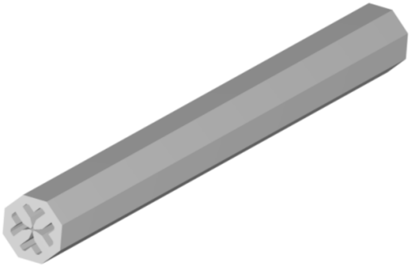
CLIC Main Beam Quadrupoles Stabilization

C. Collette, K. Artoos, M. Guinchard, A. Kuzmin, M. Sylte, F. Lackner, C. Hauviller…

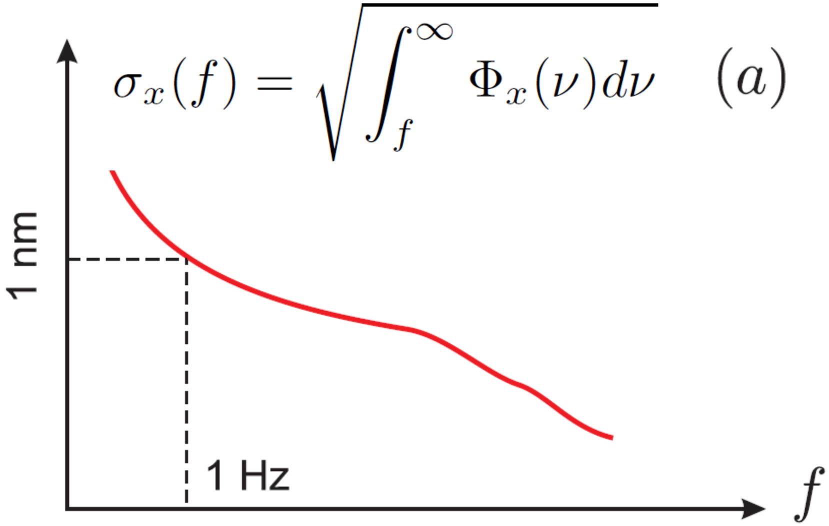
CERN/EN

Requirements

Lenth: 2m
Weigth: ~ 400 Kg



Frequency domain requirements
(stabilization)

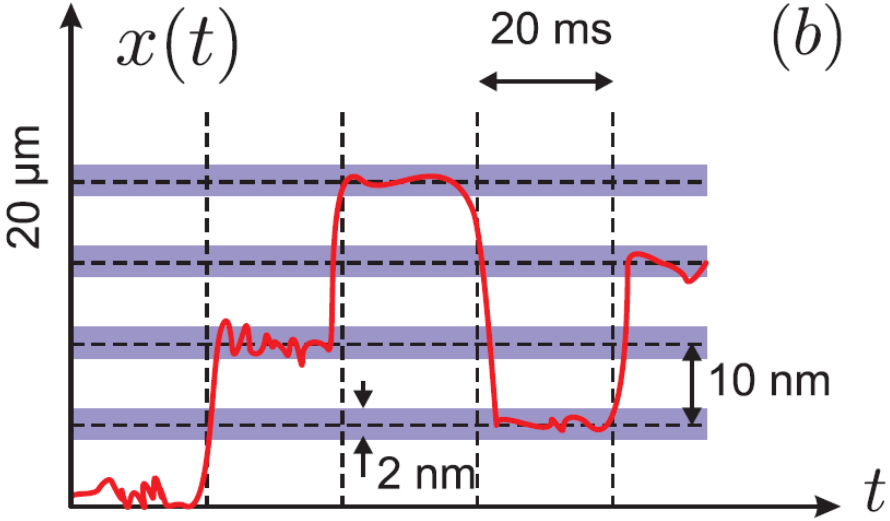


$$\sigma_x(f) = \sqrt{\int_f^\infty \Phi_x(\nu)d\nu} \quad (a)$$

(4 nm in lateral direction)

2000 quadrupoles/line

Time domain requirements
(positioning)

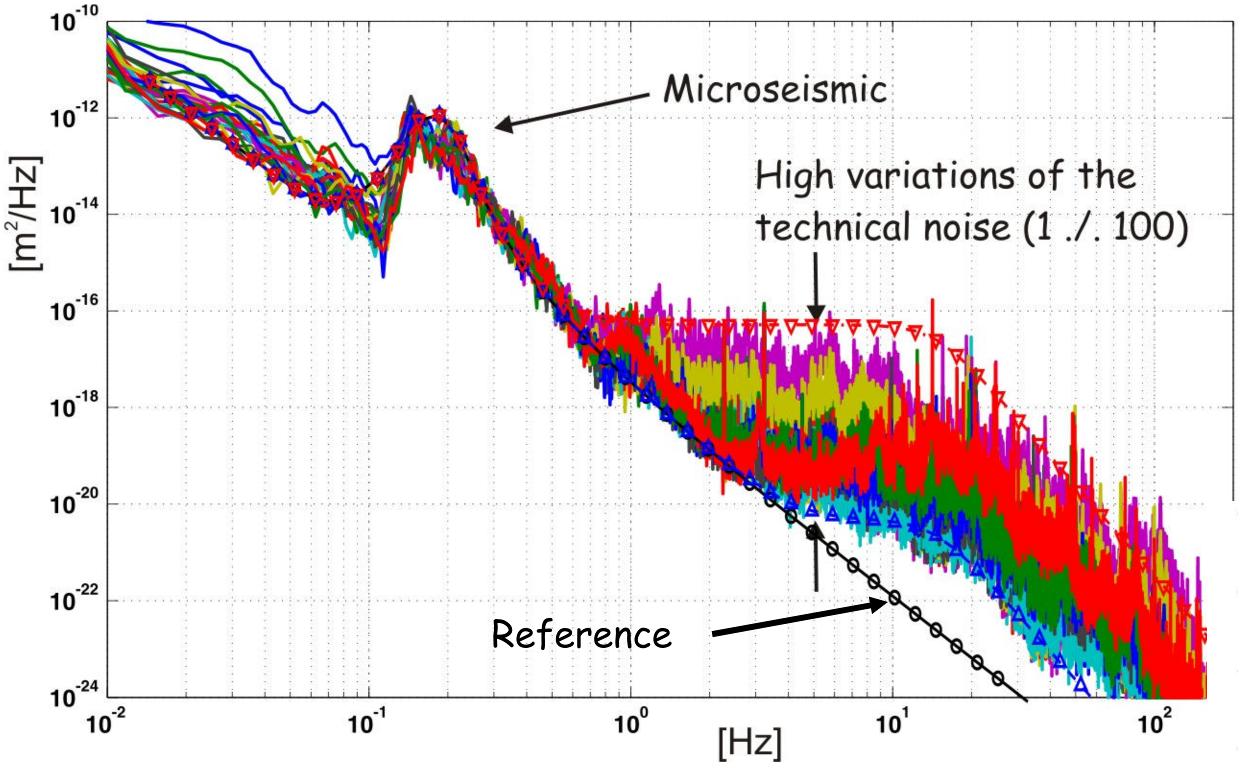


(vertical and lateral)

80 quadrupoles/line

Local excitations

Vertical ground motion



Microseismic

High variations of the technical noise (1 ./. 100)

Reference

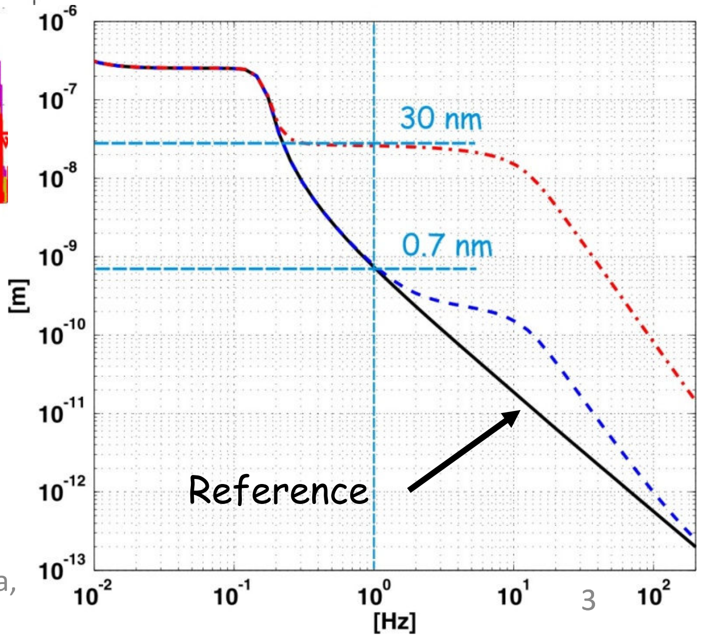
$$\text{Low technical noise: } N_0 = 5 * 10^{-3}(nm^2/Hz)$$

$$\text{High technical noise: } N_0 = 50(nm^2/Hz)$$

Additional technical noise:

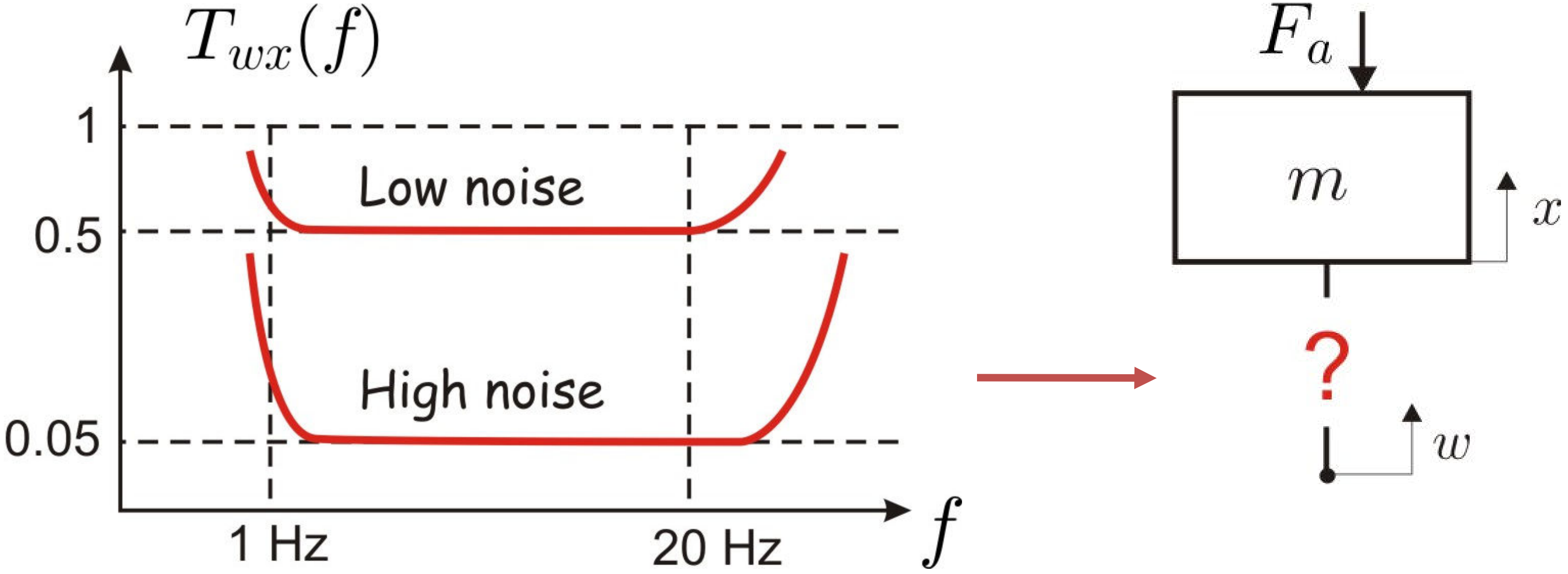
$$N(\omega) = \frac{N_0}{1 + (\frac{\omega}{\omega_0})^6}$$

$$f_0 = 2\pi(Hz)$$



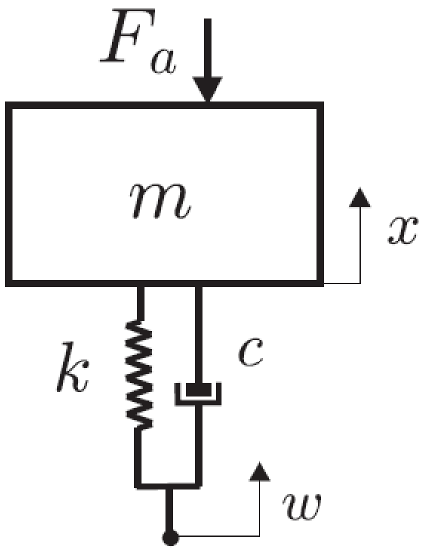
Reference

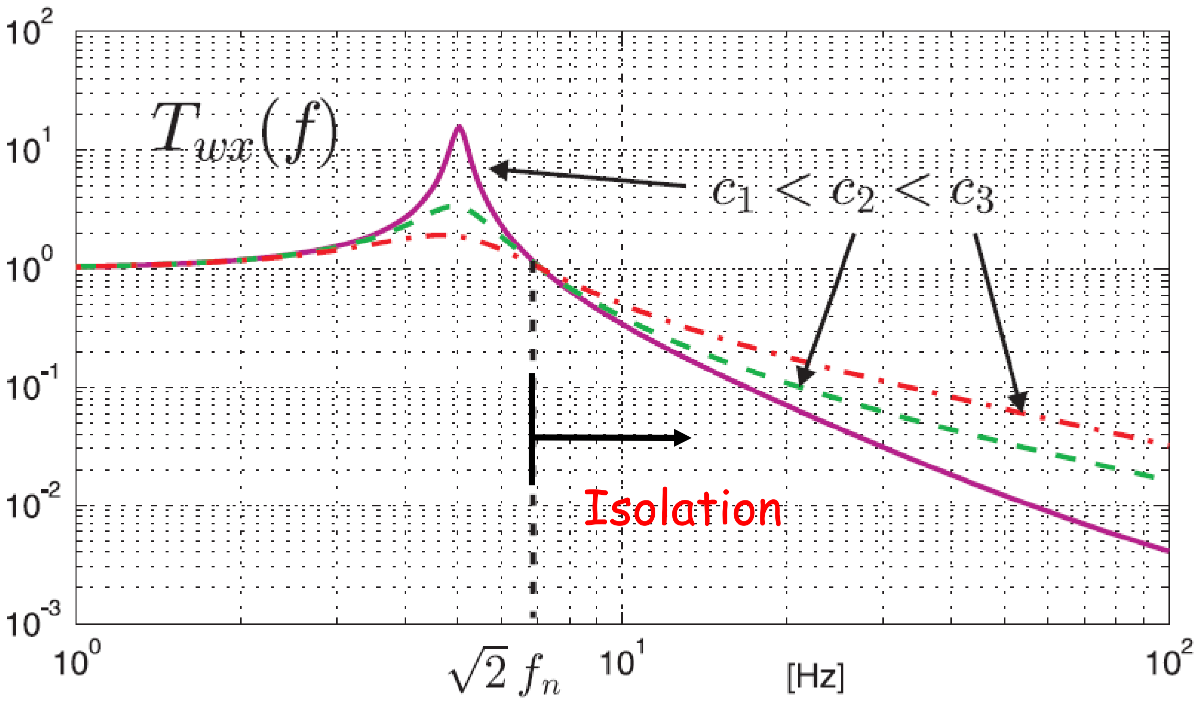
How to support the quadrupoles ?



Which type of support can fulfill the requirements ?

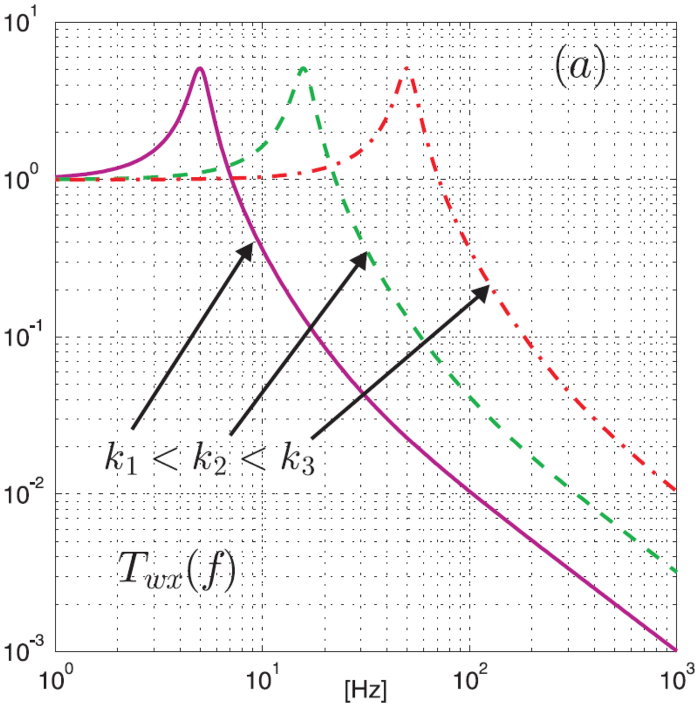
Increase the damping

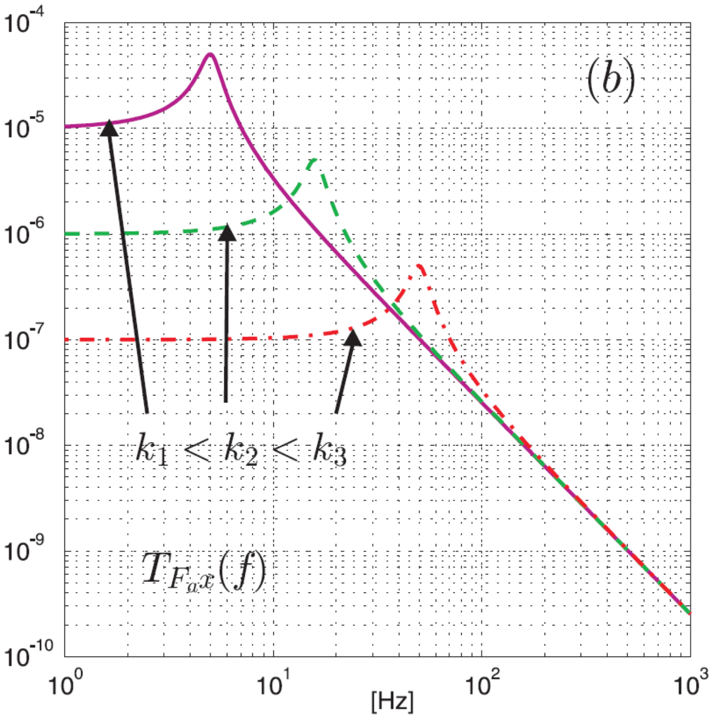




Reduces the overshsoot but degrades the isolation at high frequency

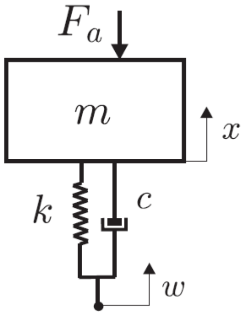
Change the stiffness





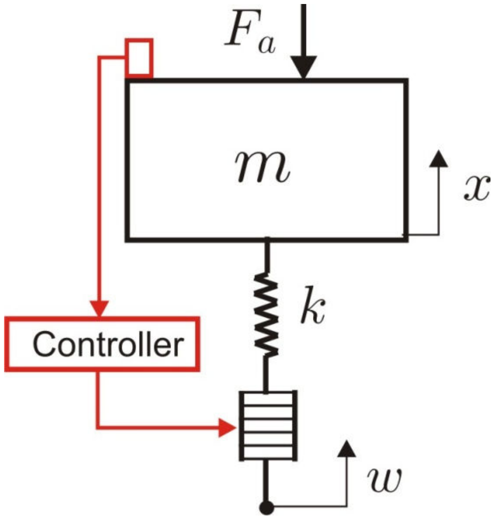
A soft support improves the isolation but :

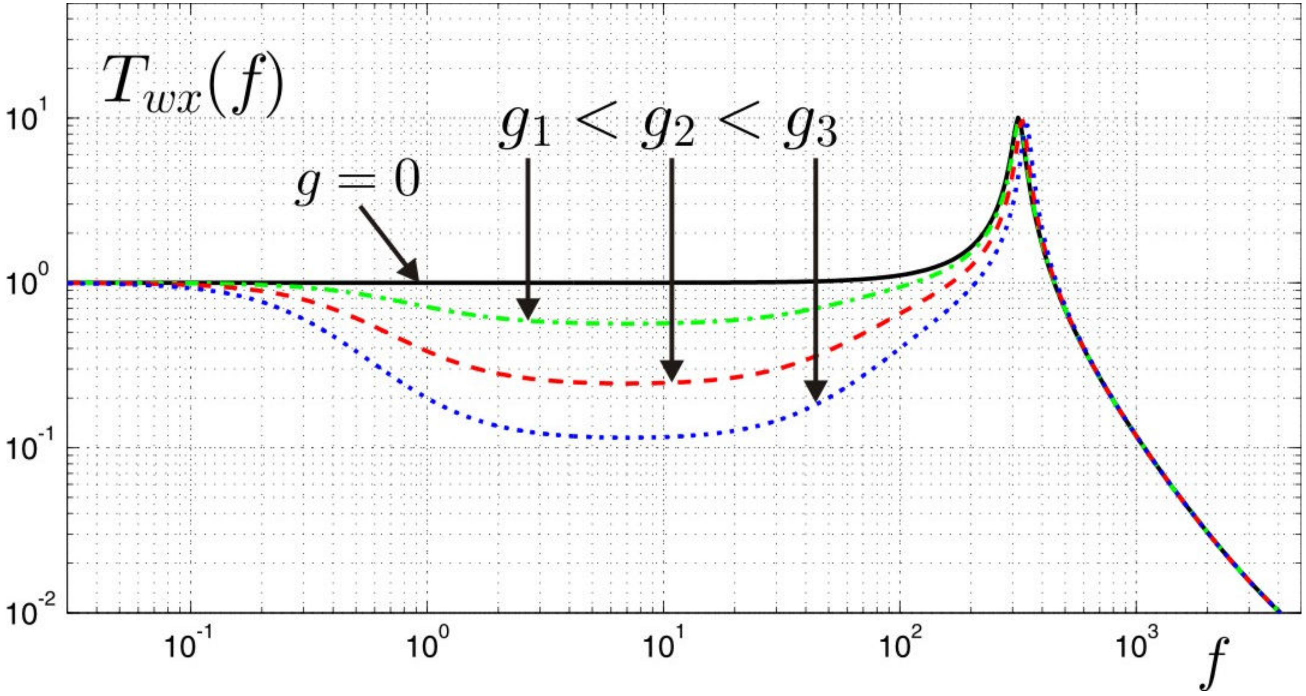
(i) Make the quadrupole more sensitive to external forces Fa
(ii) Cannot be positioned rapidly



Control strategy: position feedback

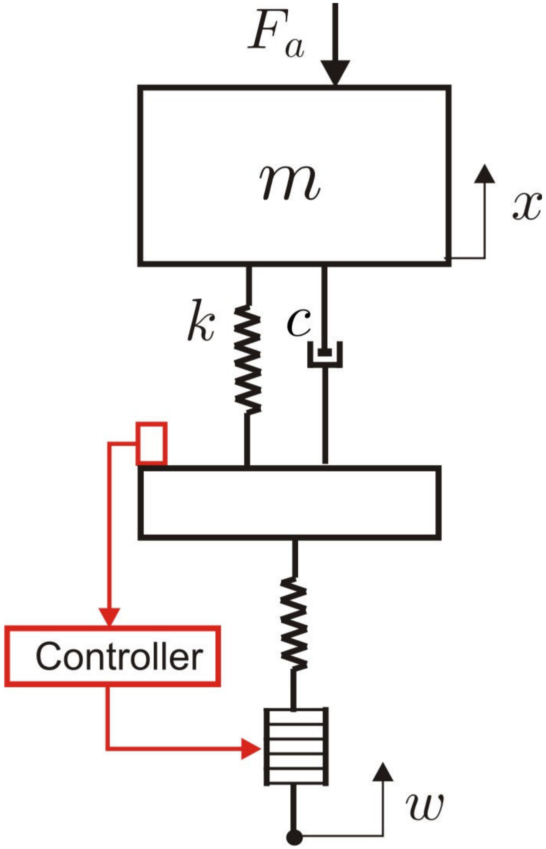
C. Montag (1996, DESY)

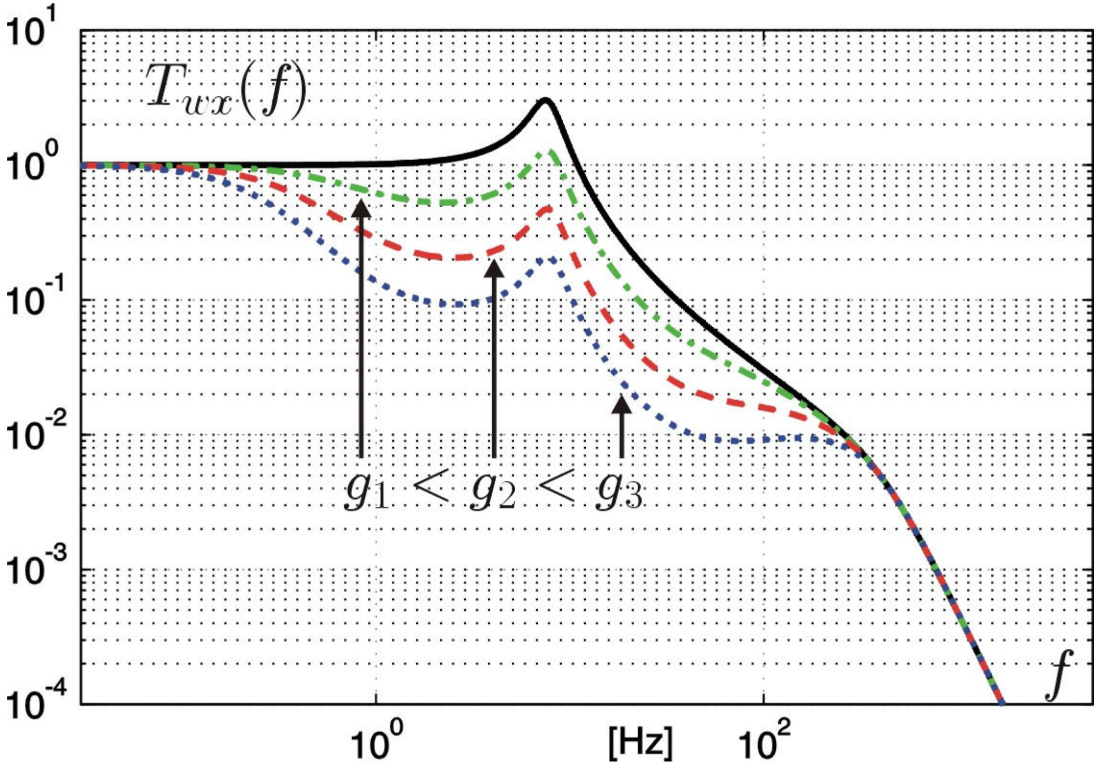




Two stages control

S. Redaelli (CERN, 2004)

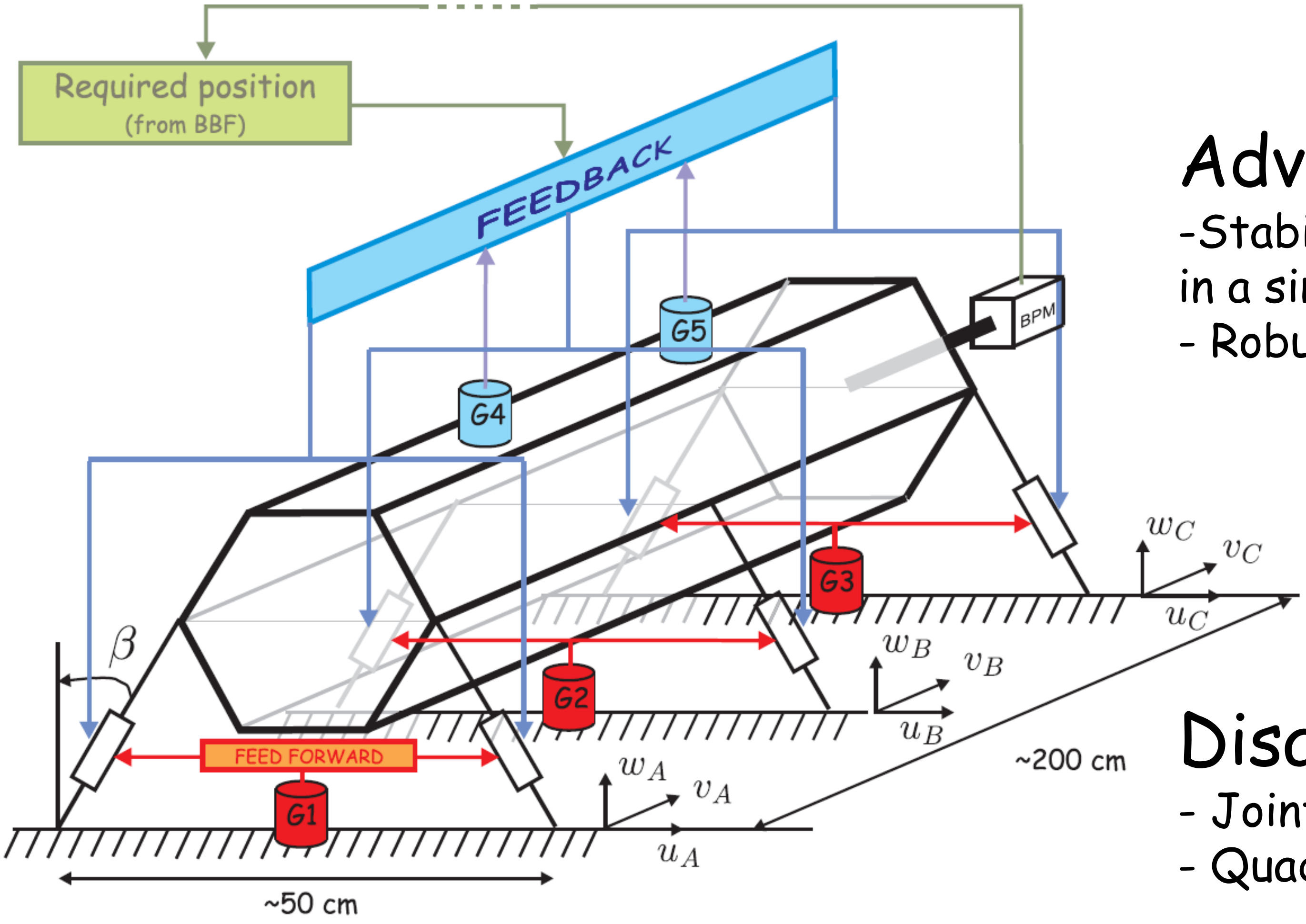




Comparison

	Stiff support	Soft support
Advantages	- Not sensitive to extenral force - Positioning capabilities - Single stage	- Isolation in a broad frequency range
Disadvantages	- Isolation in a smaller frequency range	- Sensitive to external force - No positioning capabilities - Multi-stage

Hexapod concept



Advantages:

-Stabilization & Positioning in a single stage

- Robust to external forces

Disadvantages:

- Jointure issues
- Quadrupole flexibility

System dynamics

Velocity Jacobian $\dot{\mathbf{q}} = J\dot{\mathbf{x}}$

$$J = \begin{pmatrix} \cdots & \cdots \\ \mathbf{1}_i^T & -\mathbf{1}_i^T \tilde{\mathbf{p}}_i \\ \cdots & \cdots \end{pmatrix}$$

Dynamic equations

$$M\ddot{\mathbf{x}} + K\mathbf{x} = B\mathbf{f} + E\mathbf{w}$$

$$\mathbf{f} = (f_1, f_2, ..., f_6)^T$$

$$K = kBB^T + K_e$$

$$M = \mathrm{diag}(m, m, m, I_\theta, I_\phi, I_\psi)$$

Leg orientations

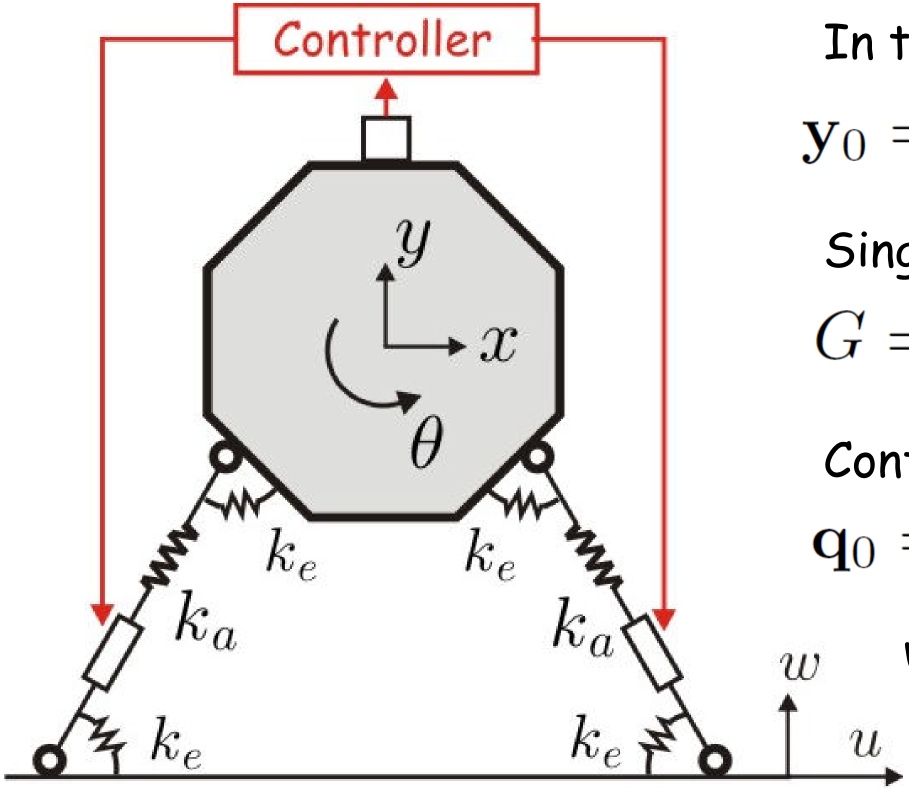
$$Q = \begin{pmatrix} \sin\beta\cos\alpha & \sin\beta\sin\alpha & \cos\beta \\ -\sin\beta\cos\alpha & \sin\beta\sin\alpha & \cos\beta \\ -\sin\beta\sin\alpha & -\sin\beta\cos\alpha & \cos\beta \\ \sin\beta\sin\alpha & \sin\beta\cos\alpha & \cos\beta \\ \sin\beta\cos\alpha & -\sin\beta\sin\alpha & \cos\beta \\ -\sin\beta\cos\alpha & -\sin\beta\sin\alpha & \cos\beta \end{pmatrix}$$

Fixation coordinates

$$P = \begin{pmatrix} -R & R & -R & R & -R & R \\ -L & -L & 0 & 0 & L & L \\ h & h & h & h & h & h \end{pmatrix}$$

Details in ACTIVE CONTROL OF QUADRUPOLE MOTION FOR FUTURE LINEAR PARTICLE COLLIDERS, C. Collette et al., *IASTED International Conference on Intelligent Systems and Control*, Cambridge (2009).

Two legs



In the observable sub-space:

$$\mathbf{y}_0 = C_0\mathbf{x}_0 = C_0 J_0^{-1}\mathbf{q}_0 = G\mathbf{q}_0$$

Singular value decomposition:

$$G = U\Sigma V^T \quad \Sigma = \mathrm{diag}(\sigma_1, ..., \sigma_\mathrm{n})$$

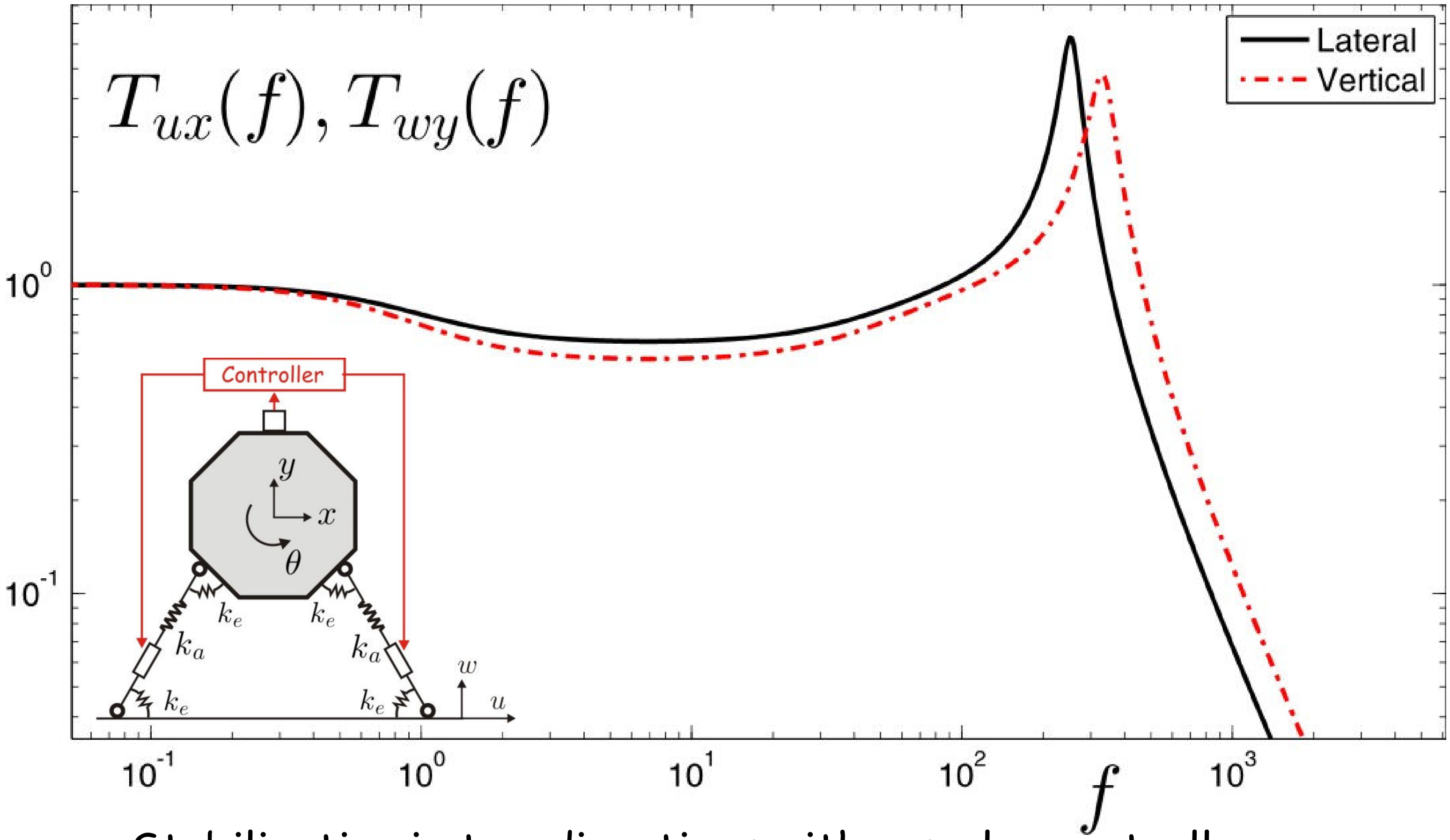
Control strategy:

$$\mathbf{q}_0 = VH(\omega)\Sigma^{-1}U^T\mathbf{y}_0$$

where $H(\omega) = Ih(\omega)$

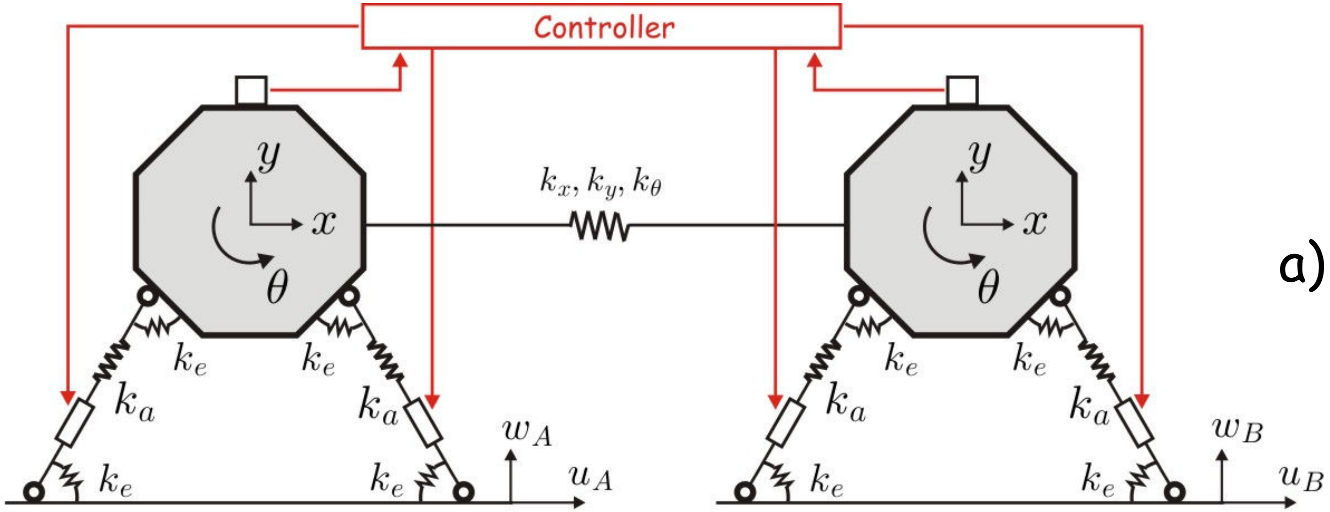
σ_1/σ_n is an estimator of the controller performances ➔ Tool for the design

Two legs

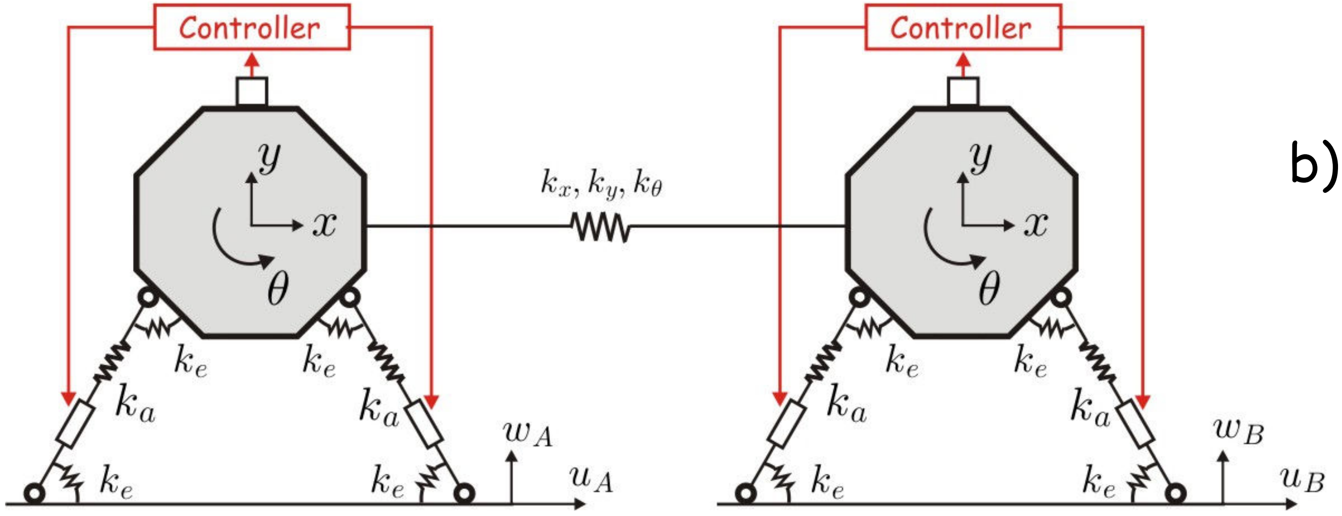


Stabilization in two directions with a scalar controller

Four legs



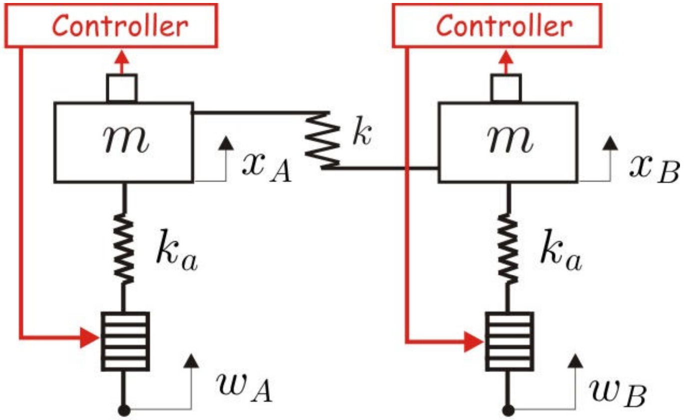
a) Centralized control



b) Decentralized control

Control architecture

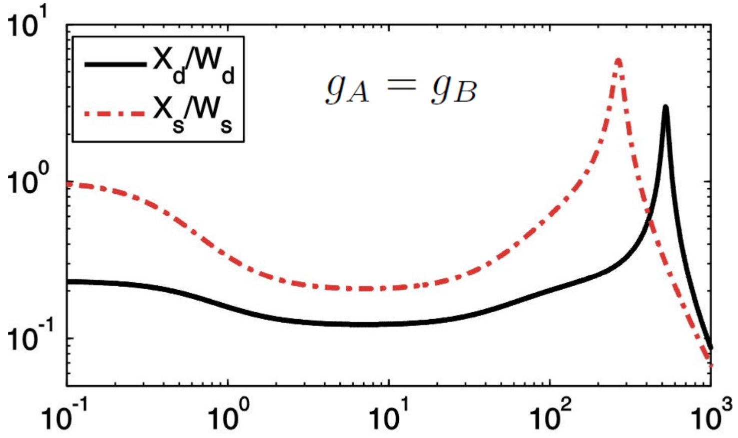
$$X_s = (x_A + x_B)/2; X_d = x_A - x_B; W_s = (w_A + w_B)/2; W_d = w_A - w_B;$$

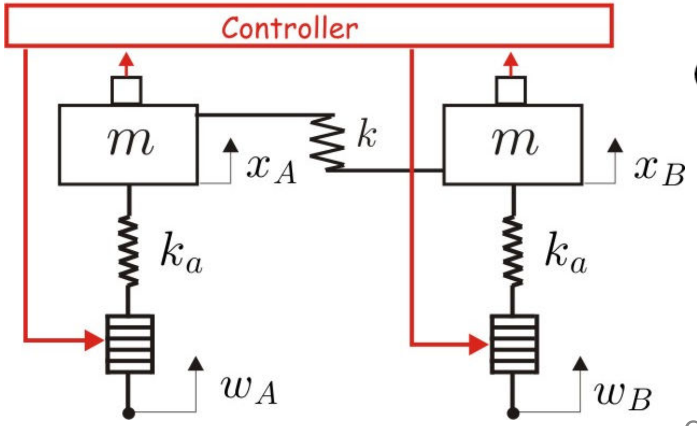


Decentralized control :

$$\delta_A = g_A x_A$$

$$\delta_B = g_B x_B$$

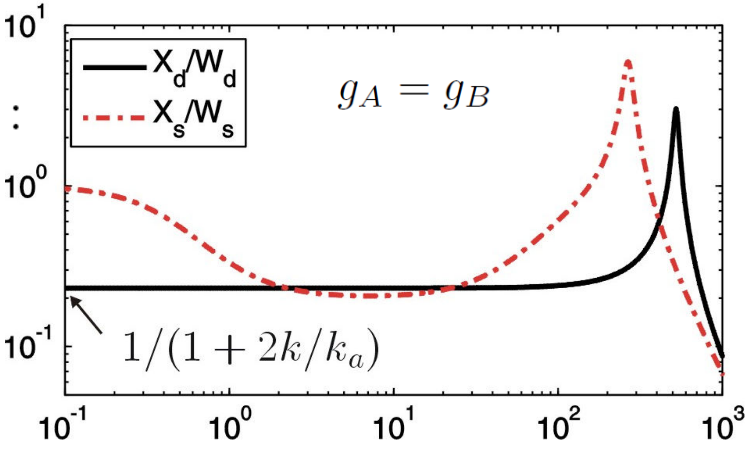




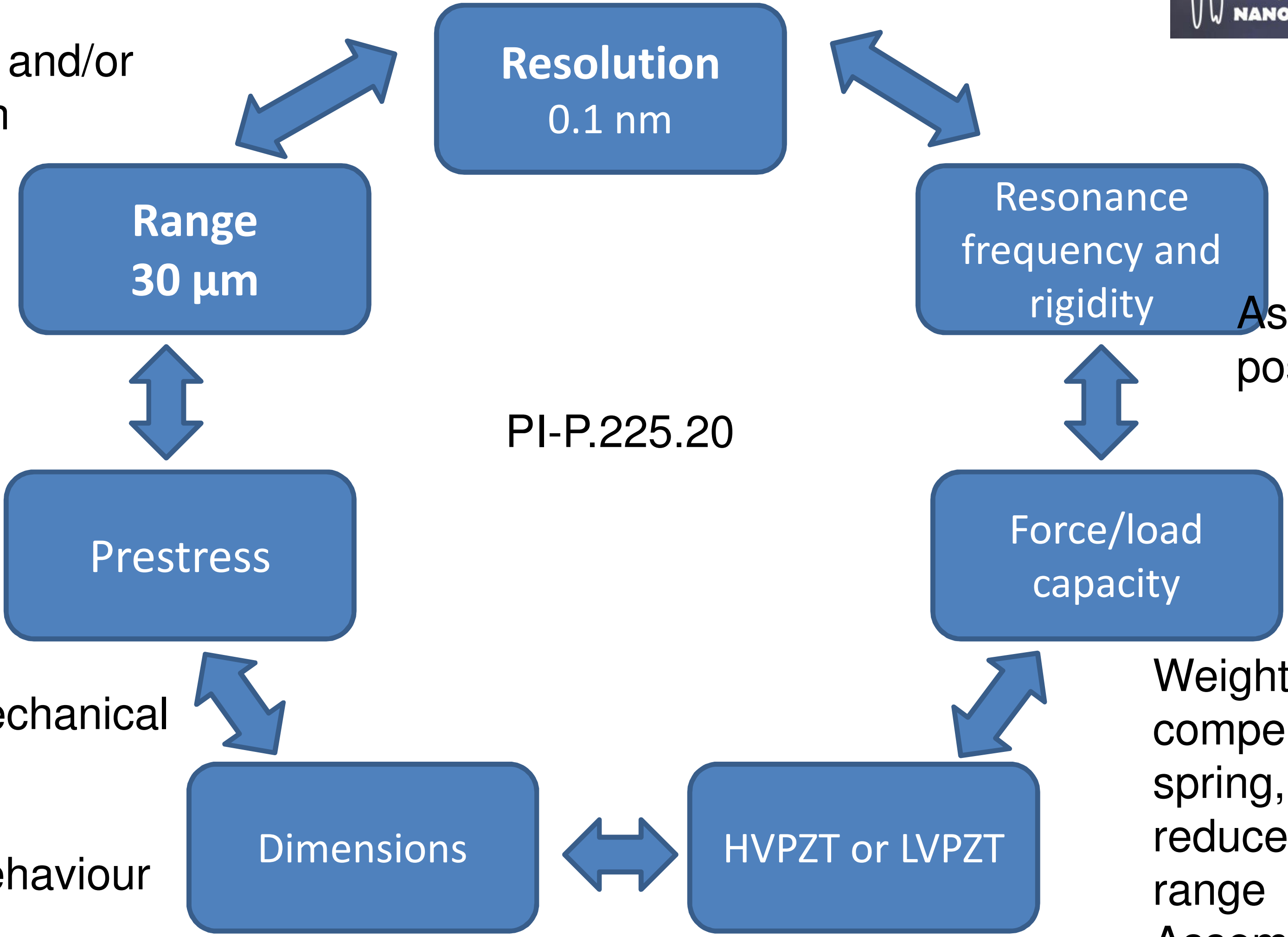
Centralized control :

$$\delta_A = g_A \frac{x_A + x_B}{2}$$

$$\delta_B = g_B \frac{x_A + x_B}{2}$$



Selection of piezo actuators



Resolution
0.1 nm

Resonance frequency and rigidity

Force/load capacity

HVPZT or LVPZT

Dimensions

Prestress

Range
30 µm

PI-P.225.20

Positioning and/or stabilisation

As high as possible

Weight compensating spring, reduces range
Assembly

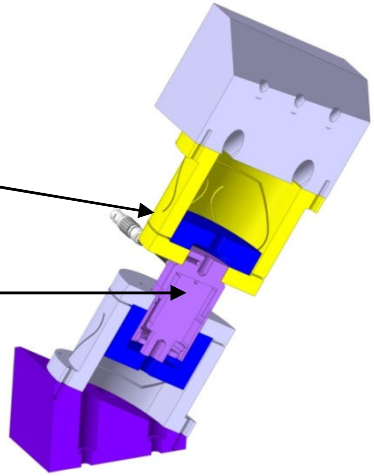
Required power, frequency range controller

(< 20 % mechanical limit)
20 MPa for dynamic behaviour

Flexible jointure design

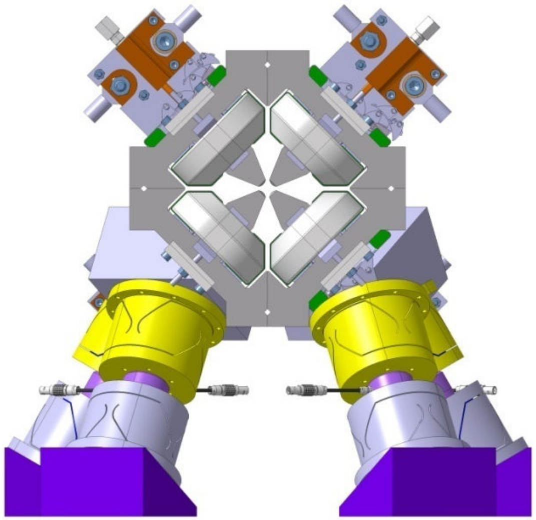
Advantages:
- No friction, no backlash
- Adaptable stiffness

Disadvantage:
- Requires custom design.



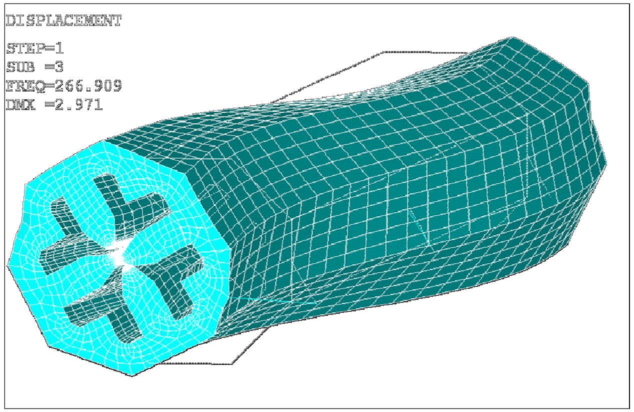
Flexible jointures

Piezoelectric actuator



Current characteristics:

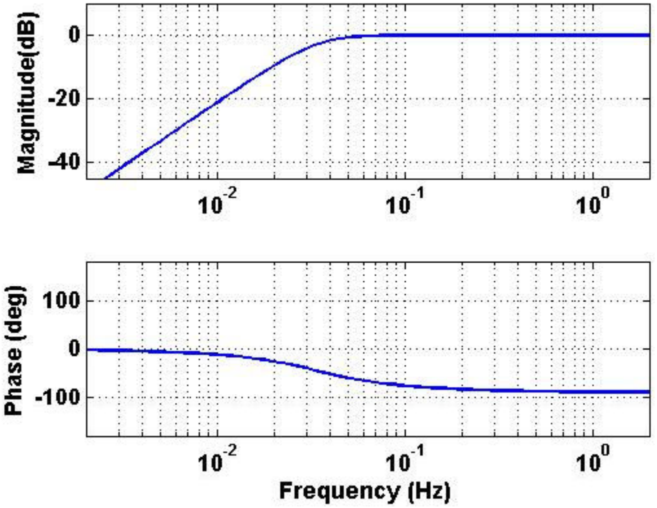
Rotational rigidity:
588 Nm/rad
Axial rigidity:
~ 1000 N/μm
Torsional rigidity:
~ 6000 Nm/rad



1st mode: 266Hz

Sensor Noise

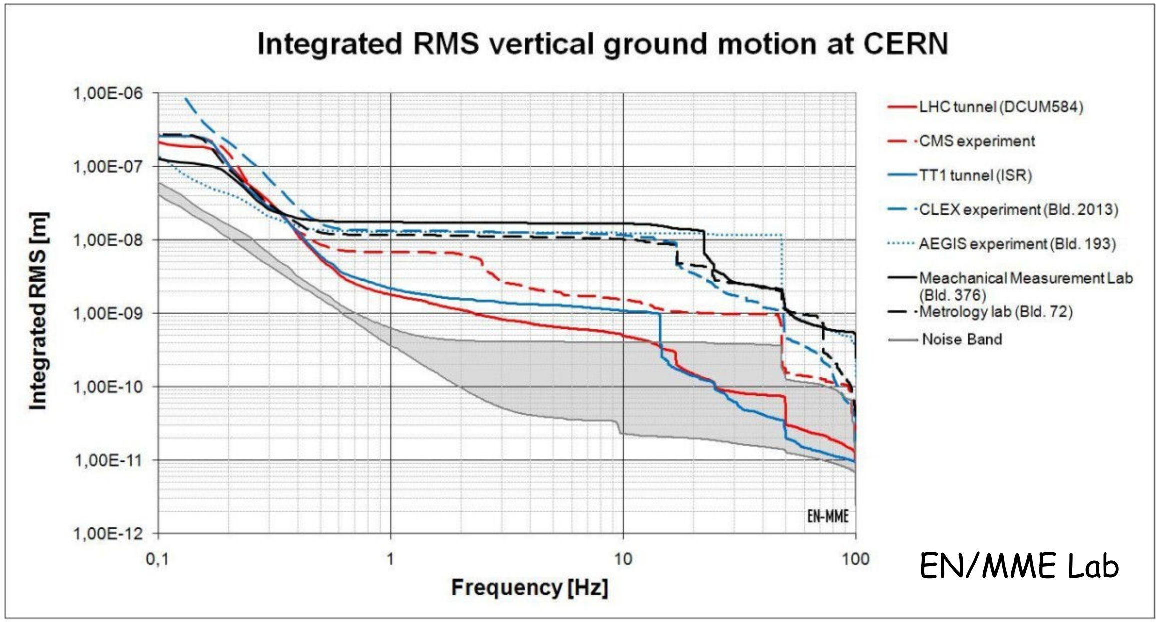
Sensor GURALP (CMG-6T)



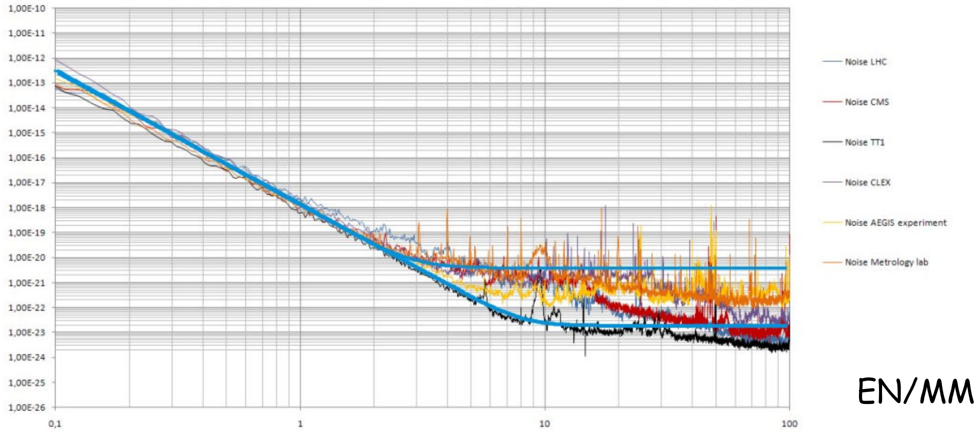
$$\Phi_n(f) = af^{-5} + bN_0$$

$$a = 10^{-18}; b = 2 * 10^{-4}$$

At high frequency, the sensor noise increases linearly with signal level

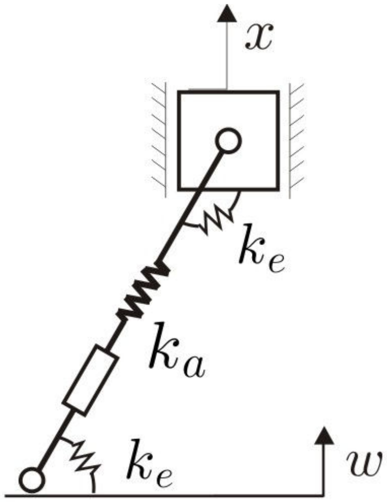


EN/MME Lab



EN/MME Lab

Scaled set up

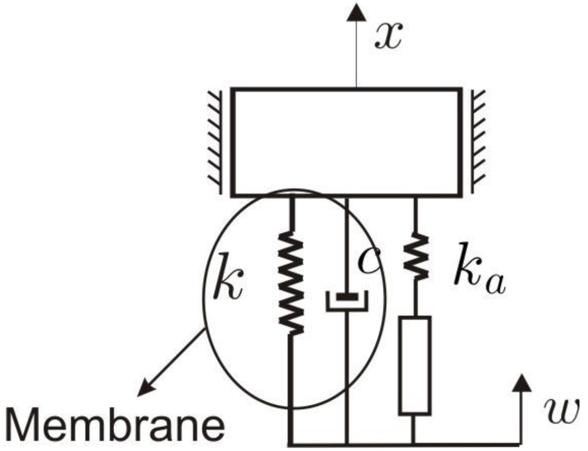


Full scale quadrupole :

- $m = 420/6 = 70\ kg$
- $k = 250\ MN/m$

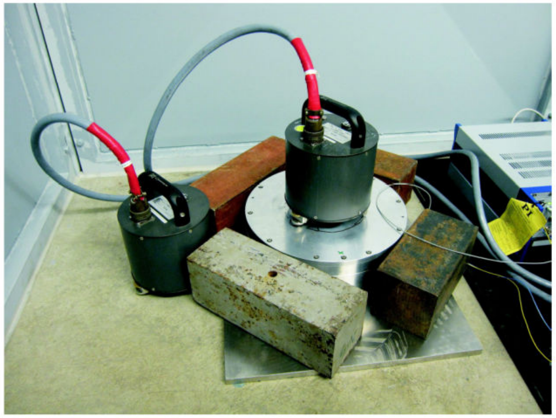
Scaling laws:

- $m = a_m m'$
- $k = a_k k'$
- $\omega = a_\omega \omega'$



Scaled set-up : $\boxed{a_\omega \simeq 1}$

- $m' = 2.5\ kg \Rightarrow a_m = 28$
- $k' = 1MN/m \Rightarrow a_k = 25$



Experimental results

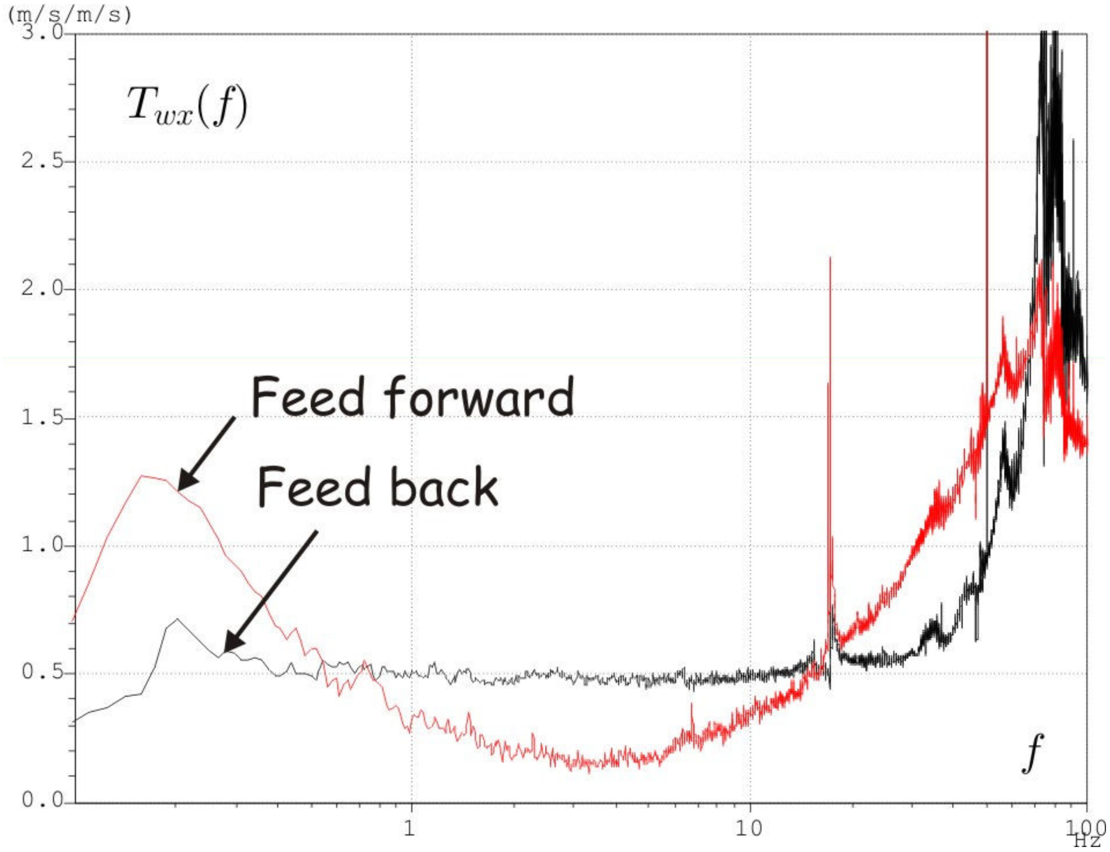
Feedback :

$$F_b = k\delta = K_p^b x$$

Feed forward :

$$F_f = k\delta = K_p^f w$$

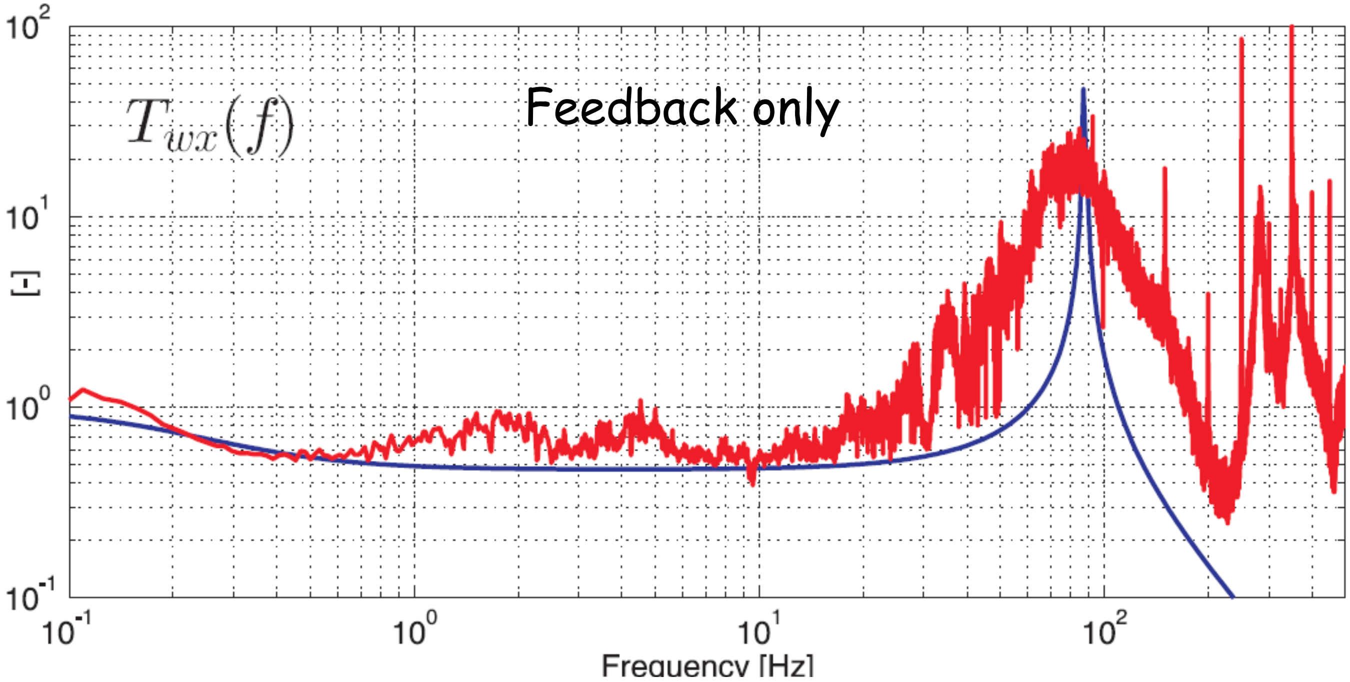
Results obtained in the lab



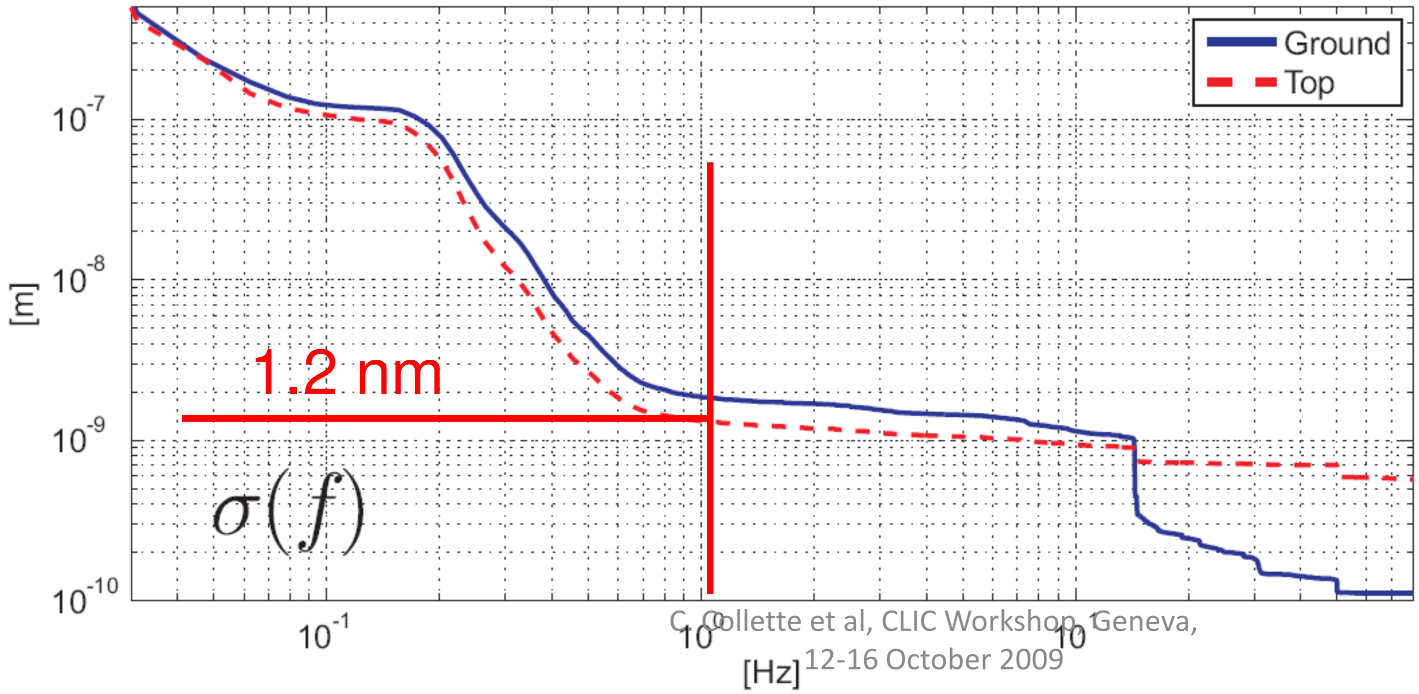
Feed forward

Feed back

Feed forward works better in a narrow frequency range

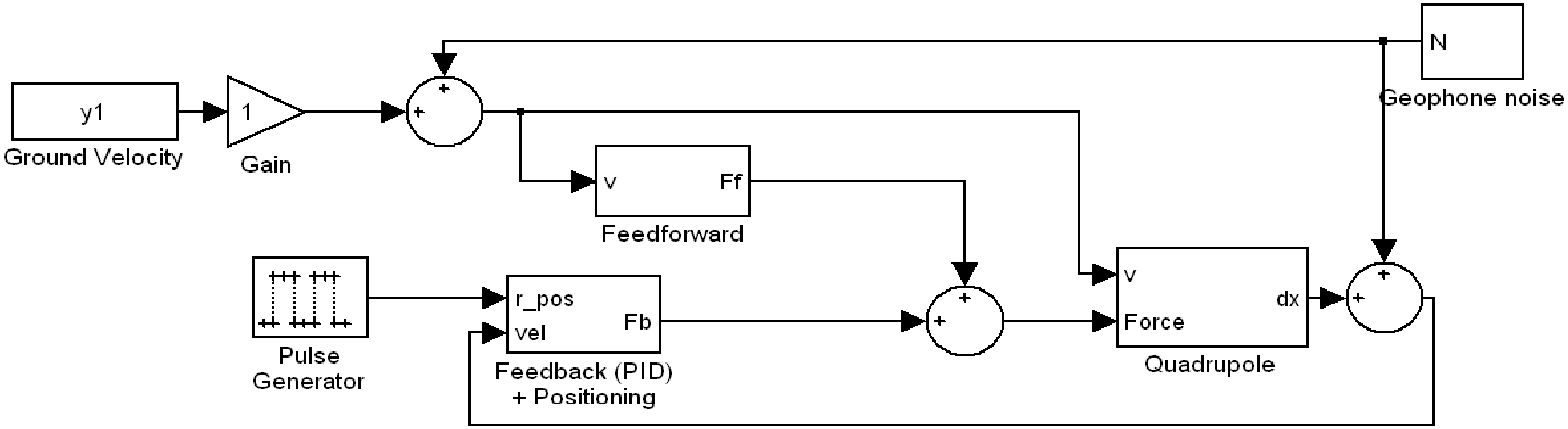


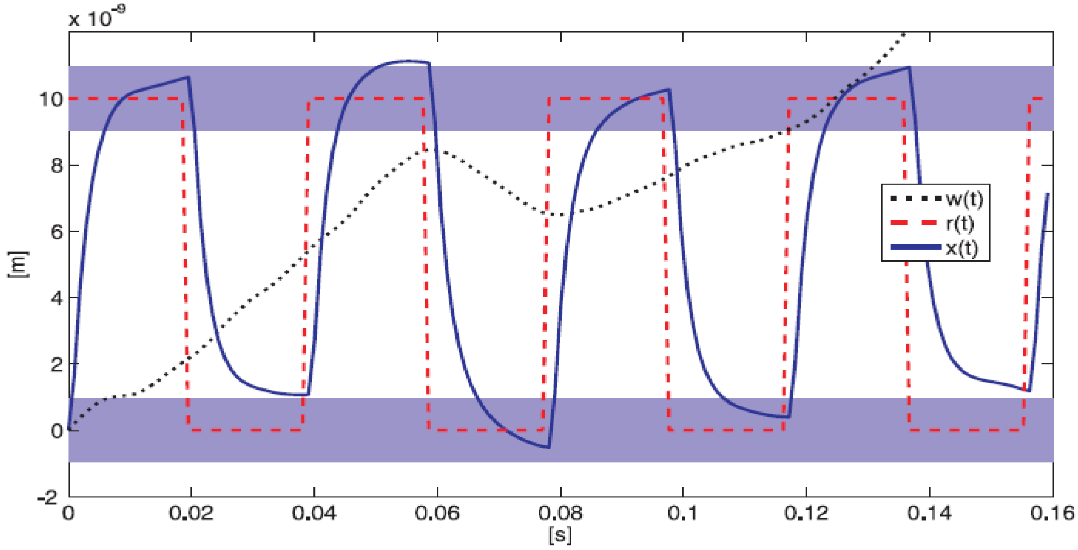
Results obtained in a quiet place (TT1)



Better results are expected with a more adapted hardware (resolution, noise…)

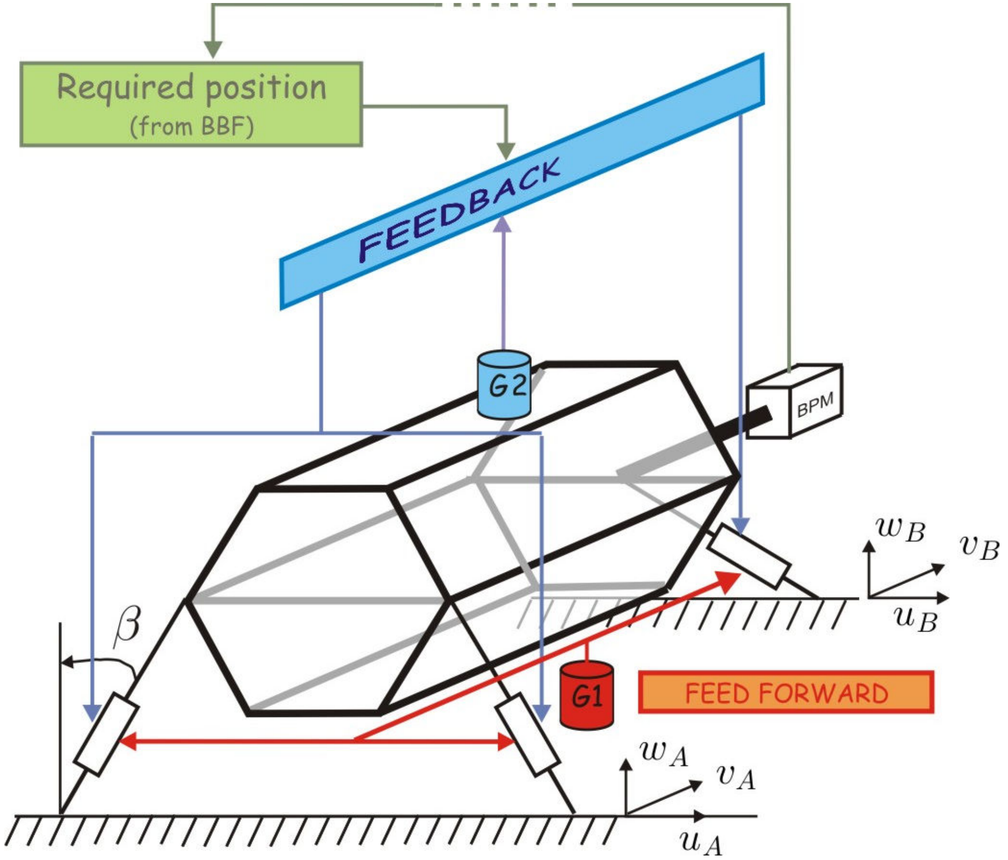
Positioning





To be tested experimentally on the membrane

Intermediate experiment: Tripod



Difficulties addressed:

- Heavy load
- Actuators and sensors
- Control law
- Flexible jointure
- Positioning capability

Conclusions

- Technical noise model
- Hexapod concept and dynamics
- Issues discussed: decentralized controller, jointure design, actuator and sensor choice
- RMS integrated of 1,2 nm with a dedicated scaled bench
- Supports include positioning capabilities