CLIC Quadrupole Stabilization at CERN

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

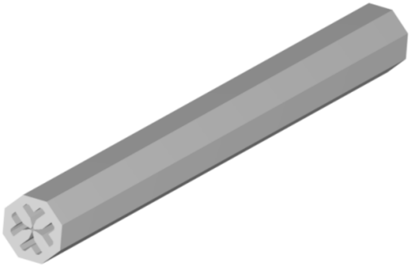
CERN/EN

Outline

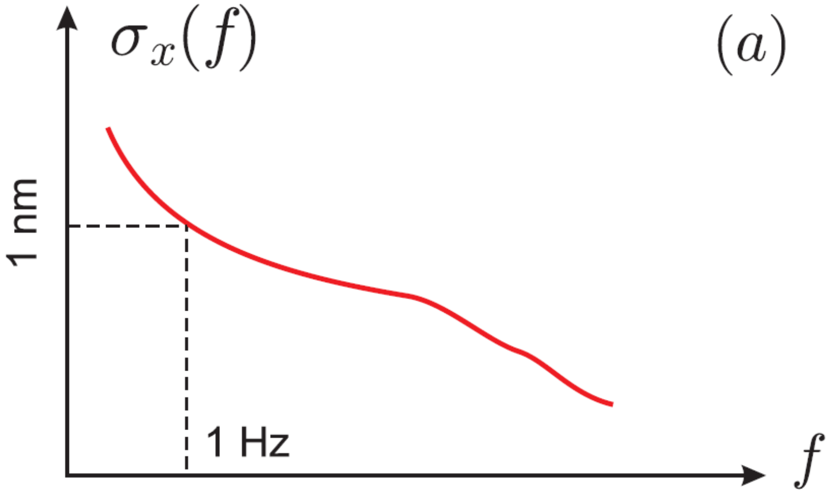
1. Description of the problem
2. Short review of isolation strategies
3. Hexapod concept and issues
4. Experimental results
5. Planned activities

1. Requirements

Lenth: 2m
Weigth: ~ 400 Kg



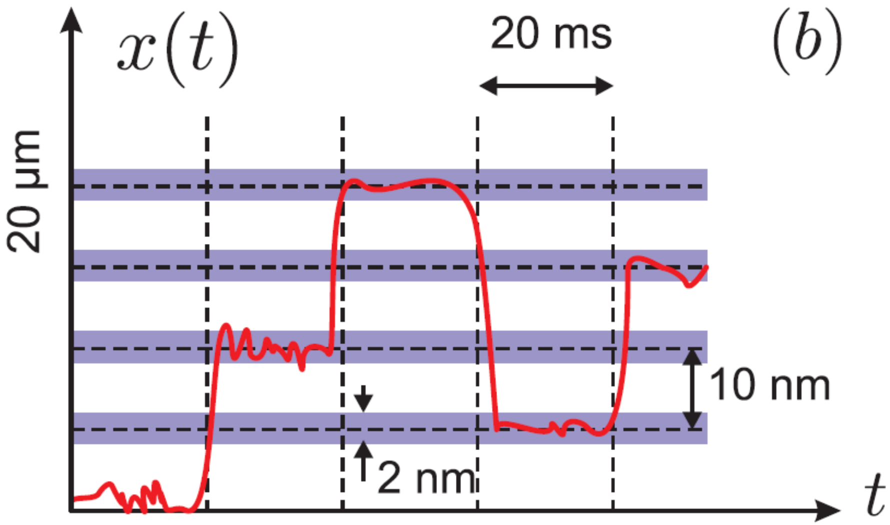
Frequency domain requirements
(stabilization)



(40 nm in lateral direction)

2000 quadrupoles/line

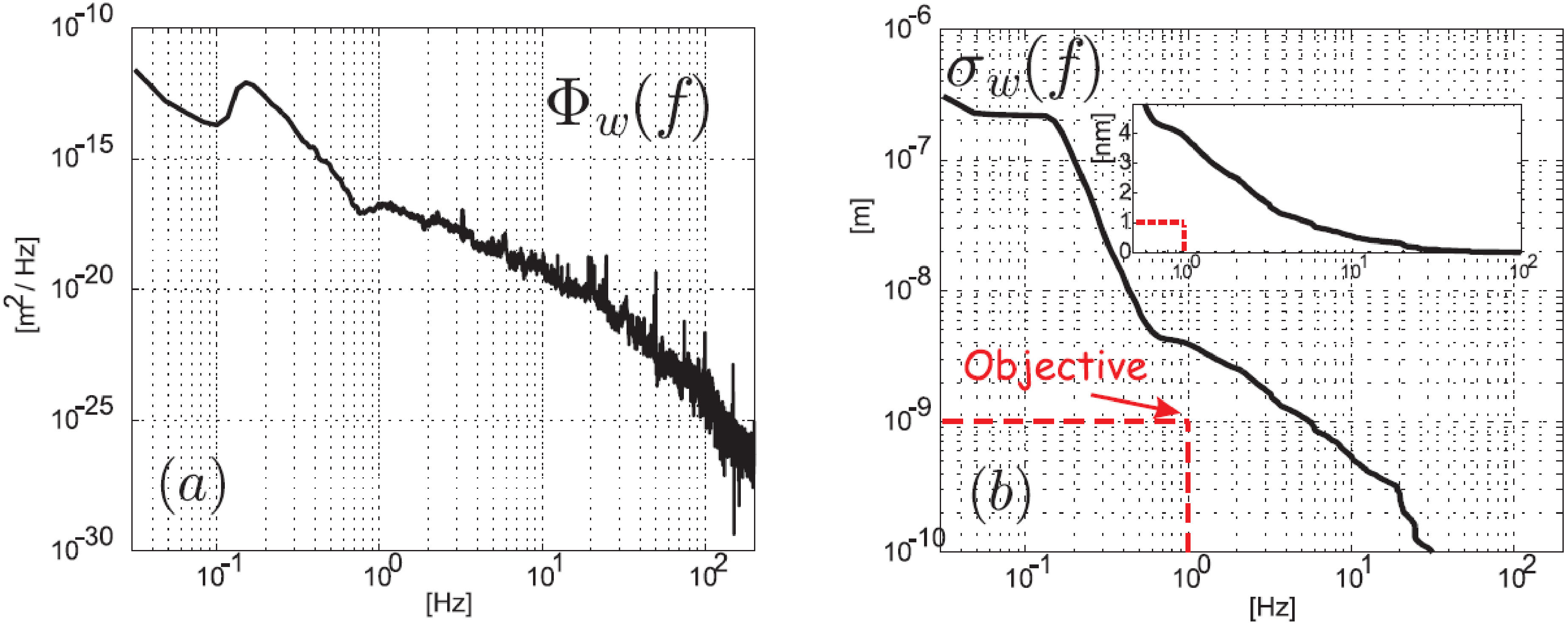
Time domain requirements
(positioning)



(5 d.o.f.)

80 quadrupoles/line

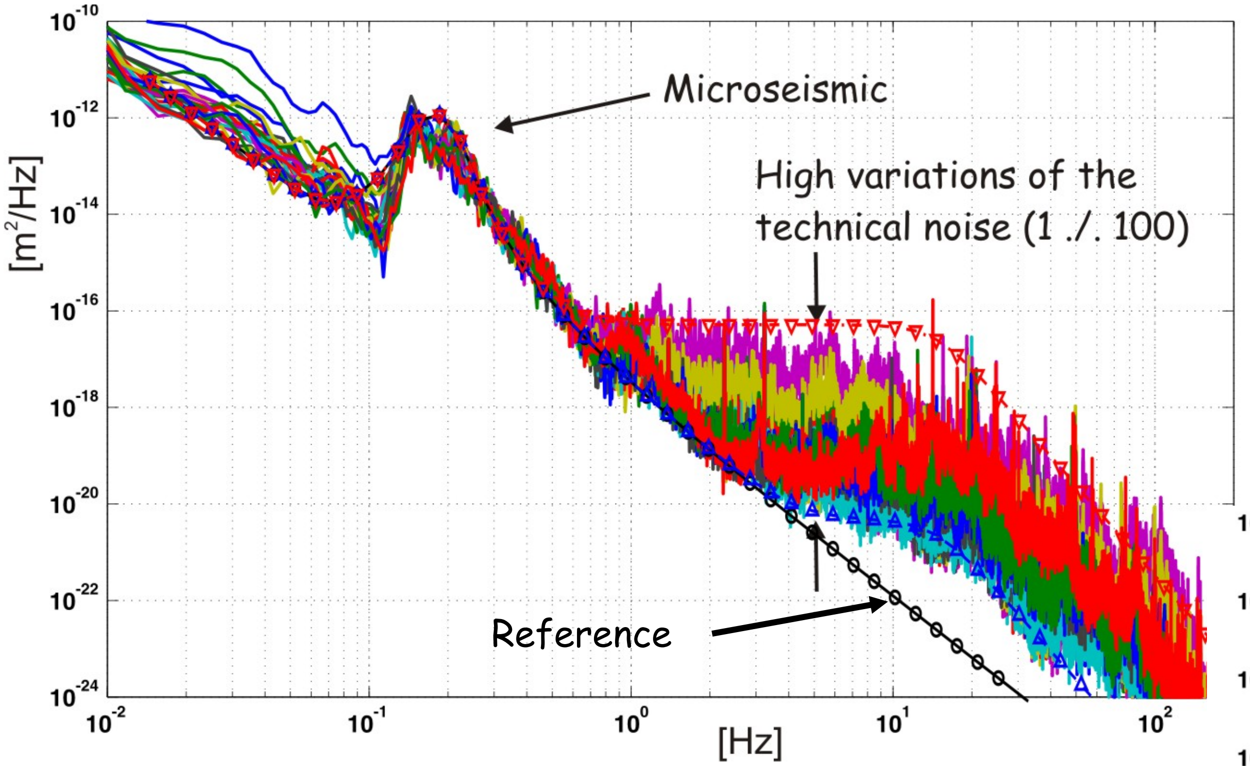
Typical ground motion



$$\sigma_x(1Hz)\ \ between\ \ 2\ \ and\ \ 20\ \ Hz$$

Local excitations

Vertical ground motion



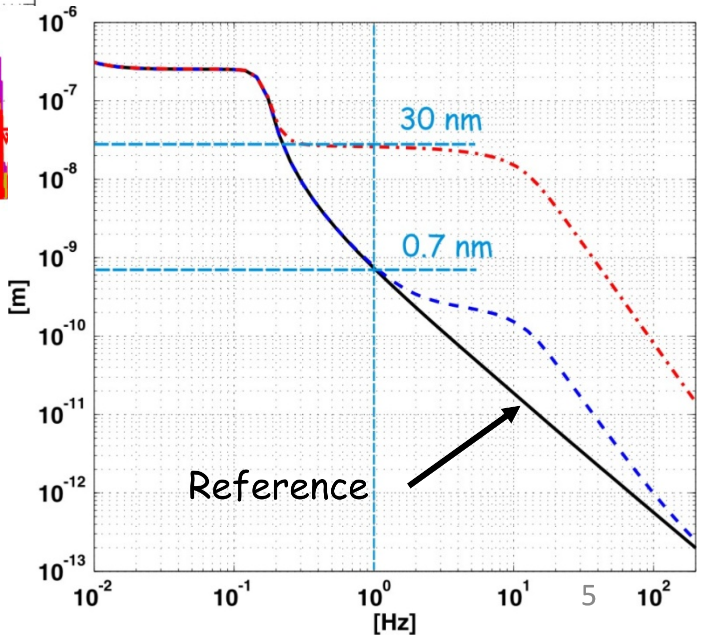
Additional technical noise:

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

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

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

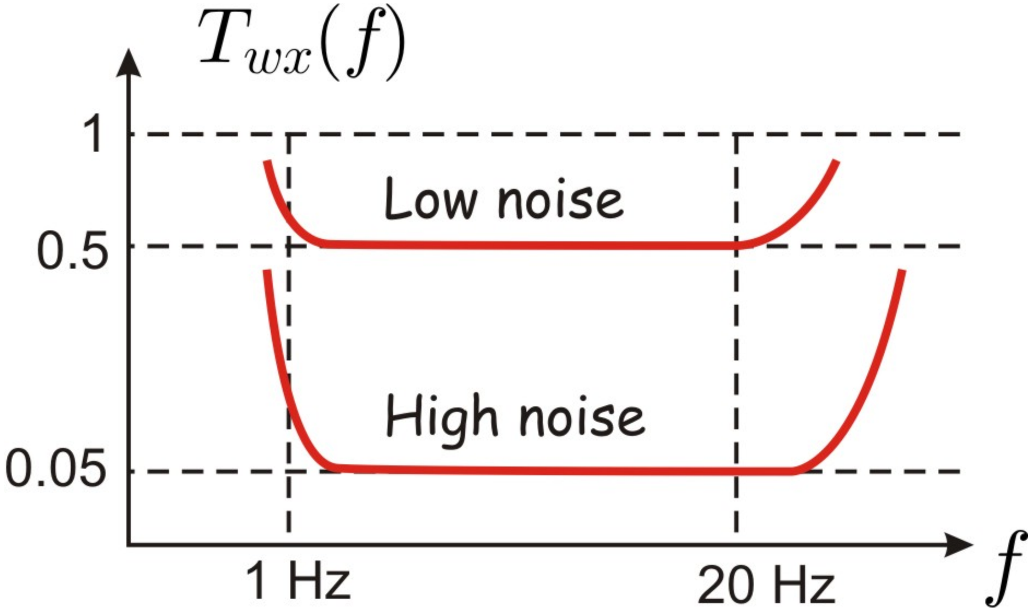
High technical noise: $N_0 = 50 (nm^2/Hz)$

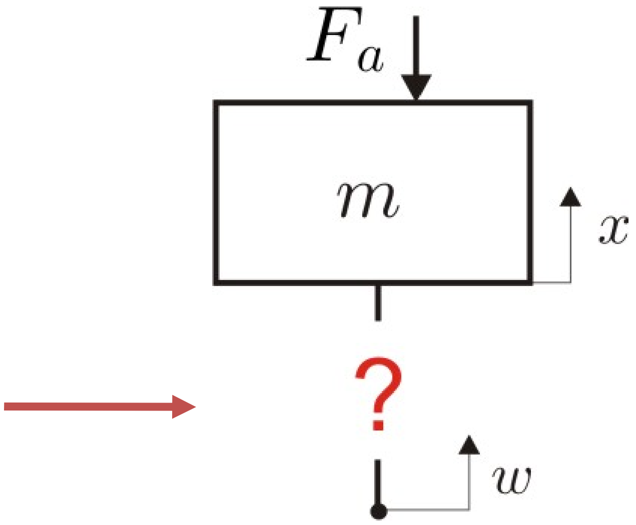


Ref.: $A = 10^{-4}\ (\mu m^2 s^{-1} m^{-1}); B = 10^{-4}\ (\mu m^2 s^{-3});$

$\omega_1 = 2\pi * 0.14\ (rad/s); d_1 = 5; a_1 = 0.1\ (\mu m^2/Hz); v_1 = 1000\ (m/s)$

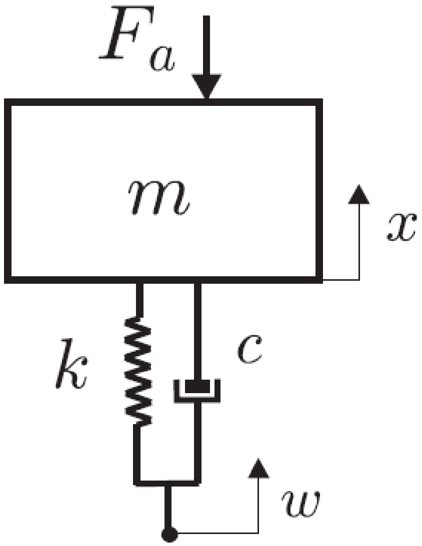
How to support the quadrupoles ?

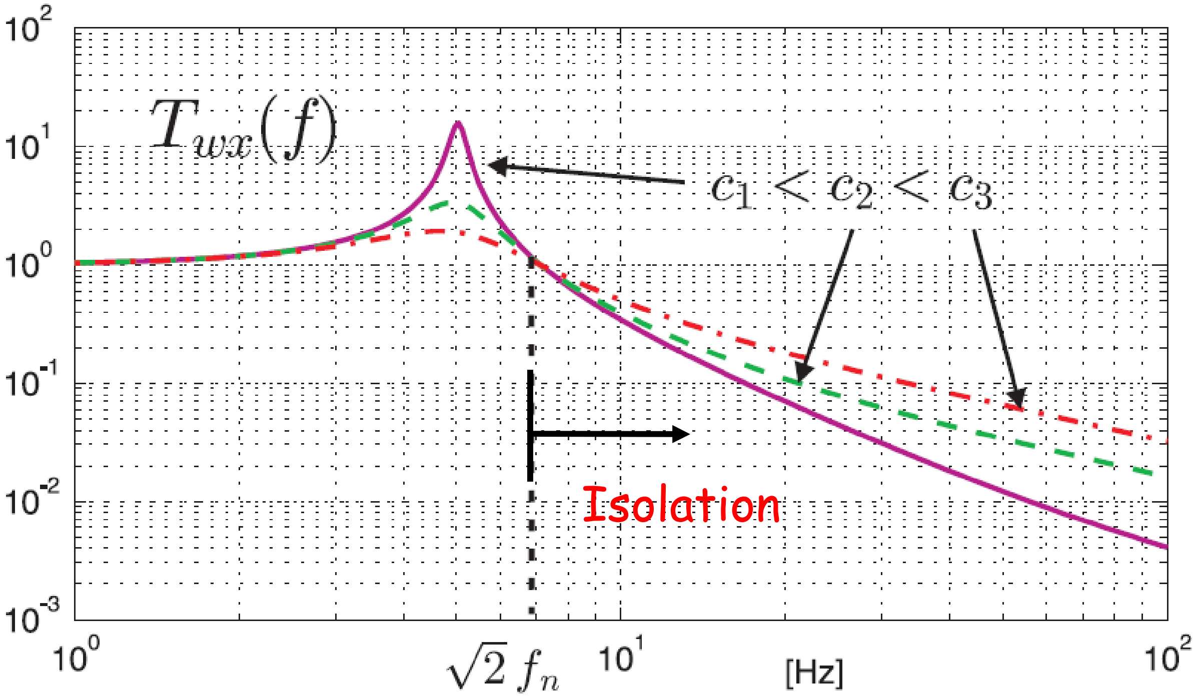




Which type of support can fulfill the requirements:
passive, semi-active or active ?

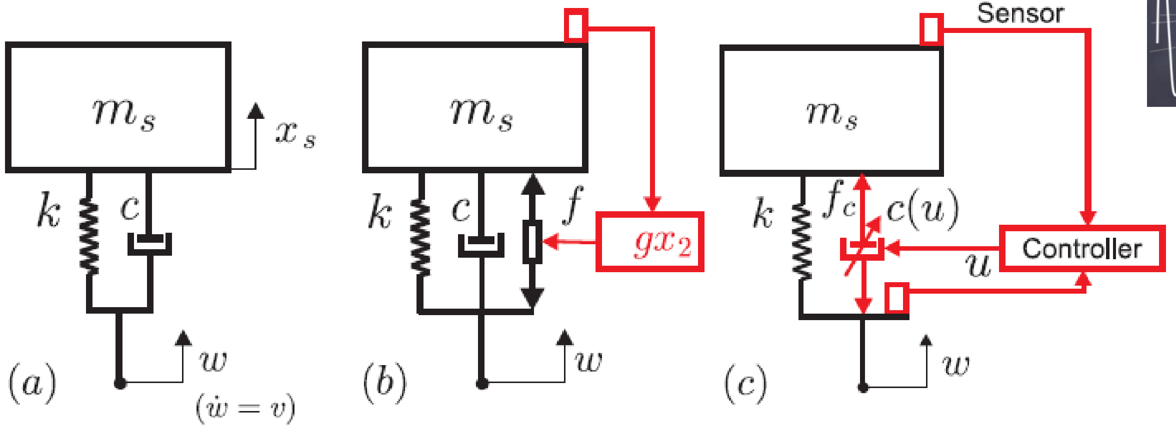
2. Increase the damping

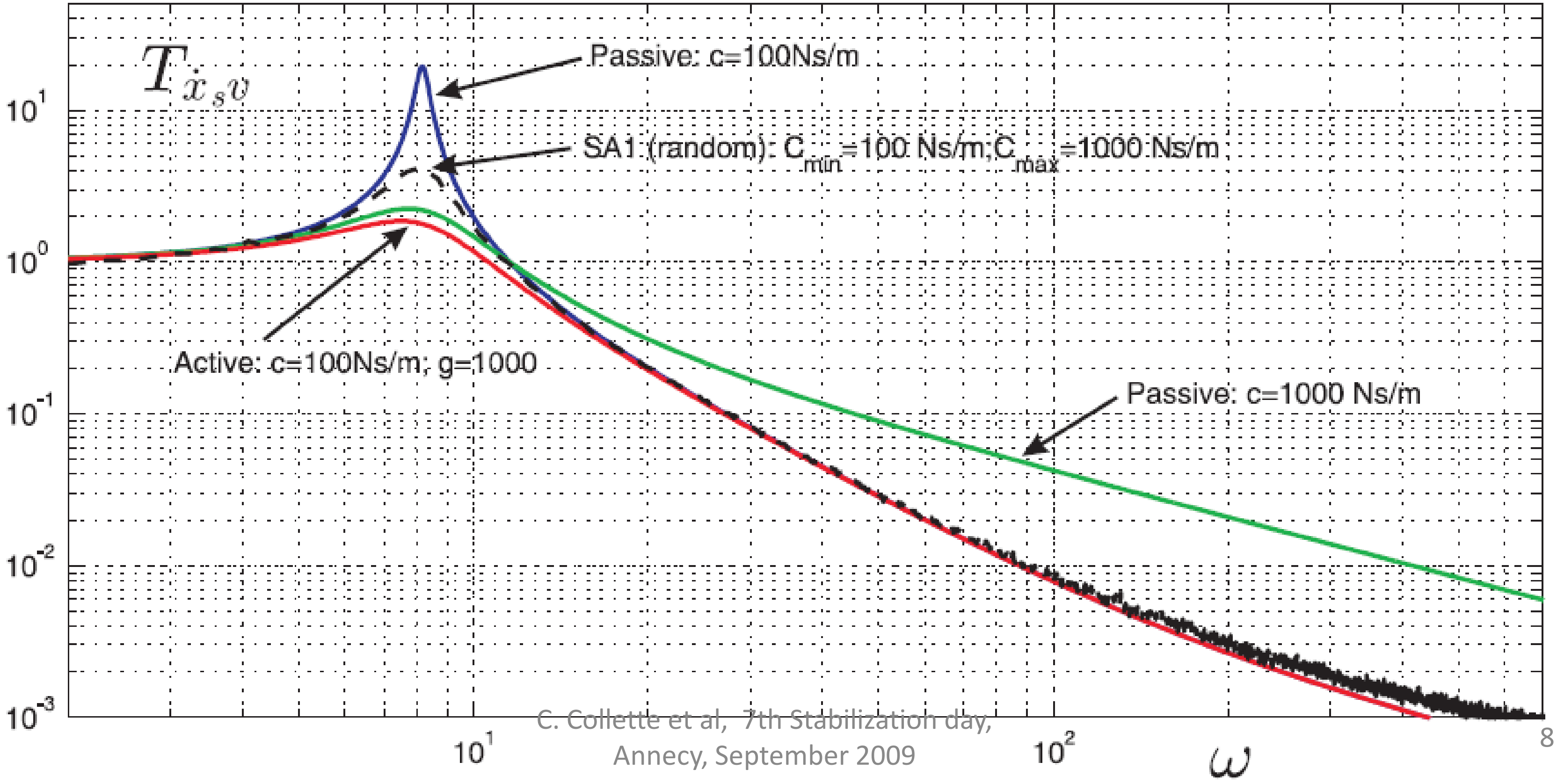




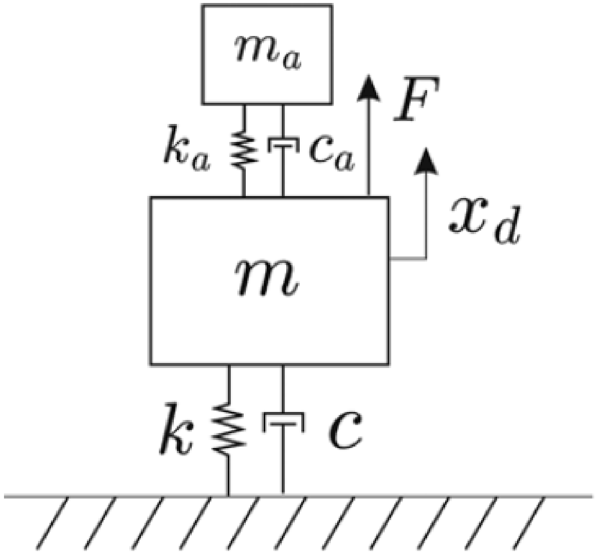
Reduces the overshsoot but degrades the isolation at high frequency

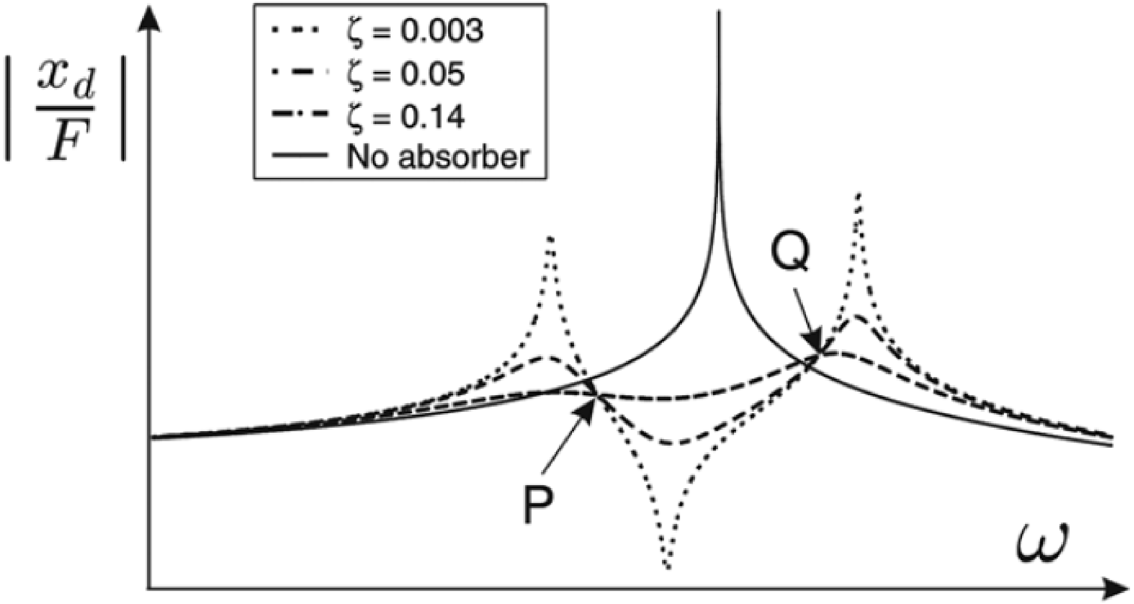
Sky-hook isolator



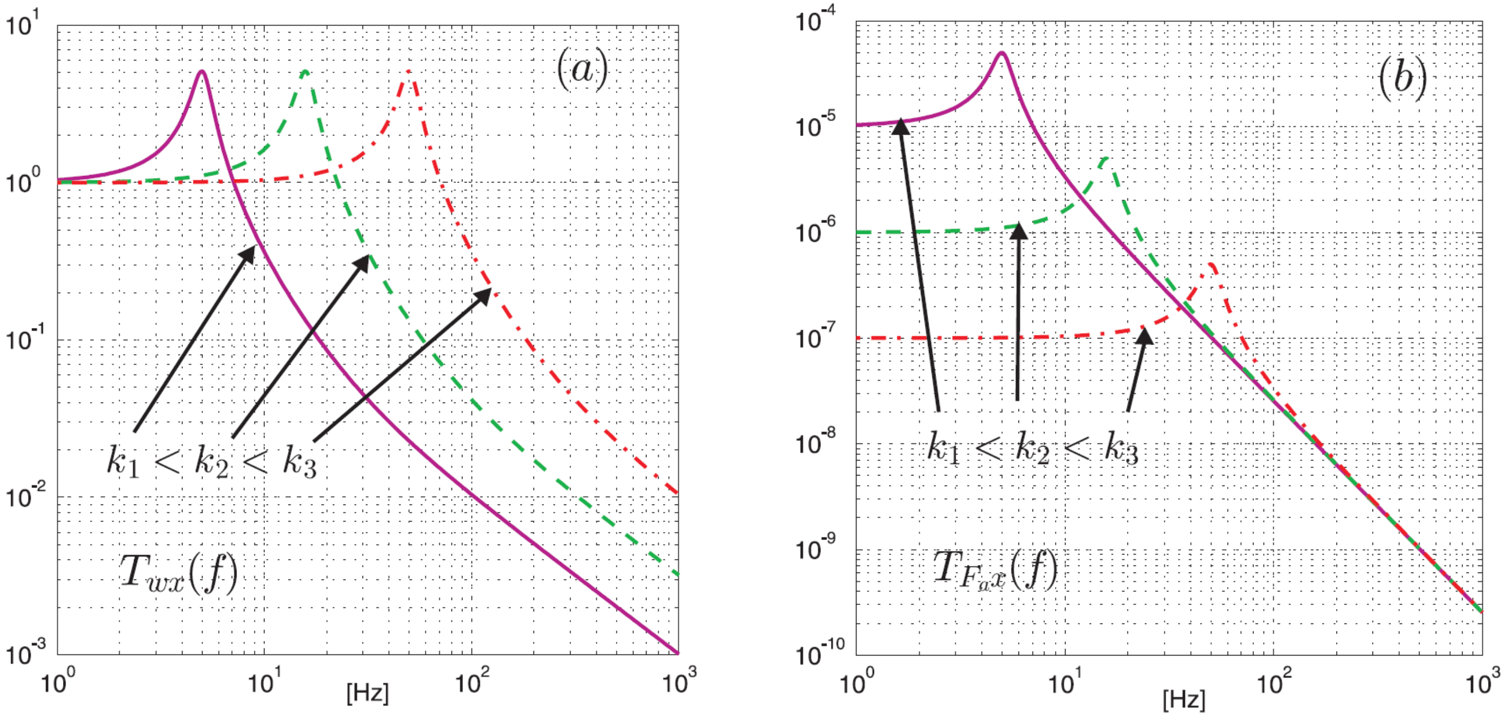


Dynamic vibration absorber





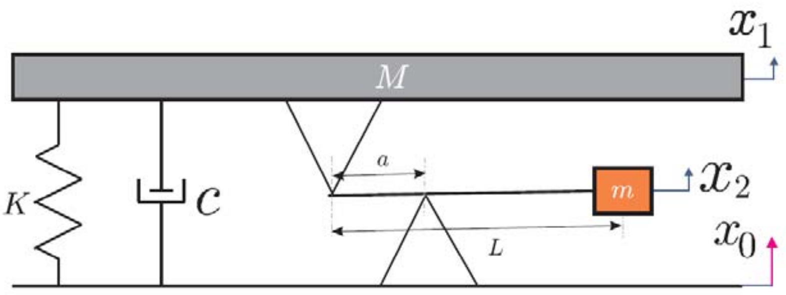
Change the stiffness

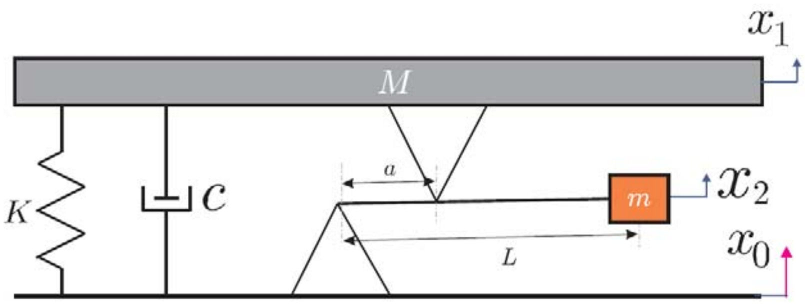


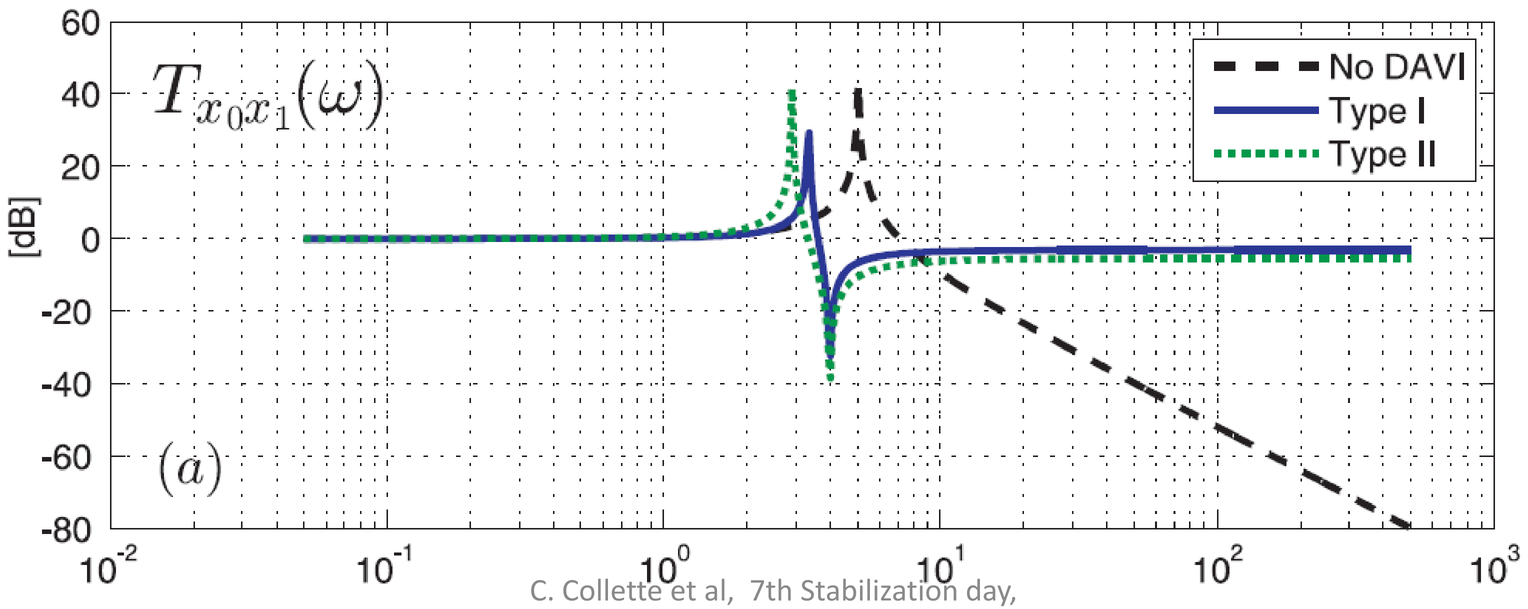
A soft support improves the isolation but :

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

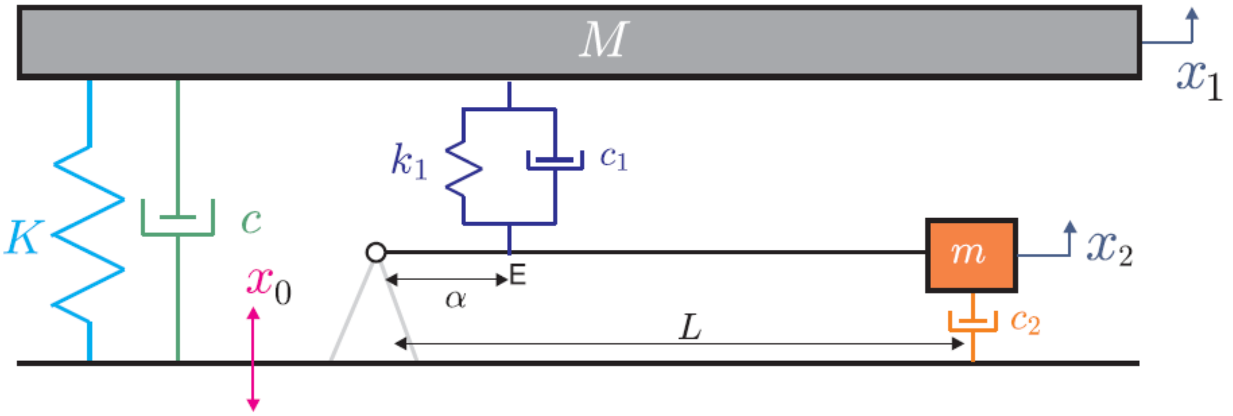
Dynamic anti-resonant Vibration Isolator

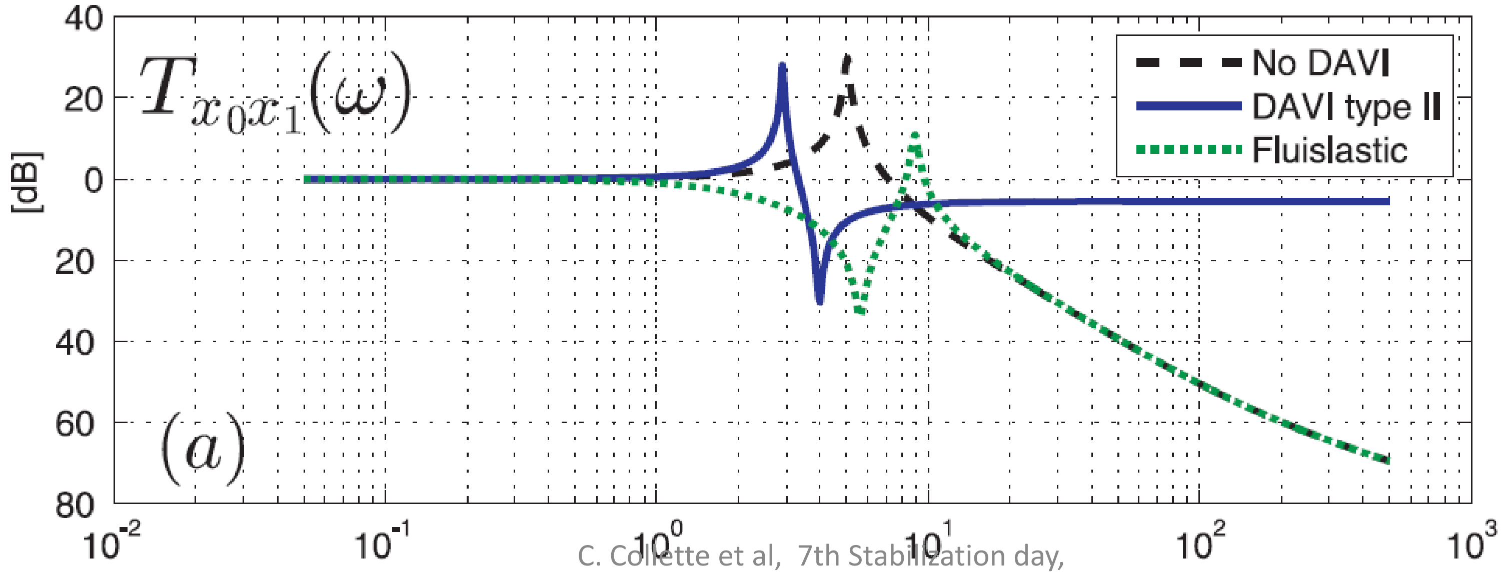




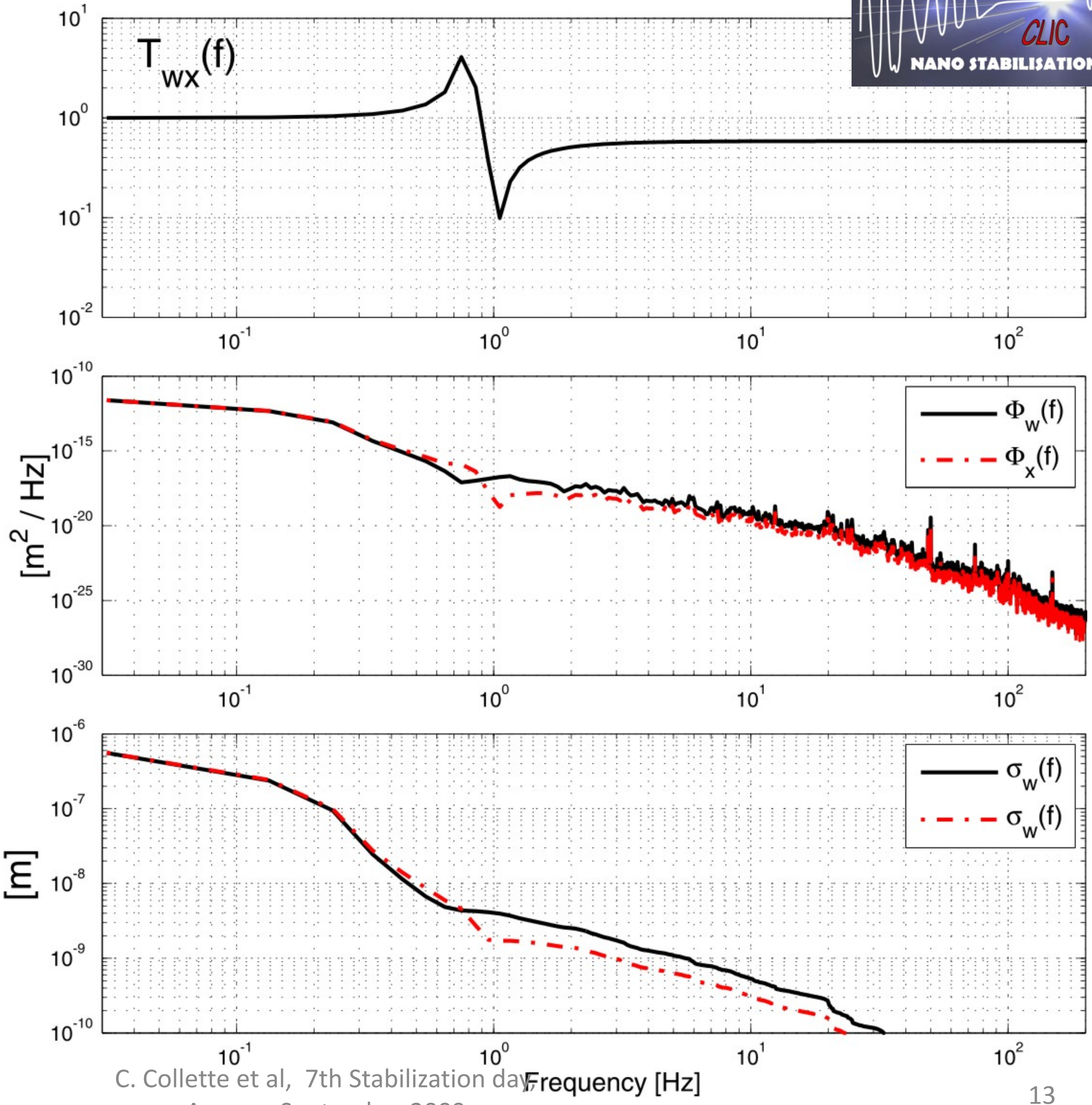


Fluidlastic Isolator





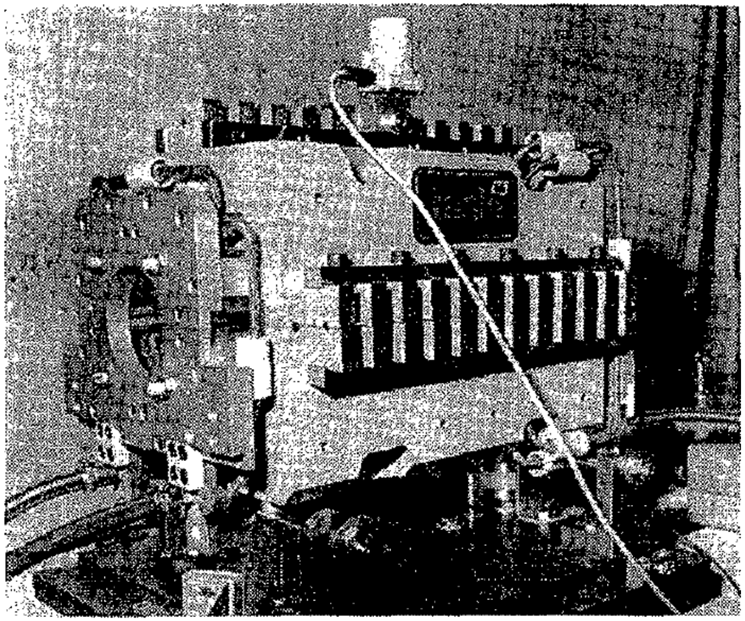
Application of DAVI type 1

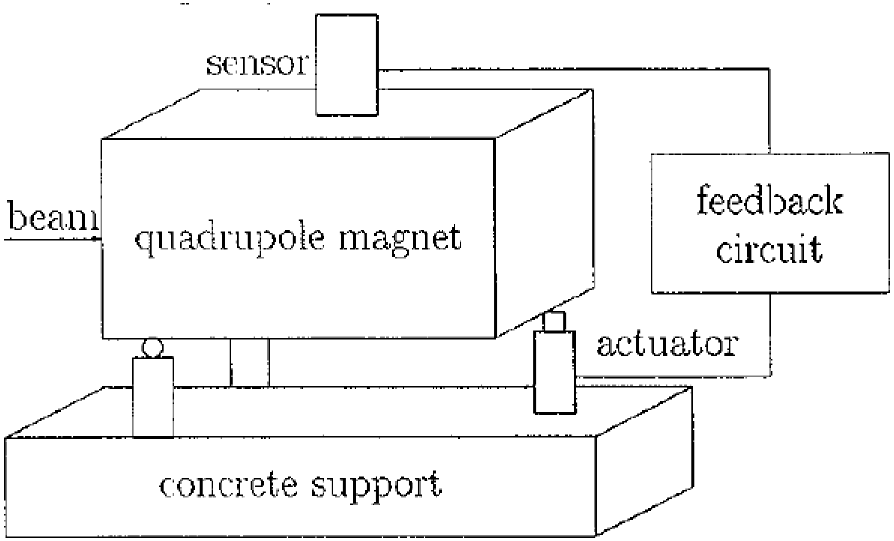


Performances are good but :
- Not controllable
- Practical application to the quadrupole is not straightforward (backash, friction, lateral stability…)

Previous experiment n°1

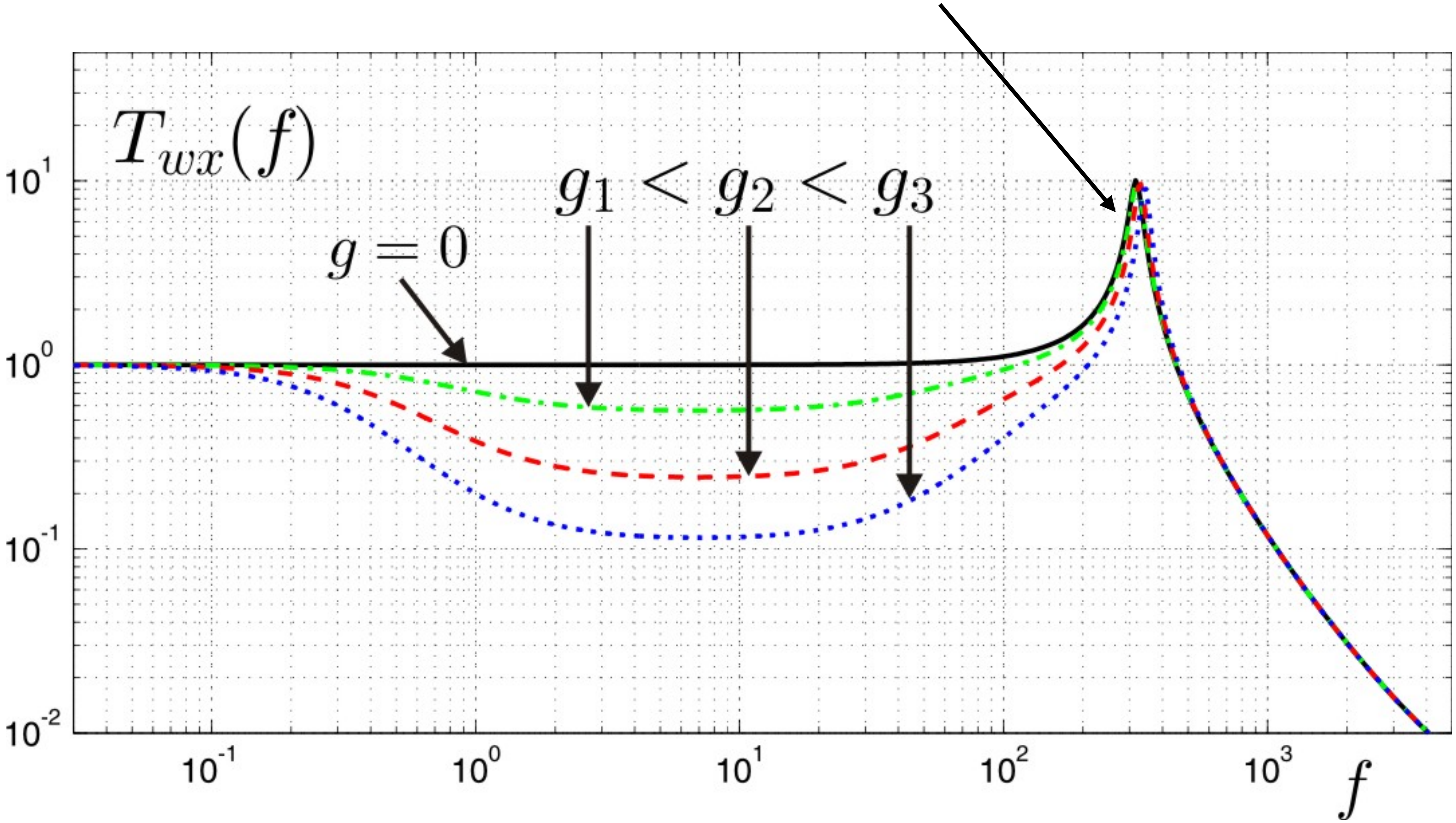
- C. Montag (1996, DESY)





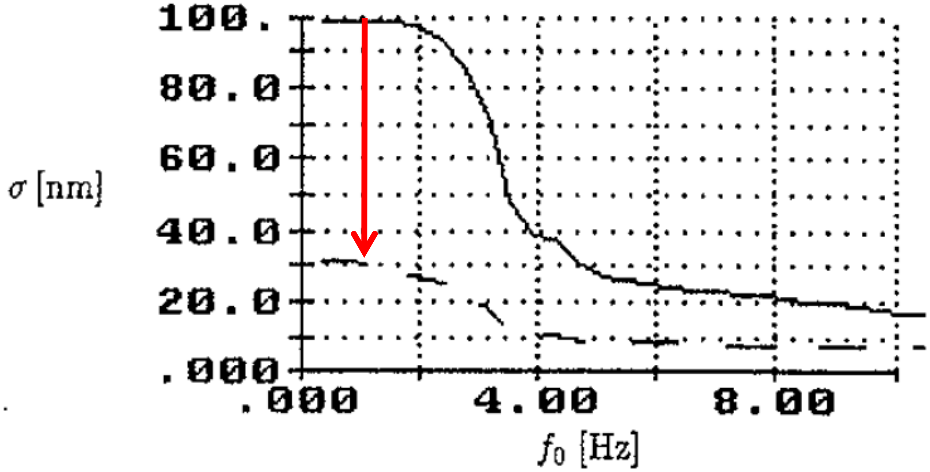
Control strategy

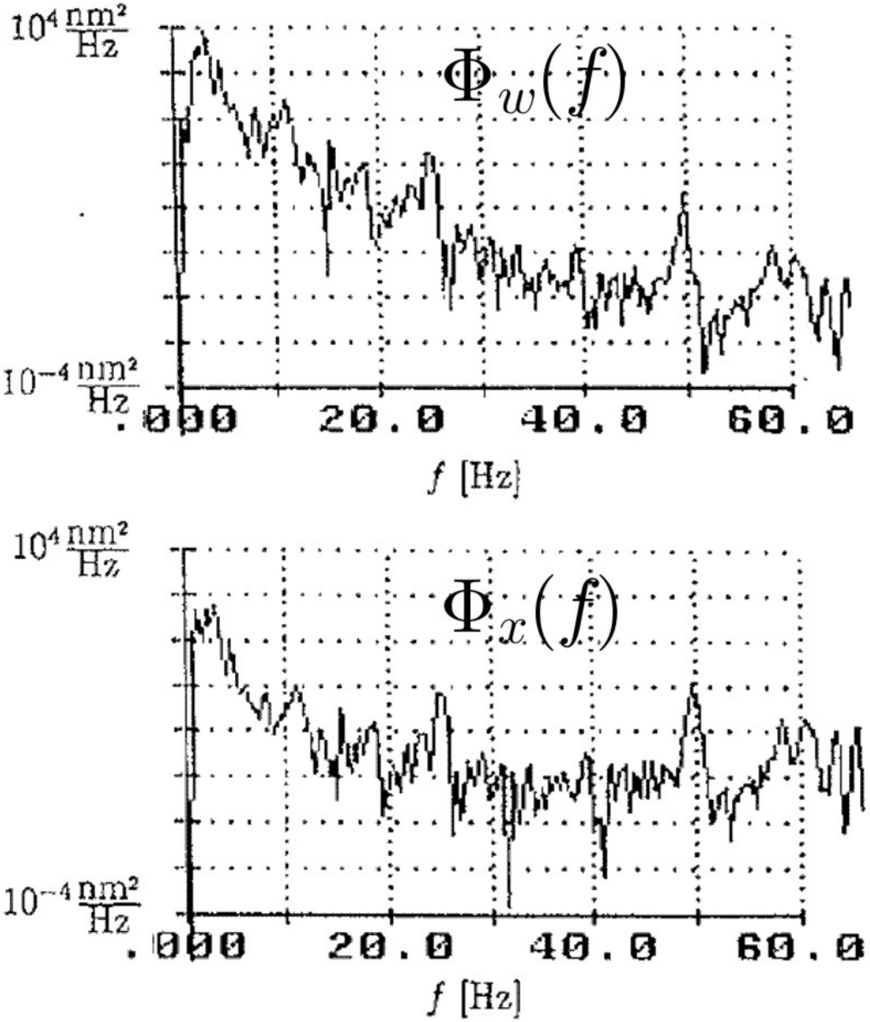
The damping factor is not important in this case



Experimental results

C. Montag (1996, DESY)

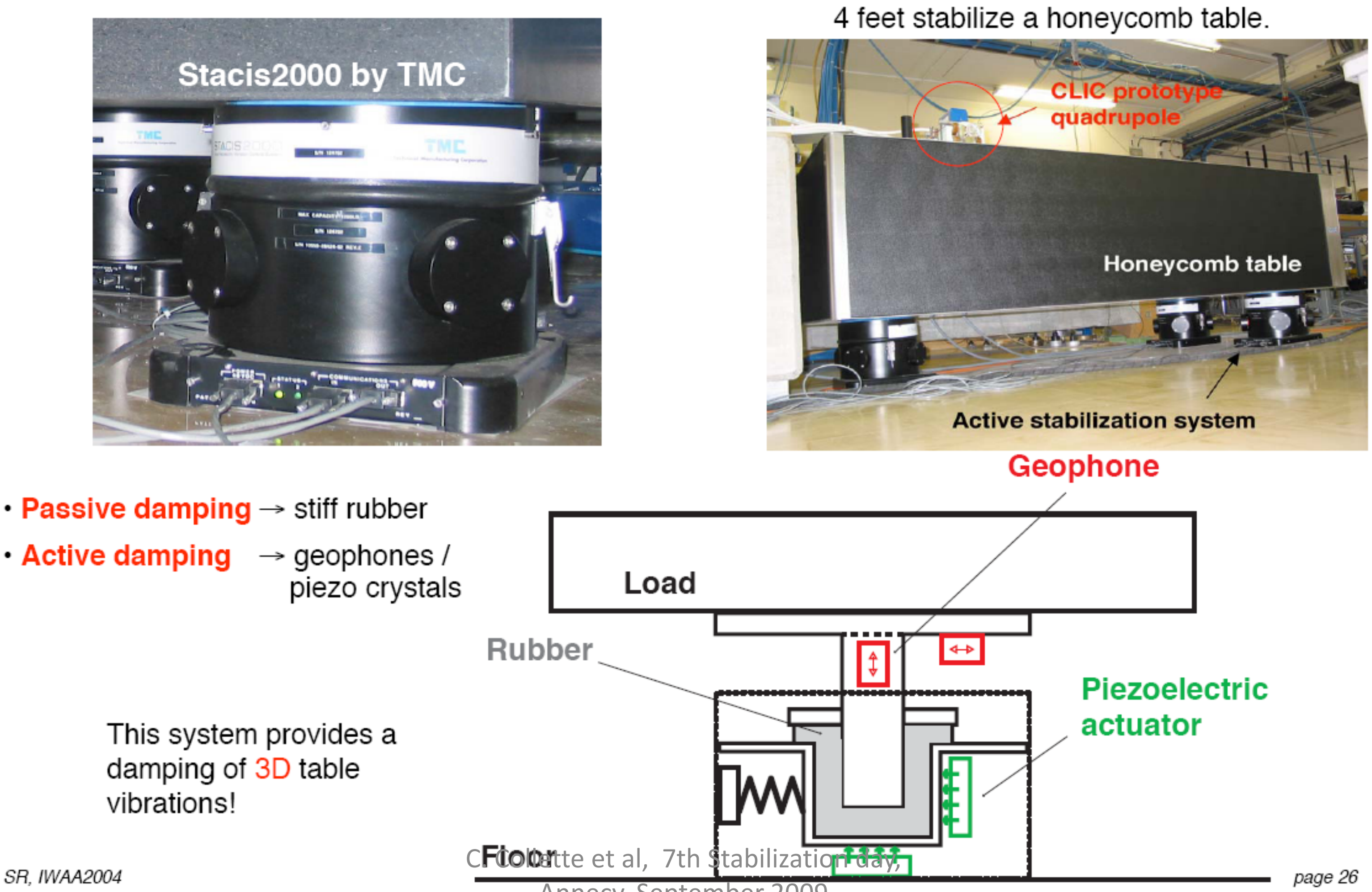




Reduction of the RMS integrated by a factor 3

Previous experiment n°2

- S. Redaelli (CERN, 2004)



4 feet stabilize a honeycomb table.

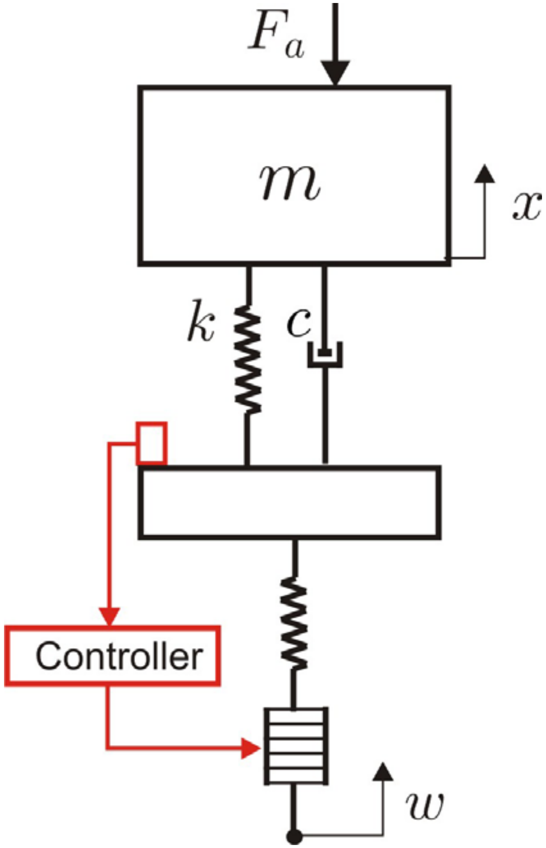
- **Passive damping** → stiff rubber
- **Active damping** → geophones / piezo crystals

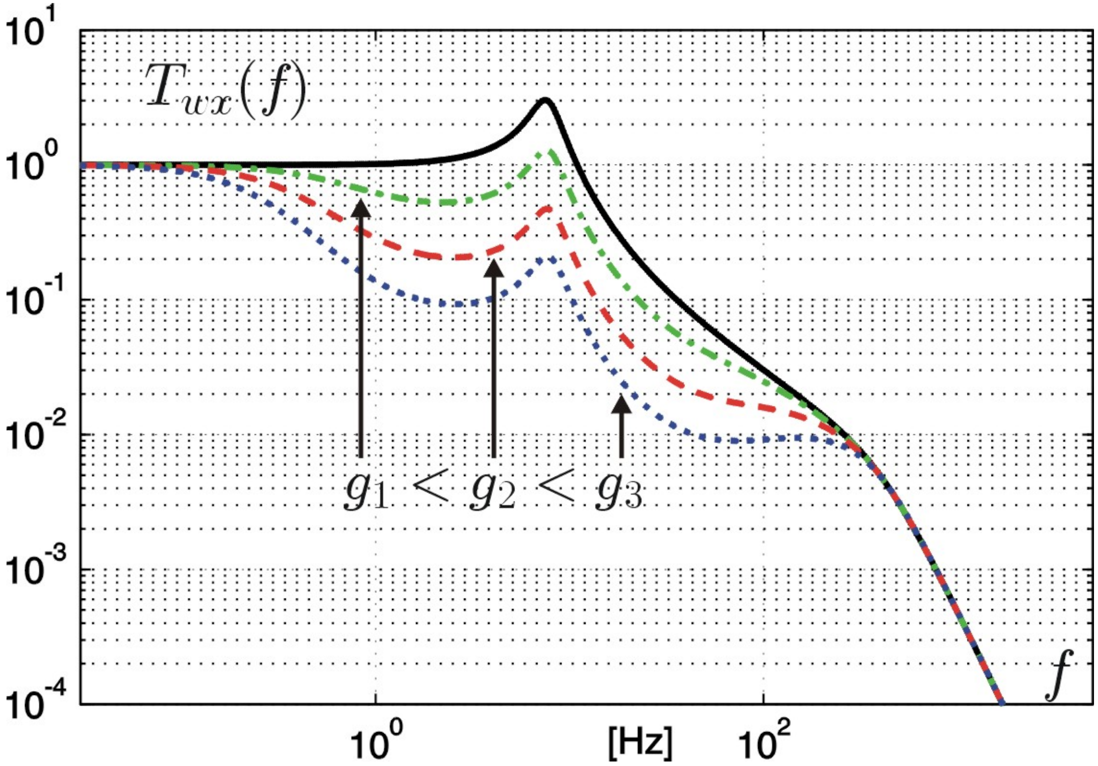
This system provides a damping of 3D table vibrations!

SR, IWAA2004

page 26

Control strategy

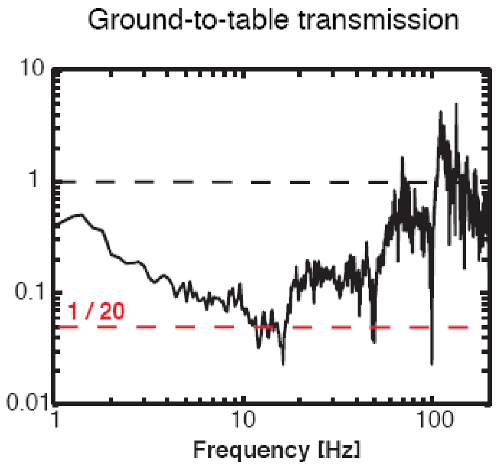




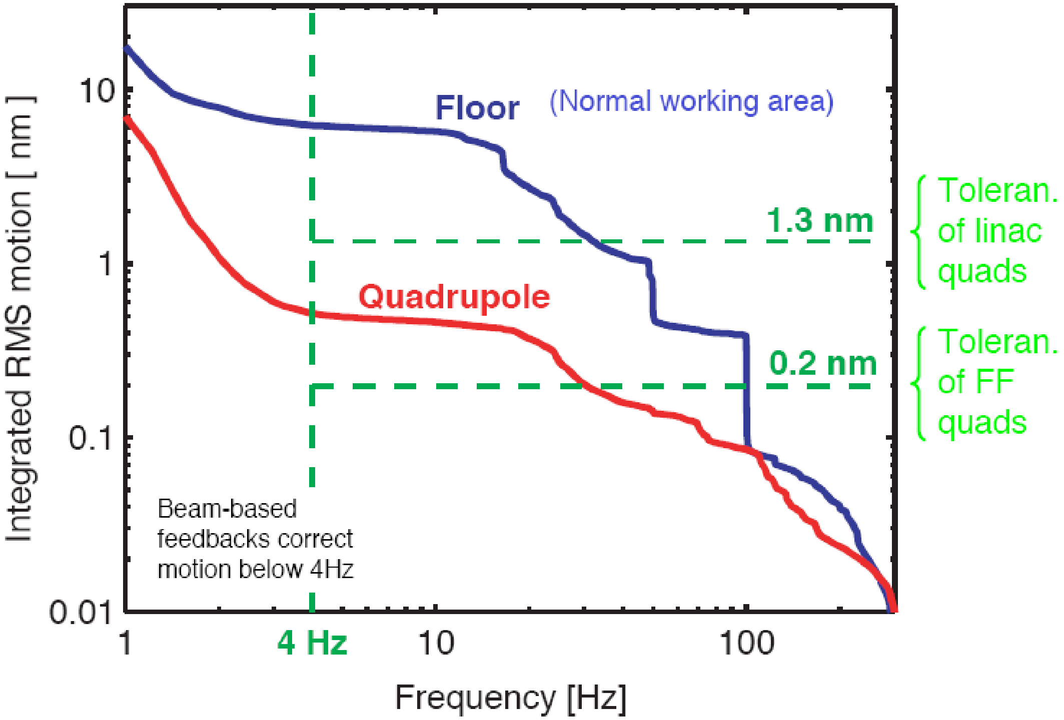
C. Collette et al, 7th Stabilization day,
Annecy, September 2009

Experimental results

S. Redaelli (CERN, 2004)


Ground-to-table transmission

Integrated *vertical* RMS motion versus frequency

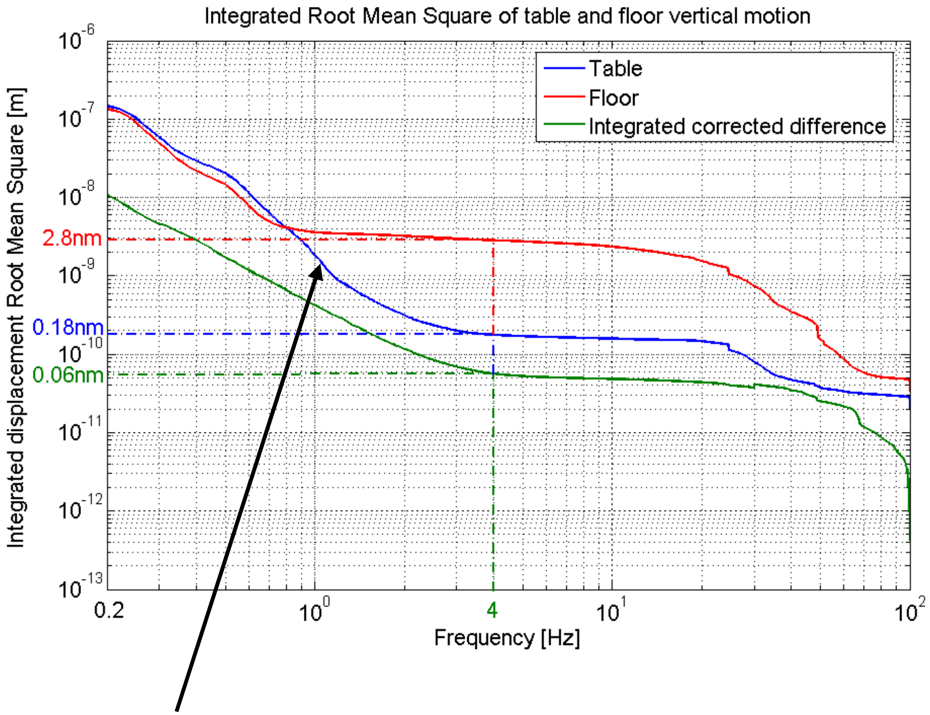


CLIC prototype magnets stabilized to the sub-nanometre level !!

Above 4Hz: **0.43 nm** on the quadrupole instead of **6.20 nm** on the ground.

Experimental results

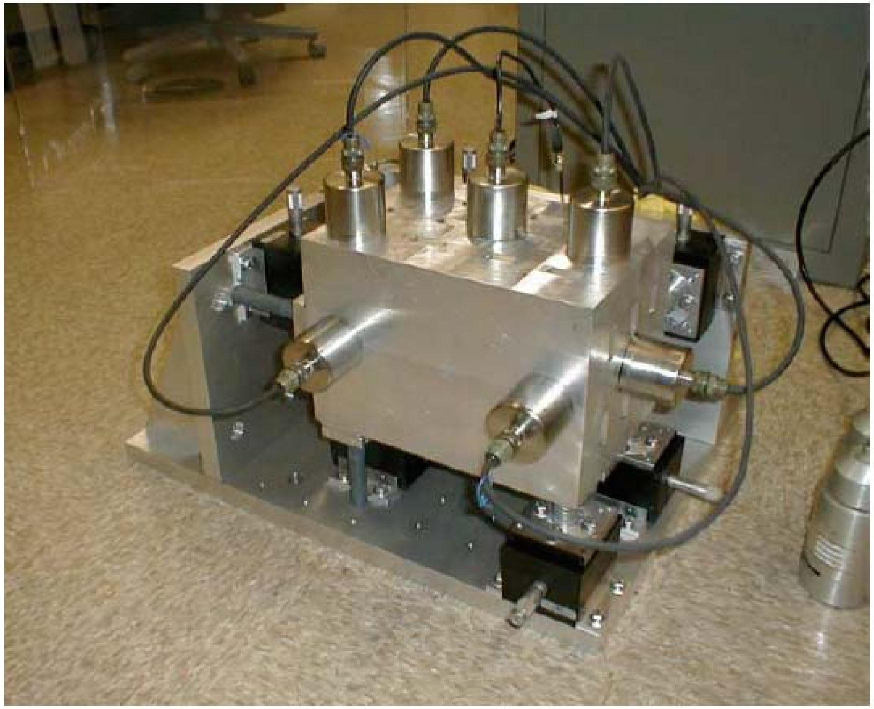
- Bolzon (LAPP,2007)



(2 nm à 1 Hz)

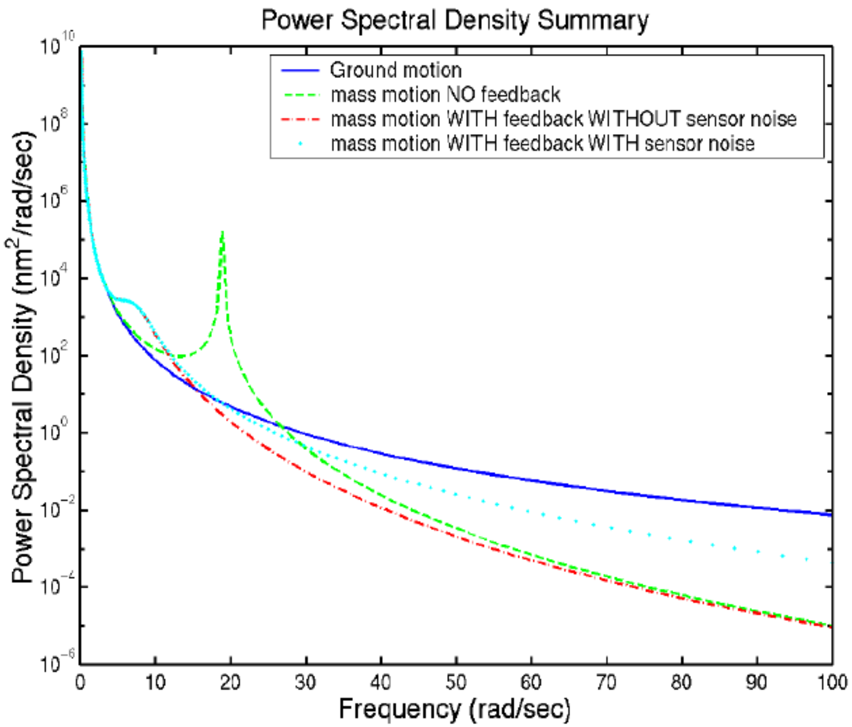
Previous experiment n°3

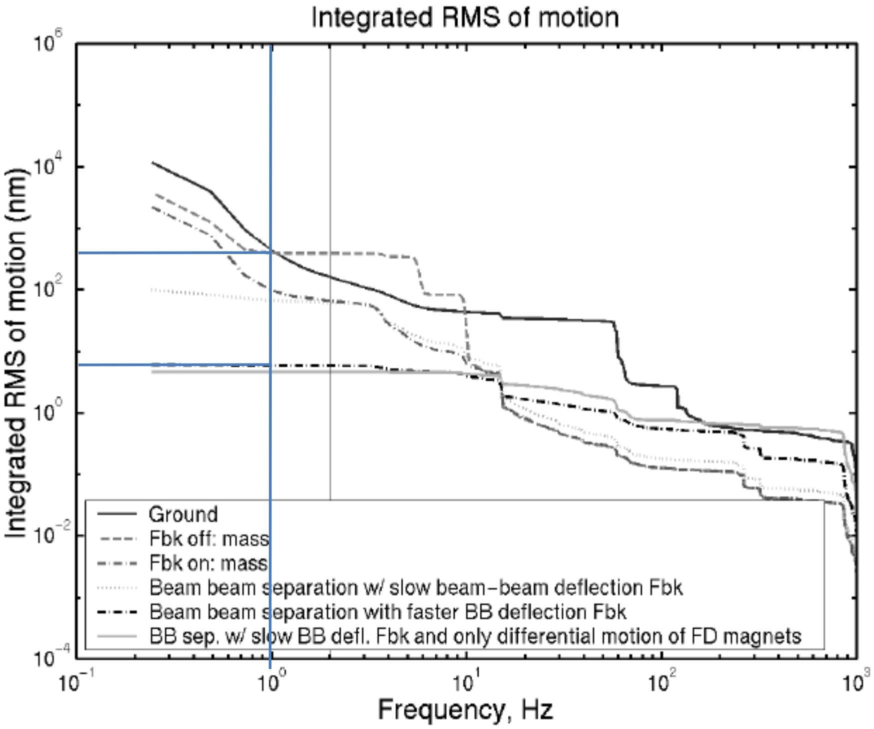
- SLAC (2002)



Experimental results

SLAC (2002)





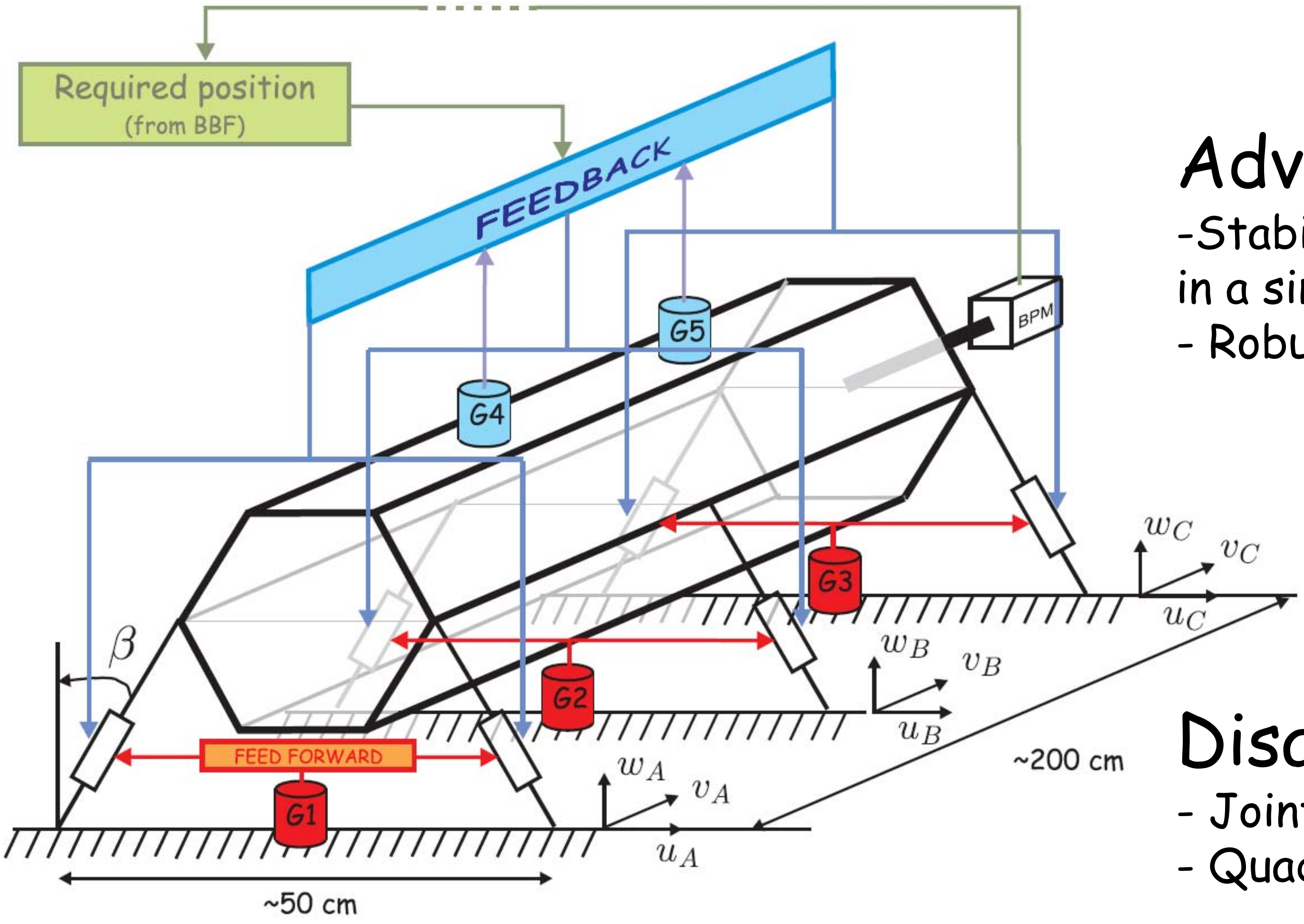
Summary

	DESY, 1996	CERN, 2004	LAPP, 2007	SLAC, 2002
Experiment description	1 d.o.f	1 d.o.f	1 d.o.f	6 d.o.f, 42 kg
Actuator	Piezo	Piezo	Piezo	Electrostatic
Control strategy	FB	TMC	TMC	FB
Positioning	NO	NO	NO	NO
Rigidity	Stiff	Soft	Soft	Soft
(RMSw/RMSx)@1Hz	~3	~3	~2	~50
Stages	1	2	2	1

Comparison

	DESY	TMC (CERN &LAPP)	SLAC
Advantages	- Not sensitive to extenral force - Positioning capabilities - Single stage	- Isolation in a broad frequency range	- High isolation performances
Disadvantages	- Isolation in a smaller frequency range	- Sensitive to external force - No positioning capabilities - Multi-stage	-Sensitive to external force - No positioning capabilities - Complicated for M.d.o.f - not commercial

3. Hexapod concept



Advantages:

-Stabilization & Positioning in a single stage

- Robust to external forces

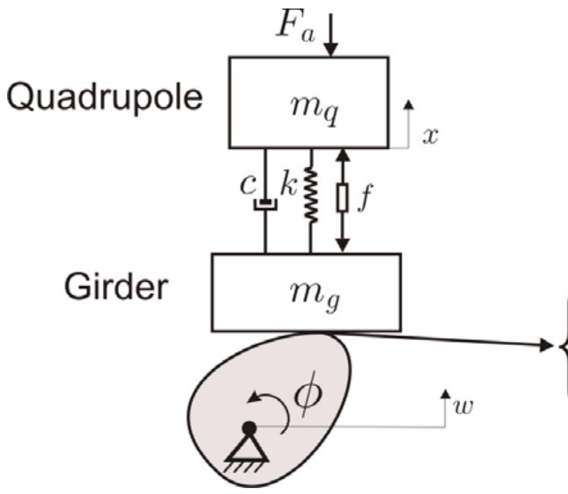
Disadvantages:

- Jointure issues
- Quadrupole flexibility

Issues addressed

a) Compatibility with alignment
b) Quadruple flexibility
c) Sensor noise
d) Choice of the actuator
e) Jointure design

a) Compatibility with alignment



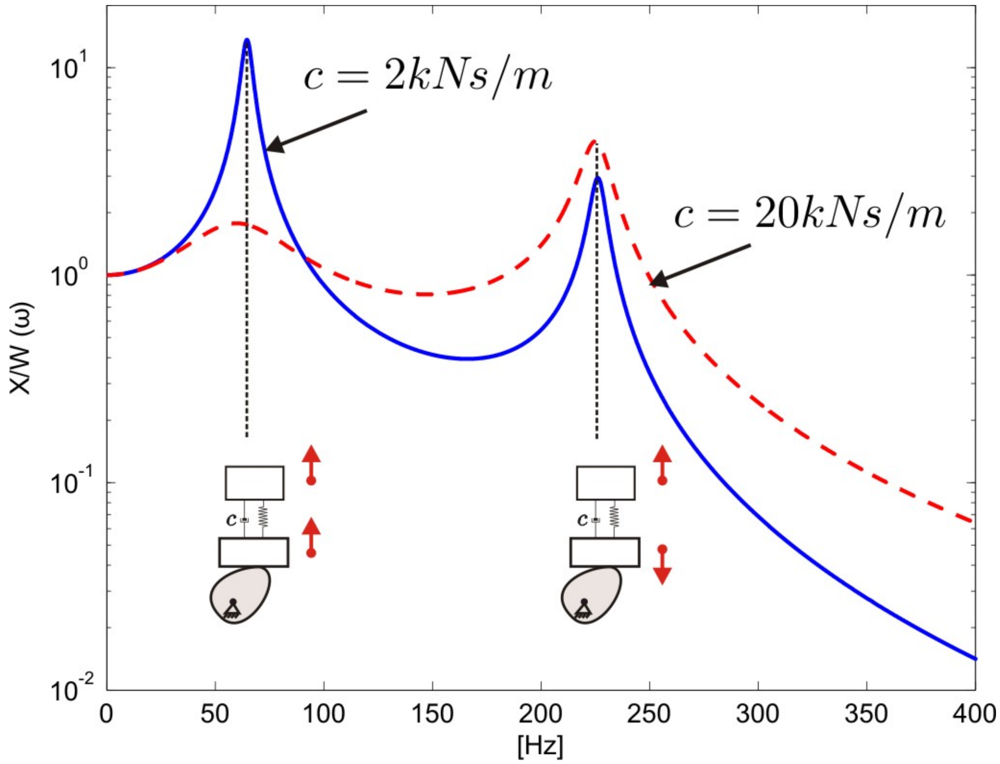
$m_q = 60\ Kg$

$m_g = 500\ Kg$

$k = 10\ MN/m$

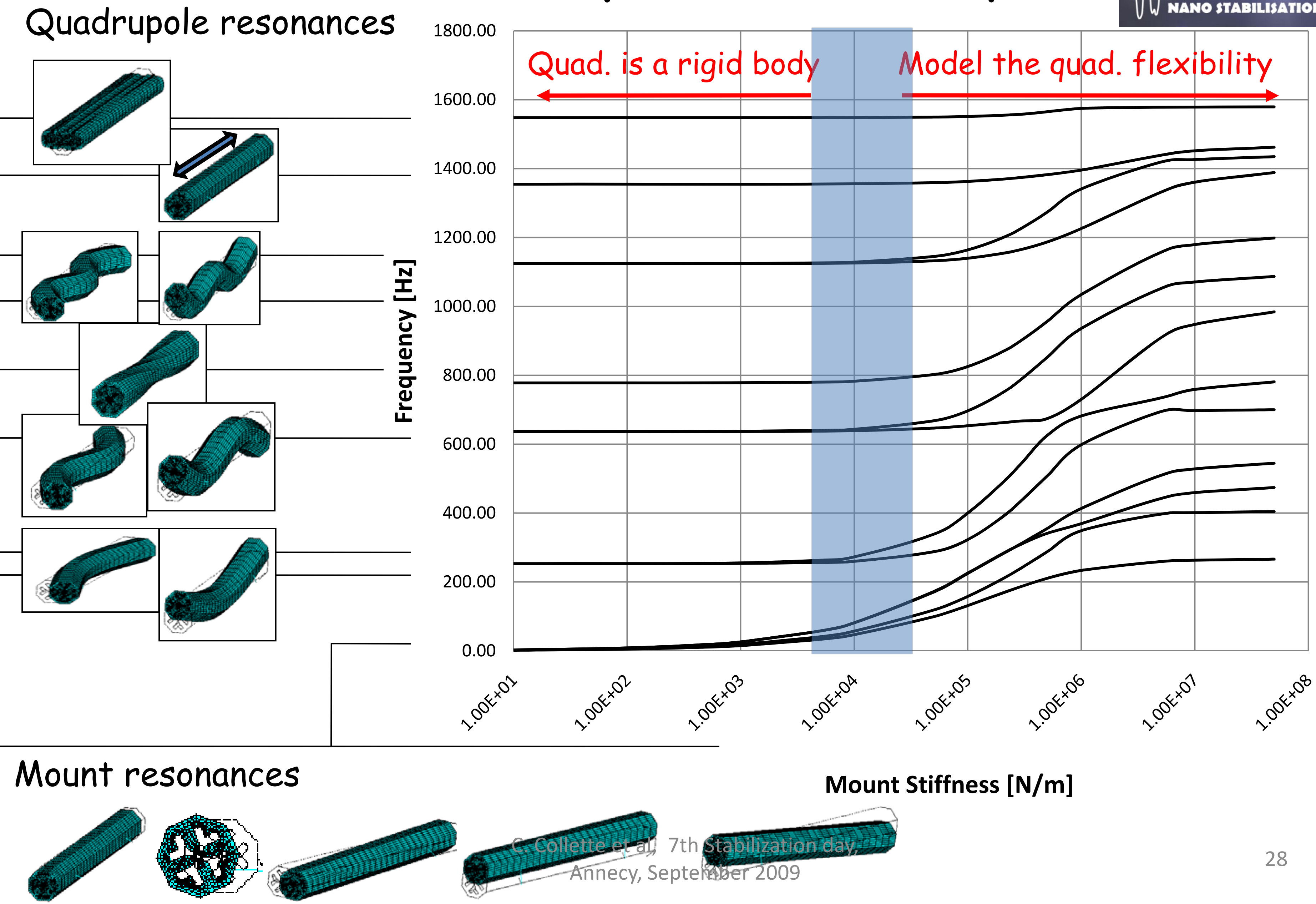
$c = 2\ kNs/m$

$$\begin{cases} k_g = 1\ GN/m \\ c_g = 20\ kNs/m \end{cases}$$

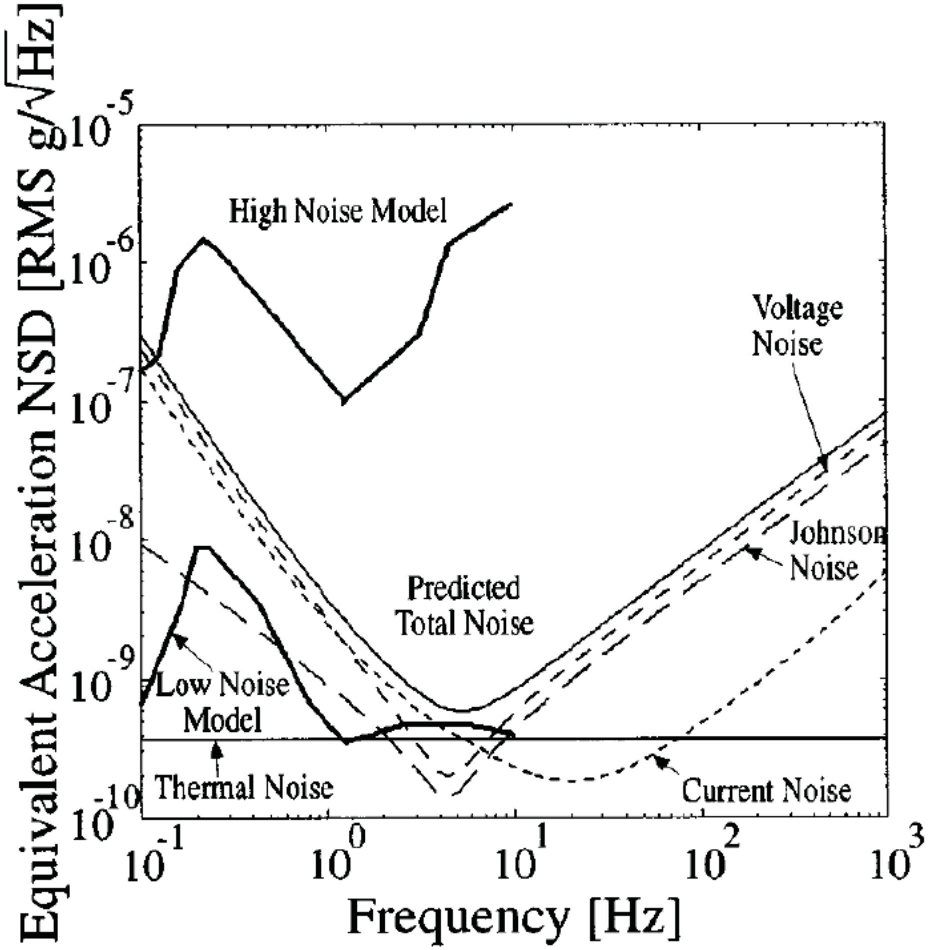


The alignment stage should be as stiff as possible to avoid any dynamic amplification between 1 and 80 Hz

b) Quadrupole flexibility



c) Sensor noise sources



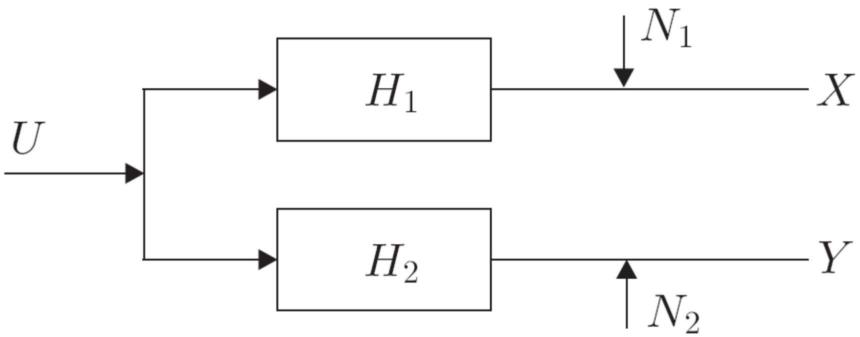
A. Bertolini et al. *Review of scientific instruments, 69:2767-2772, 1998.*

⇨ We need a technique to evaluate the overall measurement noise

Sensor noise detection

C. Montag. *PhD thesis, Hamburg University, 1996.*

Two geophones side by side:



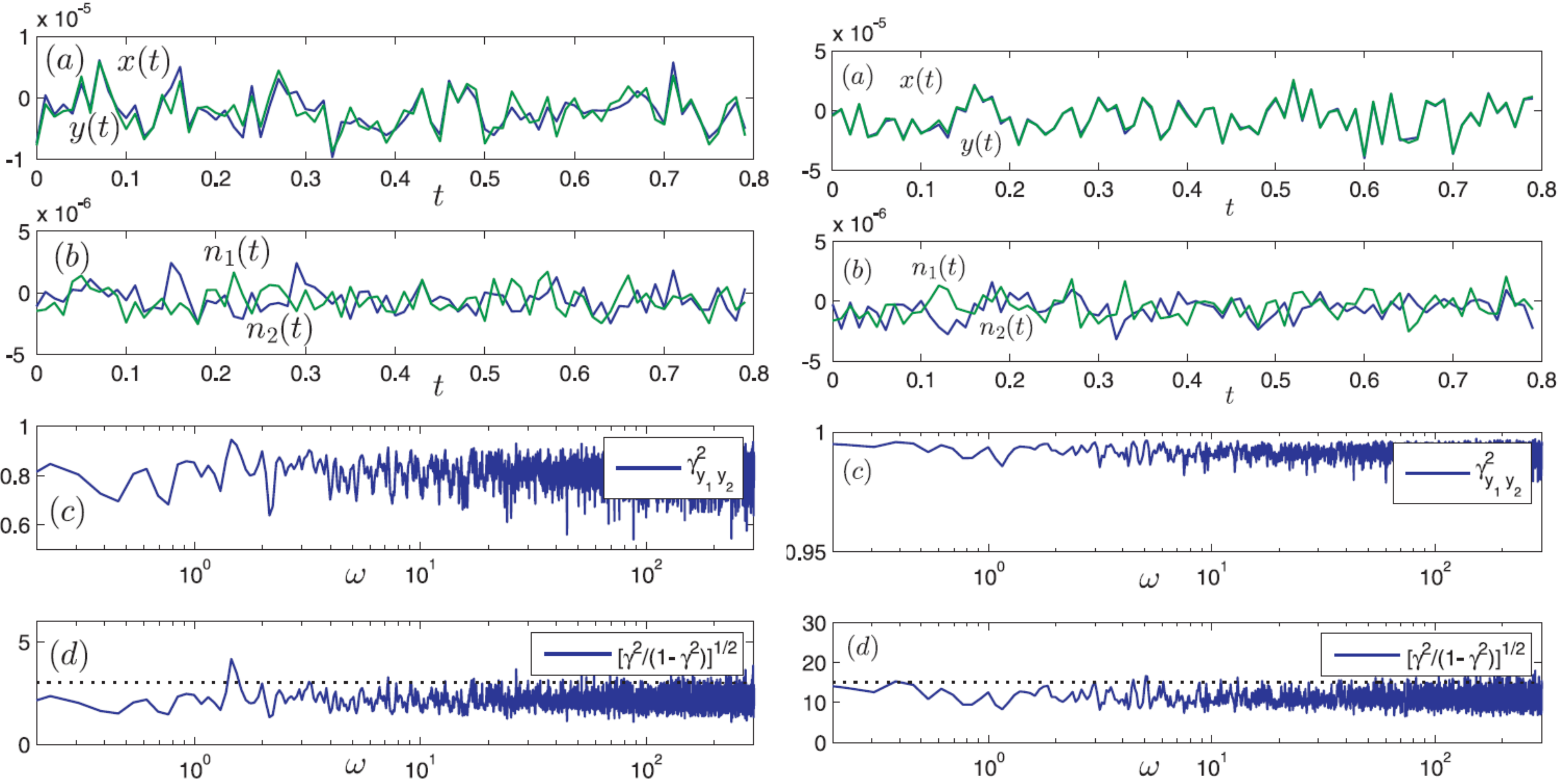
$$\begin{cases} X(\omega) = H_1(\omega)U(\omega) + N_1(\omega) \\ Y(\omega) = H_2(\omega)U(\omega) + N_2(\omega) \end{cases}$$

$$\begin{cases} \Phi_{ss} = H^2\Phi_{xx} \\ \Phi_{nn} = \Phi_{yy} - H^2\Phi_{xx} \end{cases} \Rightarrow \begin{cases} \sigma_s(\omega) = [\int_\omega^\infty \Phi_{ss}(\nu)d\nu]^{1/2} \\ \sigma_n(\omega) = [\int_\omega^\infty \Phi_{nn}(\nu)d\nu]^{1/2} \end{cases}$$

where $H(\omega) = \dfrac{\Phi_{xy}}{\Phi_{xx}}$

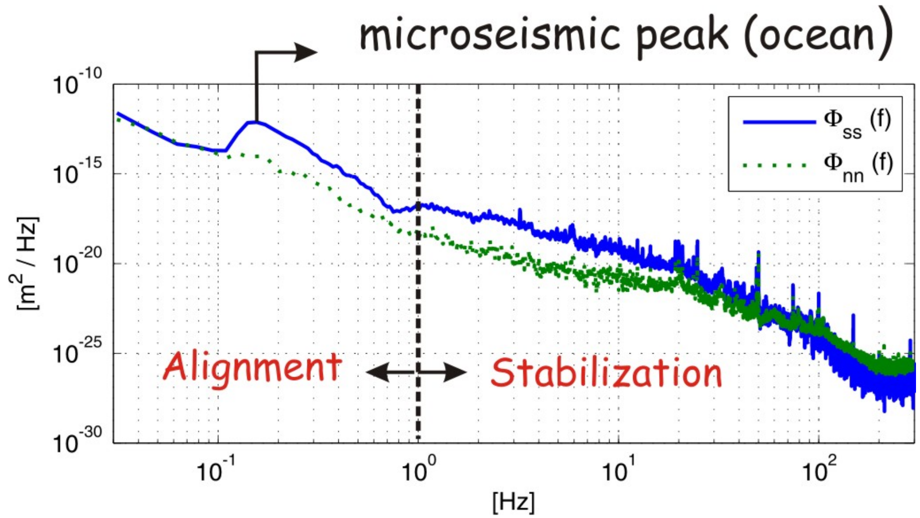
Signal to noise spectrum ratio: $\beta(\omega) = \dfrac{\Phi_{ss}}{\Phi_{nn}}$

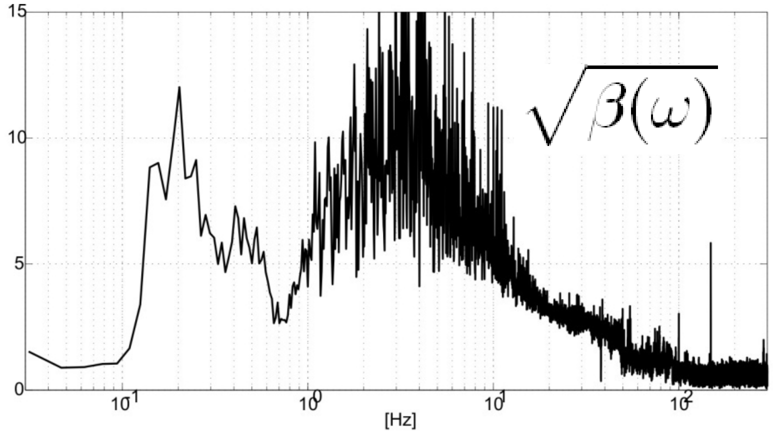
Signal to noise ratio

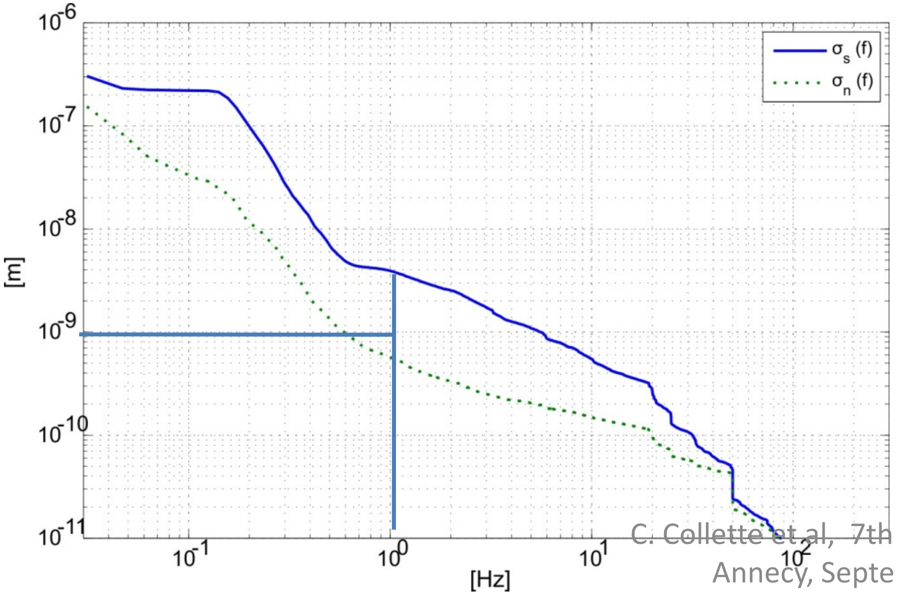


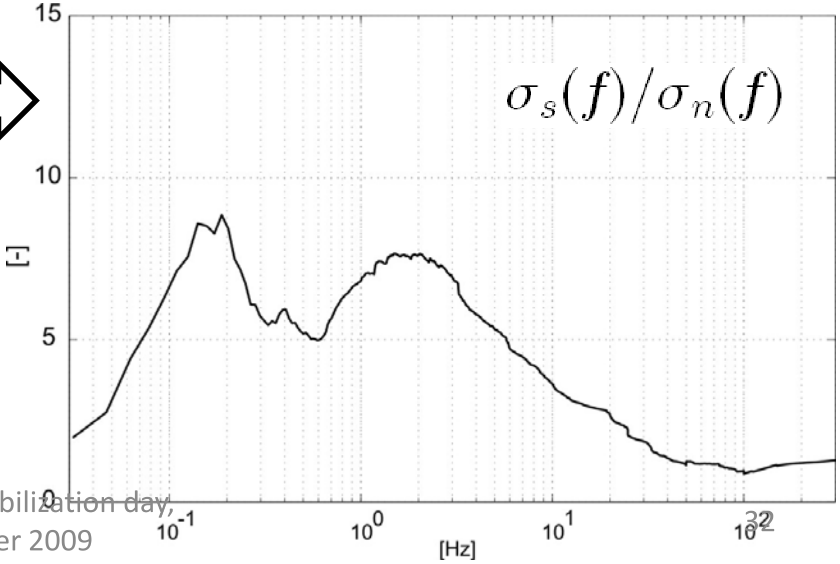
Sensor noise detection

Guralp CMG 40T, LHC tunnel (summer 2008)









d) Selection actuator type

First selection parameter: Sub nanometre resolution and precision

This excludes actuator mechanisms with moving parts and friction, we need **solid state mechanics**

Piezo electric materials	High rigidity	+ Well established - Fragile (no tensile or shear forces), depolarisation
Magneto Strictive materials		-Rare product, magnetic field, stiffness < piezo, - force density < piezo+ No depolarisation, symmetric push-pull
Electrostatic plates	No rigidity, ideal for soft supports	Risk of break through, best results with µm gaps, small force density, complicated for multi d.o.f. not commercial
Electro magnetic (voice coils)		Heat generation, influence from stray magnetic fields for nm resolution
~~Shape Memory alloys~~		Slow, very non linear and high hysteresis, low rigidity, only traction
~~Electro active polymers~~		Slow, not commercial

Selection of piezo actuators

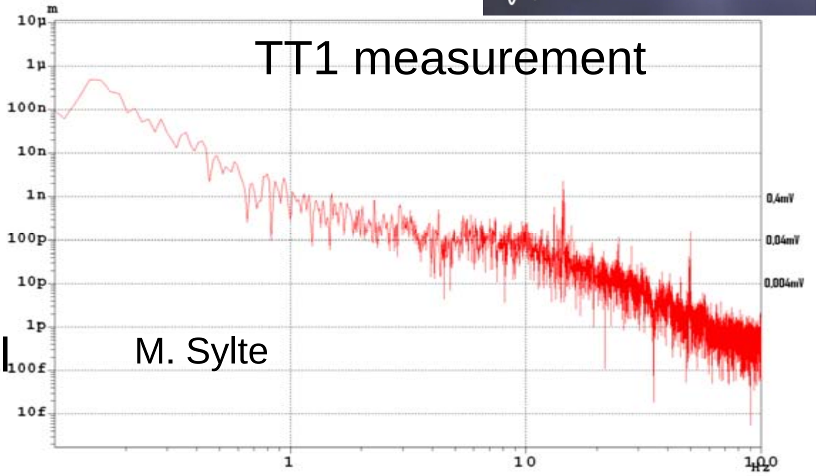
Resolution: To obtain 1 nm integrated r.m.s . displacement at 1 Hz we ideally need a resolution of 0.1 nm

Resonance frequency and rigidity

As rigid as possible

Prestress due to weight

Should be smaller than 20 % of the mechanical limit to avoid polarization. >> Cross section



TT1 measurement

M. Sylte

Range

± 10 micron + overhead for deforming the flexures >> lenght+resolution

Force capacity:

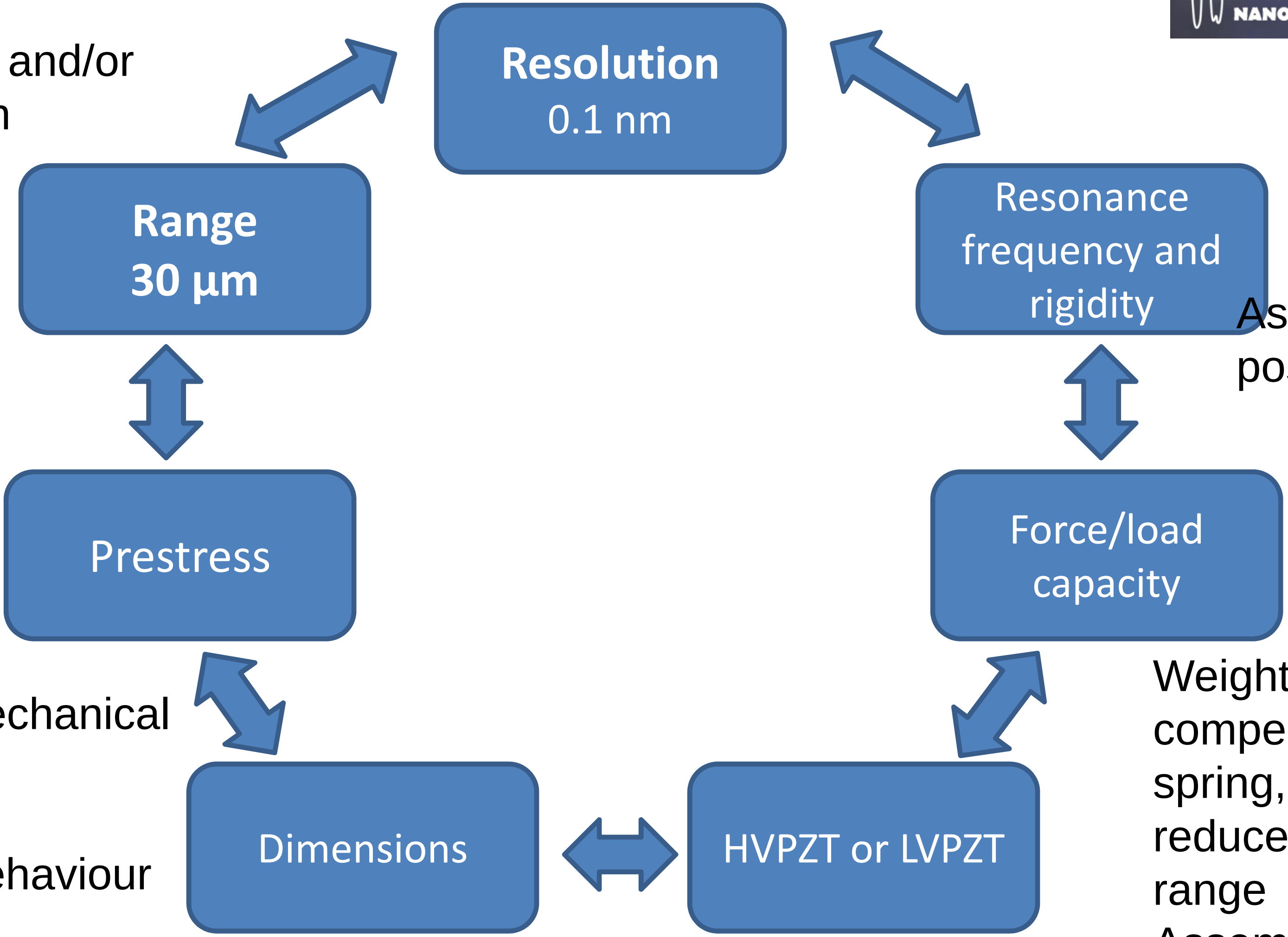
Depends if there are weight compensating measures.

Increase of compensation >> decreases range

For load carrying piezos, the choice also takes into account assembly induced forces

HVPZT or LVPZT Smaller resolutions on HVPZT (noisier high power amplifiers) but choice is fixed by the above (required power)

Selection of piezo actuators



Positioning and/or
stabilisation

Resolution
0.1 nm

Range
30 µm

Resonance frequency and rigidity

As high as
possible

Prestress

Force/load capacity

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

Dimensions

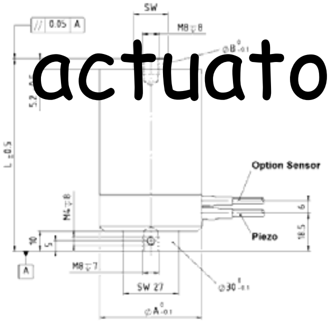
HVPZT or LVPZT

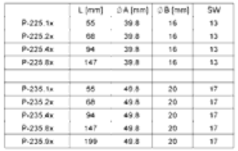
Weight compensating spring, reduces range
Assembly

Required power,
frequency range controller

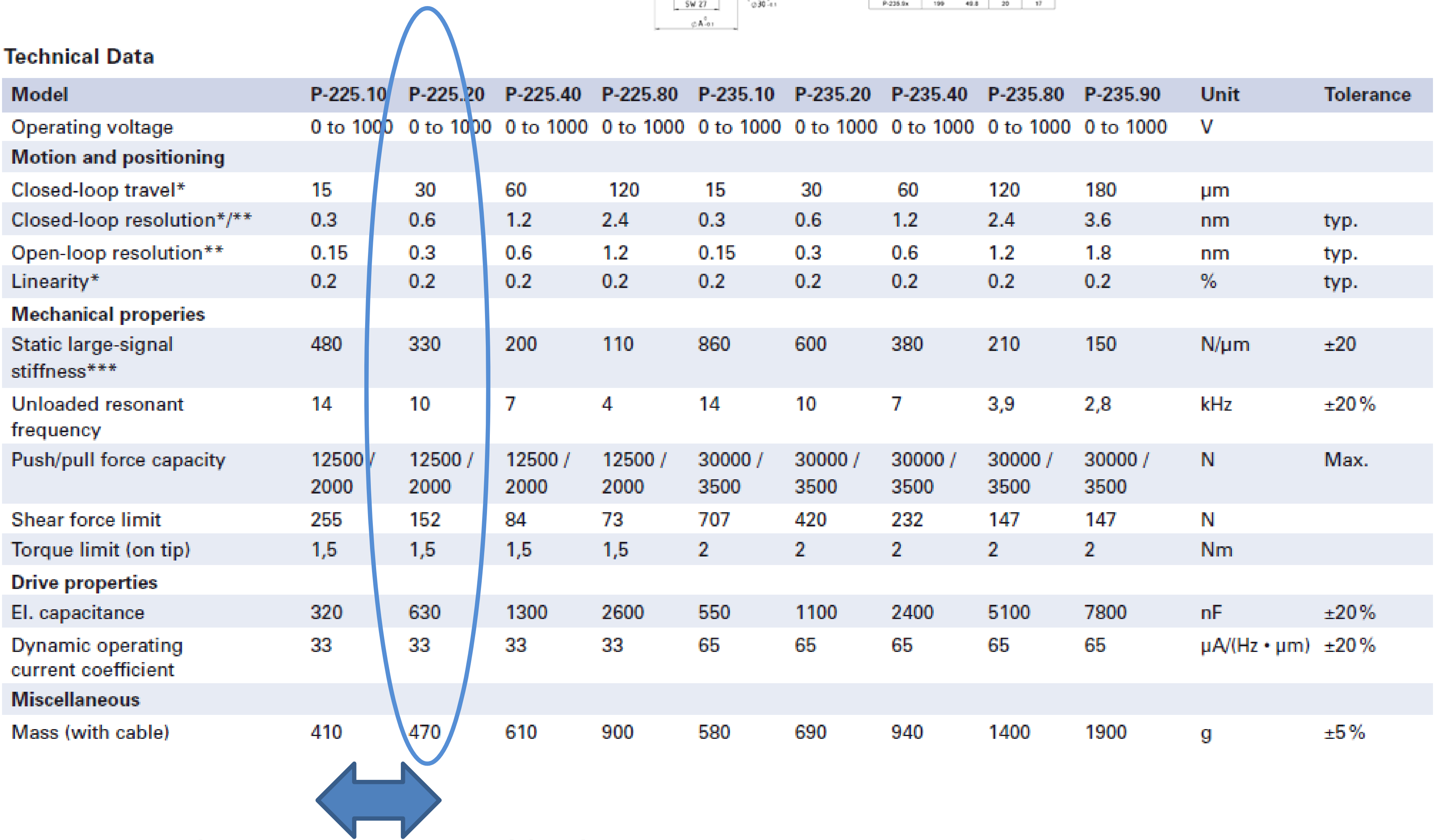
Selection of piezo actuators

Example :





	L [mm]	⌀A [mm]	⌀B [mm]	SW
P-225.1x	55	39.8	16	13
P-225.2x	68	39.8	16	13
P-225.4x	94	39.8	16	13
P-225.8x	147	39.8	16	13
P-235.1x	55	49.8	20	17
P-235.2x	68	49.8	20	17
P-235.4x	94	49.8	20	17
P-235.8x	147	49.8	20	17
P-235.9x	199	49.8	20	17



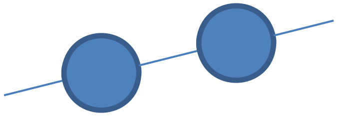
Technical Data

Model	**P-225.10**	**P-225.20**	**P-225.40**	**P-225.80**	**P-235.10**	**P-235.20**	**P-235.40**	**P-235.80**	**P-235.90**	**Unit**	**Tolerance**
Operating voltage	0 to 1000	0 to 1000	0 to 1000	0 to 1000	0 to 1000	0 to 1000	0 to 1000	0 to 1000	0 to 1000	V	
Motion and positioning											
Closed-loop travel*	15	30	60	120	15	30	60	120	180	µm	
Closed-loop resolution*/**	0.3	0.6	1.2	2.4	0.3	0.6	1.2	2.4	3.6	nm	typ.
Open-loop resolution**	0.15	0.3	0.6	1.2	0.15	0.3	0.6	1.2	1.8	nm	typ.
Linearity*	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	%	typ.
Mechanical properies											
Static large-signal stiffness***	480	330	200	110	860	600	380	210	150	N/µm	±20
Unloaded resonant frequency	14	10	7	4	14	10	7	3,9	2,8	kHz	±20%
Push/pull force capacity	12500 / 2000	12500 / 2000	12500 / 2000	12500 / 2000	30000 / 3500	30000 / 3500	30000 / 3500	30000 / 3500	30000 / 3500	N	Max.
Shear force limit	255	152	84	73	707	420	232	147	147	N	
Torque limit (on tip)	1,5	1,5	1,5	1,5	2	2	2	2	2	Nm	
Drive properties											
El. capacitance	320	630	1300	2600	550	1100	2400	5100	7800	nF	±20%
Dynamic operating current coefficient	33	33	33	33	65	65	65	65	65	µA/(Hz • µm)	±20%
Miscellaneous											
Mass (with cable)	410	470	610	900	580	690	940	1400	1900	g	±5%

Trade off for nano positioning

e) Design of joints

Options:



Combination of rotational joints

Disadvantage: complex kinematics, changing centre of rotation

Sliding spherical joints

Disadvantages: friction, backlash, 3 d.o.f. no adaptable stiffness

Spherical rolling joints

Low friction, backlash reduced to micron level

Exists for the required loads (Hephaist)

Disadvantage: 3 d.o.f. with no adaptable stiffness

Flexural joint

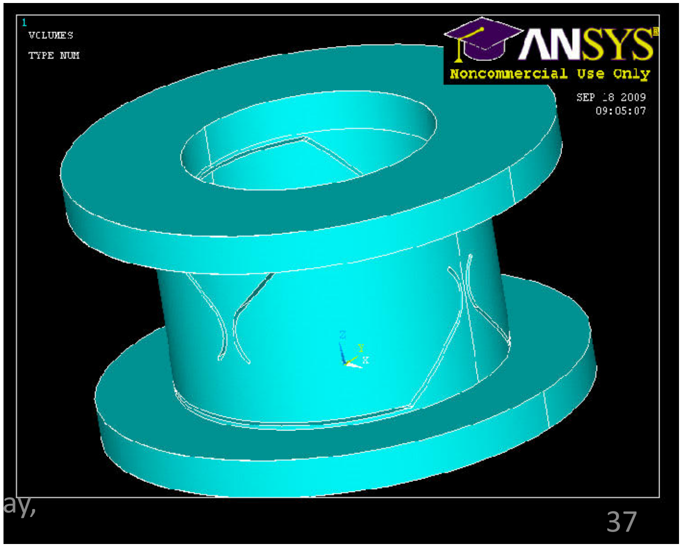
No friction, no backlash

Adaptable stiffness

Disadvantage: requires custom design.

First design: wire-cut hollow cylinder

The flexural part are two circular or elliptical notch hinges (col circulaire)



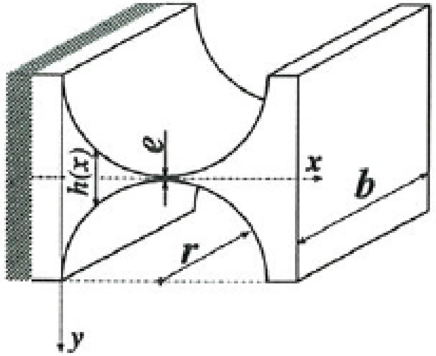
Design of joints

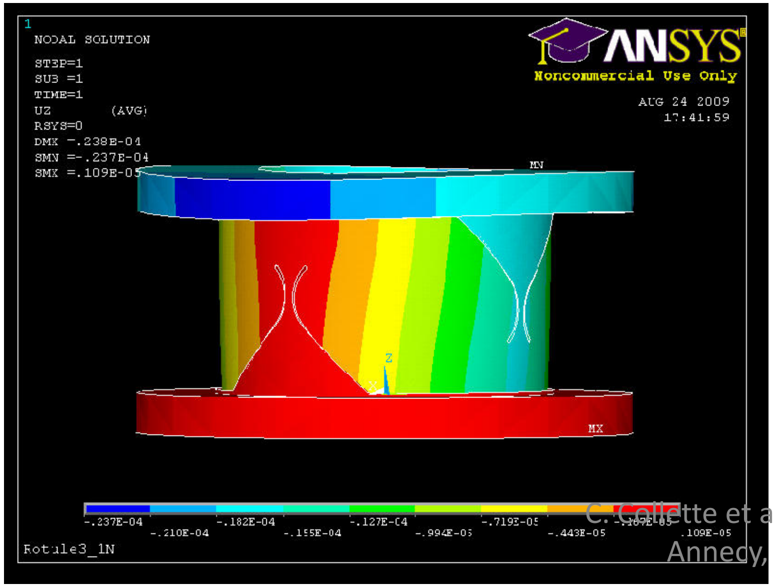
Col circulaire “standard” : e= 50 µm r/e >5

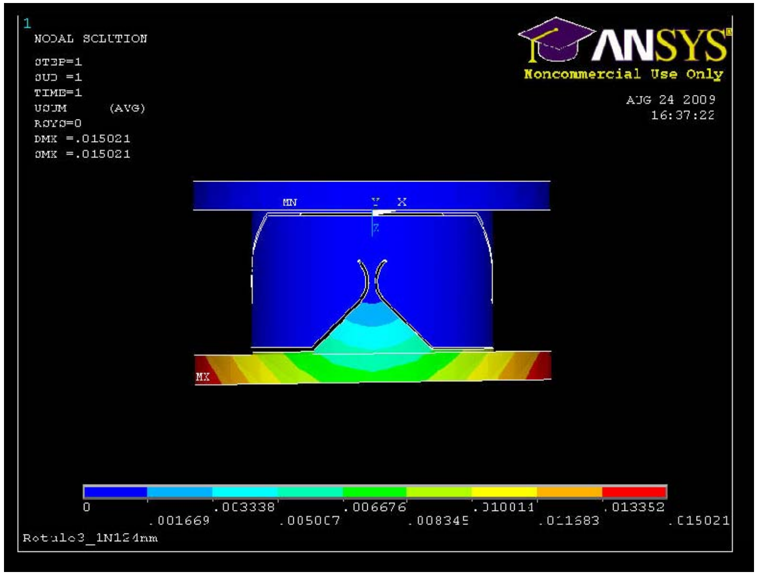
Axial load: 450 kg, 6 actuators, 60° : 850 N
First choice e = 2.1 mm to have about 20 MPa pre-stress

First draft (some results, work not finished)

Rotational rigidity: 588 Nm/rad
Example: for 125 µrad : 0.0735 Nm
Axial rigidity: ~ 1000 N/µm
Torsional rigidity: ~ 6000 Nm/rad

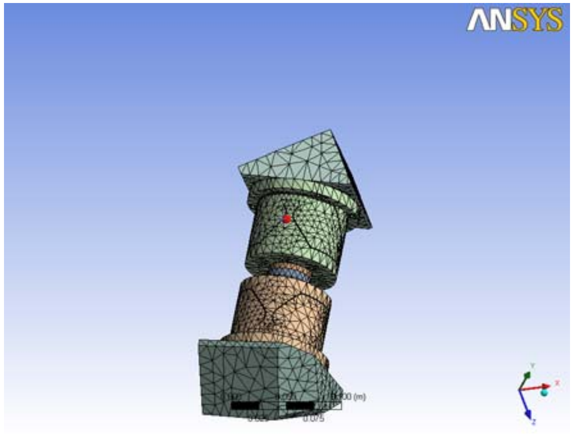




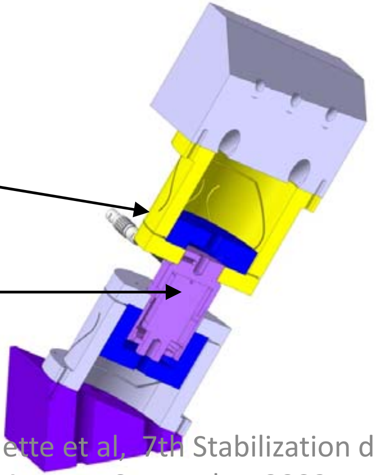


Design of joints

Steps of the design :

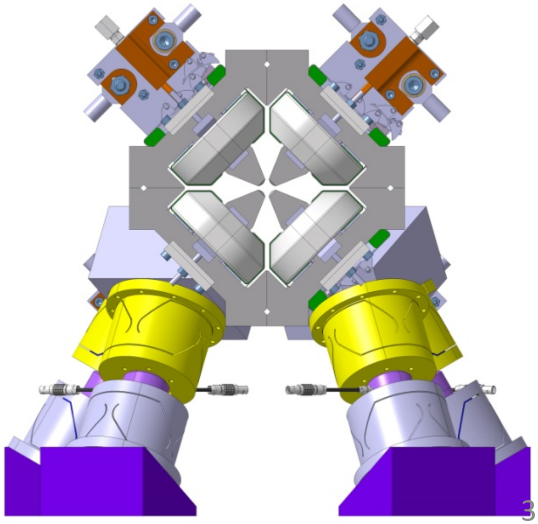


- Rigidities and first natural frequencies
- Internal stresses + stresses on piezo material
- Influence of the rigidity of the joints on structure rigidity
- Optimise the trade-off between resolution and rigidity during the selection of the angles of the legs
- Optimisation dimensions to integrate in the module

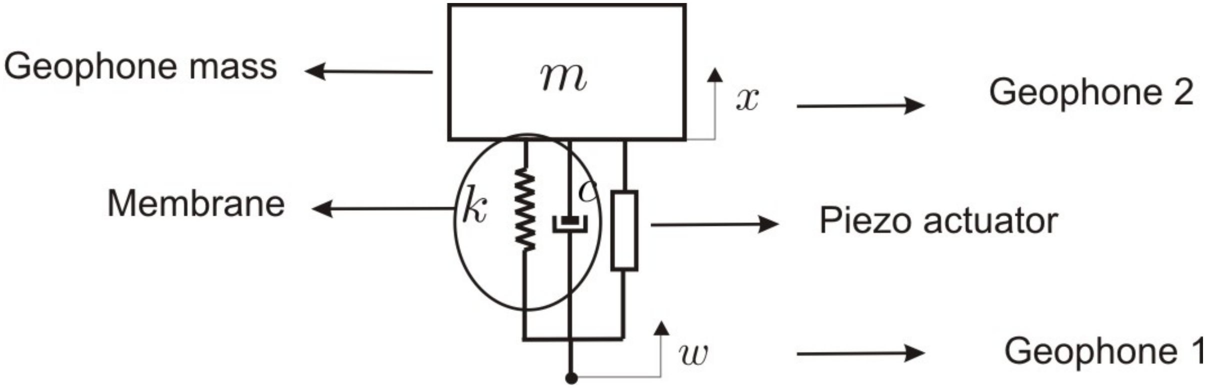


Flexible jointures

Piezoelectric actuator



4. Experimental validation



Geophone mass

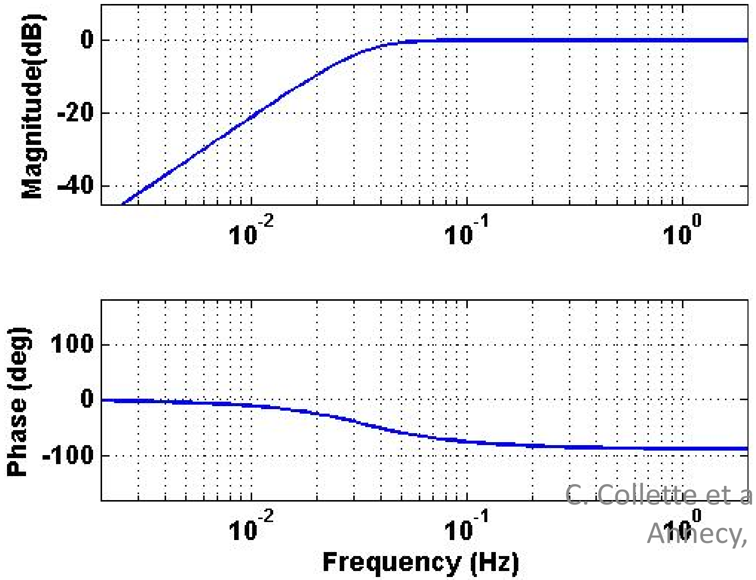
Membrane

Geophone 2

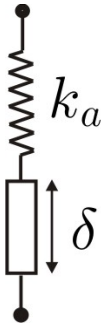
Piezo actuator

Geophone 1

Sensor GURALP (CMG-6T)



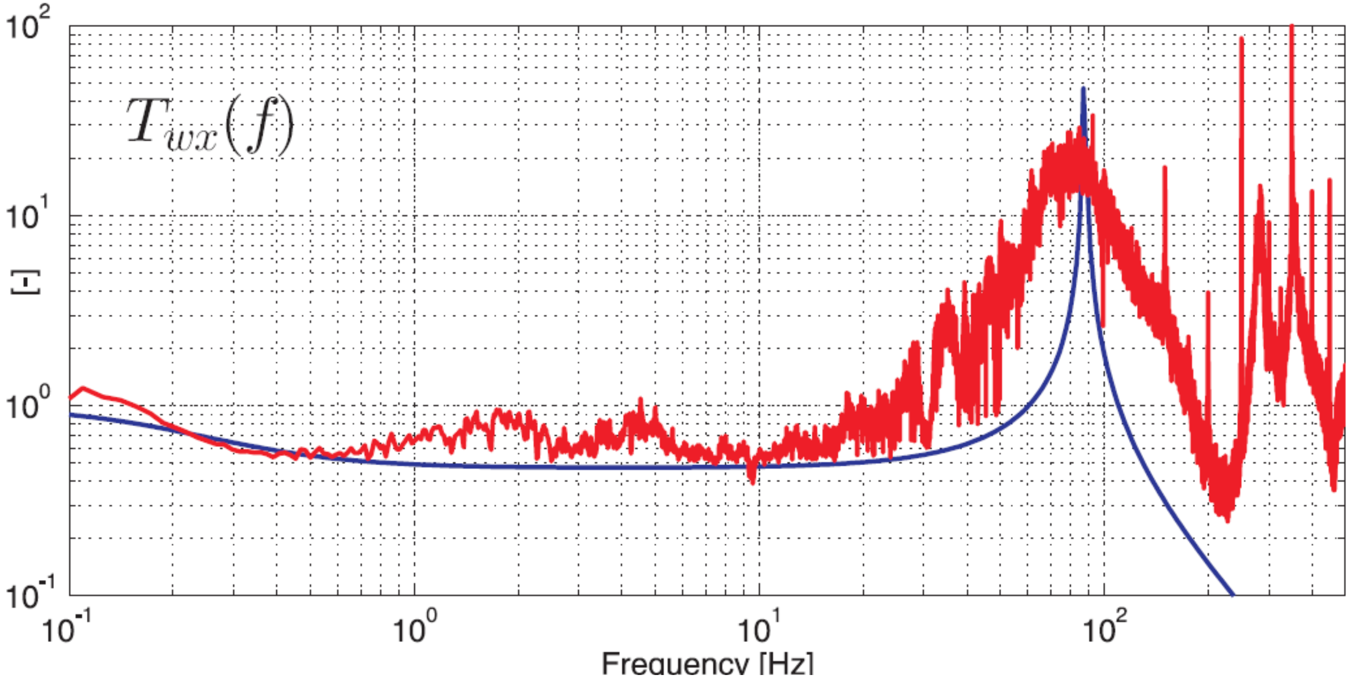
Actuator PI (P-753.21C)

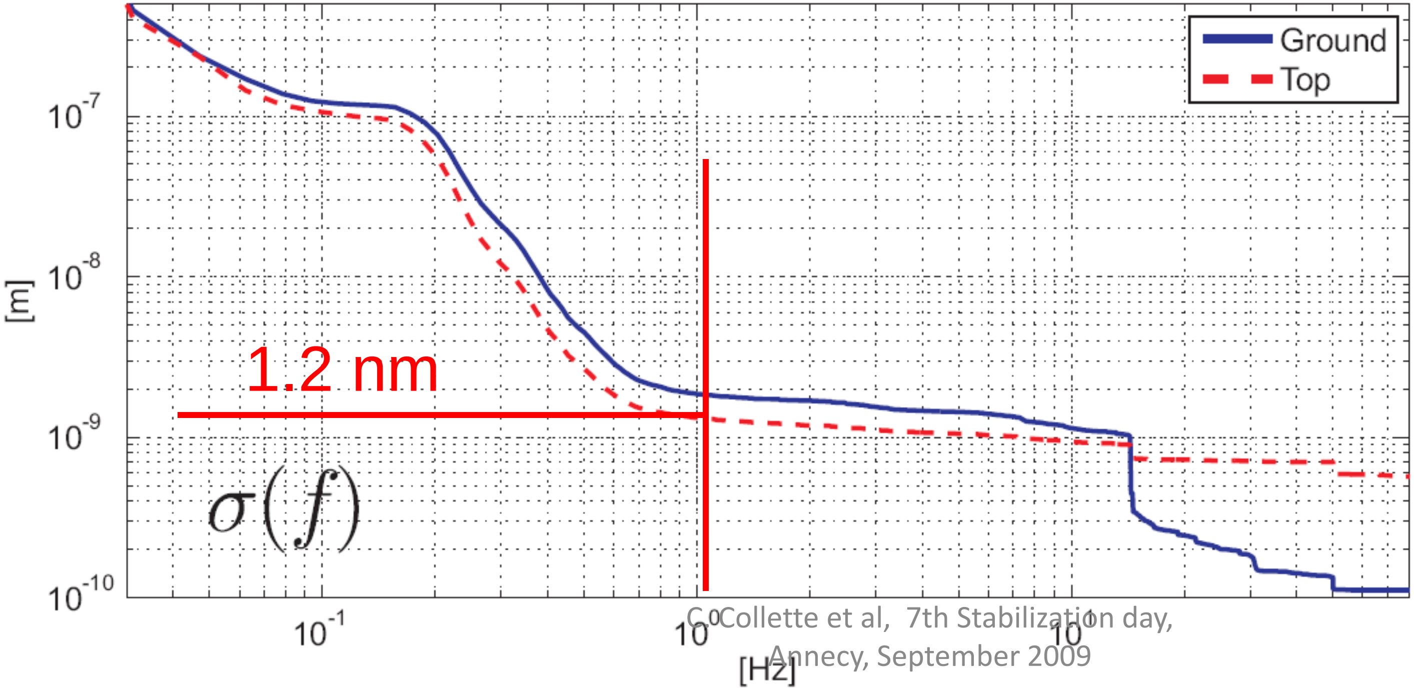


$$k_a = 25\ (MN/m)$$

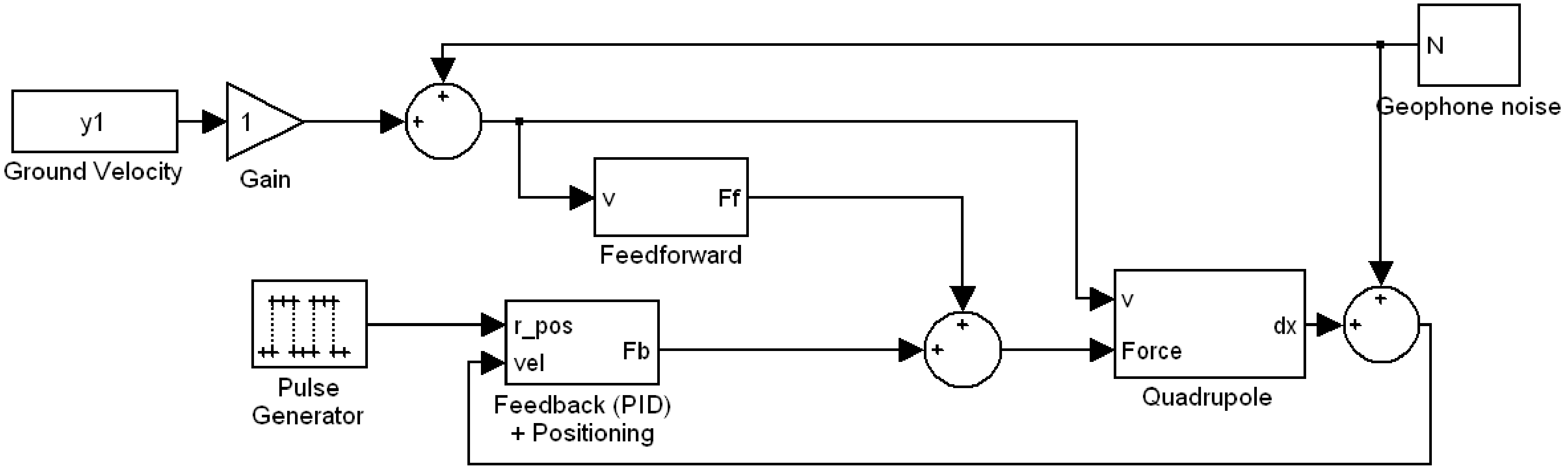
$$\delta = nd_{33}V$$

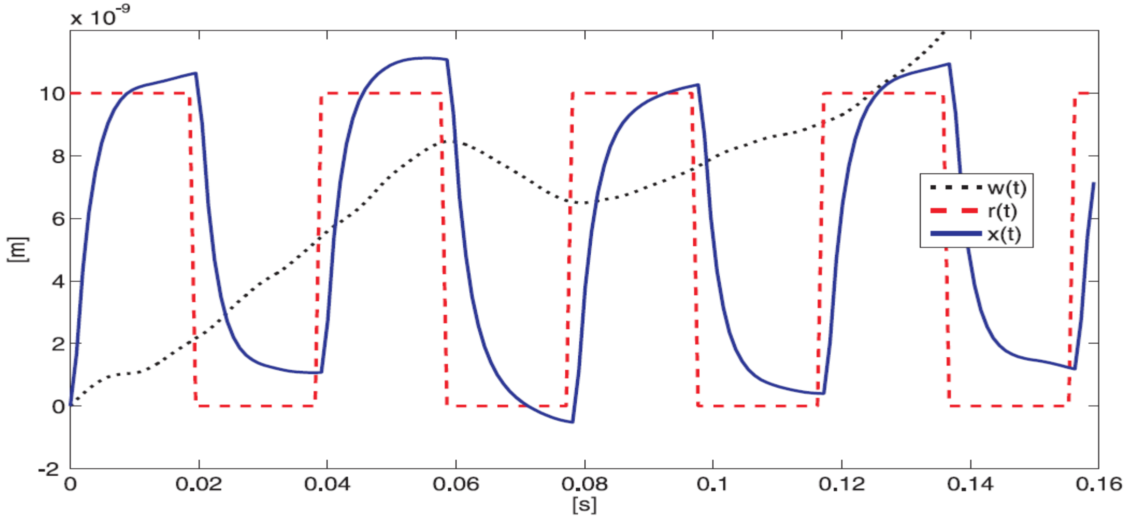
$$nd_{33} = 2.5\ (\mu m/V)$$


$T_{wx}(f)$
10^2
10^1
10^0
10^{-1}
[-]
10^{-1}
10^0
10^1
10^2
Frequency [Hz]


Ground
Top
10^{-7}
10^{-8}
10^{-9}
10^{-10}
[m]
1.2 nm
$\sigma(f)$
10^{-1}
10^0
10^1
[Hz]

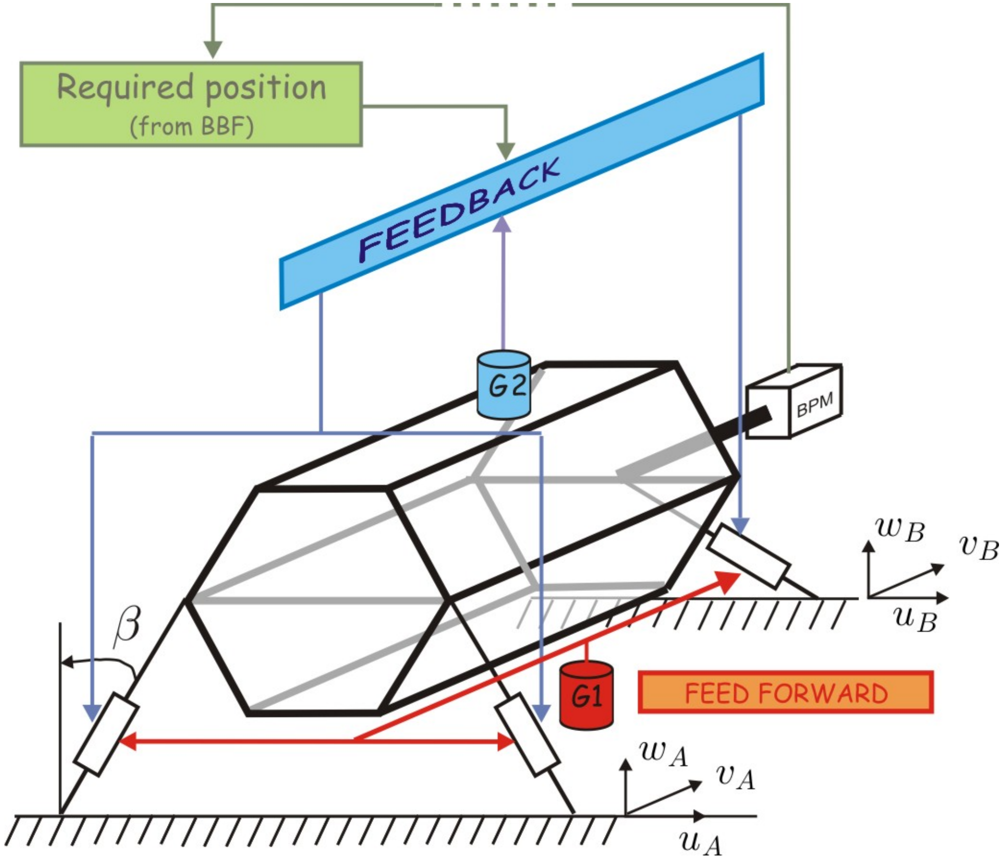
Positioning





To be tested experimentally on the membrane

5. Intermediate experiment: Tripod



Difficulties addressed:

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