - Context

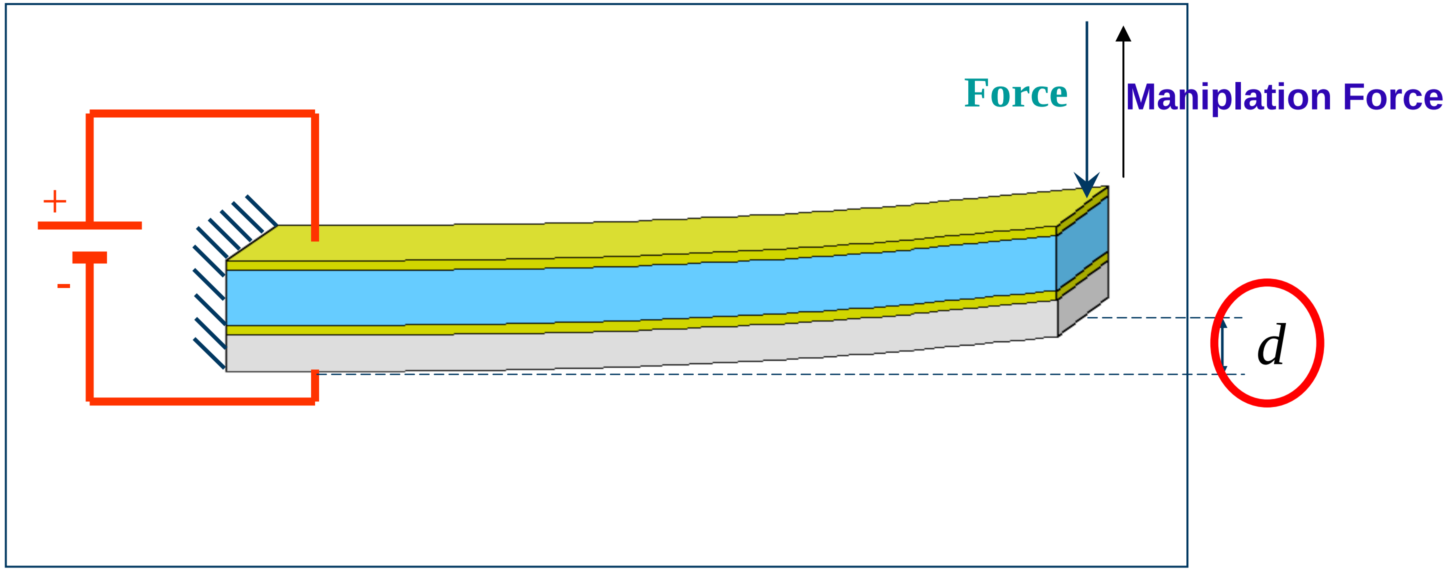


(a) (b)

- Position control of one cantilever,
- Force control of the second cantilever

2 – Observer techniques applied to piezocantilevers

A - Context

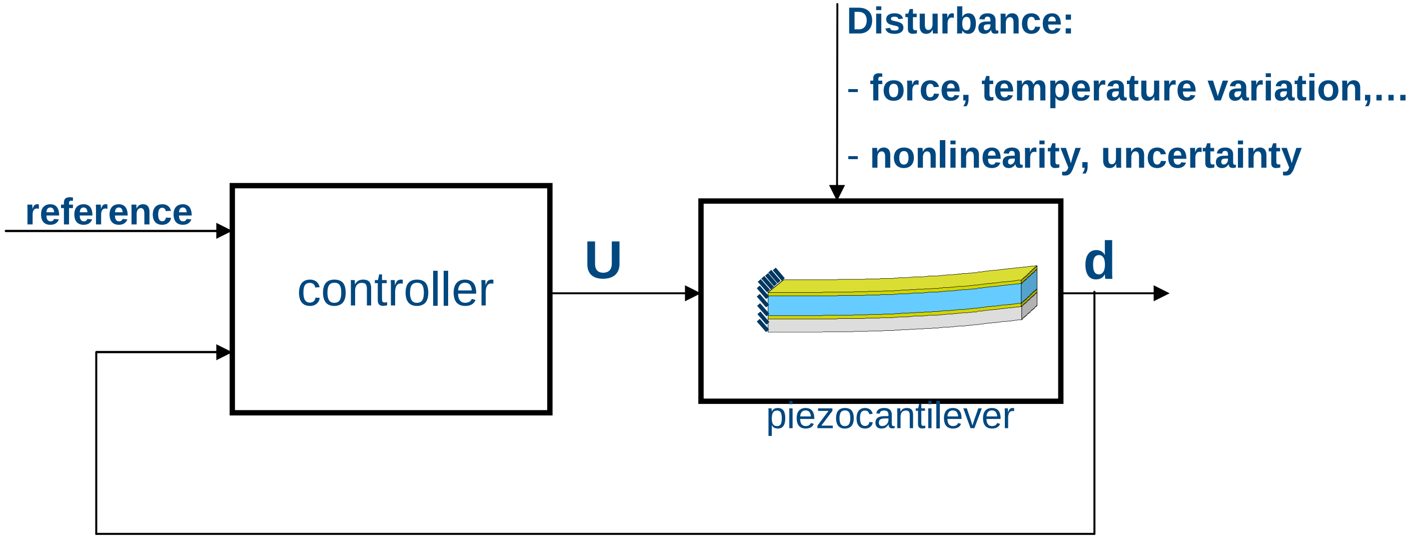


Deflection:
  - Modeling,
  - Control,
  - Measurement/estimation

Manipulation force:
  - Modeling,
  - Control,
  - Measurement/estimation

2 – Observer techniques applied to piezocantilevers

B - Deflection measurement and control



Disturbance:

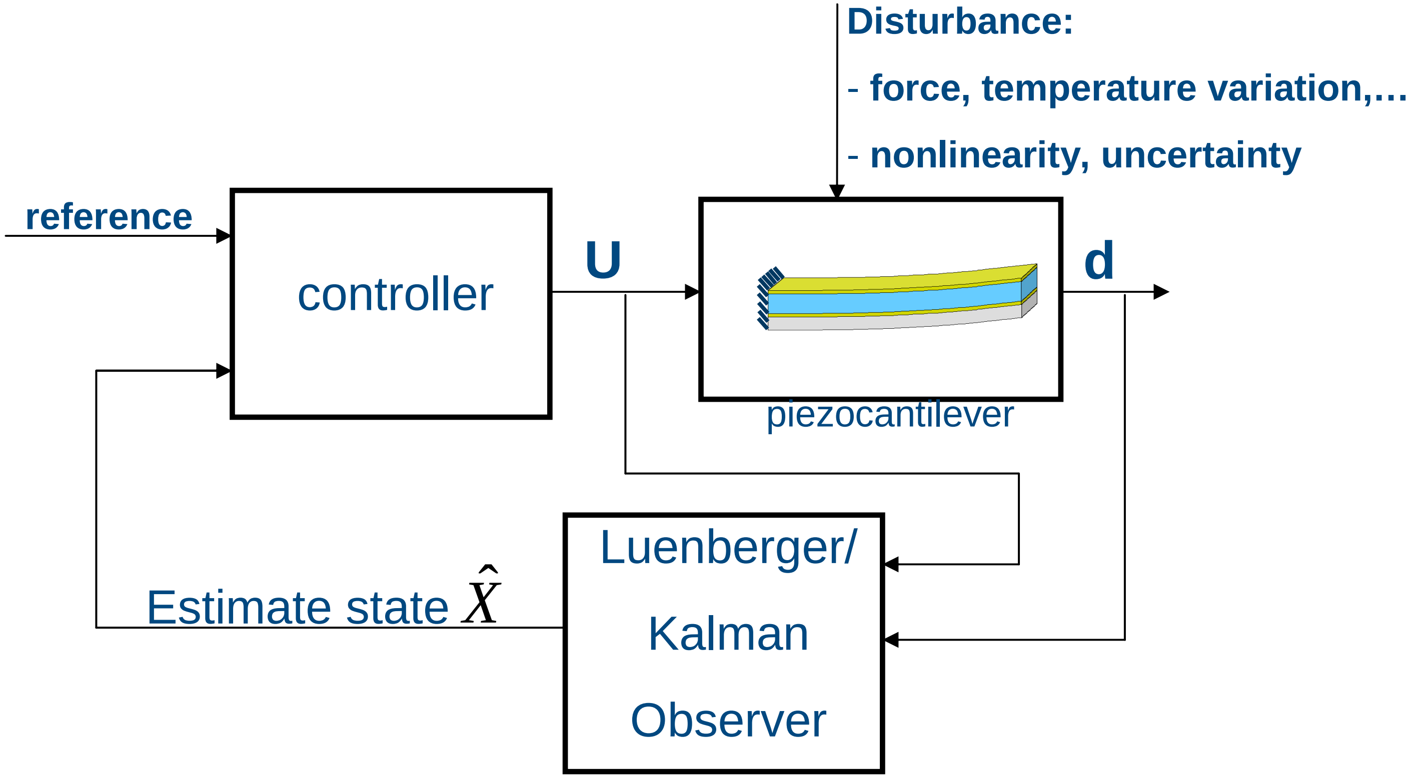
- **force, temperature variation,…**
- **nonlinearity, uncertainty**

- Frequential controller (H-inf, PID, RST…)

[CASE07]
[IROS07]
[ieeeTCST09]

2 – Observer techniques applied to piezocantilevers

B - Deflection measurement and control



Disturbance:

- **force, temperature variation,…**
- **nonlinearity, uncertainty**

reference

controller

U

d

piezocantilever

Luenberger/

Kalman

Observer

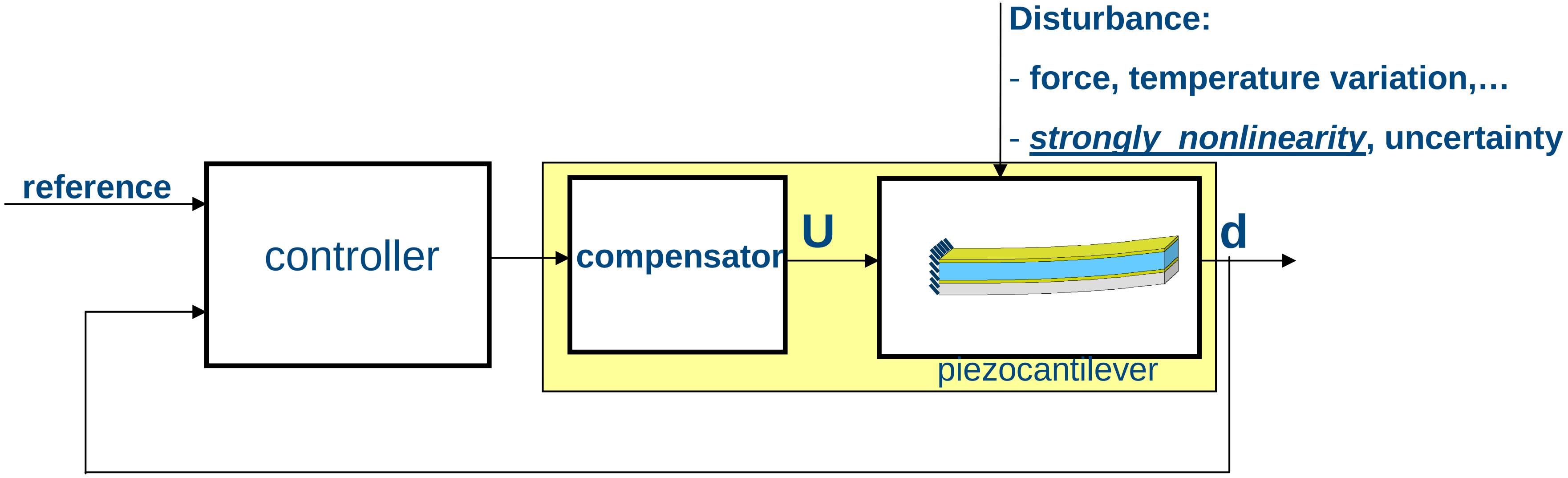
Estimate state $\hat{X}$

$$\frac{d\hat{X}}{dt} = A\hat{X} + BU + K_o\left(d - \hat{d}\right)$$

[Haddab, PhD00]

- State-Space domain (LQ, modal control, pole assignment)

B - Deflection measurement and control

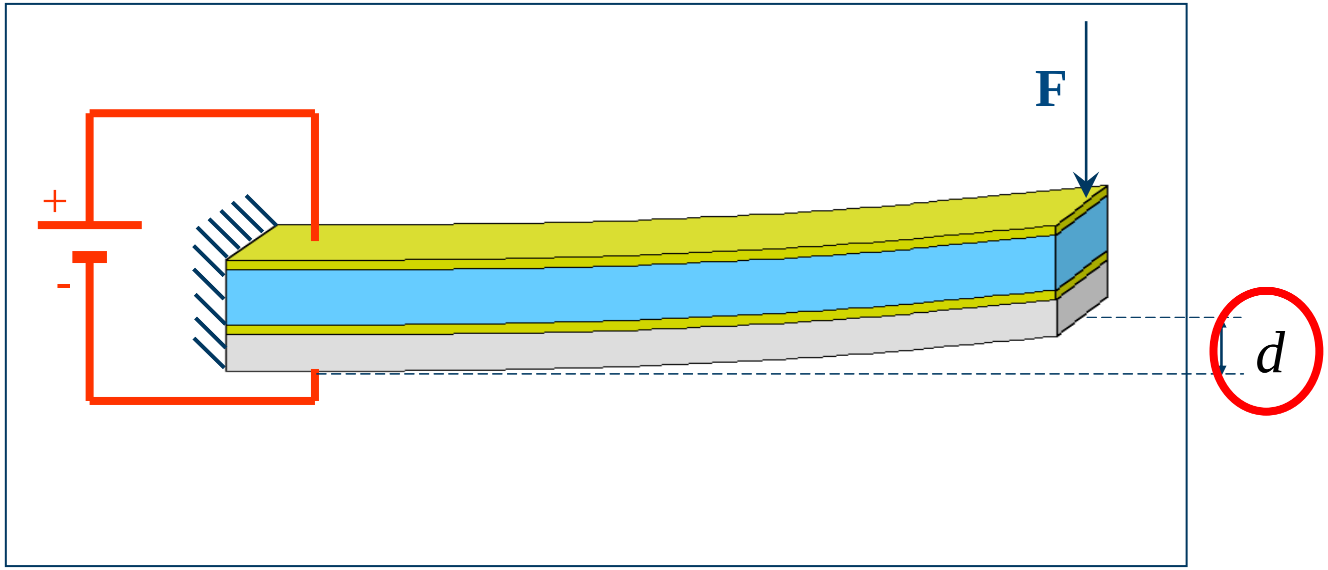


Linearization of the nonlinearity (hysteresis and creep)

[ifacWC08]
[ieeeTASE*a*]

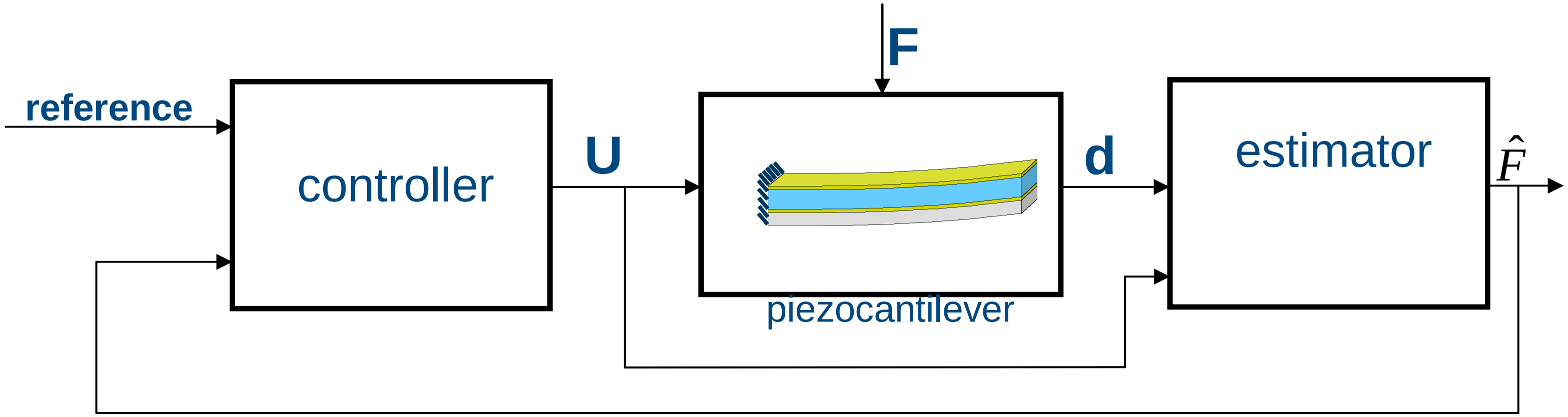
2 – Observer techniques applied to piezocantilevers

C - Force measurement and control



Information on the force: from the deflection

C - Force measurement and control

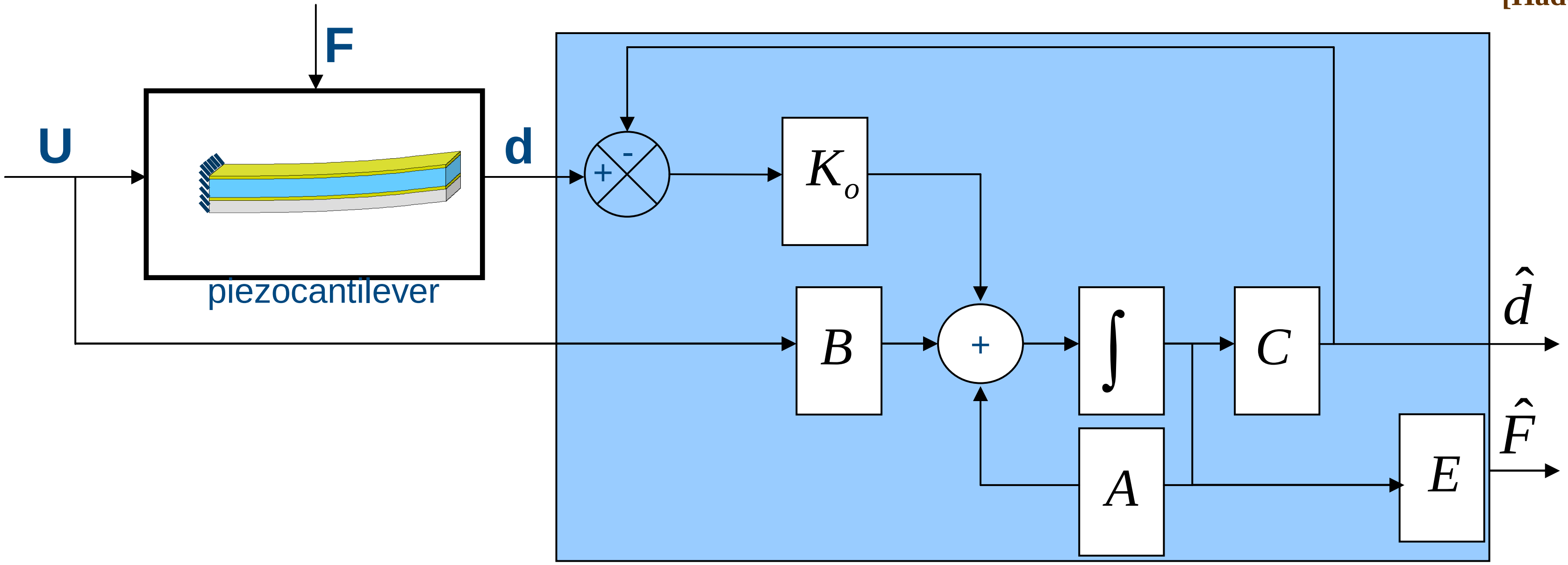


2 – Observer techniques applied to piezocantilevers

C - Force measurement and control

Luenberger state observer

[Haddab, PhD00]



$$\begin{cases} \dfrac{d}{dt}\begin{pmatrix} d\\ v\\ F\end{pmatrix} = \begin{pmatrix}0&1&0\\a&b&0\\0&0&0\end{pmatrix}\begin{pmatrix}d\\v\\F\end{pmatrix} + \begin{pmatrix}0\\k\\0\end{pmatrix}U \\ d = \begin{pmatrix}1&0&0\end{pmatrix}\begin{pmatrix}d\\v\\F\end{pmatrix}\end{cases}$$

- Do not account nonlinearities (hysteresis and creep)

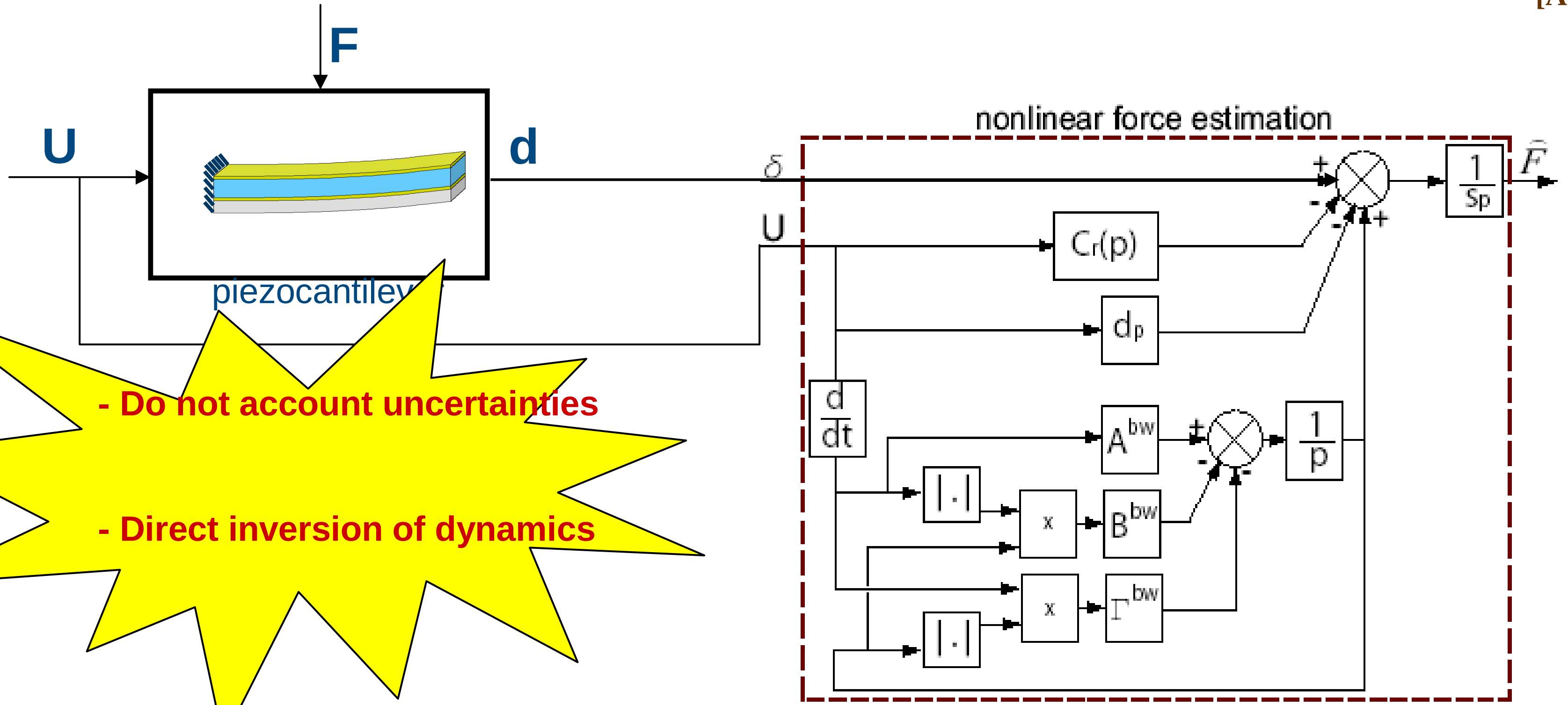
- Needs to impose dynamics

$$\begin{cases} \dfrac{d}{dt}\begin{pmatrix} \hat{d}\\ \hat{v}\\ \hat{F}\end{pmatrix} = \begin{pmatrix}0&1&0\\a&b&0\\0&0&0\end{pmatrix}\begin{pmatrix}\hat{d}\\ \hat{v}\\ \hat{F}\end{pmatrix} + \begin{pmatrix}0\\k\\0\end{pmatrix}U + \begin{pmatrix}K_1\\K_2\\K_3\end{pmatrix}\left(d-\hat{d}\right) \\ \hat{d} = \begin{pmatrix}1&0&0\end{pmatrix}\begin{pmatrix}\hat{d}\\ \hat{v}\\ \hat{F}\end{pmatrix} \\ \hat{F} = \begin{pmatrix}0&0&1\end{pmatrix}\begin{pmatrix}\hat{d}\\ \hat{v}\\ \hat{F}\end{pmatrix}\end{cases}$$

C - Force measurement and control

Open-loop estimation

[AIM07]



- Do not account uncertainties

- Direct inversion of dynamics

$$d = \Gamma\left(U\right)\cdot D(s) + C_r(s)\cdot U + s_p \cdot D(s)\cdot F$$

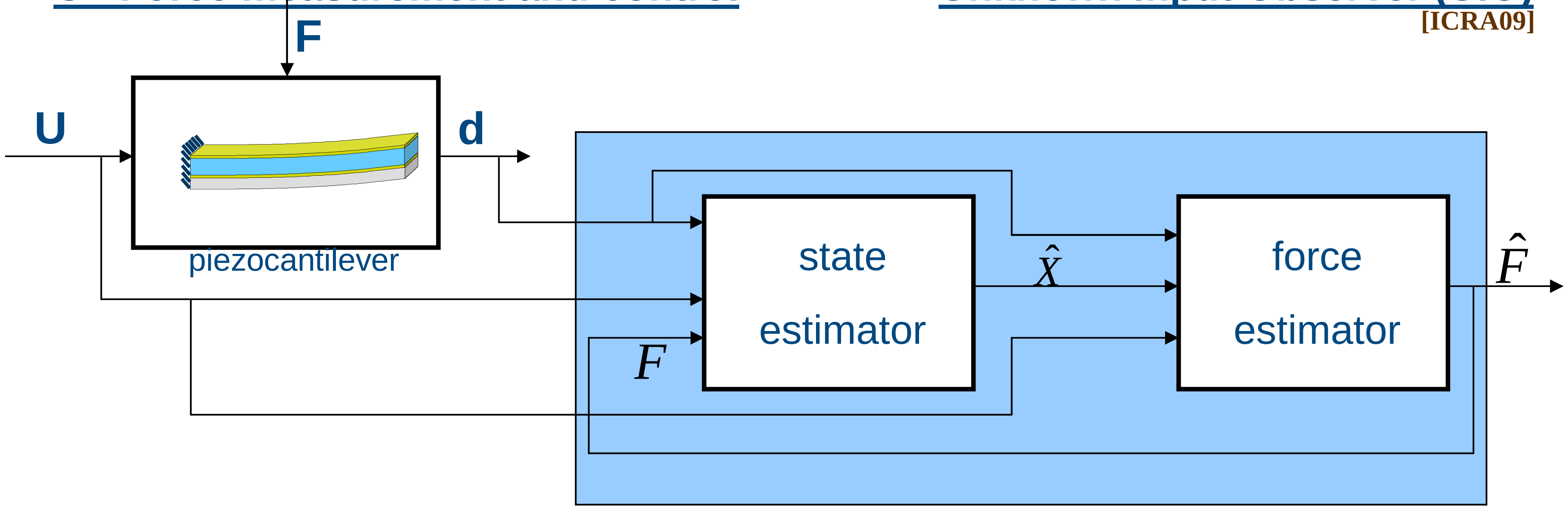
$$\Rightarrow \quad \hat{F} = \frac{1}{s_p \cdot D(s)}\left[d - \Gamma\left(U\right)\cdot D(s) + C_r(s)\cdot U\right]$$

2 – Observer techniques applied to piezocantilevers

C - Force measurement and control

Unknown Input Observer (UIO)

[ICRA09]



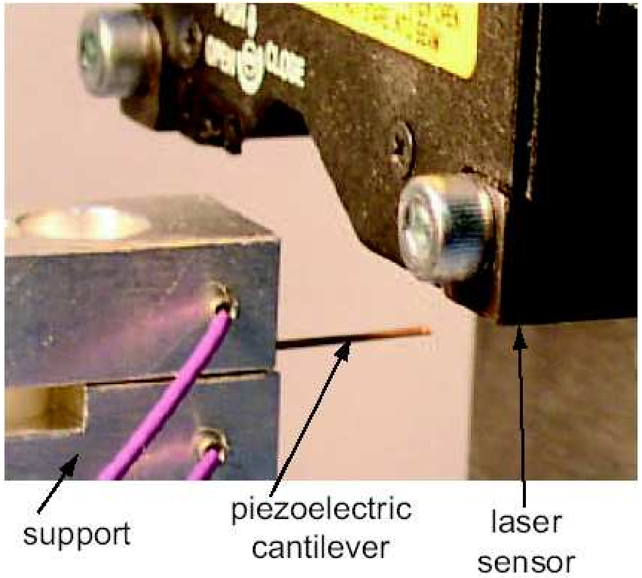
$$\begin{cases} \dfrac{dX}{dt} = A\cdot X + \Gamma\left(u,d\right) + B\cdot F \\ d = C\cdot X \end{cases}$$

$$\begin{cases} \dfrac{d\hat{X}}{dt} = A\hat{X} + \Gamma\left(u,d\right) + B.\hat{F} + K\left(d - \hat{d}\right) \\ \hat{d} = C\hat{X} \end{cases}$$

$$\hat{F} = F_1 d + F_2 \frac{dd}{dt} + G_1\hat{X} + G_2\frac{d\hat{X}}{dt} + G_3\Gamma\left(u,d\right)$$

2 – Observer techniques applied to piezocantilevers

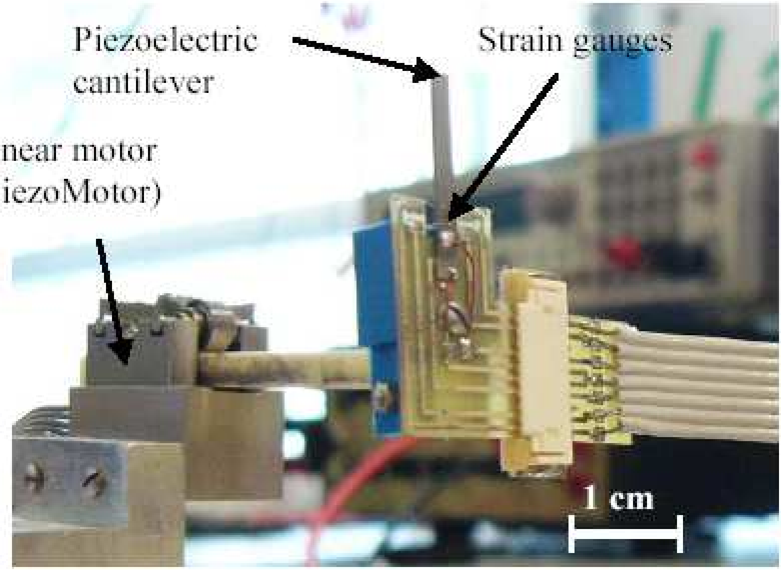
D – Limitation of using sensors

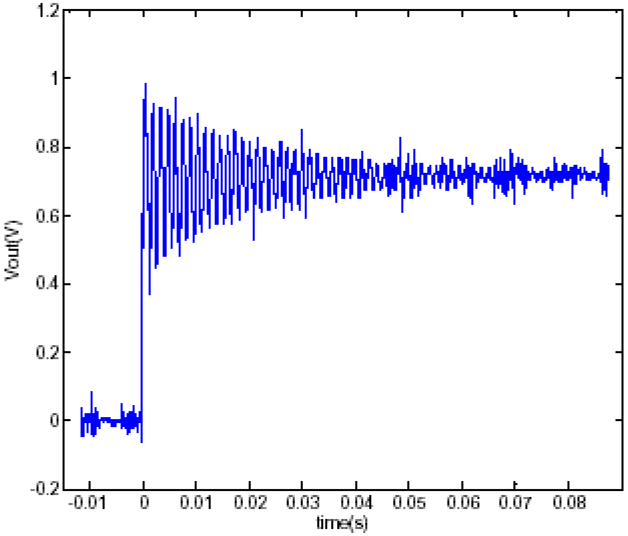


- Accurate and high bandwidth sensors (optical sensors…):

→ expensive
→ large sizes (not convenient for packaged systems)

D – Limitation of using sensors





- Embeddable sensors (strain gauge sensors):

→ **noisy**
→ **fragile**

[Haddab et al, IFAC-Mech09]

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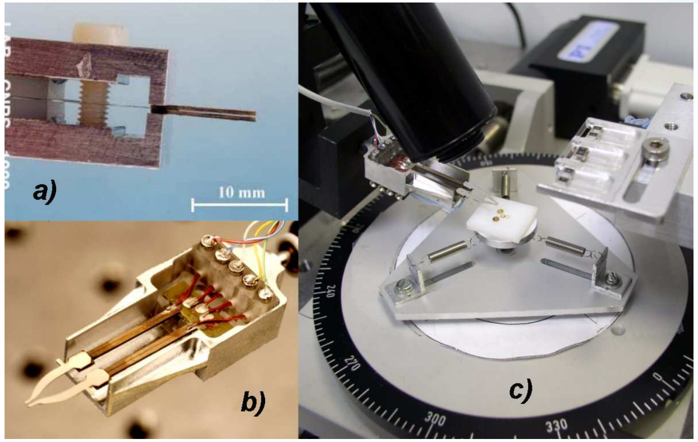
3.1 Quasi-static free displacement self-sensing

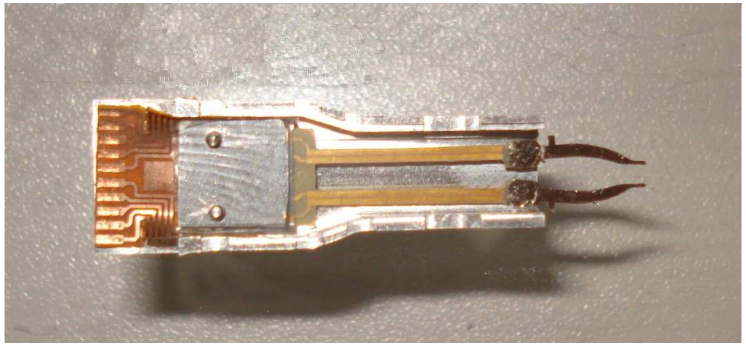
3.2 Dynamic displacement self-sensing

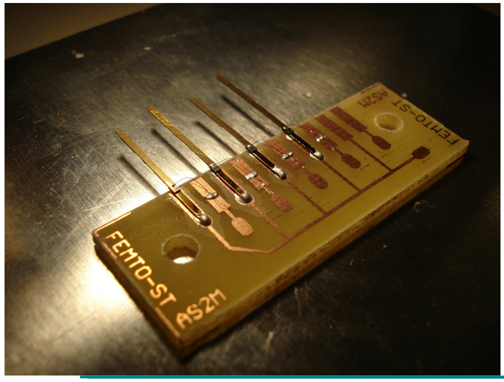
3.3 Combined Force / displacement self-sensing

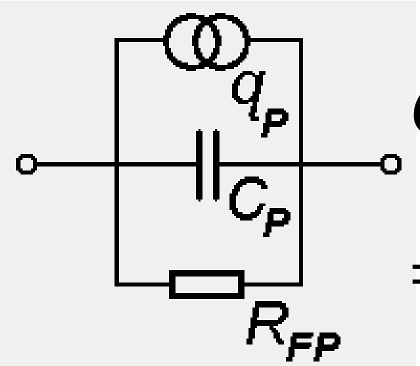
3. Self-Sensing of Piezoelectric Actuators

3.1 Quasi-static free displacement self-sensing









$$Q=\iint_A \sigma\, dx_1\, dx_2$$

$F_{ext}=0$ → *Free displacement*

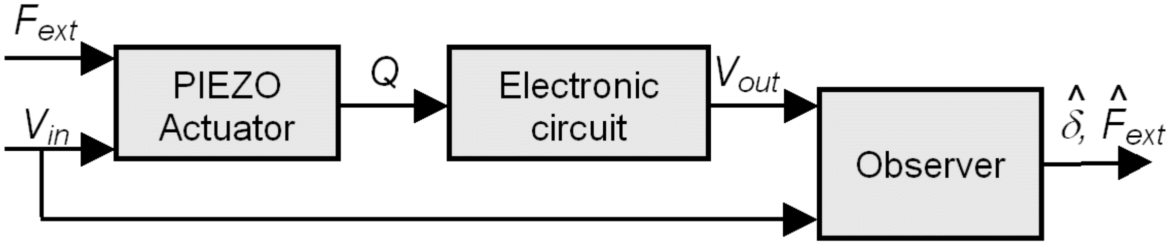
$$Q=\frac{4wh\varepsilon_{33}}{3d_{31}L}\left(1+\frac{d_{31}^{2}}{4s_{11}^{E}\varepsilon_{33}^{S}}\right)\delta=$$

$$=\alpha\delta$$

$F_{ext}\neq 0$ → *Force/Displacement*

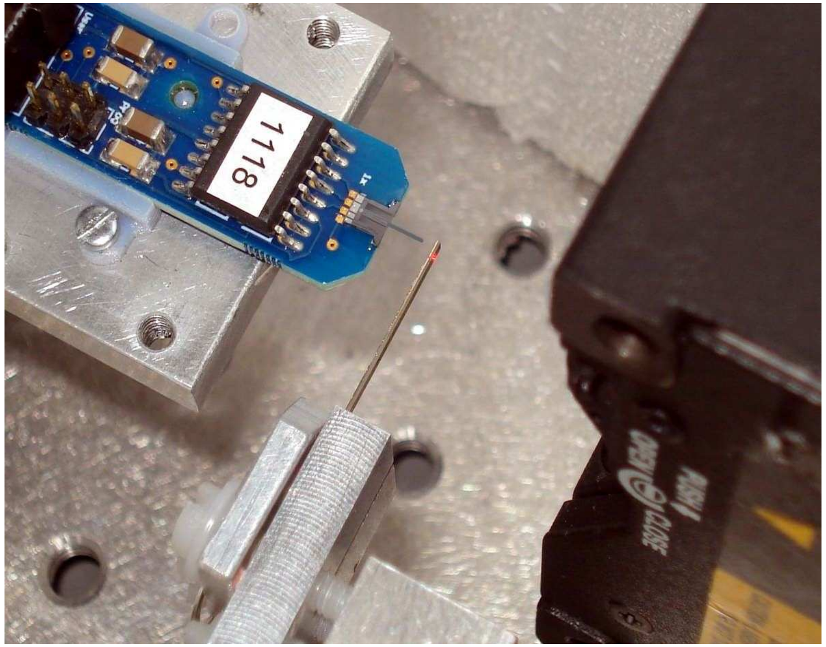
$$Q=-3e_{31}s_{11}\frac{L^2}{h^2}F_{ext}+\frac{4Lw\varepsilon_{33}V_{in}}{h}=$$

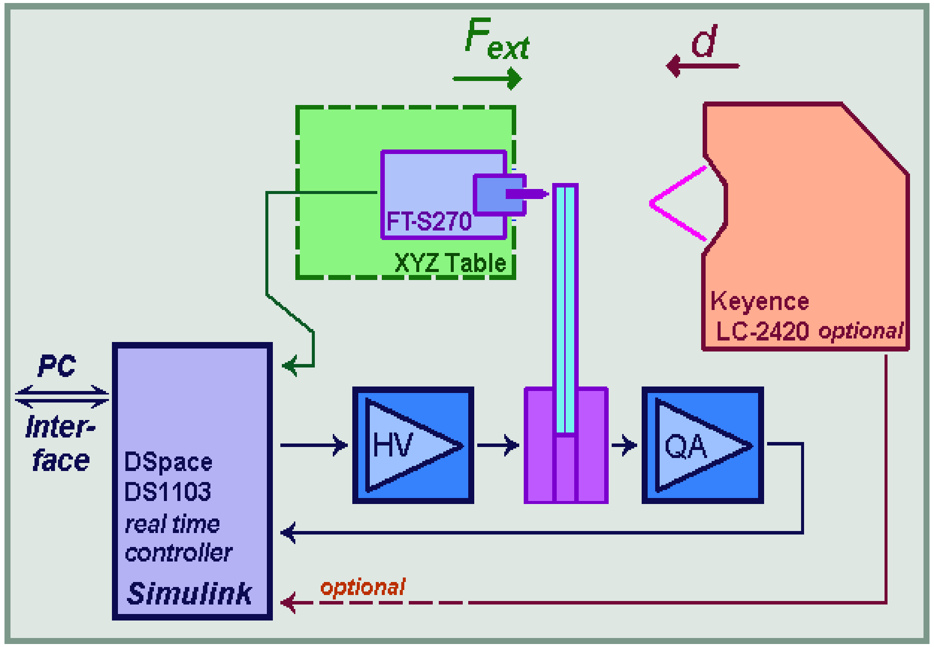
$$=\beta F_{ext}+C_P V_{in}$$



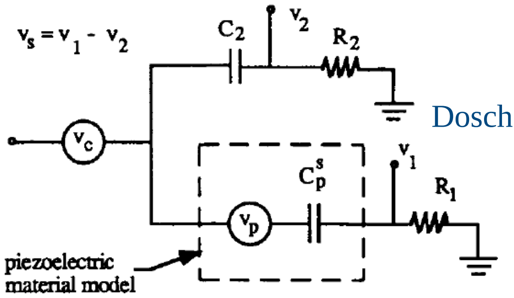
Sensorless method

Observer may be further used in a closed loop control

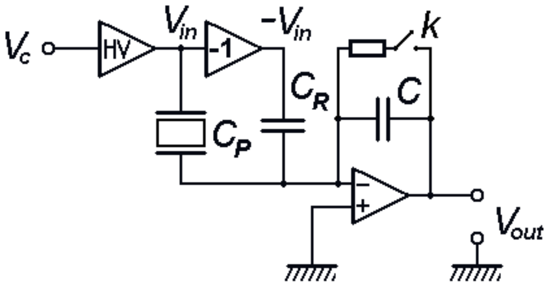




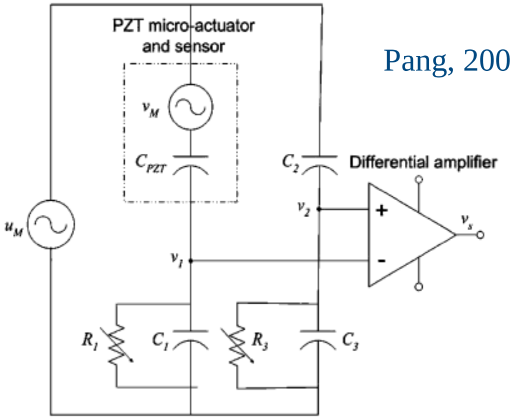
Current integrators.



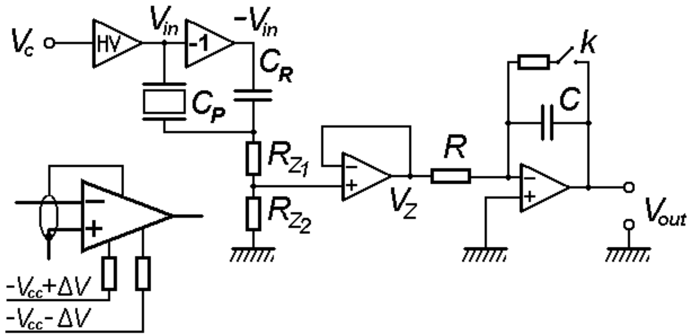
Dosch, 1992



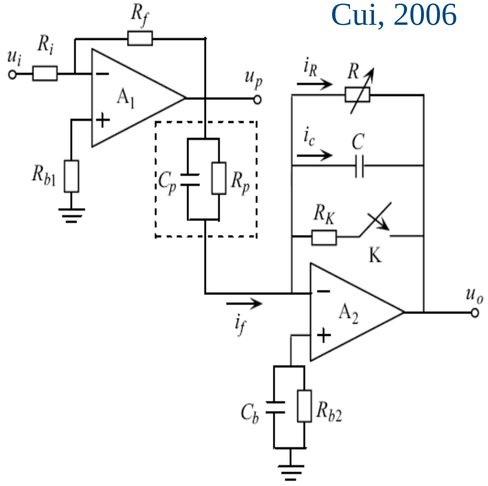
Direct charge conv.



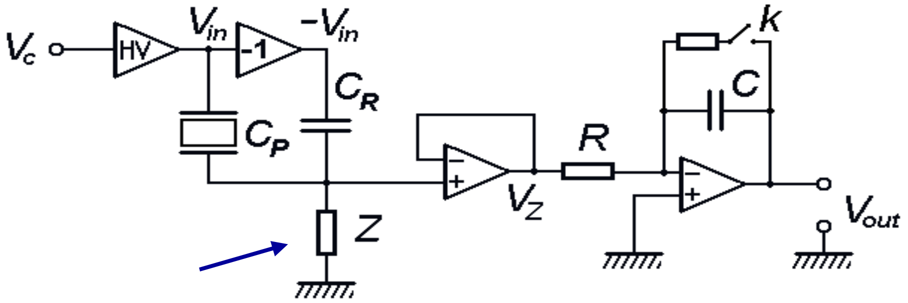
Pang, 2006



Resistive divider



Cui, 2006



Impedance (dynamic)

Quasi-static free displacement self-sensing OBSERVER

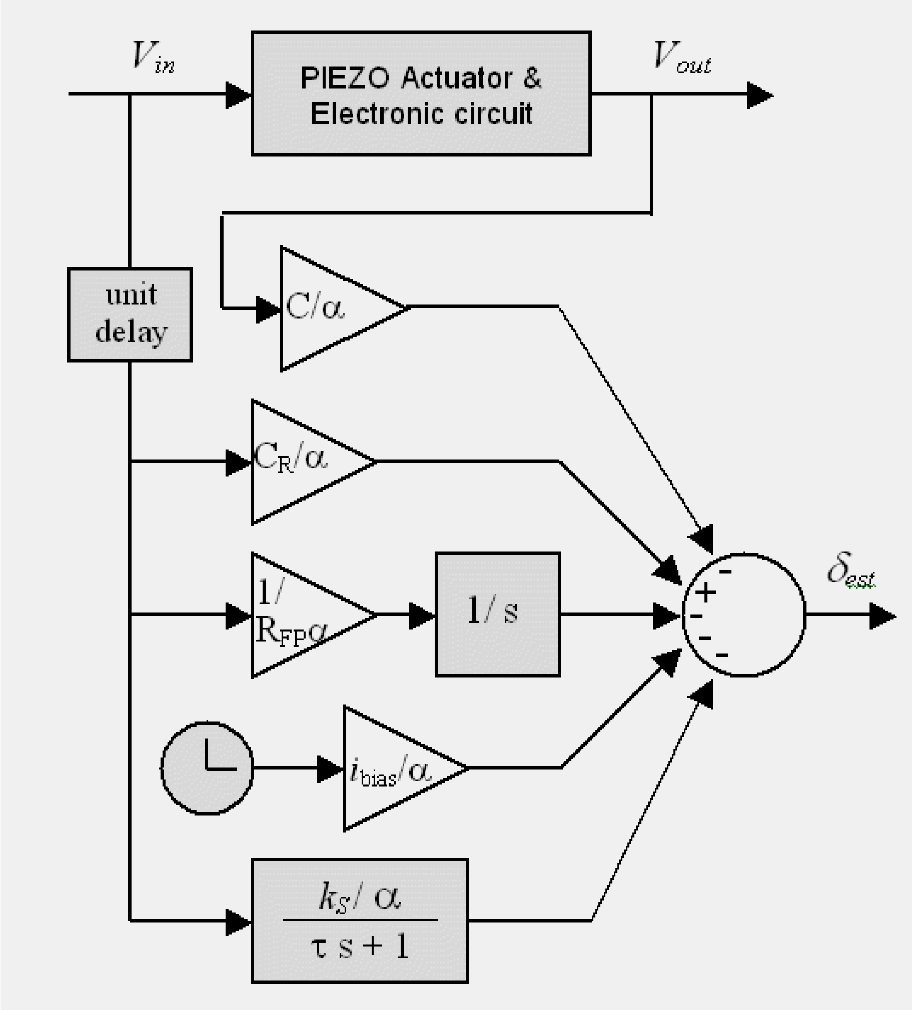
$$Q = -C_R V_{in} + \alpha\delta$$

$$V_{out} = \frac{C_R}{C} V_{in} - \frac{\alpha\delta + Q_{DA}}{C} -$$

$$- \frac{1}{C}\int \frac{V_{in}(t)}{R_{FP}} dt - \frac{1}{C}\int i_{BIAS}(t) dt$$

$$\delta_{est} = -\frac{C}{\alpha} V_{out} - \frac{Q_{DA}(V_{in}, t)}{\alpha} + \frac{C_R}{\alpha} V_{in} -$$

$$- \frac{1}{R_{FP}\alpha}\int V_{in}(t) dt - \frac{1}{\alpha}\int i_{BIAS}(t) dt$$



Identification des parametres Self-Sensing

Connus: C et C_R

Inconnus: α, i_{BIAS}, R_{FP} et Q_{DA}

$$F_{ext}=0$$

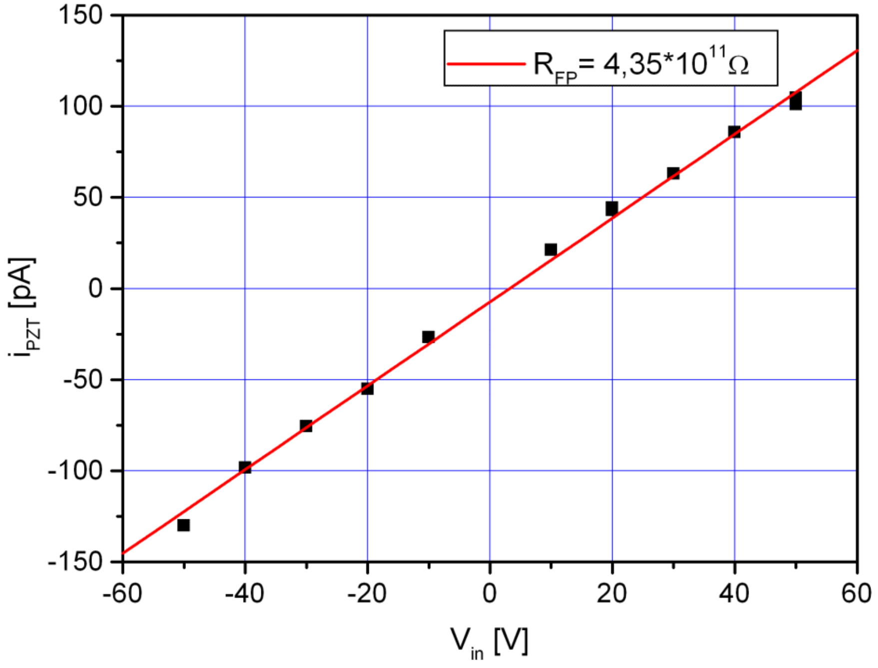
Etapes:

1) *Courant polarisation* i_{BIAS} : $Vin=0 \rightarrow$ *taux de variation Vout*

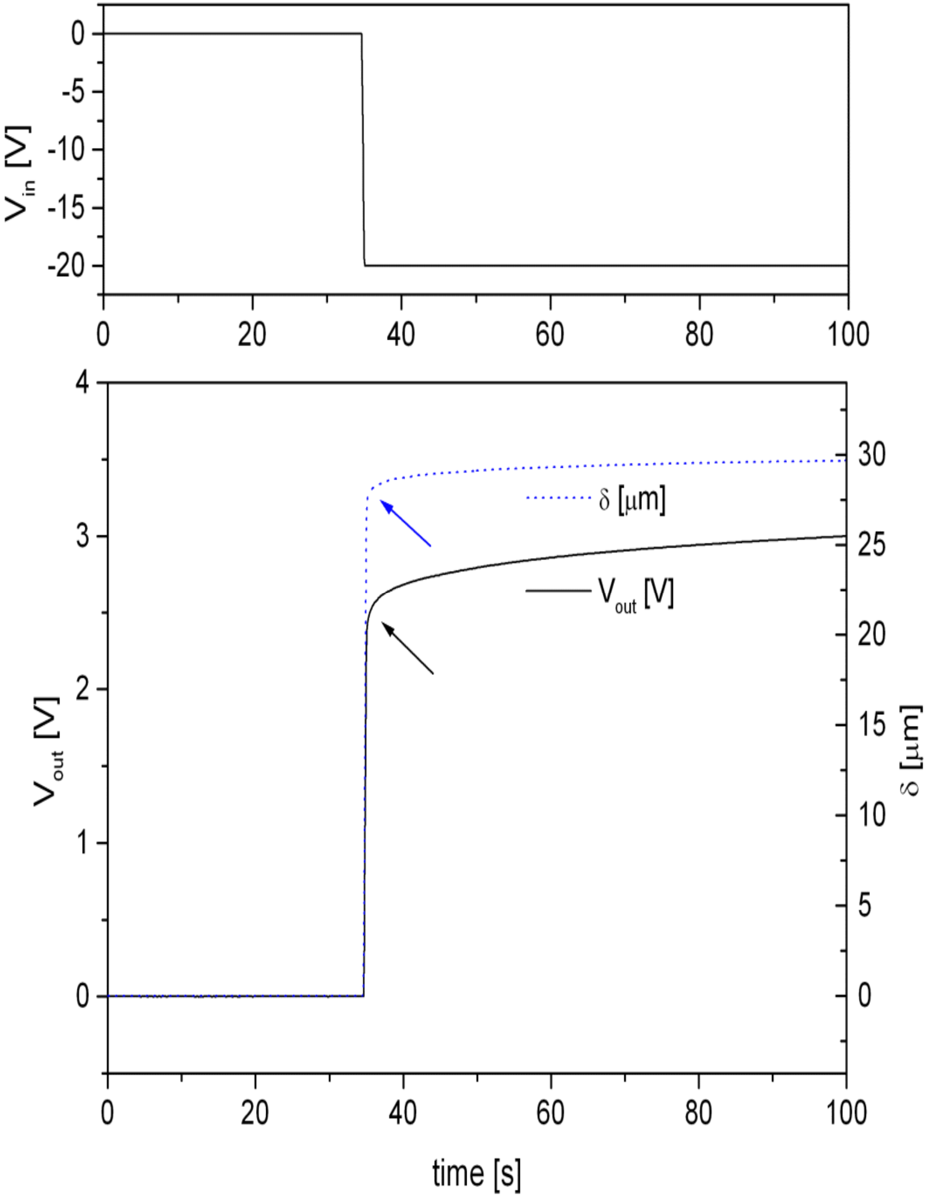
2) *Resistance de fuite* R_{FP}: echelon $Vin \neq 0 \rightarrow$ *derive Vout apres >1000 s.*

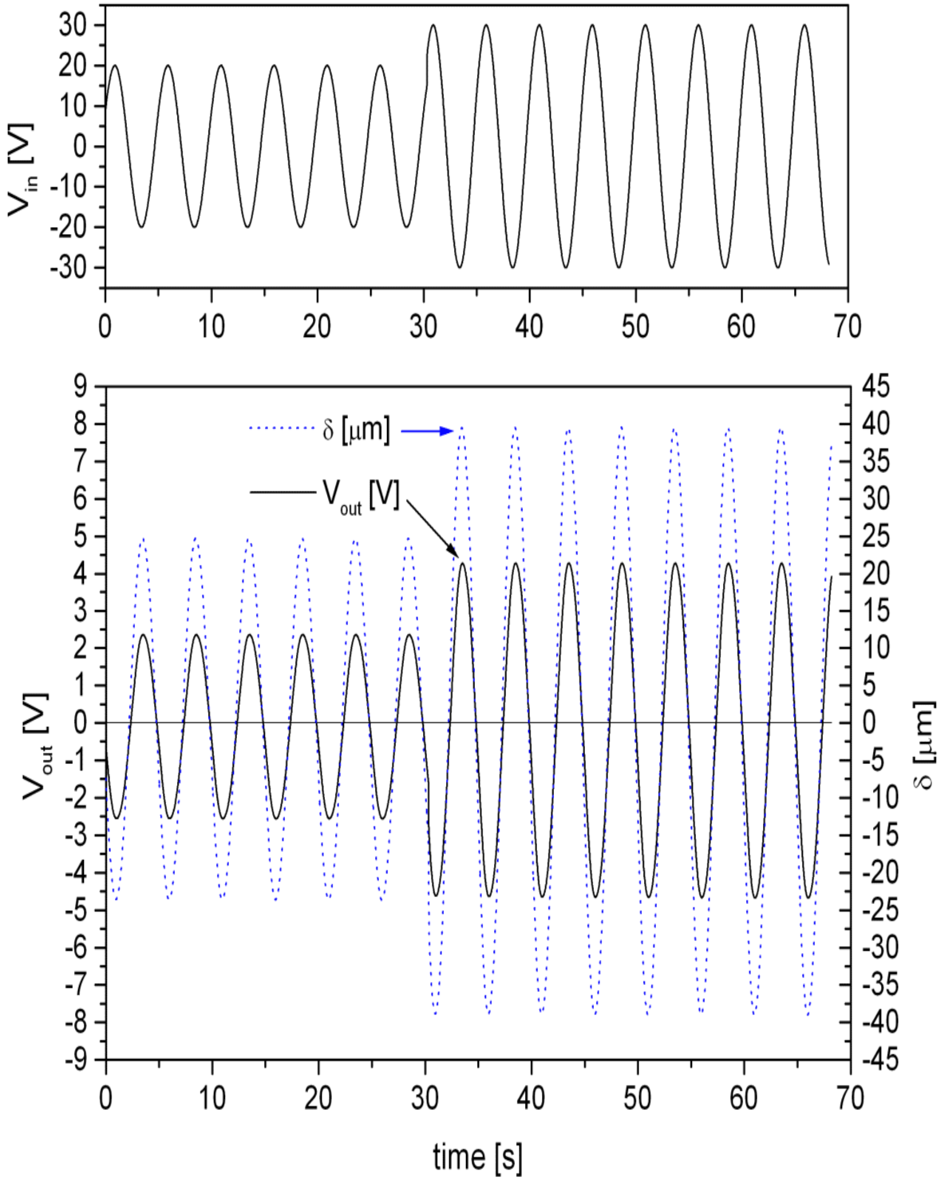
3) *Coeff. de deplacement* α [C/m]:
echelon *Vin* ou signal sinusoidal

$$\rightarrow \quad \alpha = (-CV_{out} + C_R V_{in}) / \delta$$



Identification parametres Self-Sensing - suite





Identification parametres Self-Sensing - suite

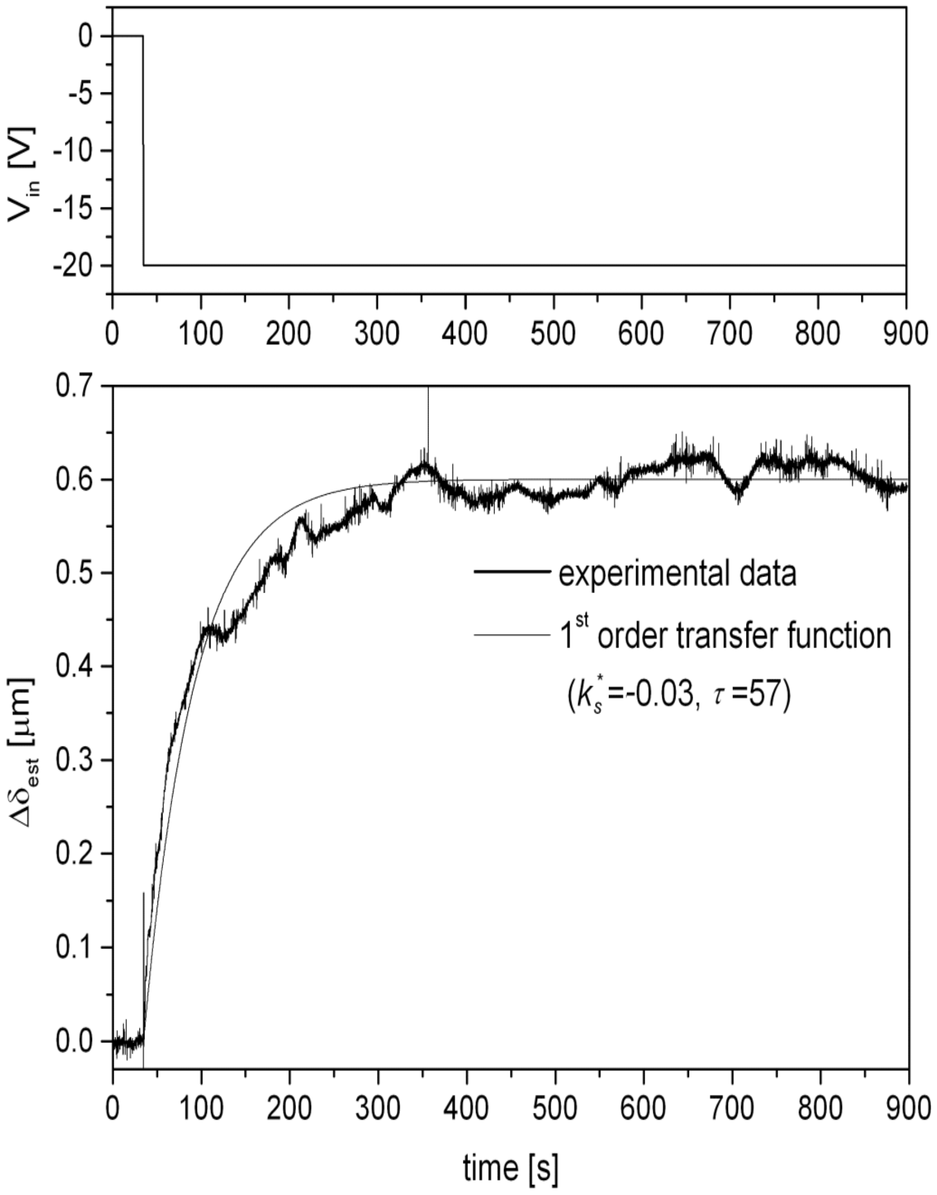
4) *Absorption dielectrique* Q_{DA} identification fonction de transfer de premier ordre.

$$\Delta\delta_{est} = \delta_{est} - \delta$$

$$\rightarrow \Delta\delta_{est}(s) = Q^{*}_{DA}(s)V_{in}(s)$$

$$Q^{*}_{DA}(s) = \frac{Q_{DA}(s)}{\alpha} = \frac{k^{*}_{s}}{\tau s + 1}$$

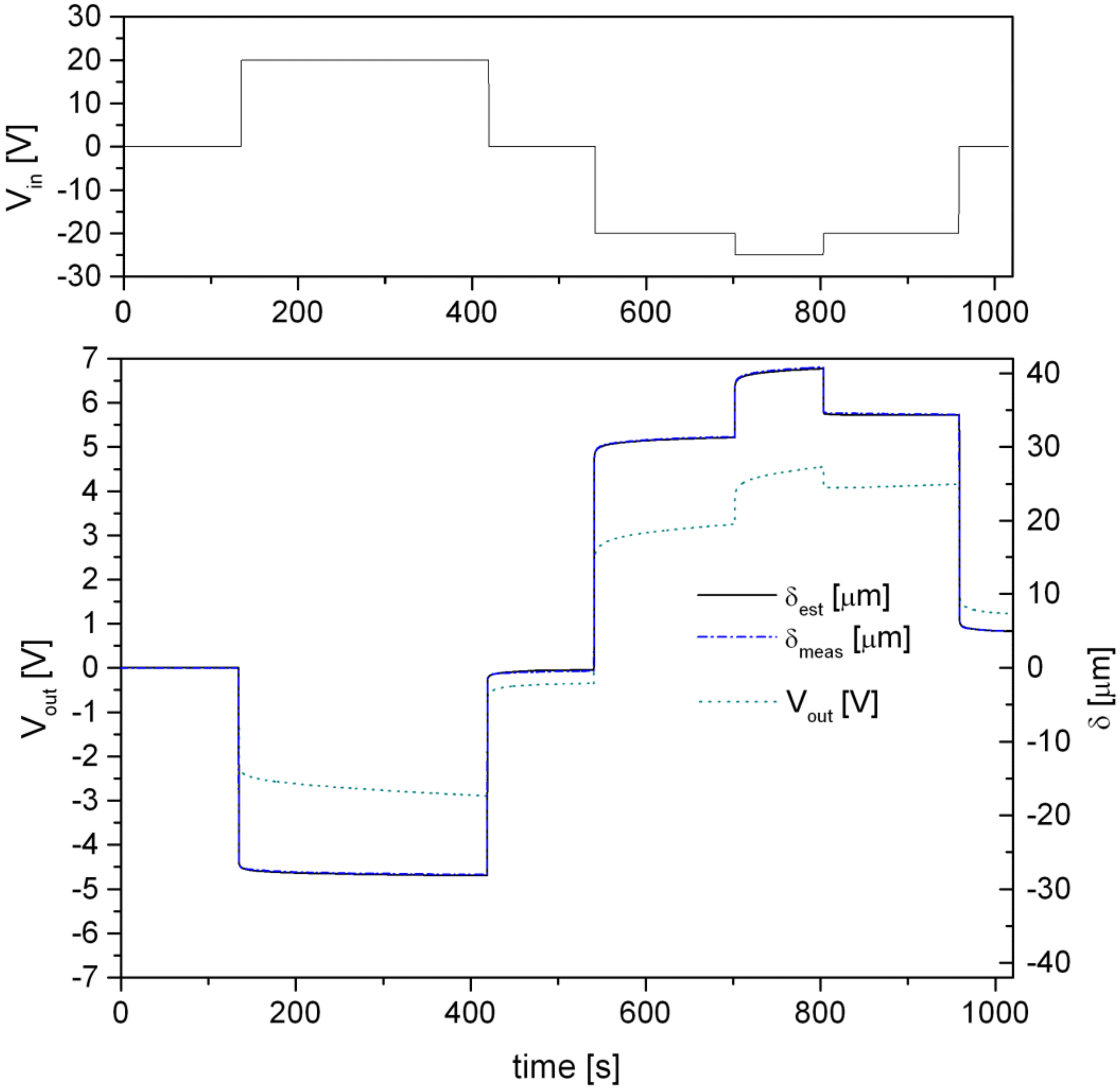
$$k^{*}_{s} = k_s / \alpha$$



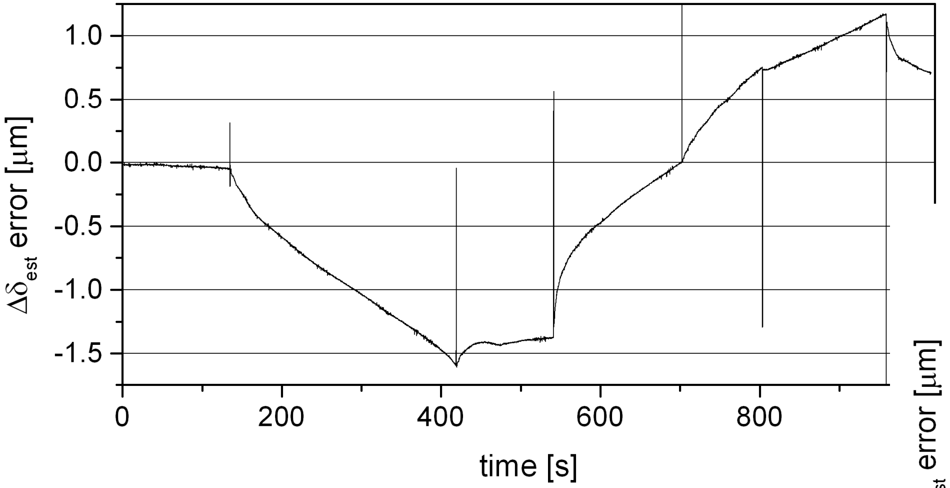
Resultats Self-Sensing en deplacement

Matlab Simulink:

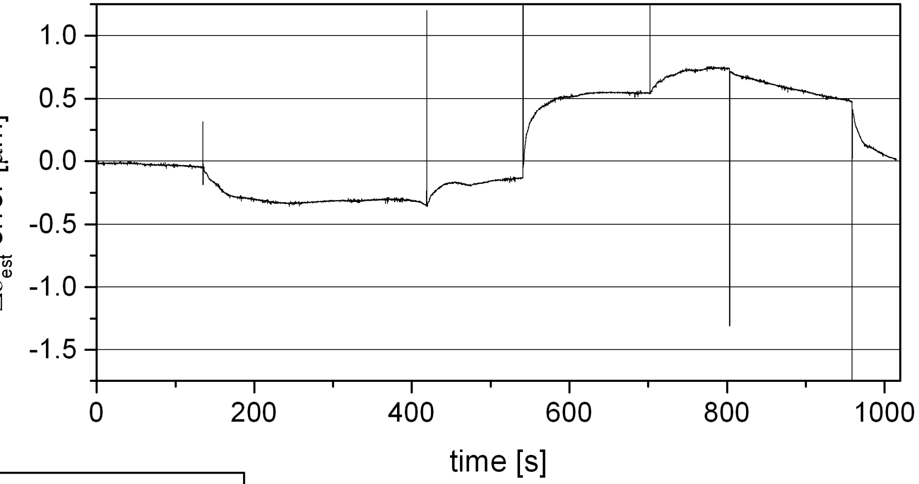
```
alpha=-10.05e-9;
C=47e-9;
Cr=8.2e-9;
Rfp=0.435e12;
ibias=-1.7e-12;
tau=57;
ks=3.02e8;
```



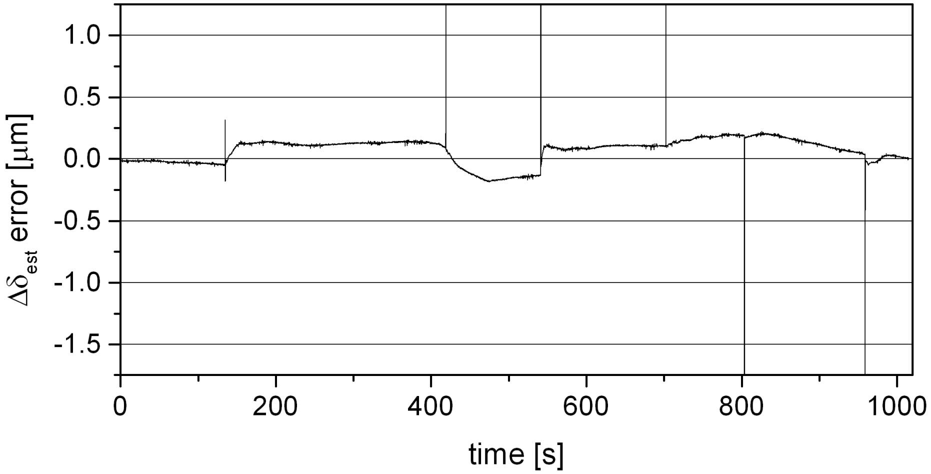
Resultats Self-Sensing en deplacement



sans compensation
erreur 2.75 µm

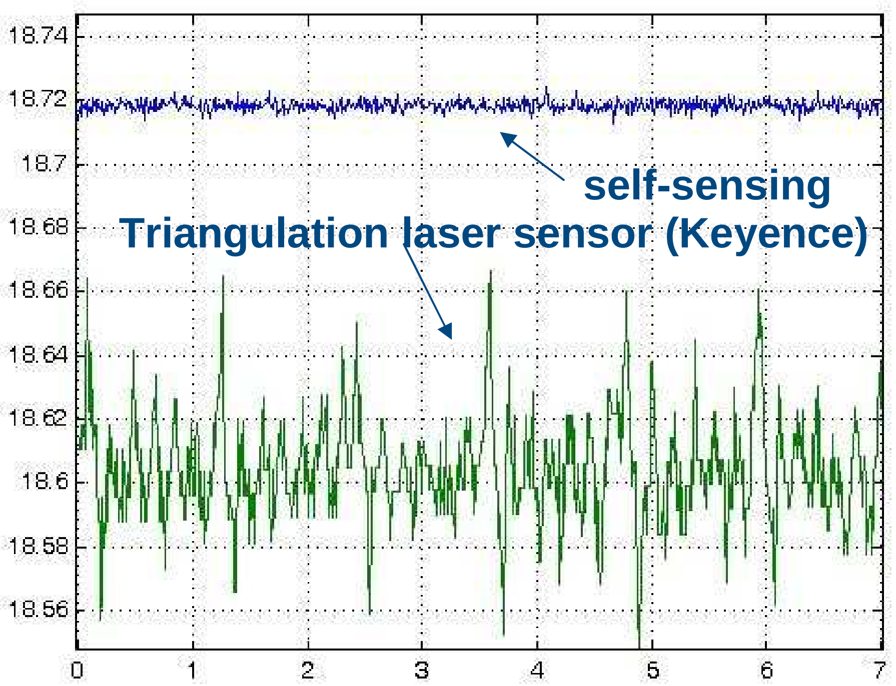


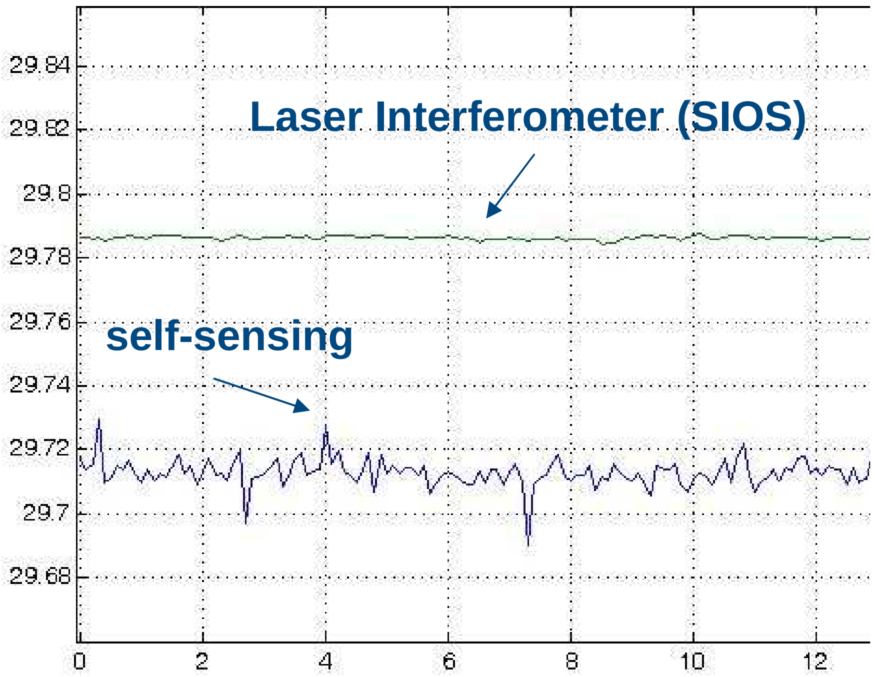
compensation R_{FP} erreur 1.05 µm



compensation
R_{FP} et Q_{DA} :
erreur 0.38 µm
0.55%

Resultats Self-Sensing en deplacement





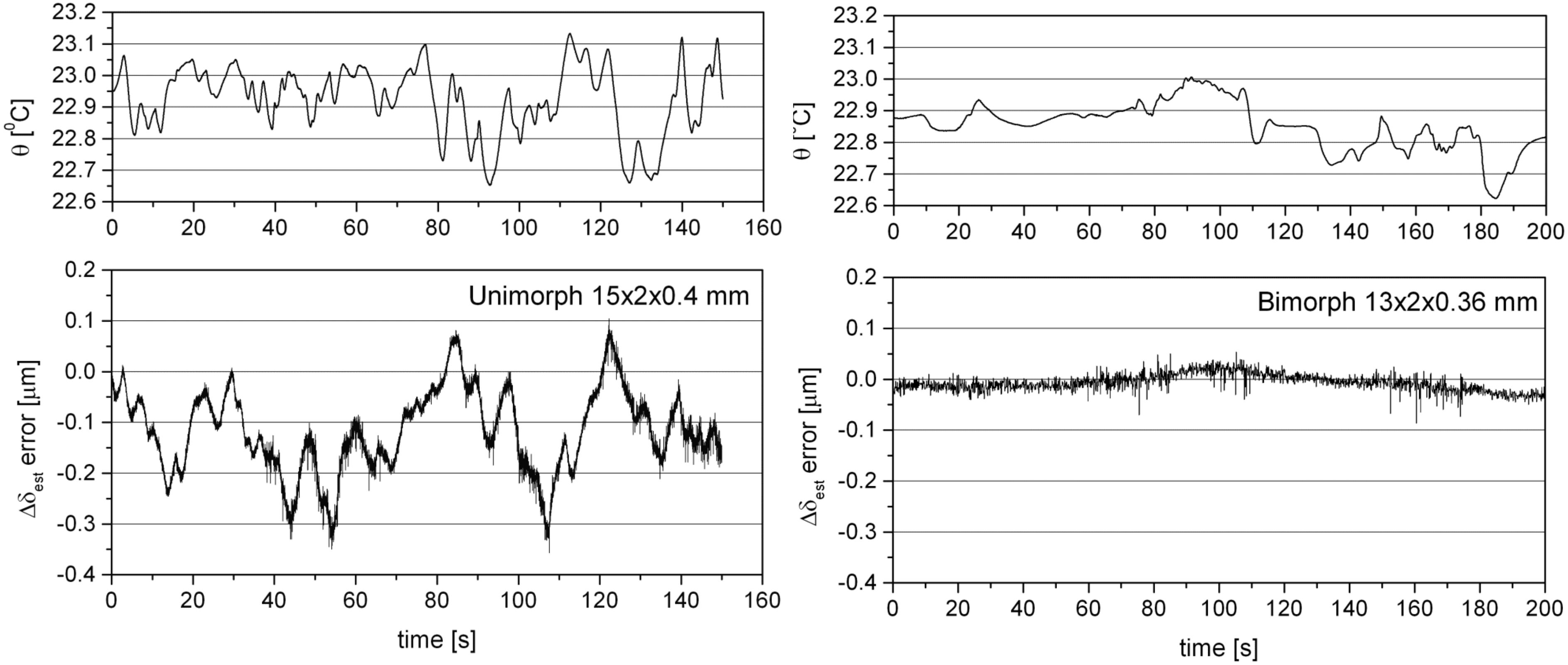
Noise measurement

16.7 nm (RMS) Keyence

2 nm (RMS) self-sensing (temperature isolated)

0.55 nm (RMS) SIOS

Resultats Self-Sensing en deplacement



Self-sensing Error due to ambient temperature variations

Unimorph cantilever
~1µm/^{0}C

Bimorph cantilever
~0.2µm/^{0}C

3. Self-Sensing of Piezoelectric Actuators

3.2 Dynamic displacement self-sensing

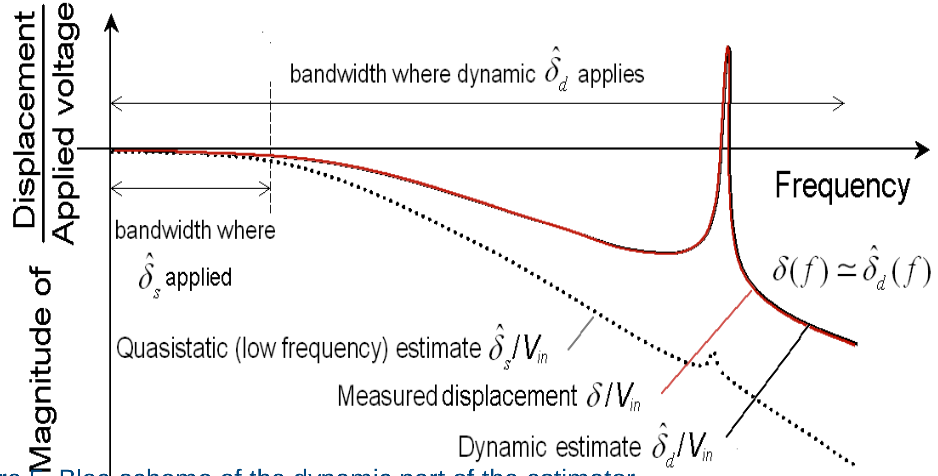
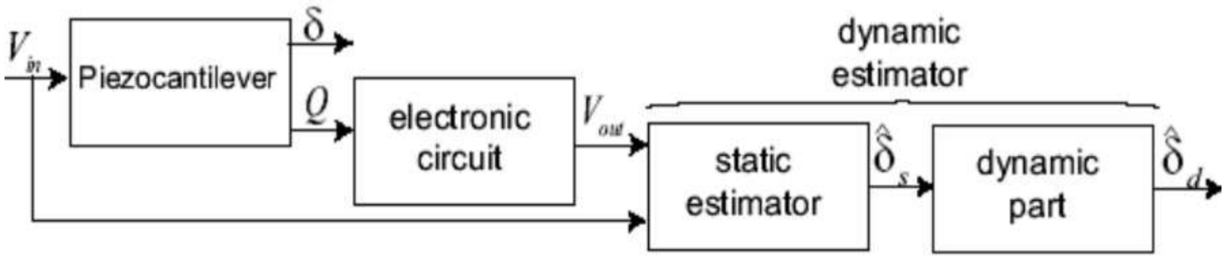
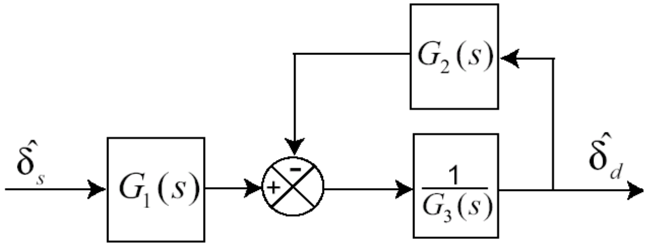


Figure 5. Bloc-scheme of the dynamic part of the estimator.

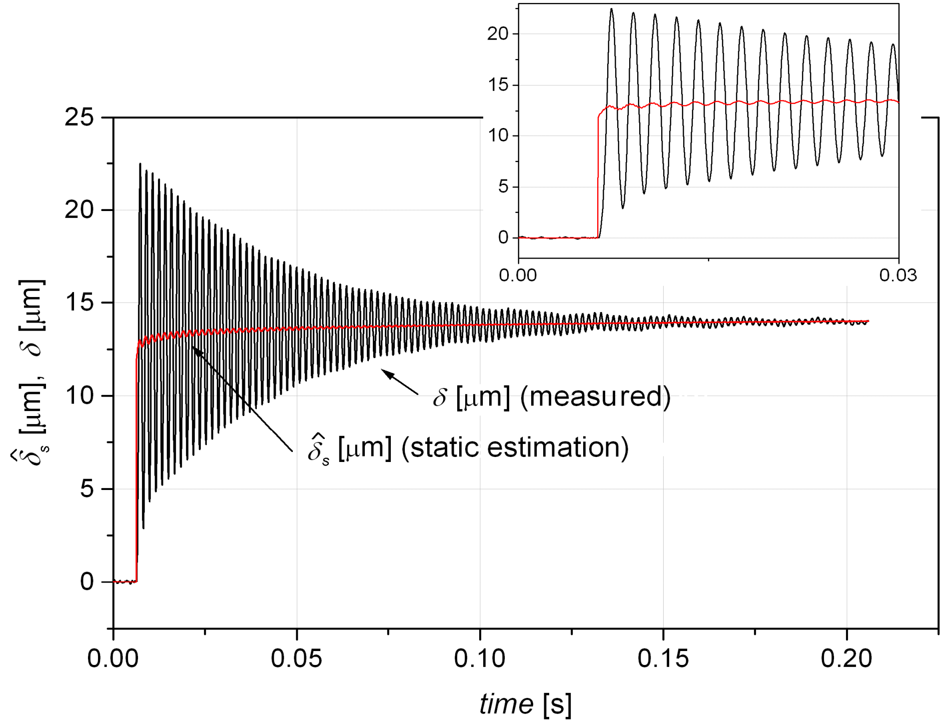
Static (low frequency) Self Sensing and required dynamic self-sensing intended to superpose real (externally measured) displacement.



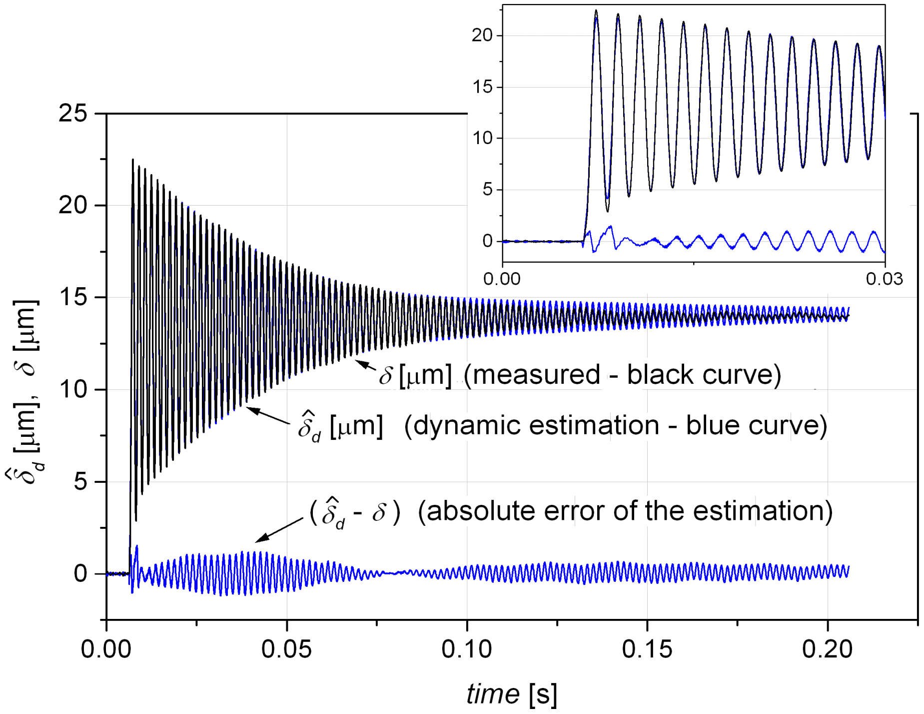
Principle scheme of the dynamic self-sensing technique.



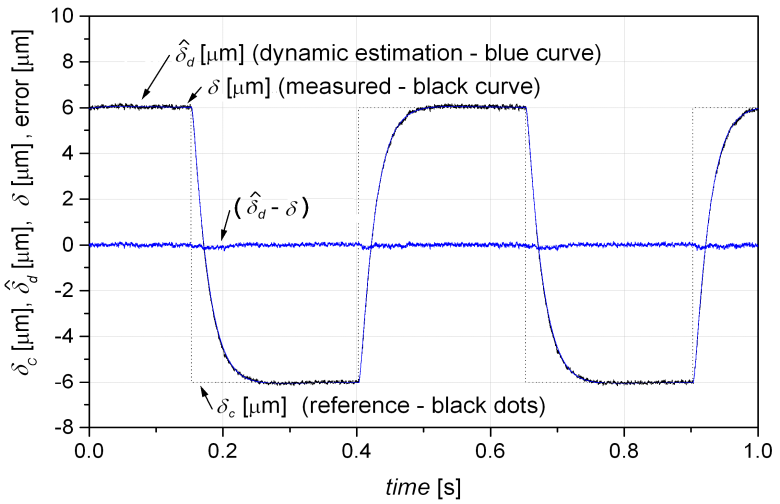
Dynamic Estimator – Reverse Multiplivcative form



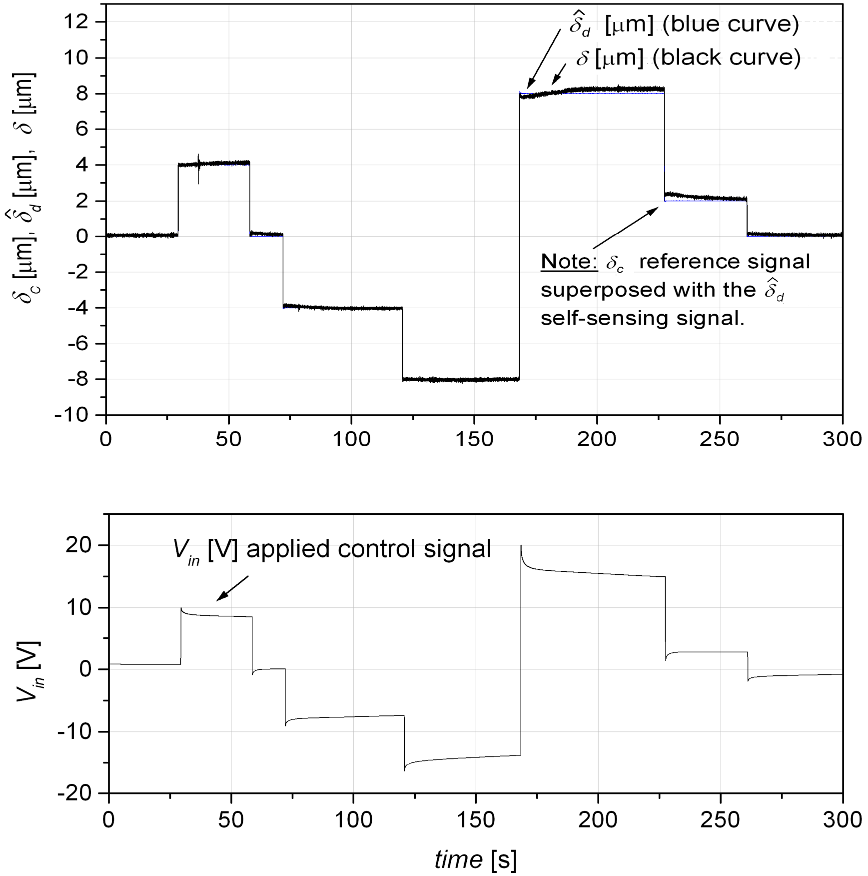
Result with static self-sensing (step input of 20V).



Result with dynamic self-sensing.



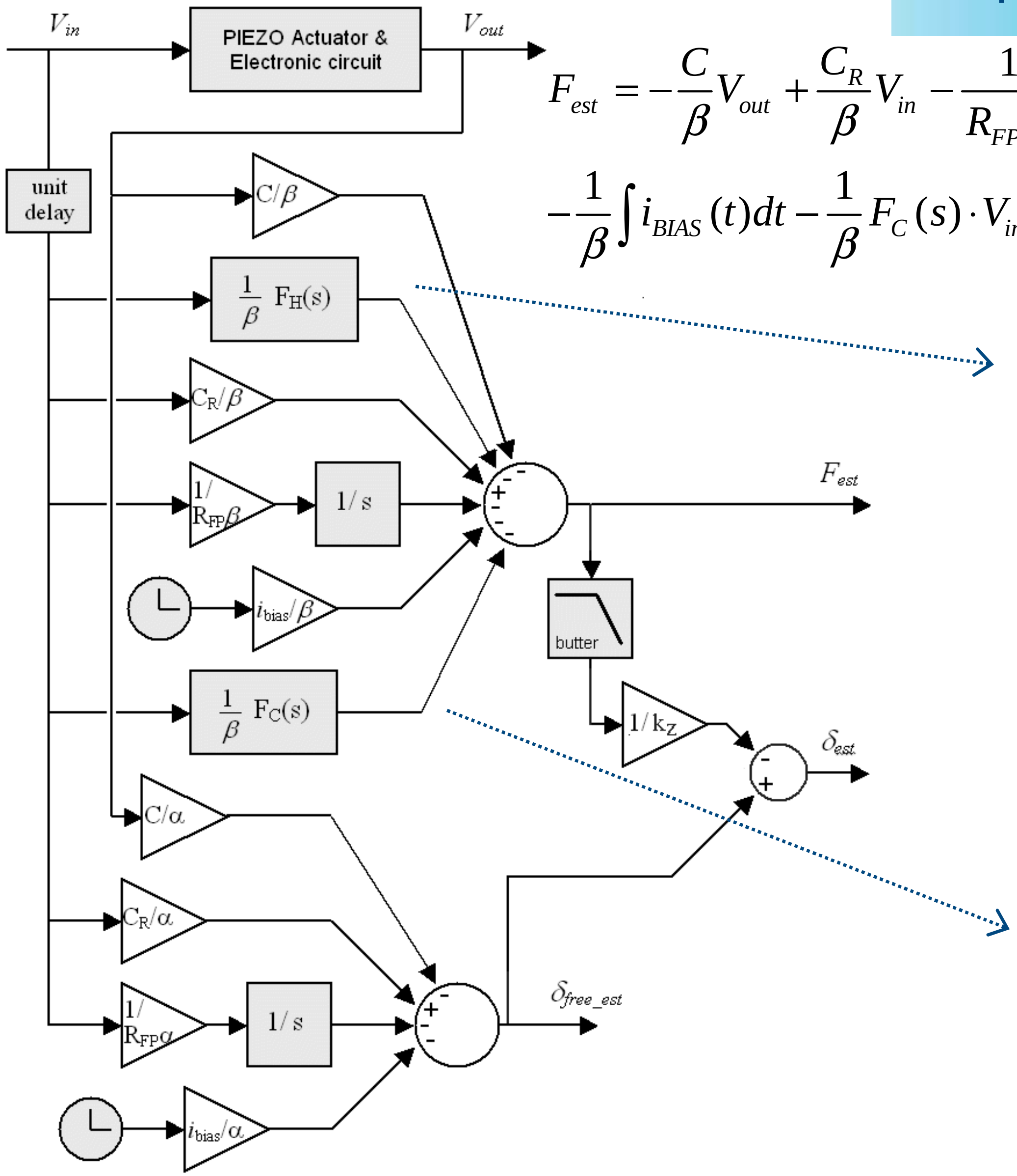
Step response of the closed-loop system.
Settling time : 30 ms
Dynamic error: 5%



Complete short and long term response of the closed-loop system.

3. Self-Sensing of Piezoelectric Actuators

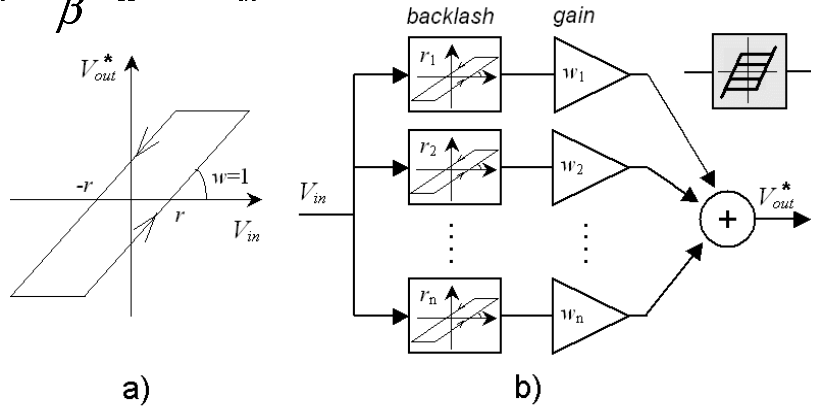
3.3 Combined Force / Displacement self-sensing



$$F_{est} = -\frac{C}{\beta}V_{out} + \frac{C_R}{\beta}V_{in} - \frac{1}{R_{FP}\beta}\int V_{in}(t)dt - \frac{1}{\beta}\int i_{BIAS}(t)dt - \frac{1}{\beta}F_C(s)\cdot V_{in} - \frac{1}{\beta}F_H(s)\cdot V_{in}$$

Force and displacement observation

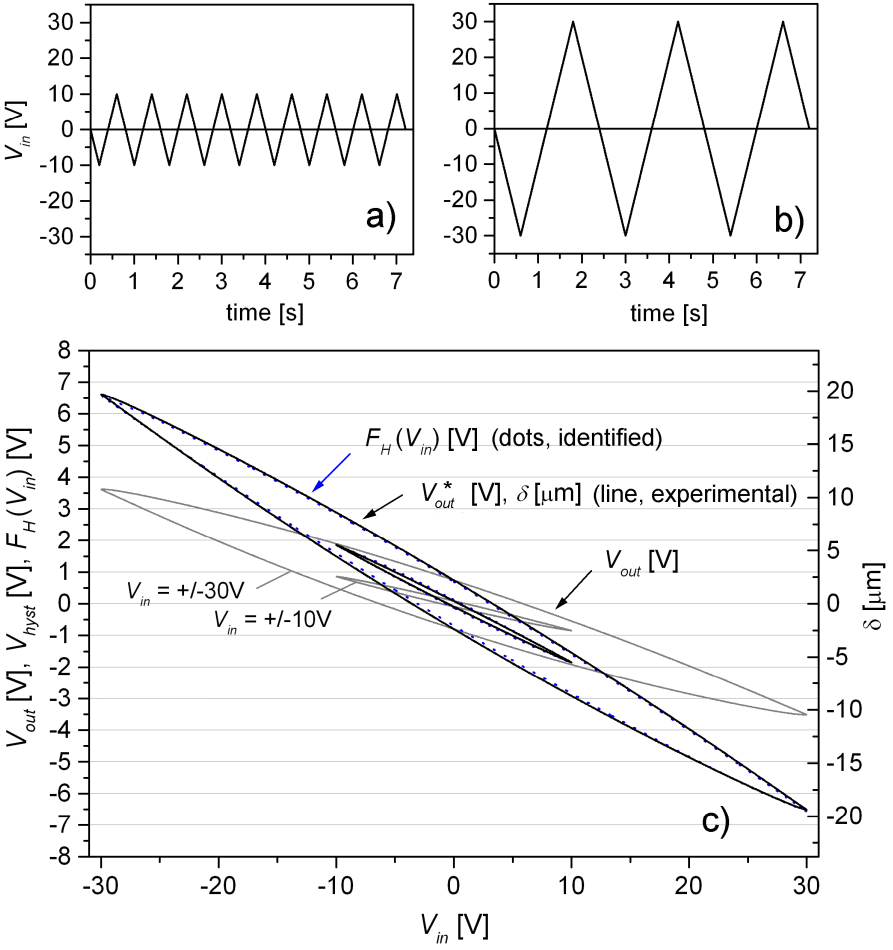
$$\delta_{est} = \delta_{free\_est} - F_{est} / k_Z$$

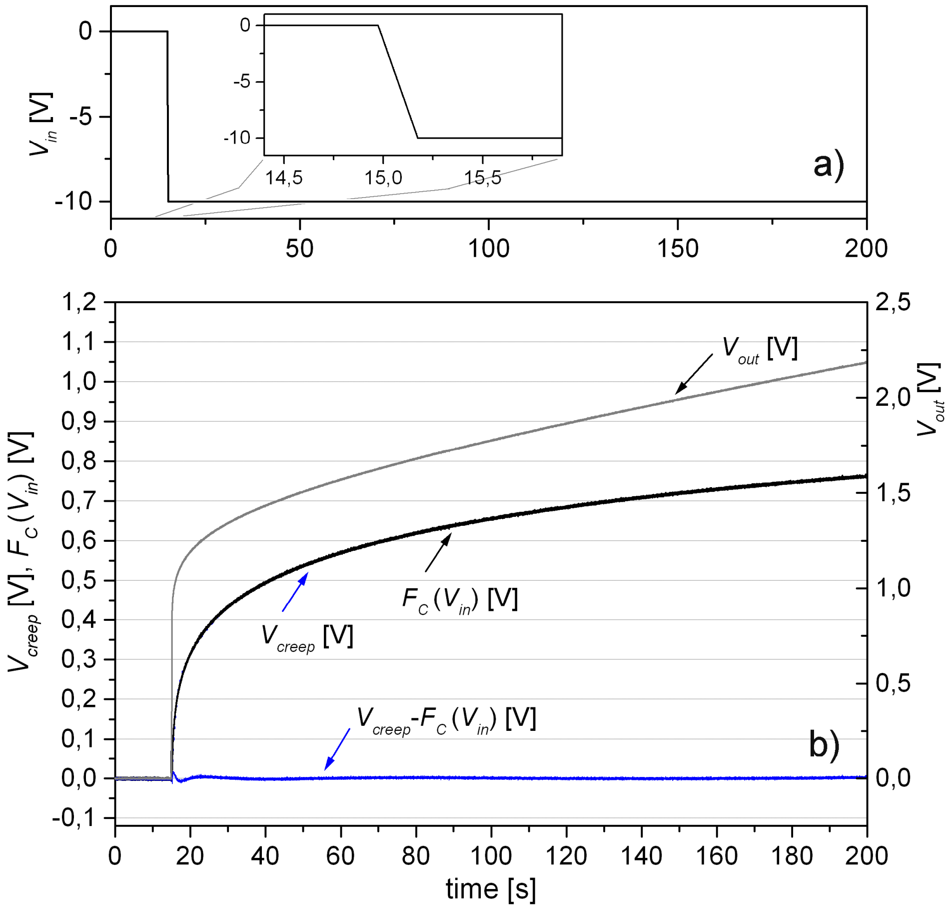


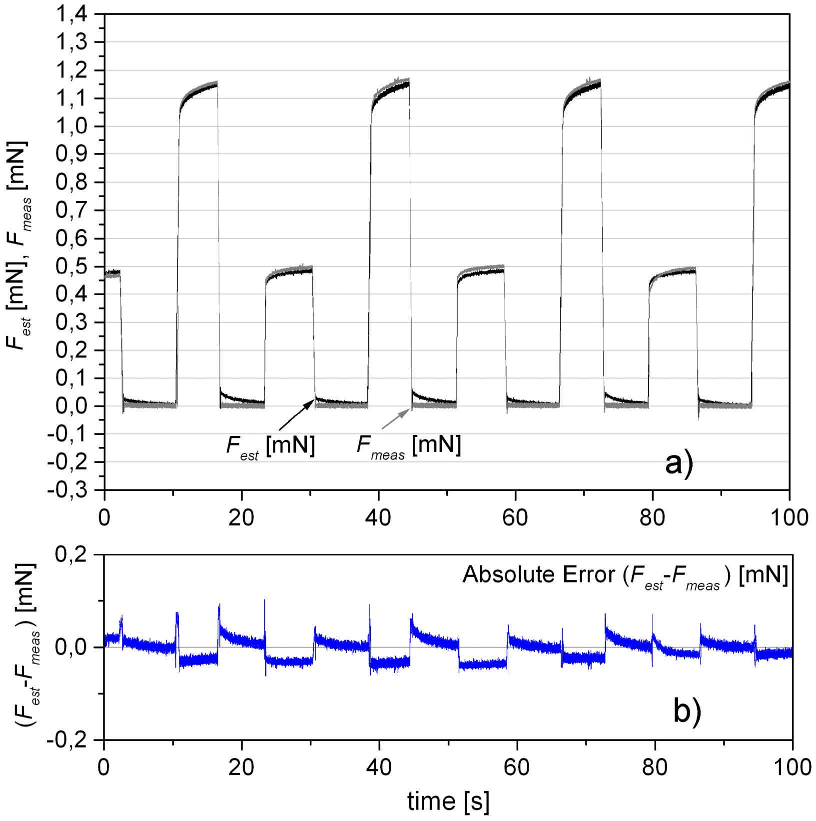
Hysteresis Model a) The play operator; b) Prandtl-Ishlinskii (PI) hysteresis model.

$$F_C(s) = \frac{V_{creep}(s)}{V_{in}(s)} = \frac{a_0 s^4 + a_1 s^3 + a_2 s^2 + a_3 s^1 + a_4}{s^4 + b_1 s^3 + b_2 s^2 + b_3 s^1 + b_4}$$

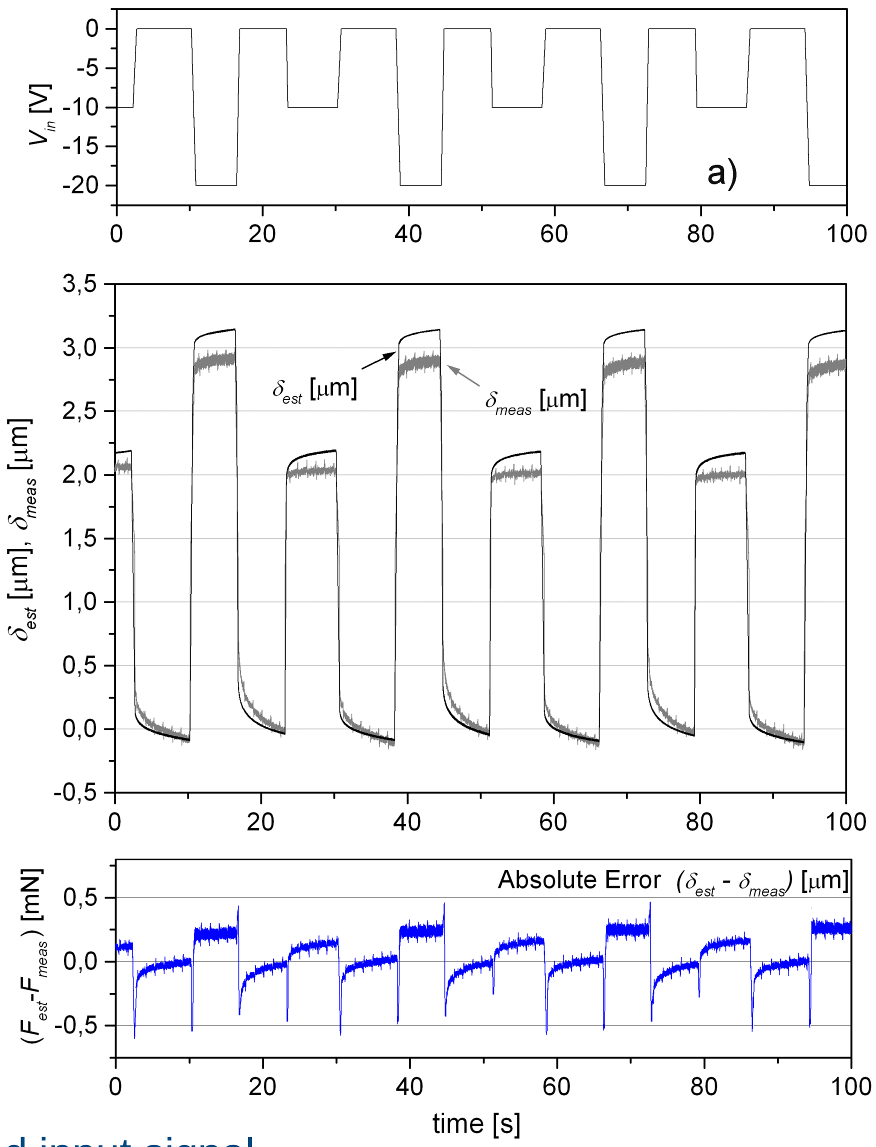
Creep TF Model


30
20
10
0
-10
-20
-30
V_{in} [V]
0 1 2 3 4 5 6 7
time [s]
a)
b)
8 7 6 5 4 3 2 1 0 -1 -2 -3 -4 -5 -6 -7 -8
V_{out} [V], V_{hyst} [V], $F_H(V_{in})$ [V]
20 15 10 5 0 -5 -10 -15 -20
δ [µm]
$F_H(V_{in})$ [V] (dots, identified)
V^*_{out} [V], δ [µm] (line, experimental)
V_{out} [V]
V_{in} = +/-30V
V_{in} = +/-10V
-30 -20 -10 0 10 20 30
V_{in} [V]
c)


0
-5
-10
V_{in} [V]
0
-5
-10
14,5
15,0
15,5
0 50 100 150 200
a)
1,2 1,1 1,0 0,9 0,8 0,7 0,6 0,5 0,4 0,3 0,2 0,1 0,0 -0,1
V_{creep} [V], $F_C(V_{in})$ [V]
2,5 2,0 1,5 1,0 0,5 0,0
V_{out} [V]
V_{out} [V]
$F_C(V_{in})$ [V]
V_{creep} [V]
V_{creep}-$F_C(V_{in})$ [V]
b)
0 20 40 60 80 100 120 140 160 180 200
time [s]



.a) Measured and estimated force.
 b) Absolute error (force).



a) Applied input signal
b) Measured and estimated tip displacement.
c) Absolute error (displacement)

- 1 – FEMTO-ST and SAMMI group activities

- 2 – Observer techniques applied to piezocantilevers

- 3 – Self sensing of piezocantilevers

THANK YOU!