



Nanoforce estimation with Kalman filtering applied to a force sensor based on diamagnetic levitation.

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Only force **effects** can be directly measured

A force sensitive part (transducer) is needed

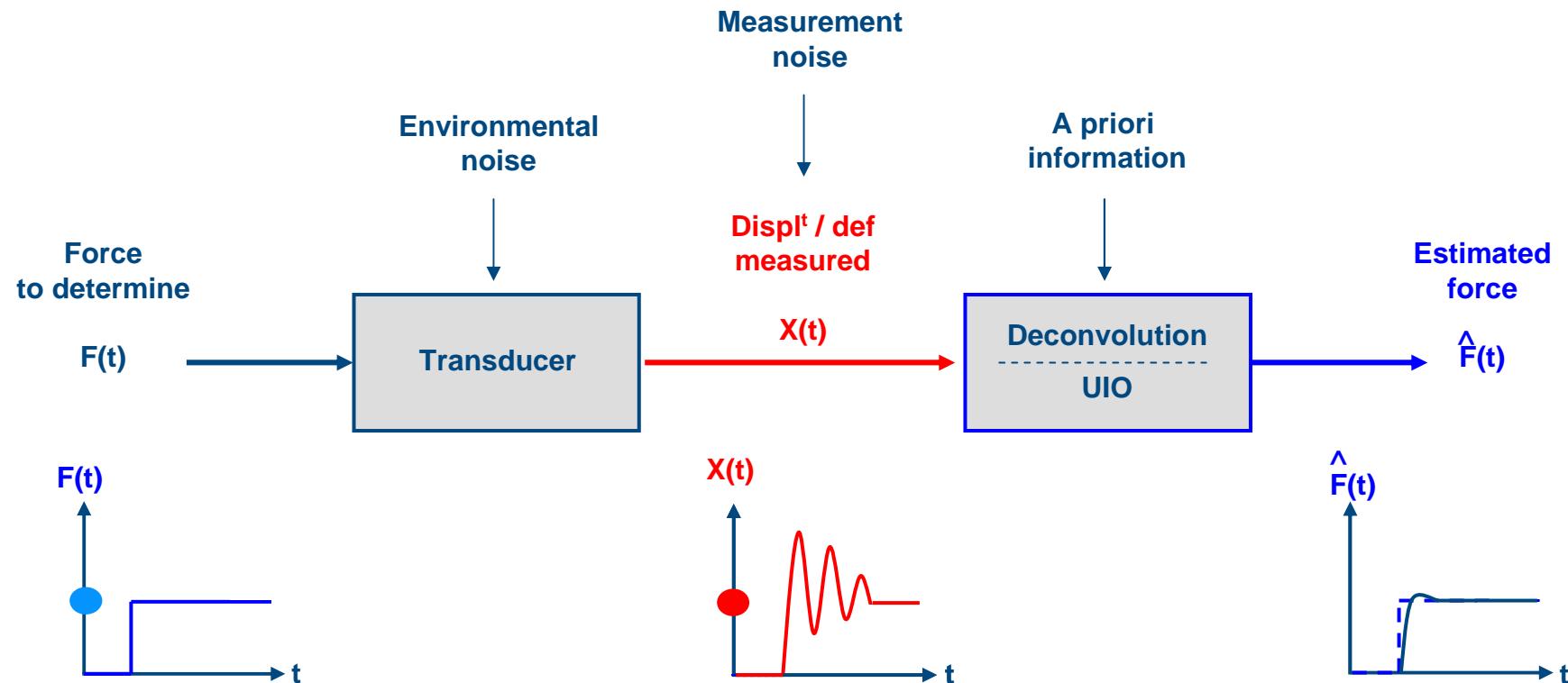
Deformation
of an elastic μ structure
when a force is applied on it

Displacement
of a rigid seismic mass
when a force is applied on it

Deformations or displacements measured with appropriate sensors

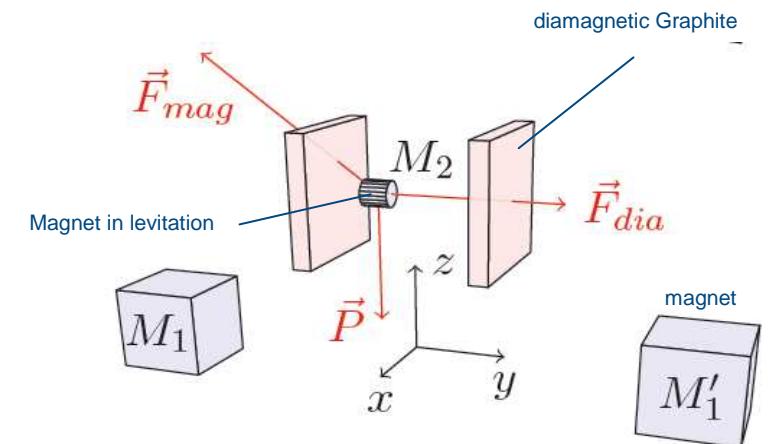
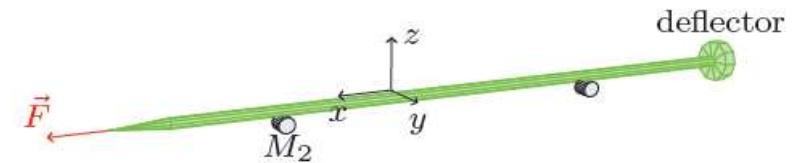
Knowing the **effect**, the cause (ie the force) must be reconstructed

Passive μ force sensor

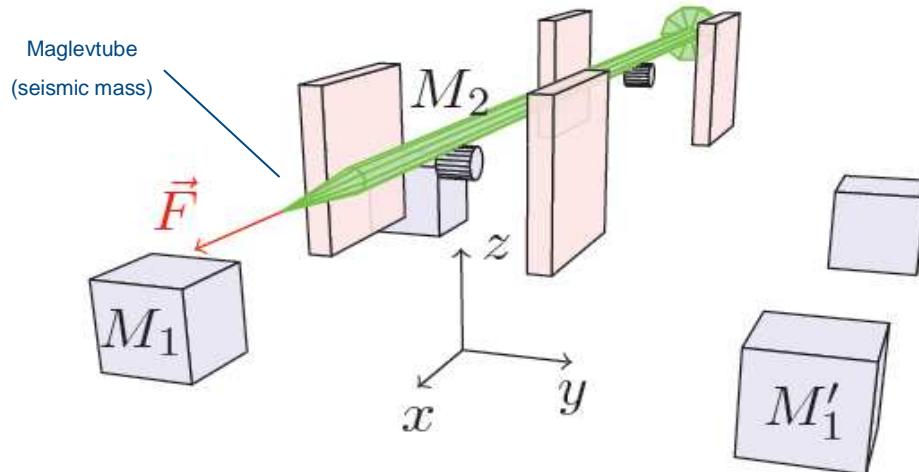


Development of a new sensor with small stiffness and a large force measurement range

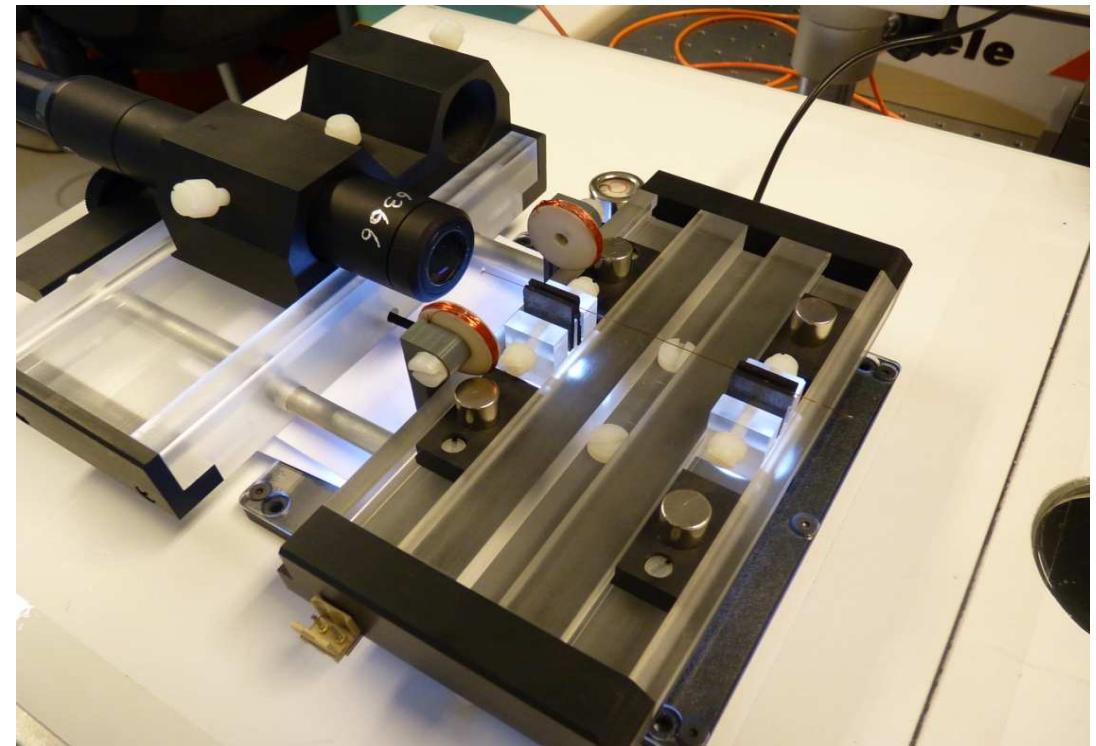
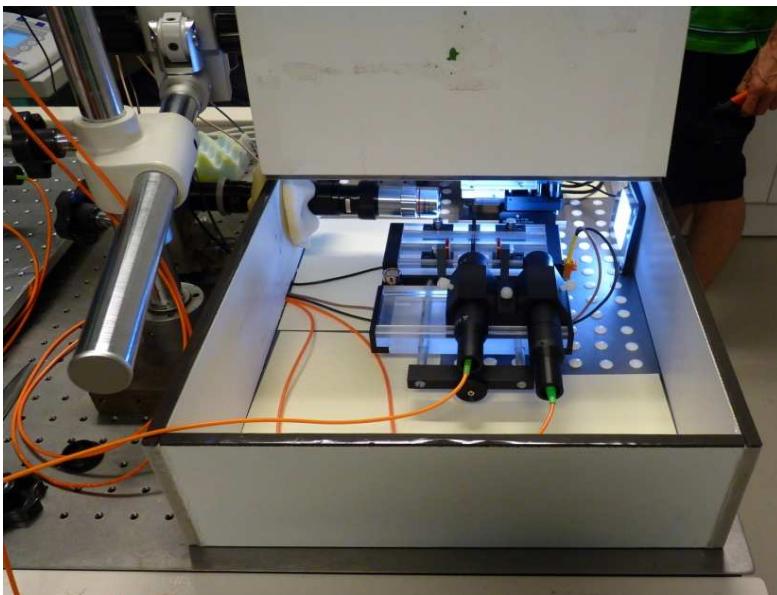
Transducer	=	Macroscopic seismic mass Naturally stable with 6 dof
Passive stability	=	Done with magnetic springs & a repulsive physical principle
Diamagnetic effect		
Passive force sensor with magnetic springs easy to produce with classical assembly approaches		



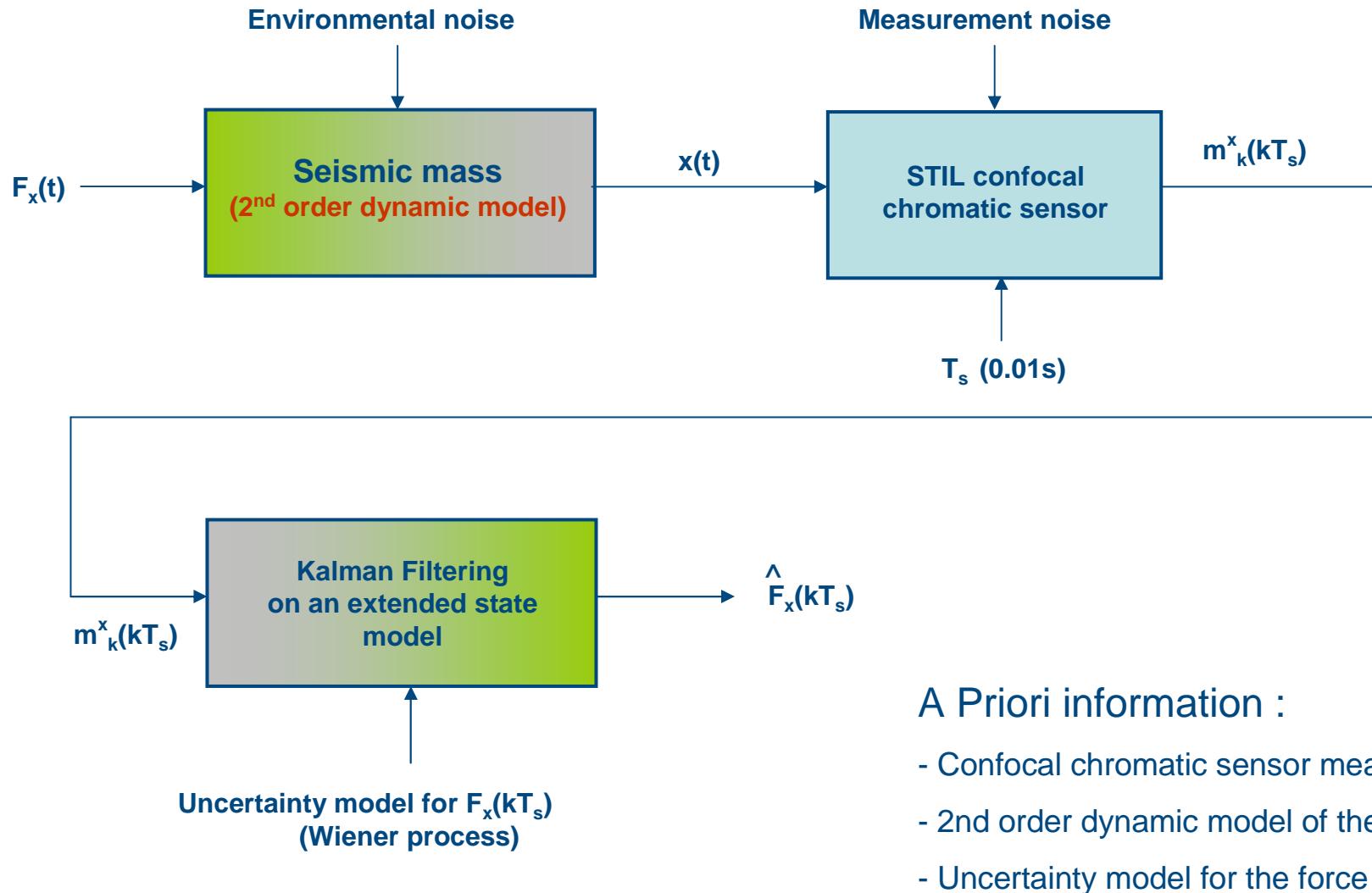
Sensor configuration



Force measured: along x axis
Stiffness: 0.005 N/m to 0.03 N/m
Typ. resolution: 0.5 to 5 nN
Range: 1 nN to 40 μ N
Mass: 20 to 80 mg



Non steady state measurement

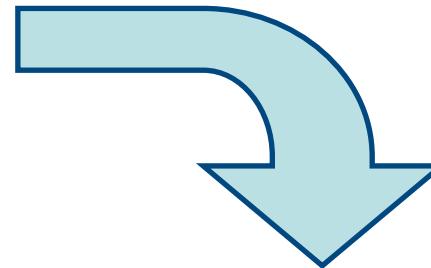


Confocal chromatic sensor



Confocal Chromatic sensor specifications (CL2 + MG140) :

- Measuring range : 300 µm
- Working distance : 11 mm
- Axial resolution : 0.012 µm

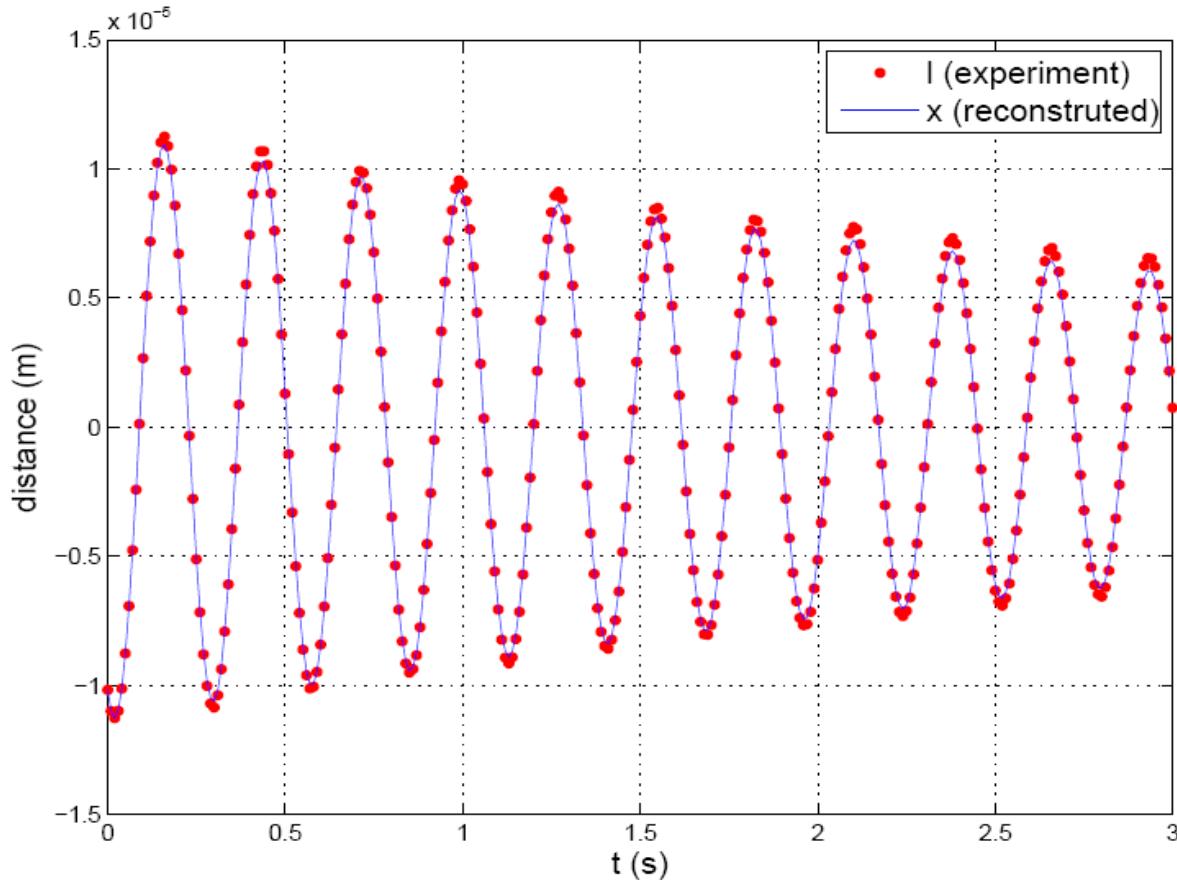


Zero-mean white gaussian
noise v_k

with $E[v_k^2] = R$

$$R = 1.44 \times 10^{-16} \text{ m}^2$$

Seismic mass dynamic model identification



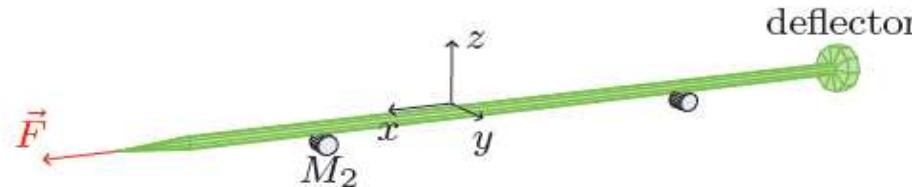
Identification done using **Zero Input Response (ZIR)** of the maglevtube

Gives the parameters of the maglevtube dynamic model, including :

- magnetic stiffness K_m^x
- viscous damping coeff K_v^x
- maglevtube mass m

$$\begin{array}{c} \dot{X}(t) = A X(t) + B F^x(t) \\ x(t) = C X(t) \\ \hline A = \begin{bmatrix} 0 & 1 \\ -\frac{K_m^x}{m} & -\frac{K_v^x}{m} \end{bmatrix} \quad B = \begin{bmatrix} 0 \\ \frac{1}{m} \end{bmatrix} \quad C = [1 \quad 0] \end{array}$$

Uncertainty model of the force



Input force model based on a stochastic Wiener process :

$$\dot{F}(t) = \omega(t)$$

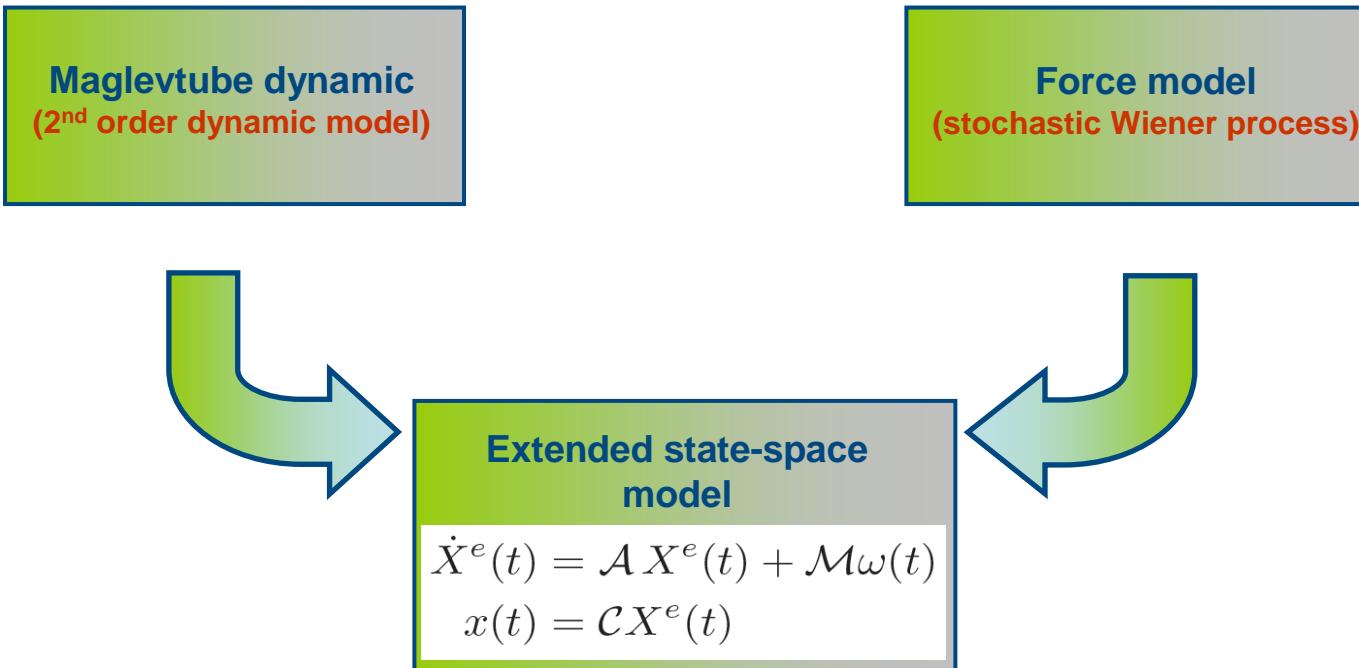
with $\omega(t)$ a zero-mean infinite-variance white gaussian
stochastic process

Autocorrelation function of the $\omega(t)$ process is :

$$\phi_{\omega,\omega}(\tau) = W_{\dot{F}} \delta(\tau) \quad \forall \tau \in \mathbb{R}$$

with $W_{\dot{F}}$ its power spectral density

Extended state-space model



$$X^e(t) = [x \quad \dot{x} \quad F]^T$$

$$\mathcal{A} = \begin{bmatrix} 0 & 1 & 0 \\ -\frac{1}{K_m^x} & -\frac{1}{K_v^x} & \frac{1}{m} \\ 0 & 0 & 0 \end{bmatrix} \quad \mathcal{M} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \quad \mathcal{C} = [1 \quad 0 \quad 0]$$

Discretization of extended model

Extended state-space
model

$$\begin{aligned}\dot{X}^e(t) &= \mathcal{A} X^e(t) + \mathcal{M} \omega(t) \\ x(t) &= \mathcal{C} X^e(t)\end{aligned}$$



zoh discretization
(sampling period T_s)

Discrete extended
state-space model

$$\begin{aligned}X_{k+1}^e &= \mathcal{F} X_k^e + \Omega_k \\ x_k &= \mathcal{C} X_k^e\end{aligned}$$

with : $\mathcal{F} = e^{\mathcal{A} T_s}$

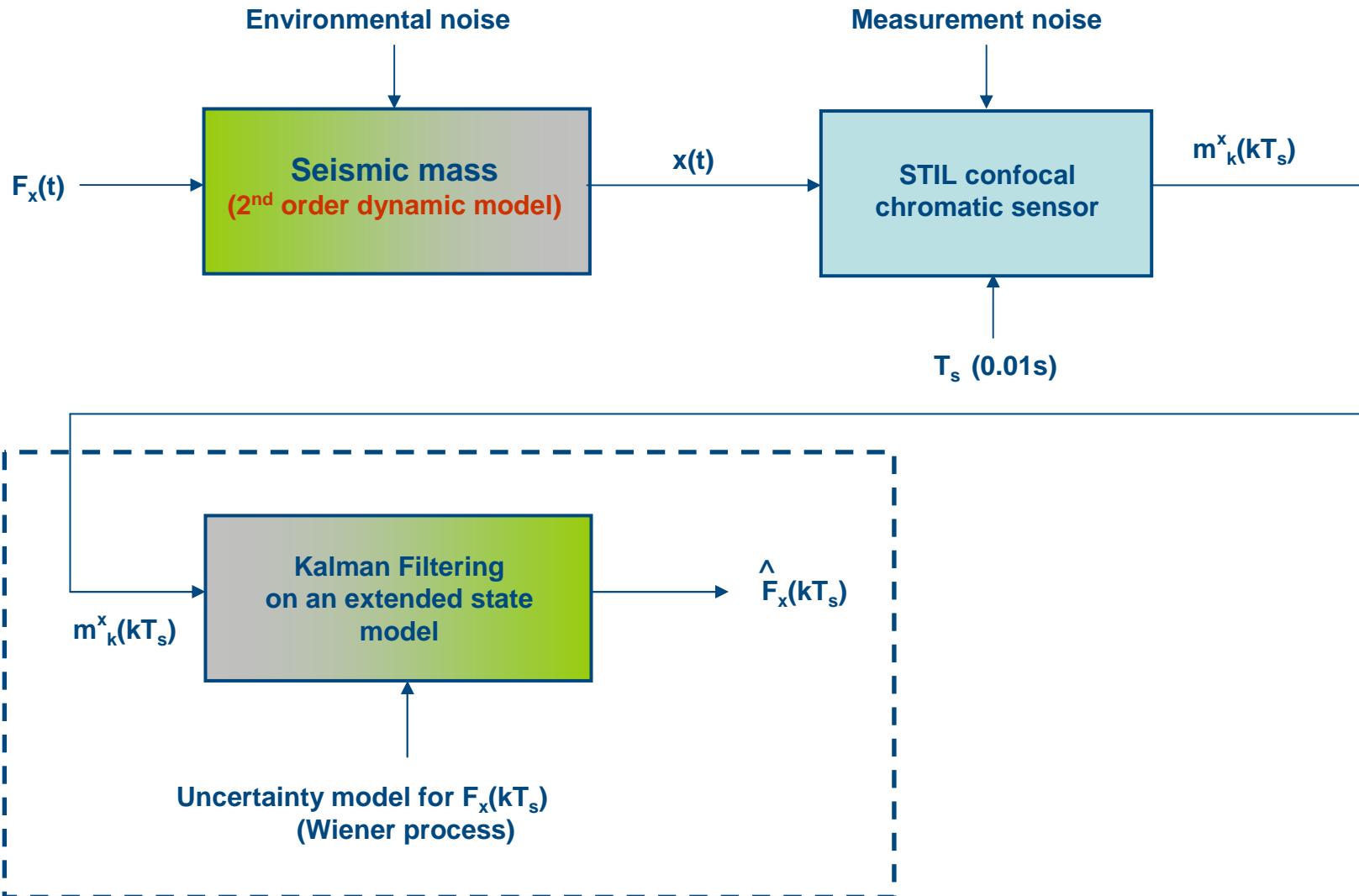
$$\Omega_k = [\omega_k^x \quad \omega_k^{\dot{x}} \quad \omega_k^F]^T$$

$$X_k^e = [x_k \quad \dot{x}_k \quad F_k]^T$$

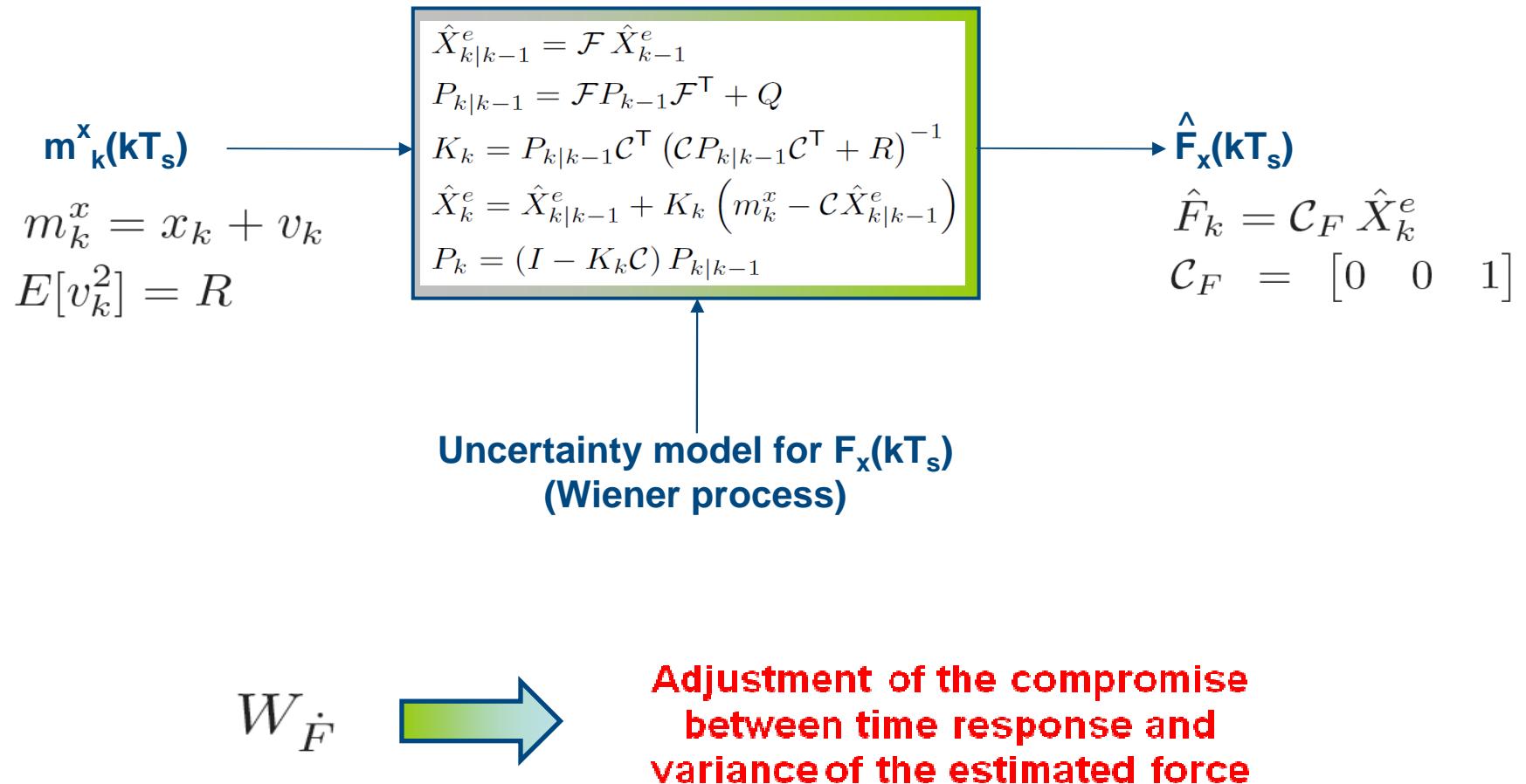
and : $Q = E[\Omega_k \Omega_k^T] = W_F \eta(T_s)$

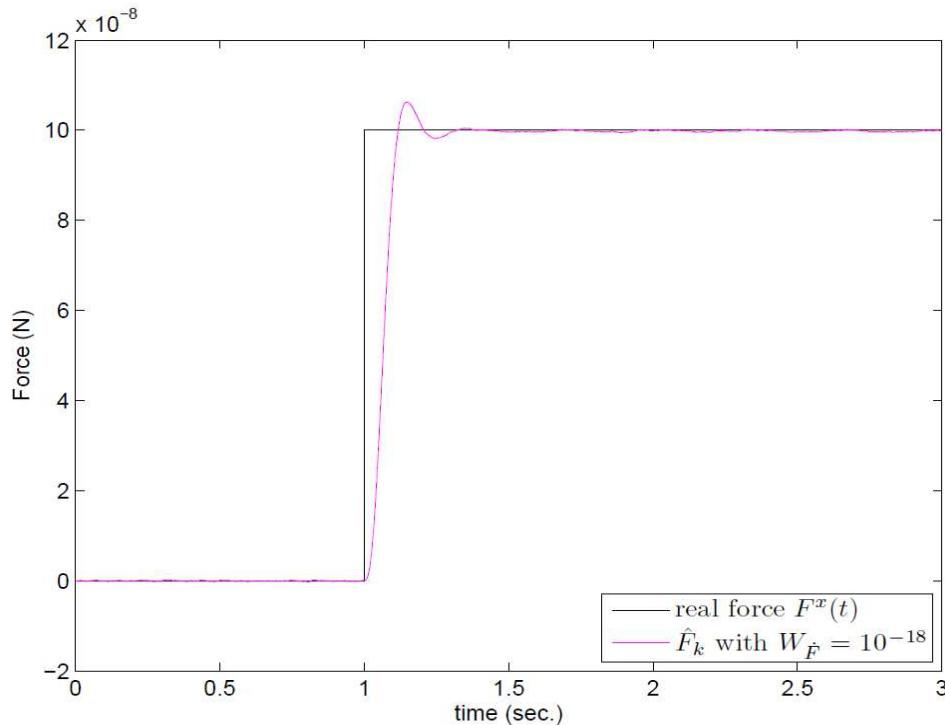
$$\eta(T_s) = \int_0^{T_s} e^{\mathcal{A} t} \mathcal{M} \mathcal{M}^T e^{\mathcal{A}^T t} dt$$

Force estimation using Kalman filter

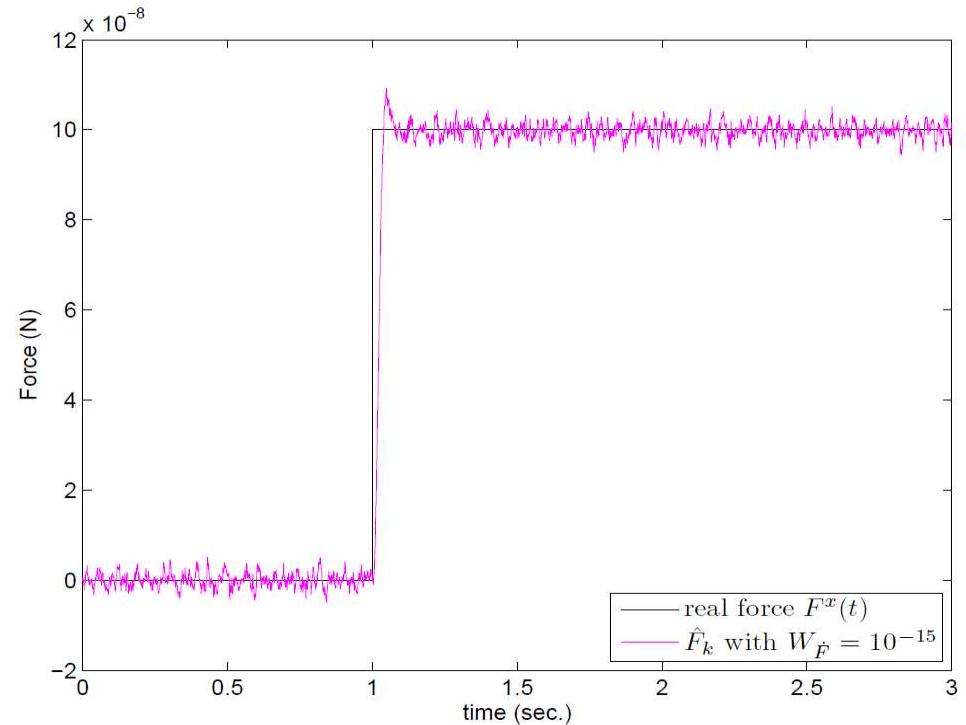


Force estimation using Kalman filter

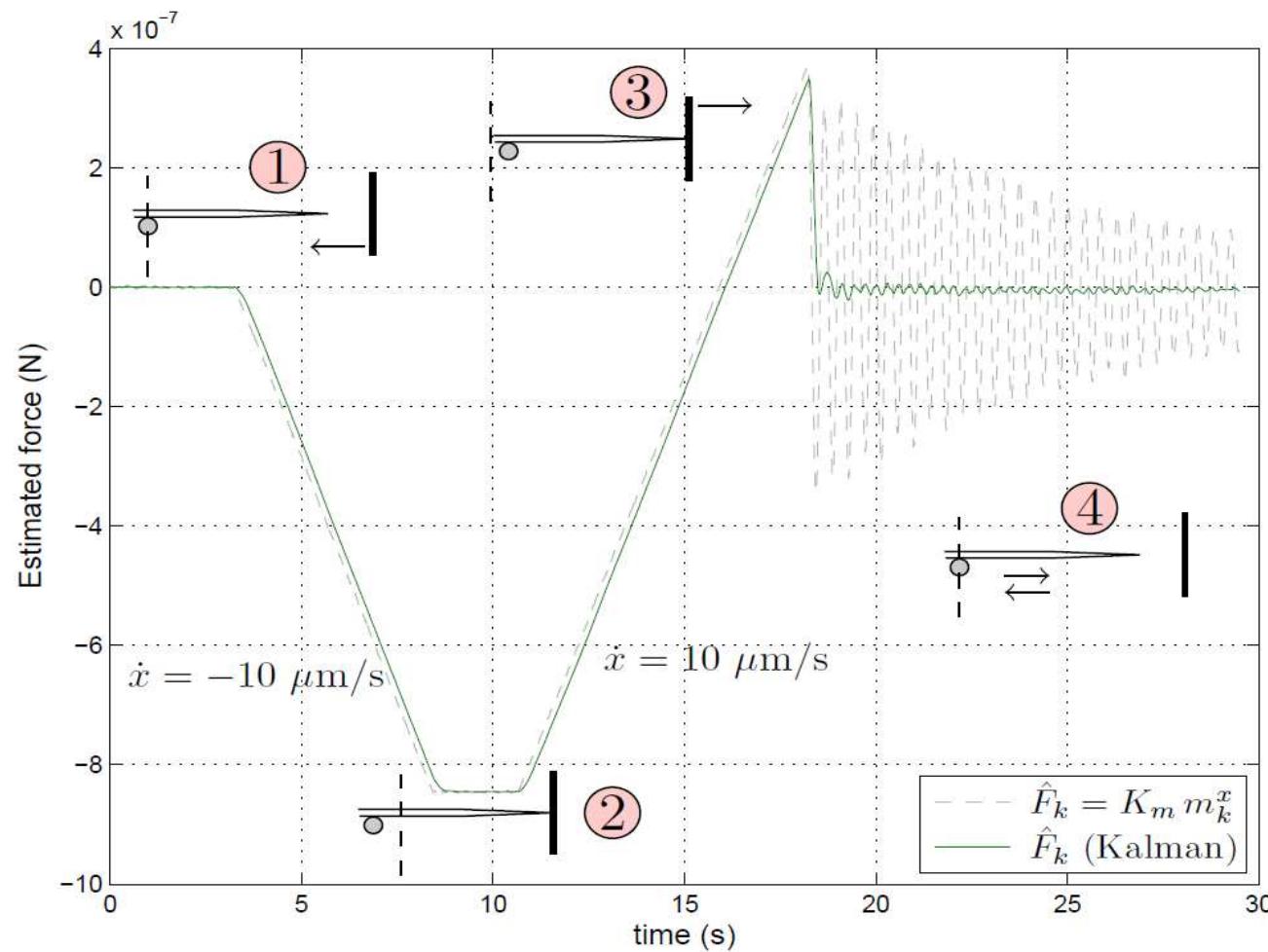




step-force estimation with $W_{\dot{F}} = 10^{-18} \text{ N}^2/\text{Hz}$

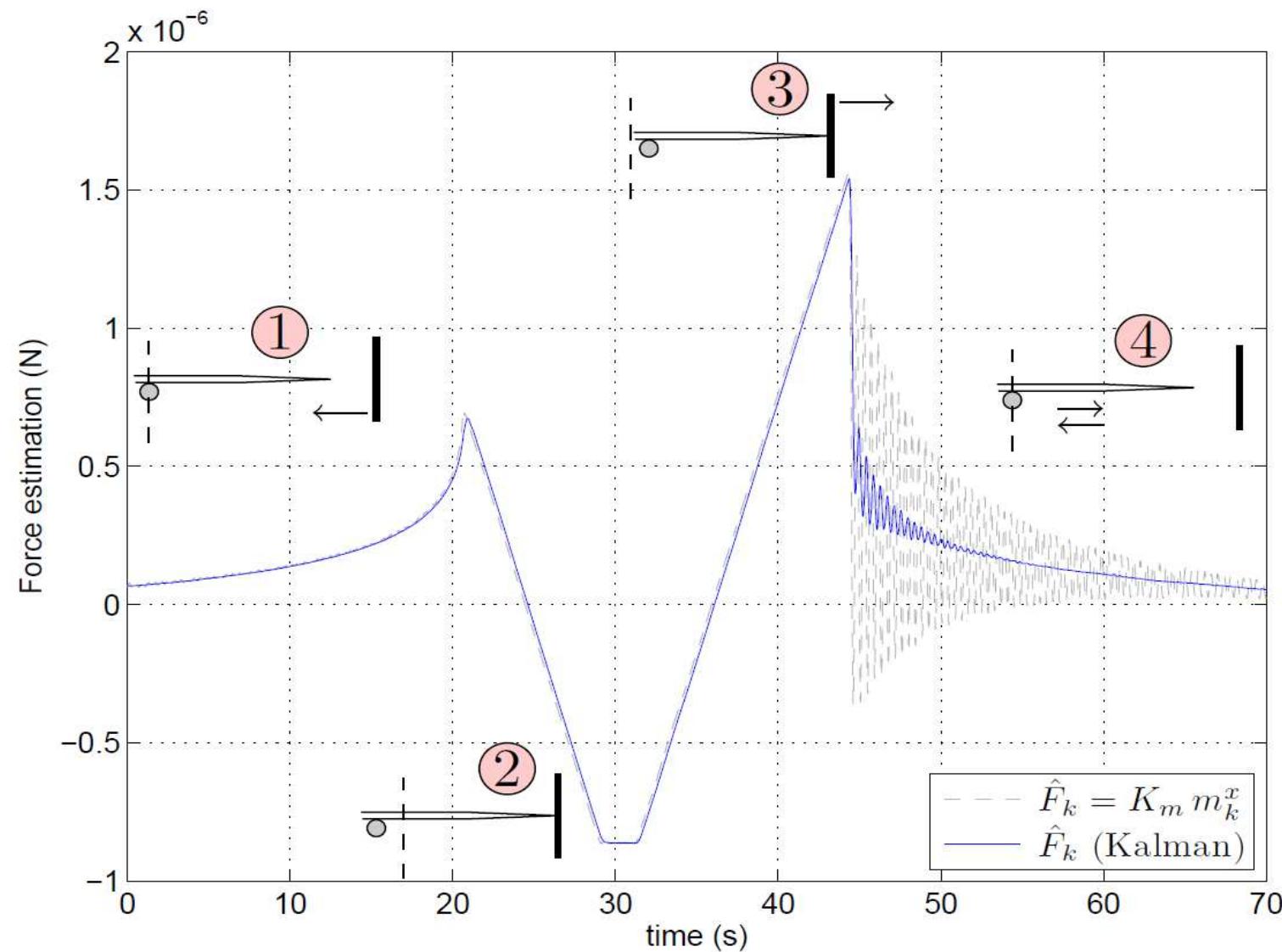


step-force estimation with $W_{\dot{F}} = 10^{-15} \text{ N}^2/\text{Hz}$



Experimental pull-off force measurement

Pull-Off measurement with electrostatic force

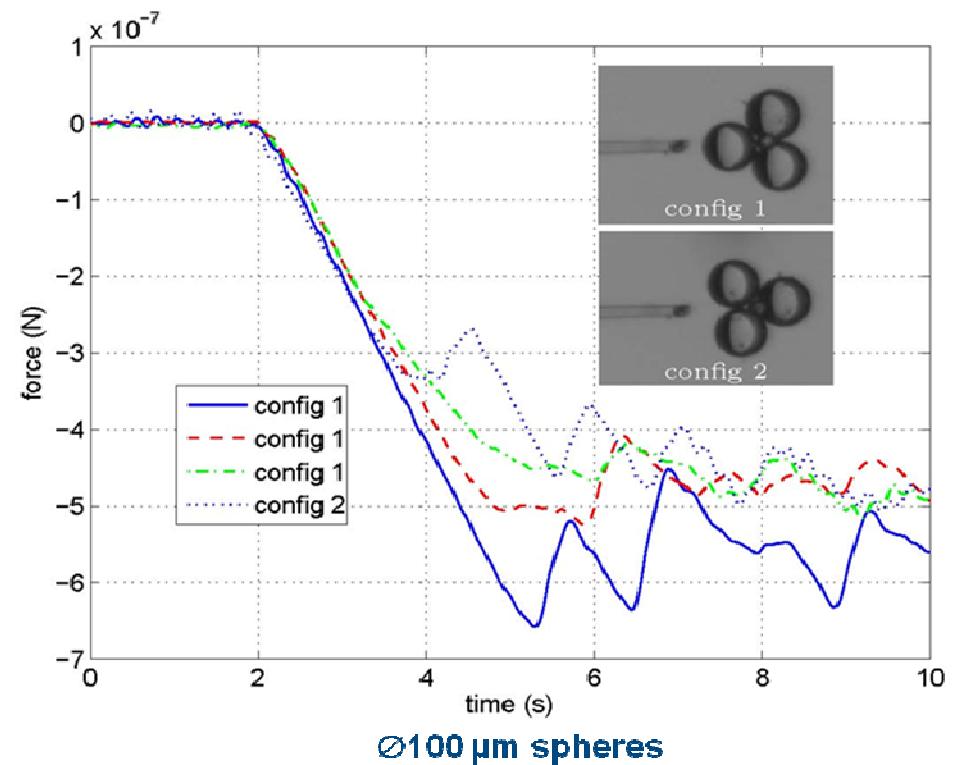
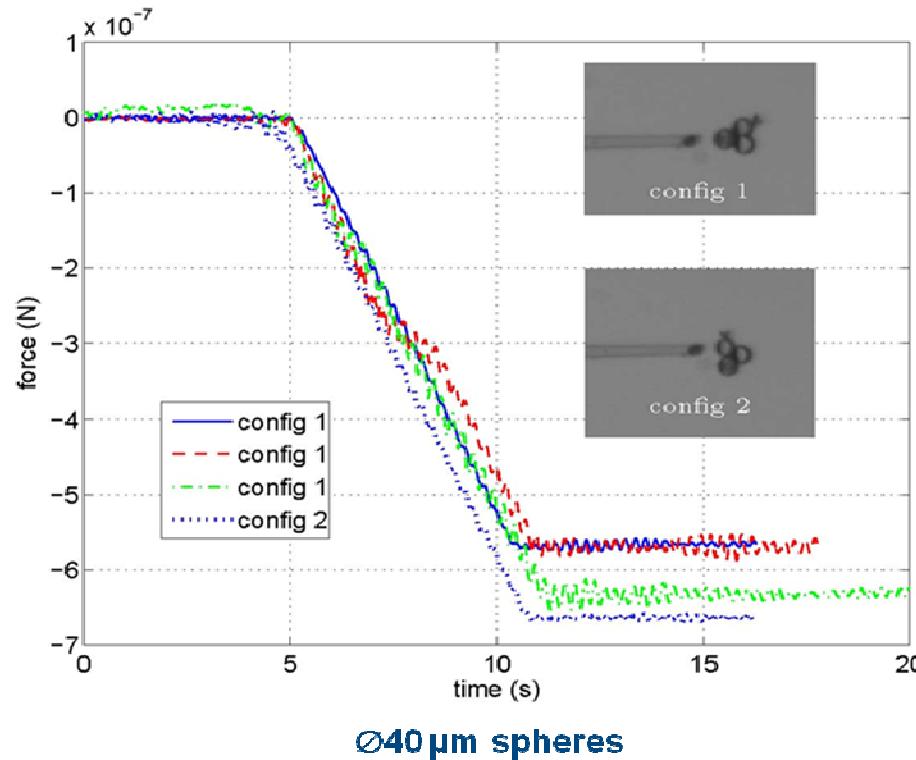
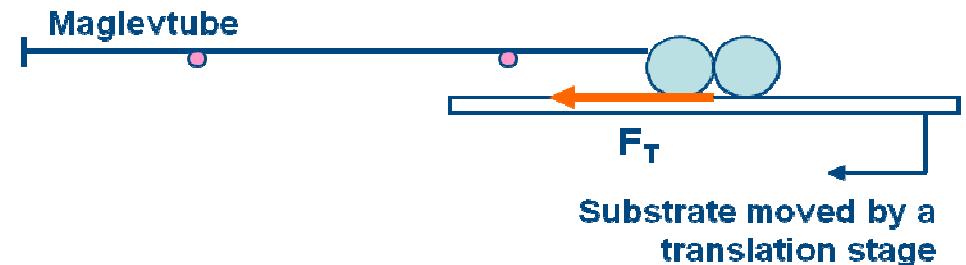


Friction study conditions :

μstructures with Ø40 µm and Ø100 µm spheres

Glass substrate cleaned in ethanol

20% to 30% relative humidity



- μ and nanoforce estimation based on a Kalman filter
- One parameter to set for adjusting the trade-off between resolution and response time.
- Process implemented in DSP on a experimental platform with good results.

The screenshot shows the homepage of the [femto-st](http://www.femto-st.fr/en/) website. The top navigation bar includes links to Vivitek, Les offres de forfait..., Projecteurs digitaux..., News & Media, Google Traduction, and Forum ORANGE / Le... A search bar and a menu icon are also present.

The main header features the **femto-st** logo with the tagline "SCIENCES & TECHNOLOGIES". To the right, there's a banner for "TROPHÉES INPI DE L'INNOVATION 20 ANS Lauréat national 2011" with a "View video" link. Below the header, a hexagonal grid background is overlaid with text labels: "Automatic control AS2M | Computer science", "DISC | Energy | Applied mechanics", "Mec'Appli | Micro nano MN2S | Optics | Time frequency".

The navigation menu includes links to "THE INSTITUTE", "RESEARCH", "TECHNOLOGY", "PARTNERSHIP / VALORISATION", and "OPEN POSITIONS". The "RESEARCH" link is highlighted with a green arrow pointing to the "AS2M" section. The "AS2M" section is circled in blue and contains links for "Presentation", "Organization chart", "Research groups", and "Research Projects". Other research sections shown include "DISC", "ENERGY", "APPLIED MECHANICS" (with sub-links for Presentation, Human resources, Significant results, Research groups), "MN2S", "OPTICS", and "TIME and FREQUENCY" (with sub-links for Presentation, Organization, Research groups).

A yellow banner on the left side of the page reads "A RESEARCH LABORATORY AT THE EUROPEAN SCALE" and "700 people for a multidisciplinary approach". A green banner below it says "News of FEMTO-ST". A text box in the center of the page announces "Two ERC Grants for FEMTO-ST" for Prof John DUDLEY & Dr Yanne CHAUMELET. The FEMTO-ST Institute (UMR 6174) both received a financial Grant from the European Research Council to support the top level scientific excellence.

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