Active stabilization of a mechanical structure

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Overview

1. **Introduction and our approach of the stabilization problem :**
   - Problem of structure stabilization and our point of view
   - Active control at a nanometer scale at given frequencies
   - Limitations of this method

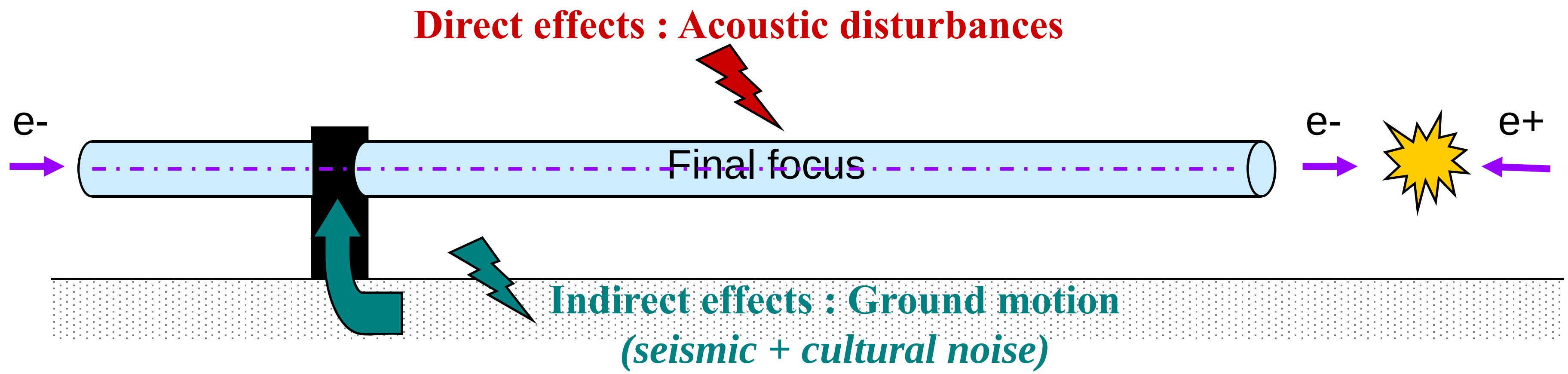
2. **The last tested algorithm : command with local internal model**
   - Brief description
   - Numerical approach to increase the tests possibilities
   - Results in simulation mode
   - Results at the nanometer scale with the prototype

3. **A beginning of active isolation study :**
   - Previous study and the interest in exploring this aspect
   - Current work

4. **Conclusion and perspectives**

The problem of the stabilization

✓ **The sources of the structure motion :**



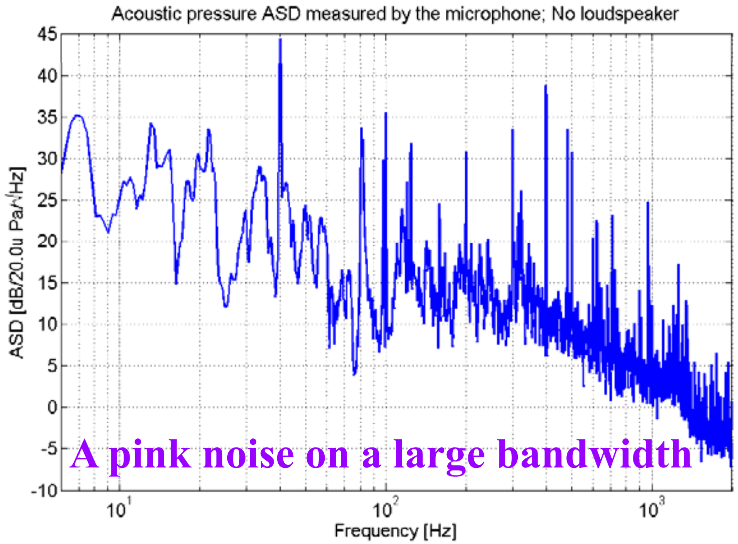
- Direct effects : - excite particularly the resonant modes of the structure
- Indirect effects : - create a vertical displacement of the clamping
  - excite particularly the vertical flexion mode of the structure

✓ **The different required approaches of this problem :**

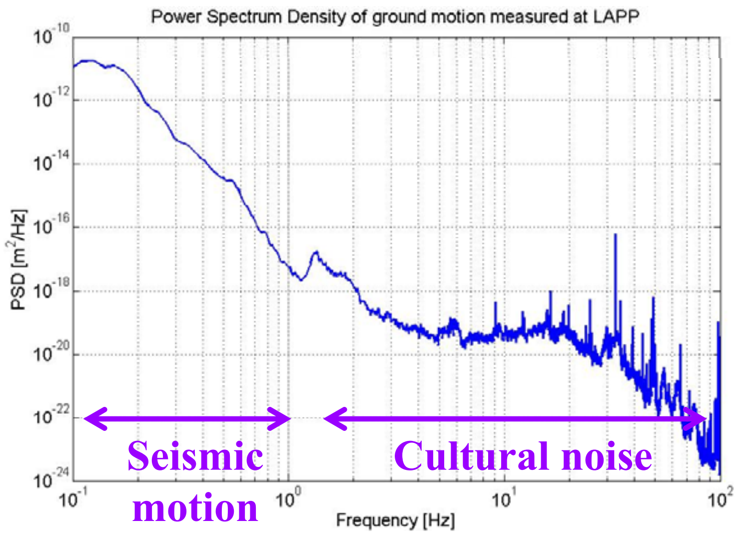
- Active compensation : - maintain the structure in a straight horizontal position along its axe
- Active and passive isolation : - obtain a null absolute displacement of the clamping, so of the entire system.

Example of spectral analysis of different disturbance sources

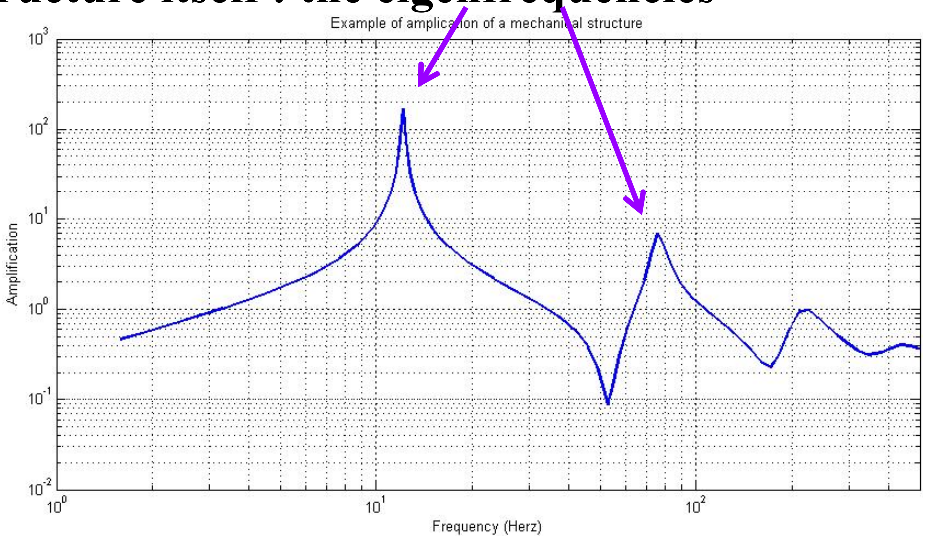
✓ **Acoustic disturbance :**



✓ **Ground motion :**

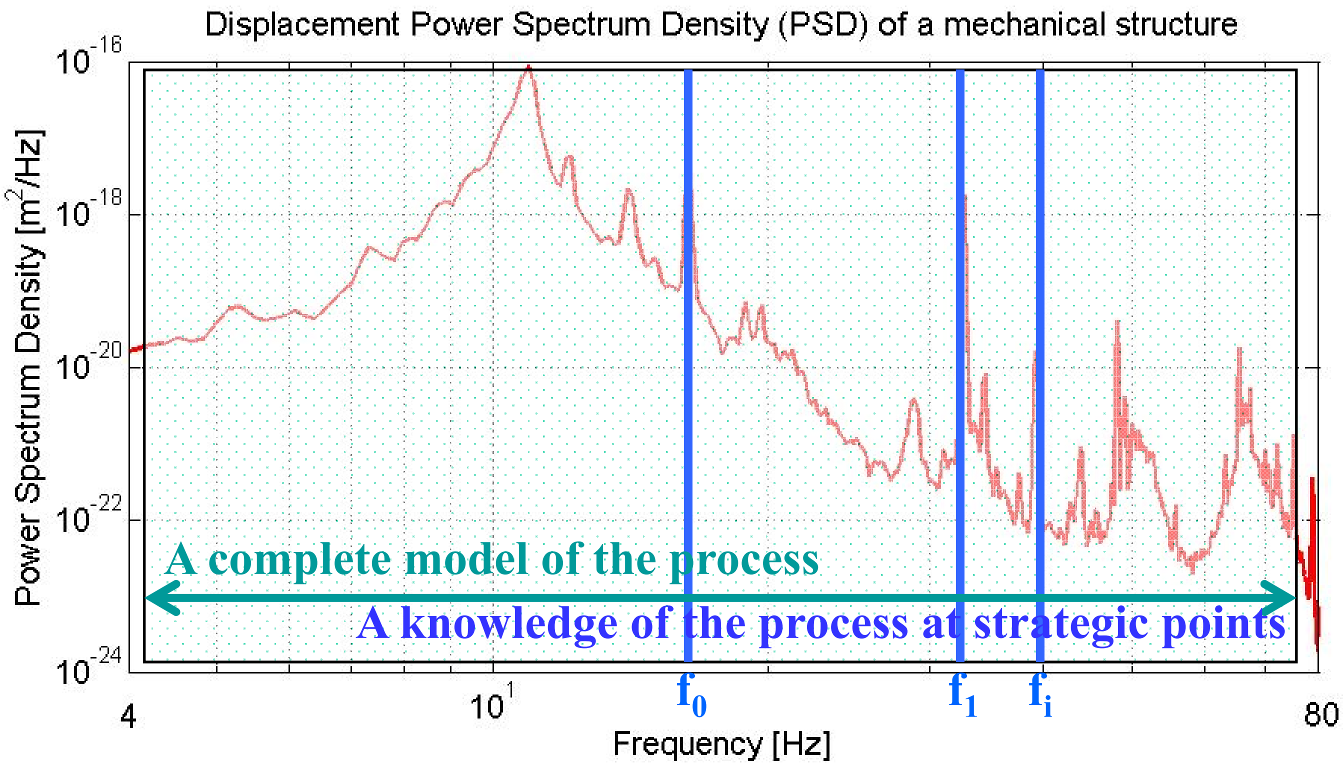


✓ **Amplified by the structure itself : the eigenfrequencies**



Different approaches of the problem

✓ **An example of displacement of a mechanical structure :**



✓ **What is the feedback loop based on?**

1 - A complete model of the structure : *too complex*

2 - A knowledge of the structure at strategic points : the initially developed algorithm

The first developed algorithm

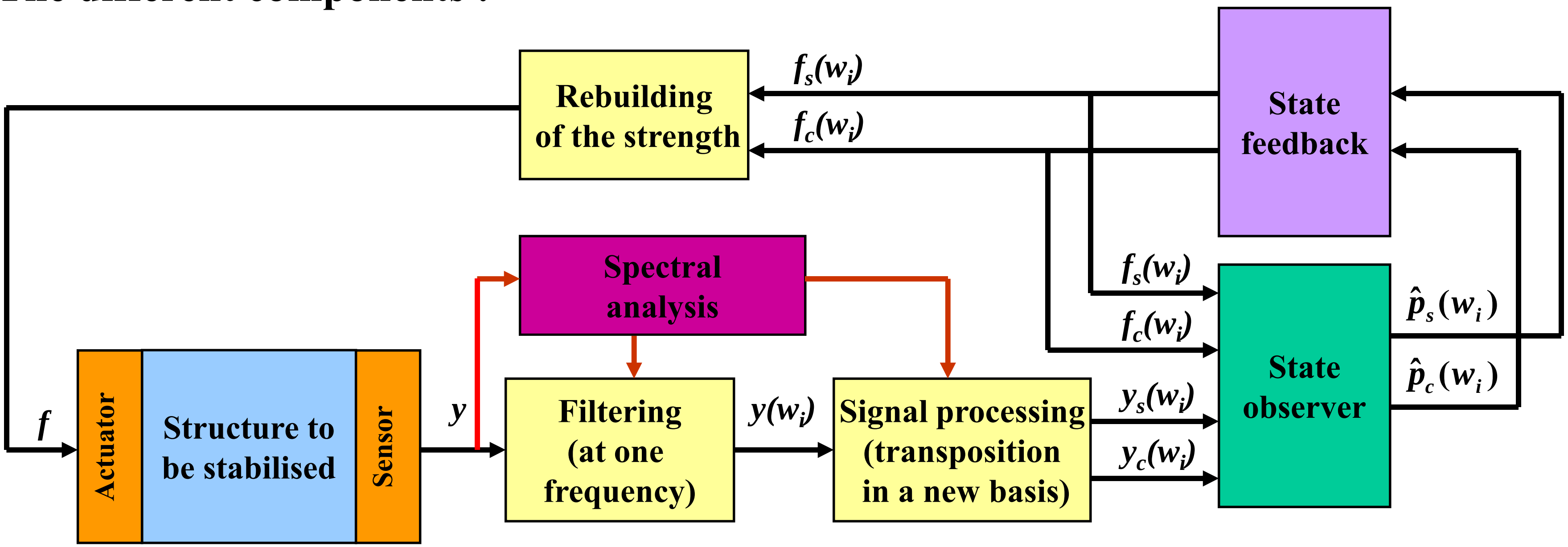
✓ **The originality :**

Not based on a model of the system (classical algorithm), but only on a few characteristics of the system, computed in open loop for each selected frequency :

- The gain and the phases differences between output / input.

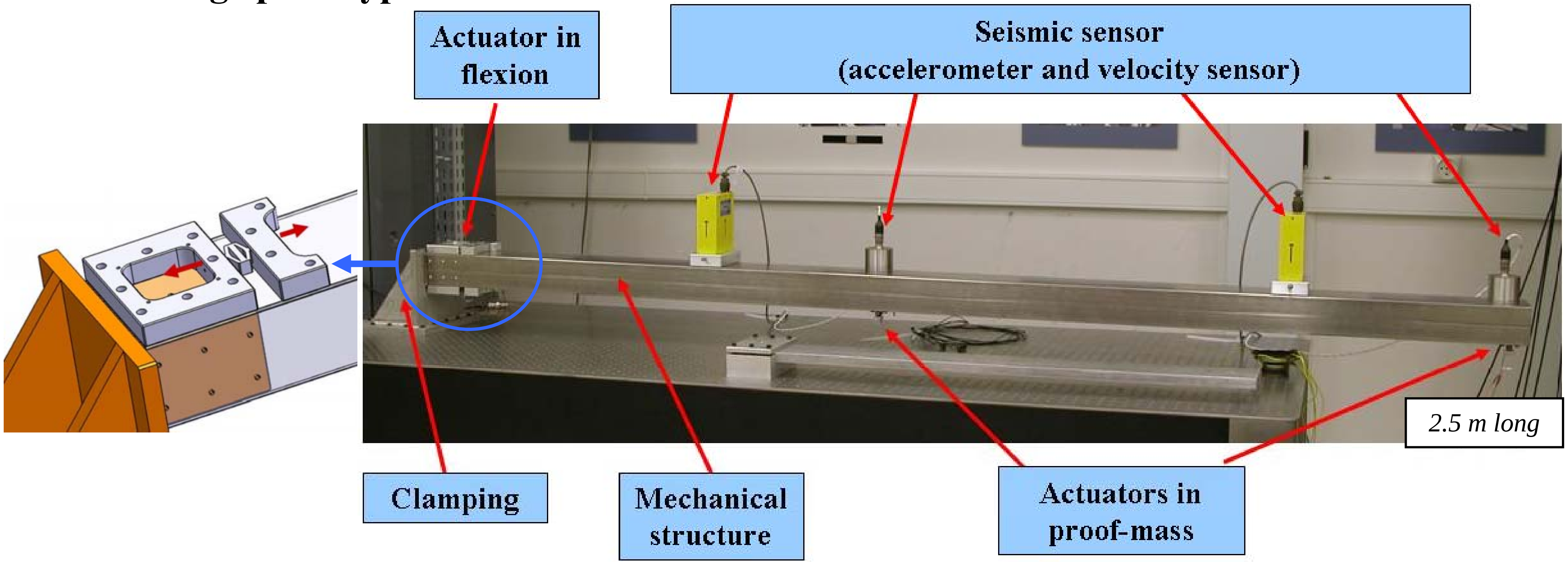
- The setting time.

✓ **The different components :**



The prototype

✓ **The large prototype and its instrumentation :**



✓ **Actuators used for the active control of vibration :**

- A stacking of PZT patches -

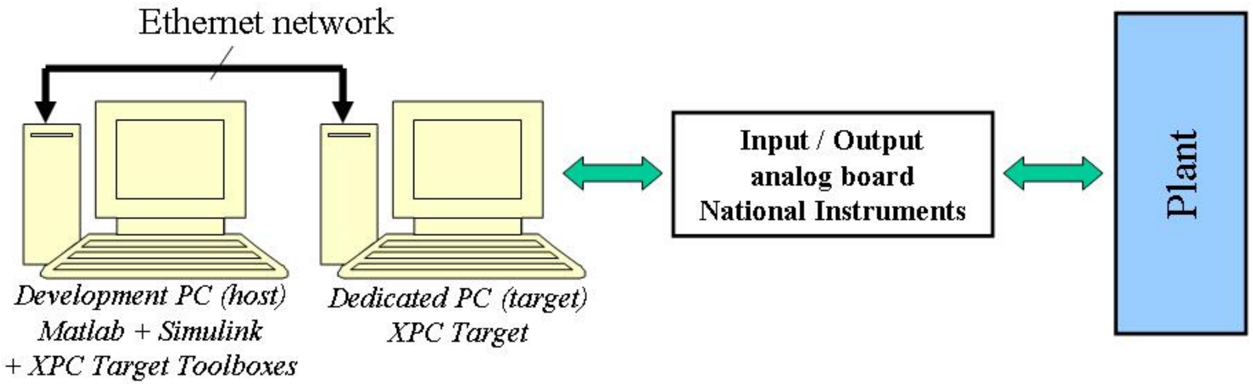
- Force = 19.3 N
- Maximal displacement = 27,8 µm
- Resolution = 0,28 nm

The components of the prototype

✓ **Sensors are used to measure the structure motion (non magnetic) :**

Sensors	SP500B	ENDEVCO86
Sensitivity	2000V/m/s	10V/g
Frequency range	0.0167 – 75Hz	0.01 – 100 Hz
Integrated electronic noise above 4Hz	0.085nm	0.6nm
Quantity	2	2

✓ **Real time solution : a rapid prototyping of Mathworks (XPC Target)**



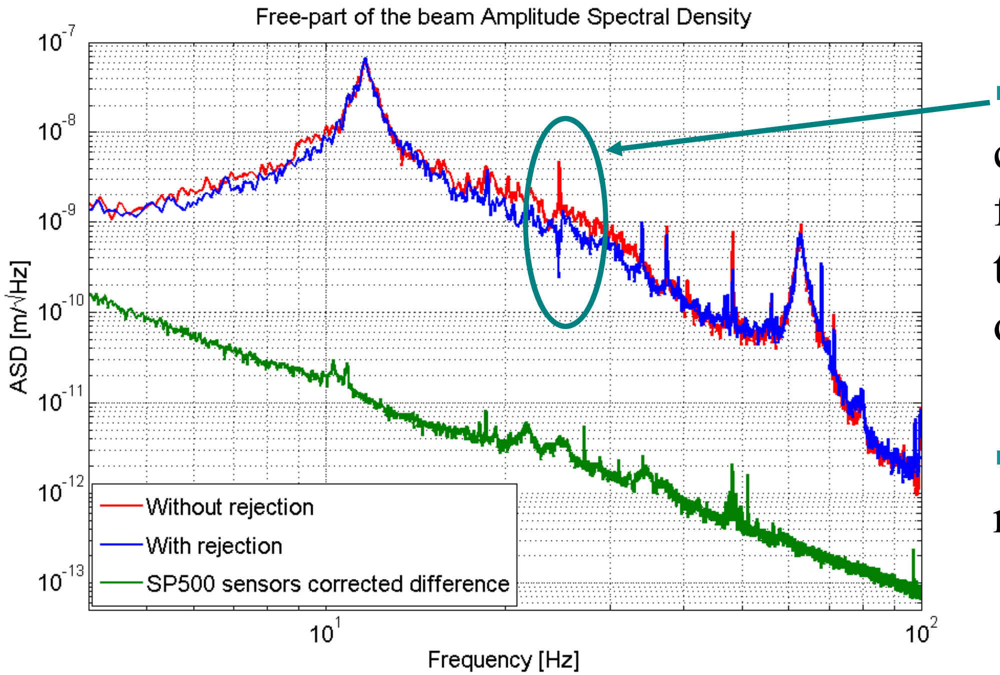
✓ **Analogical digital cards : PCI 6052E (NI)**

PCI-6052E	Quantity	Resolution	Rate	Conversion	Range	Noise
Analog Input	8 Differential/ 16 Single-ended	16bits	Up to 333kS/s	Successive approximation	±0.05 to 10V	60uV from DC to 1MHz
Analog output	2 Single-ended	16 bits	333kS/s	Successive approximation	±10V	

Fast card (Resolution, Rate, Conversion) — **Low noise card** (Range, Noise)

Results with the first developed algorithm

✓ **The first results at the nanometer scale :**



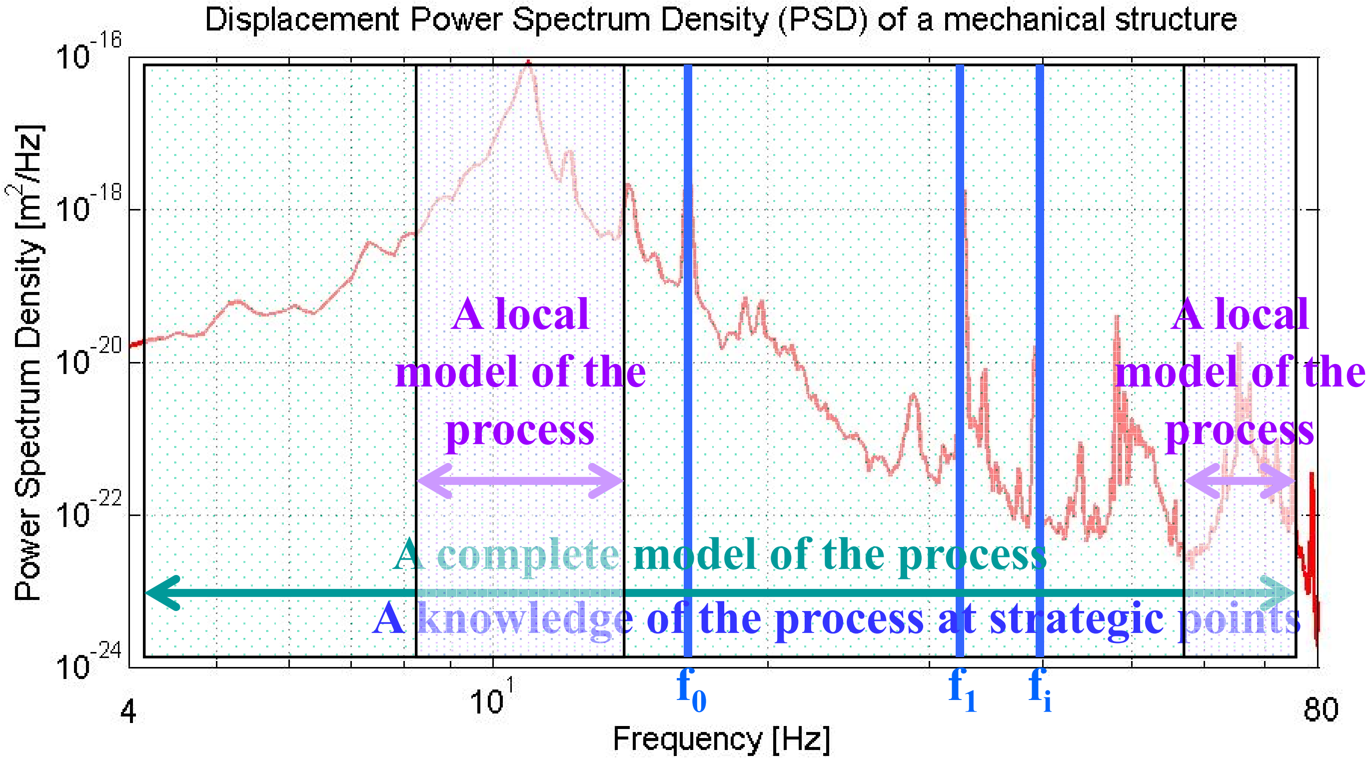
- Example of active compensation of an unknown frequency disturbance, excited by the natural environment (motion of the ground + acoustic noise).
- Possibilities to increase the number of rejected disturbances.

➢ **Active compensation is efficient with this initial algorithm for narrow peaks.**

➢ **For eigenfrequencies, the need of controlling a larger bandwidth.**

Another approach of the problem

✓ **Test an intermediary solution : to control a larger bandwidth**



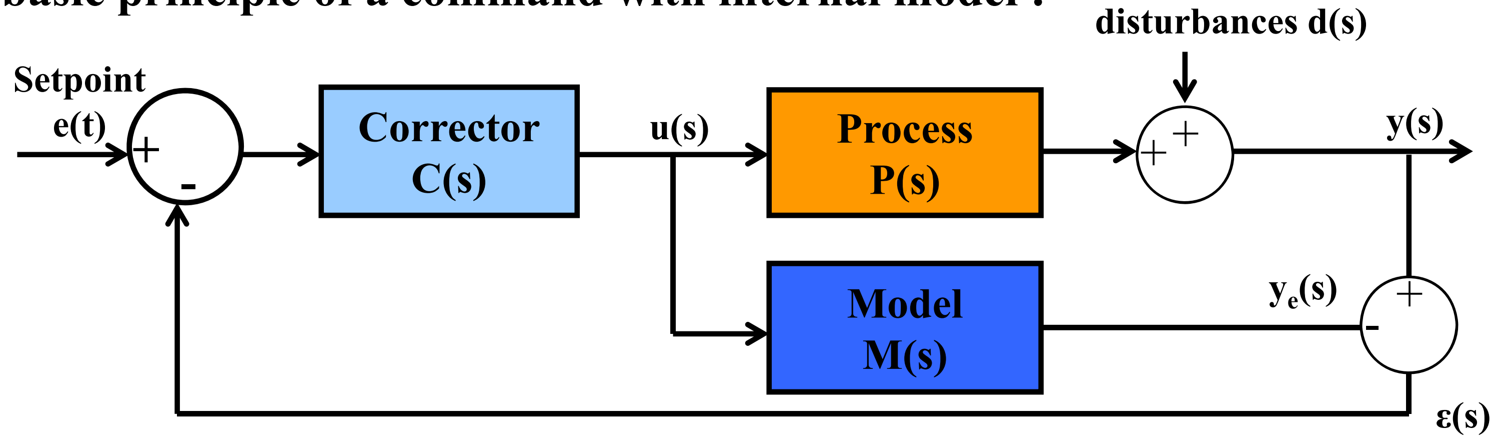
1 - A complete model of the structure : ***too complex***

2 - A knowledge of the structure at strategic points : ***the initially developed algorithm***

3 - A local model of the structure : ***for the disturbances amplified by eigenfrequencies.***

Command with internal model

✓ **The basic principle of a command with internal model :**

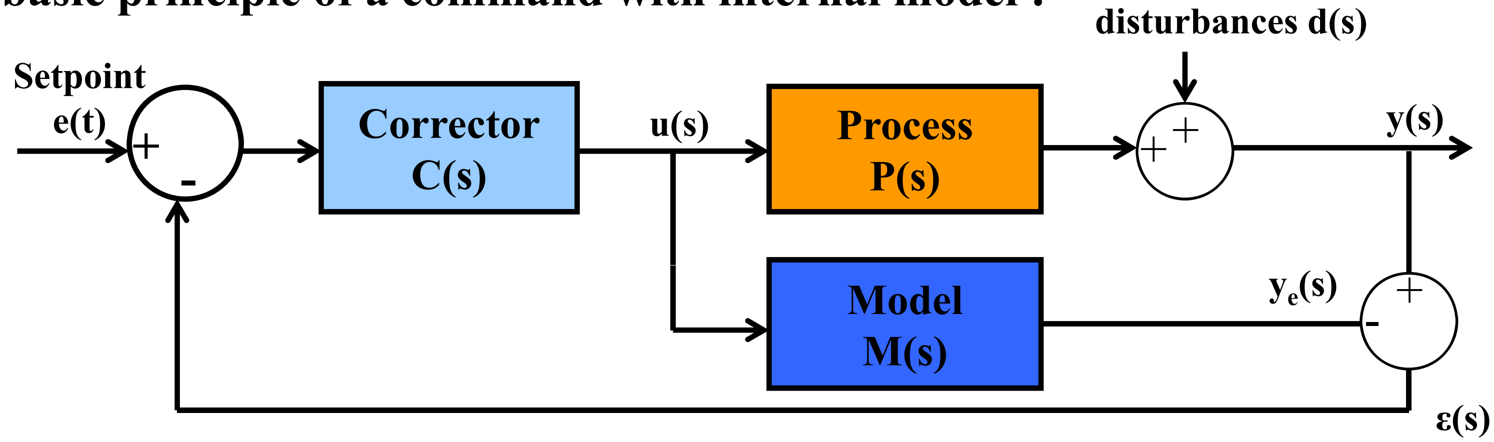


- The command u(s) :
  - is applied simultaneously to the process and to the model.
  - is not computed in function of the output y(s) but of the difference between the measured output and the output of the model.
- The output y(s) is compared to the output of the model :

  $\varepsilon(s)=[P(s)-M(s)].u(s)+d(s)$ with $u(s)=[e(s)-\varepsilon(s)].C(s)$
- The controller C(s) is built in function of the model.

Command with internal model

✓ **The basic principle of a command with internal model :**



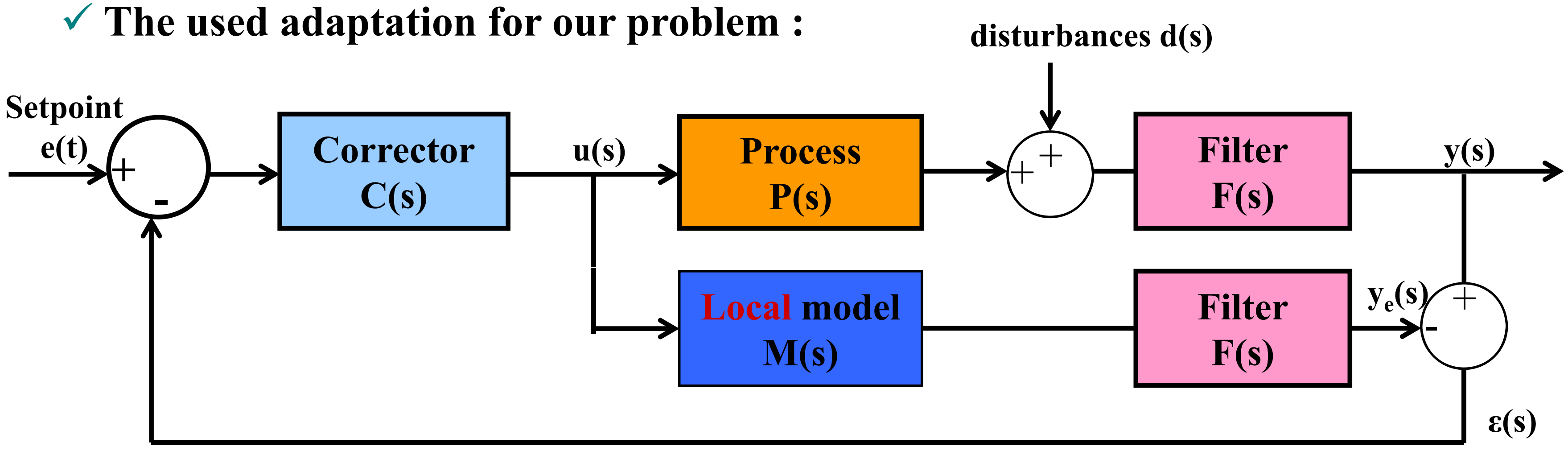
- The transfer function of CIM in closed loop is :

$$Y(s) = \frac{C(s).P(s).e(s) + [1 - C(s).M(s)].d(s)}{1 + [P(s) - M(s)].C(s)}$$

- To cancel the disturbance : C(s) = M(s)$^{-1}$ → **Controller = inverse (Model)**
- To follow the setpoint : M(s) ~ P(s) → **Model ~ Process**

Command with internal model

✓ **The used adaptation for our problem :**



- The model M(s) is an elementary model, which corresponds locally to the process, so it is defined in function of a basic knowledge of the process :
  - The amplification and the phase at the selected resonant frequency.
  - The damping of the selected resonant mode (hammer test, in function of the gain)

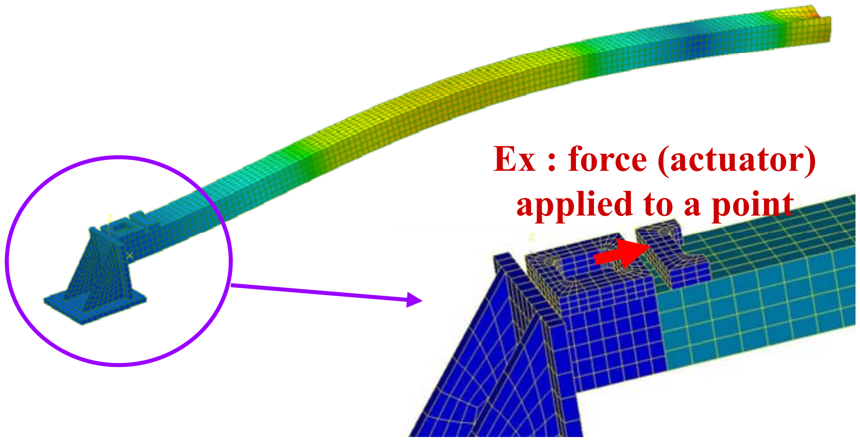
- The filter F(s) selects the bandwidth of the algorithm.

→ The requirements of this algorithm are a bit more complex but still basic, so realistic !!

→ There are as many algorithms in parallel as there are eigenfrequencies to stabilize.

Tests in simulation

✓ **A finite element model of the structure :**



✓ **Dynamics equation :**

$$M.\ddot{u}(t)+C.\dot{u}(t)+K.u(t)=f_p(t)$$

- **M** : Mass matrix
- **C** : damping matrix
- **K** : stiffness matrix

➢ **A prediction of the mechanical structure response**

✓ **The interest of the simulation :**

- To adjust the feedback loop
- To increase the tests possibilities (multiple configuration for sensors, actuators…)
- To analyse the behaviour of the entire beam

➢ **Require an updating to be as representative as possible to the real setup**

Tests in simulation

✓ **Integration of a finite element in a feedback loop :**

SAMCEF		MATLAB		Simulink
FE Model Creation	→	**State-Space Model Creation**	→	**State-Space Model Use**

$$\mathbf{M}\,\ddot{\mathbf{u}}(t) + \mathbf{C}\,\dot{\mathbf{u}}(t) + \mathbf{K}\,\mathbf{u}(t) = \mathbf{f}_p(t)$$

M : mass matrix

C : damping matrix

K : stiffness matrix

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

x : state vector

u : input vector

y : output vector

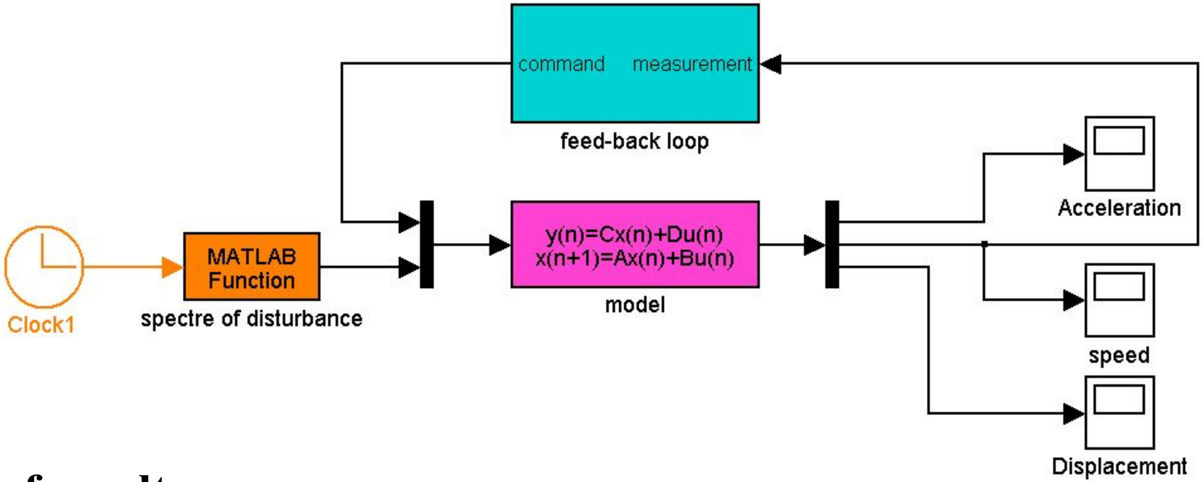
in 1, in 2, …, in "k" → $\dot{x} = Ax + Bu$, $y = Cx + Du$ → out 1, out 2, …, out "n"

in : accel / force perturb. + force actuator

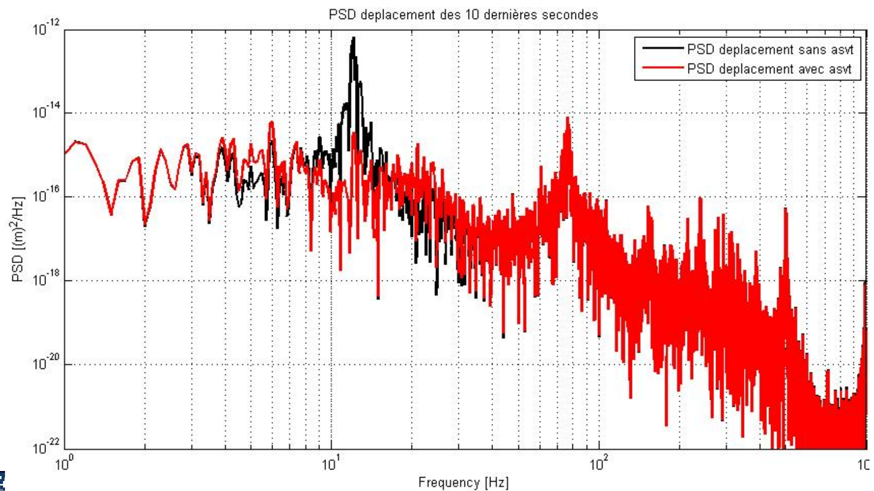
out : accel / velocity / displacement

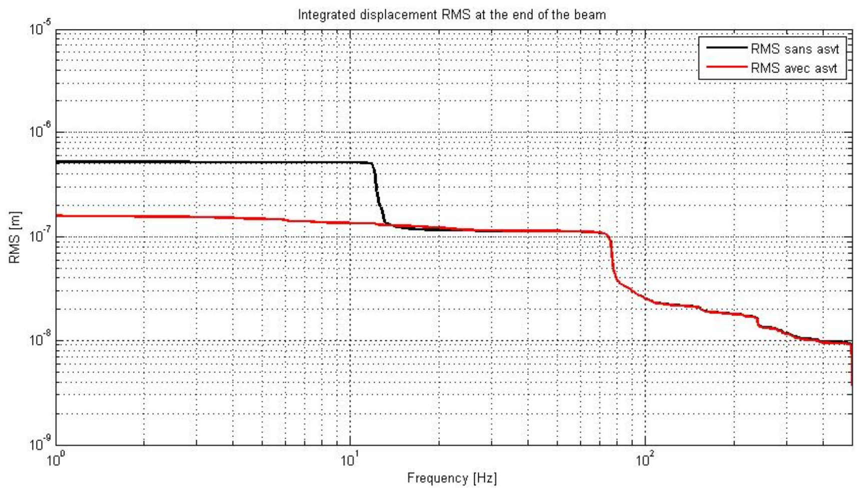
Tests in simulation

✓ **Integration of the finite element model in the feedback loop :**



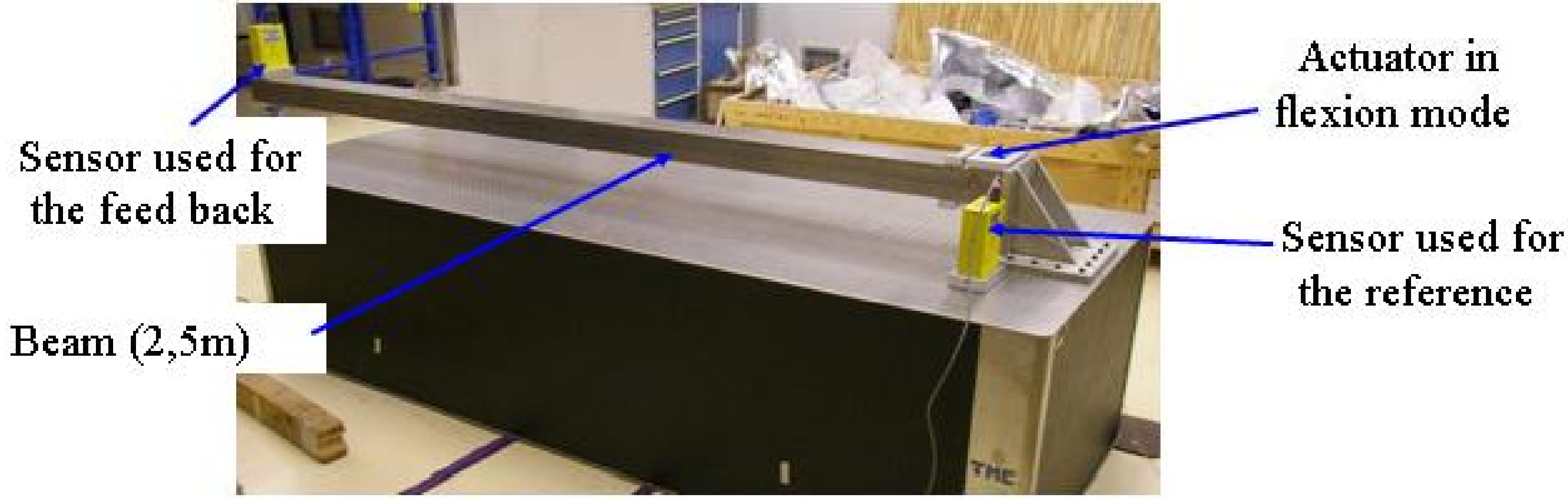
✓ **Example of result :**





Tests with the large prototype

✓ **Test at an nanometer scale with natural disturbance sources :**

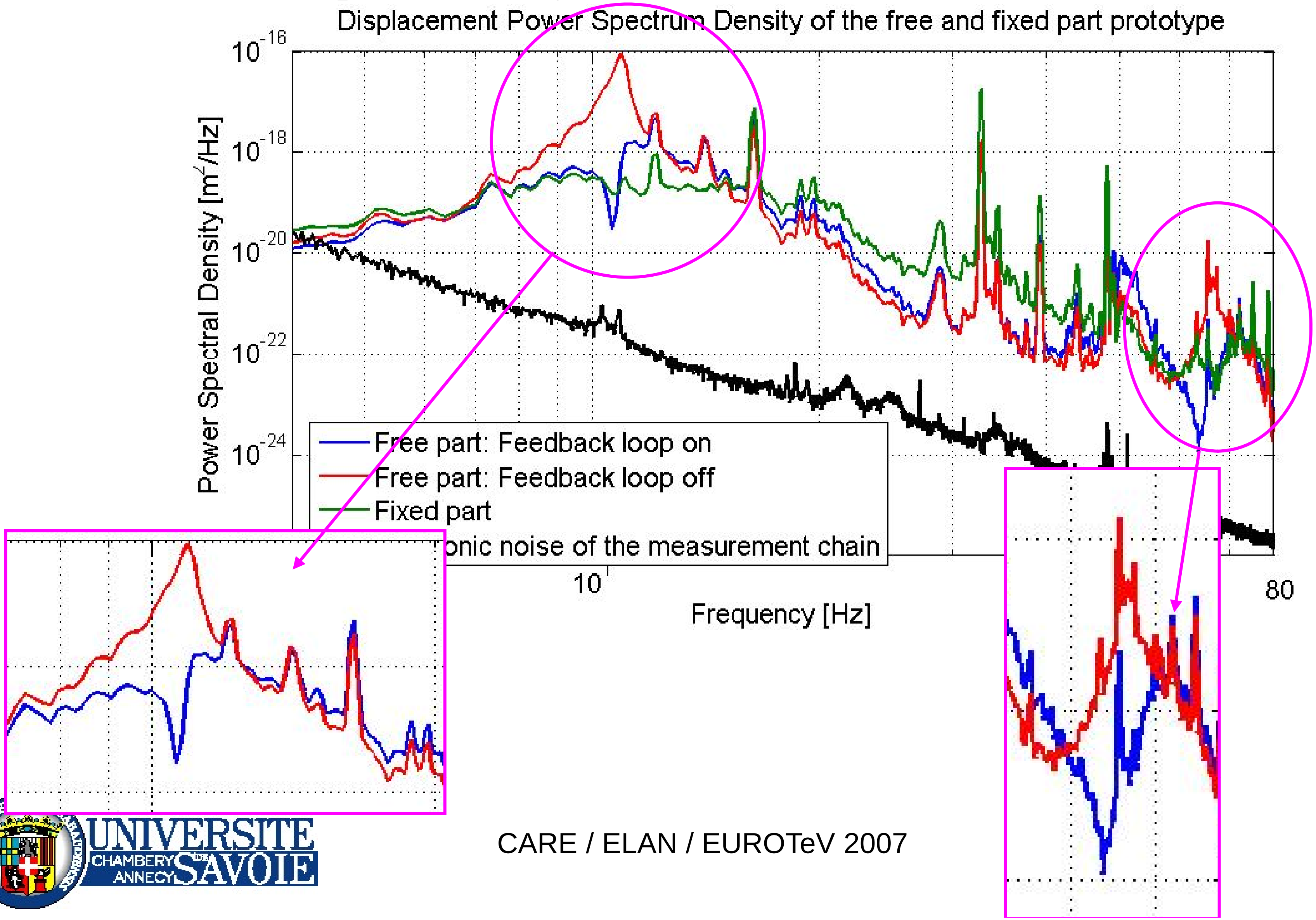


✓ <u>Sensor</u> : velocity sensor at the end of the beam.

✓ <u>Actuator</u> : actuator in flexion mode as close as possible on the clamping

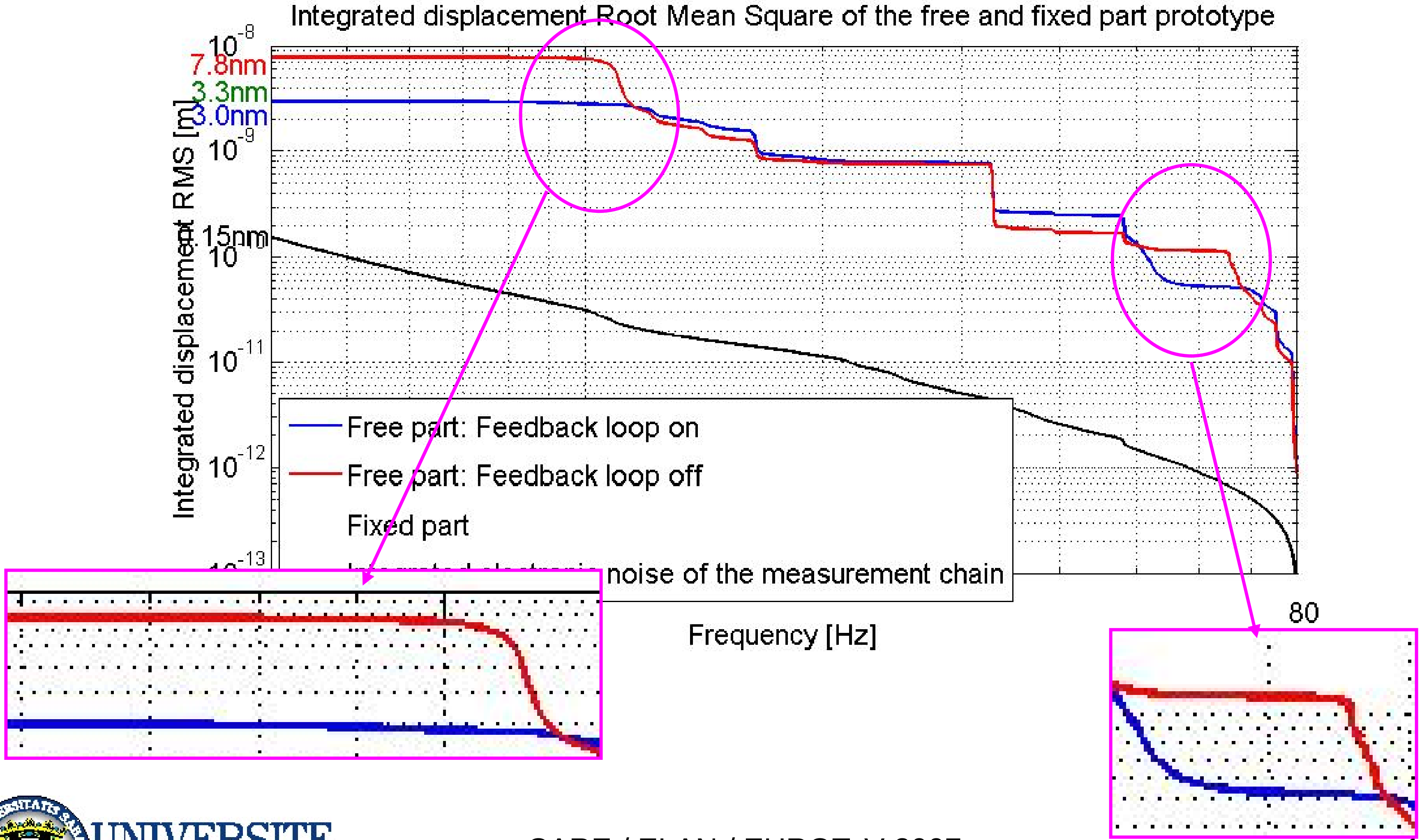
Tests with the large prototype

✓ **Results : Power spectral density**



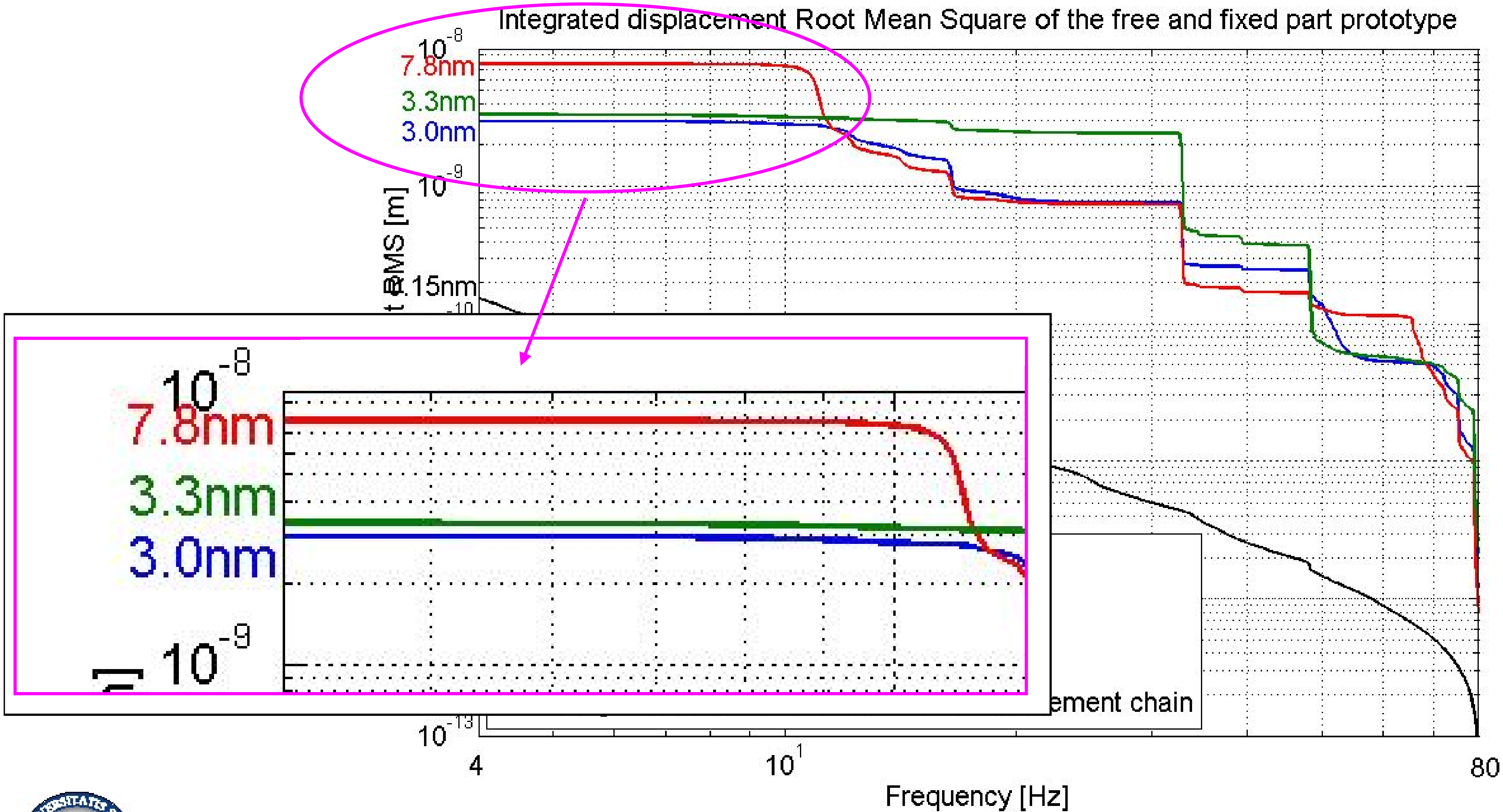
Tests with the large prototype

✓ **Results : integrated displacement RMS**



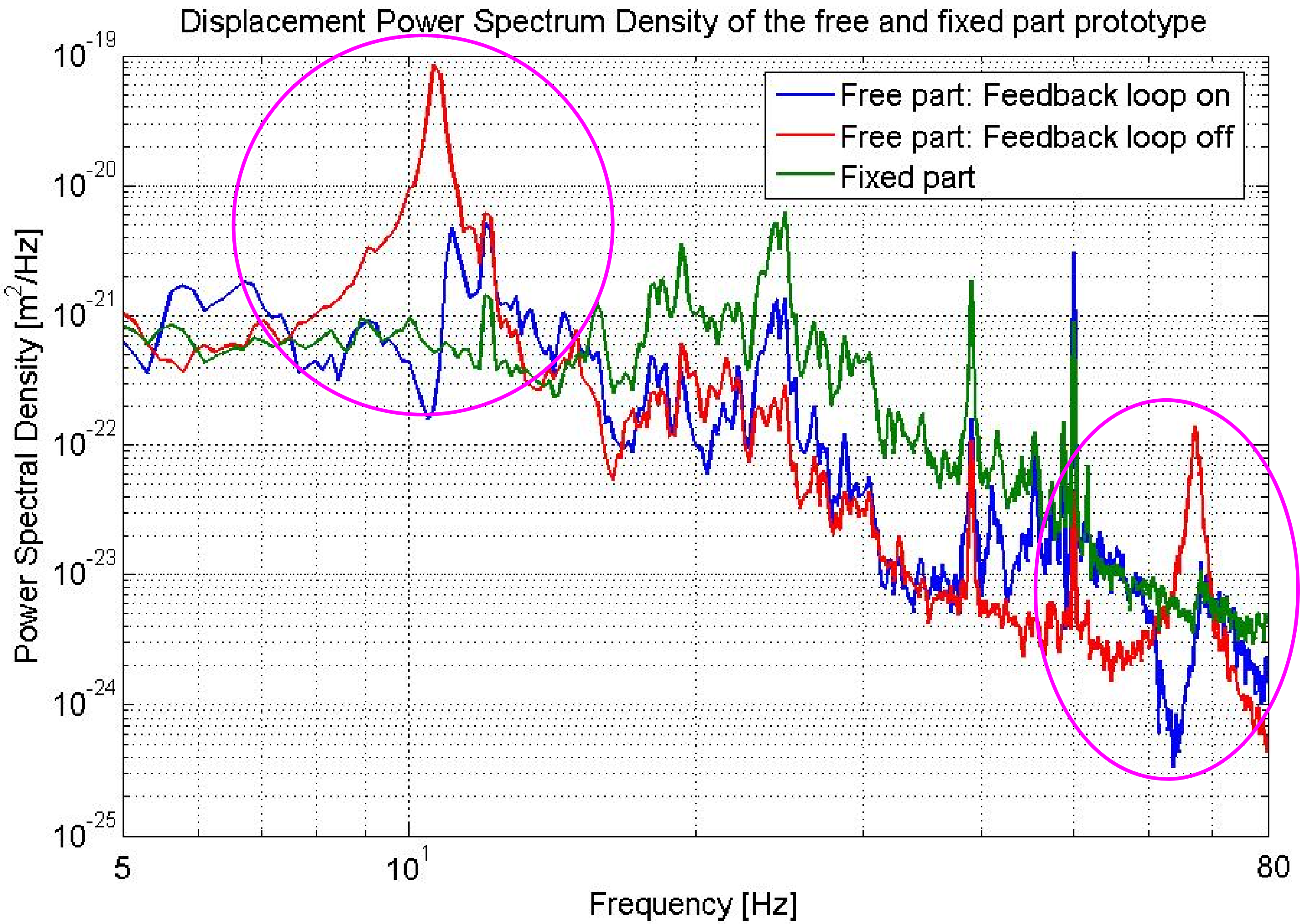
Tests with the large prototype

✓ **Results : integrated displacement RMS**



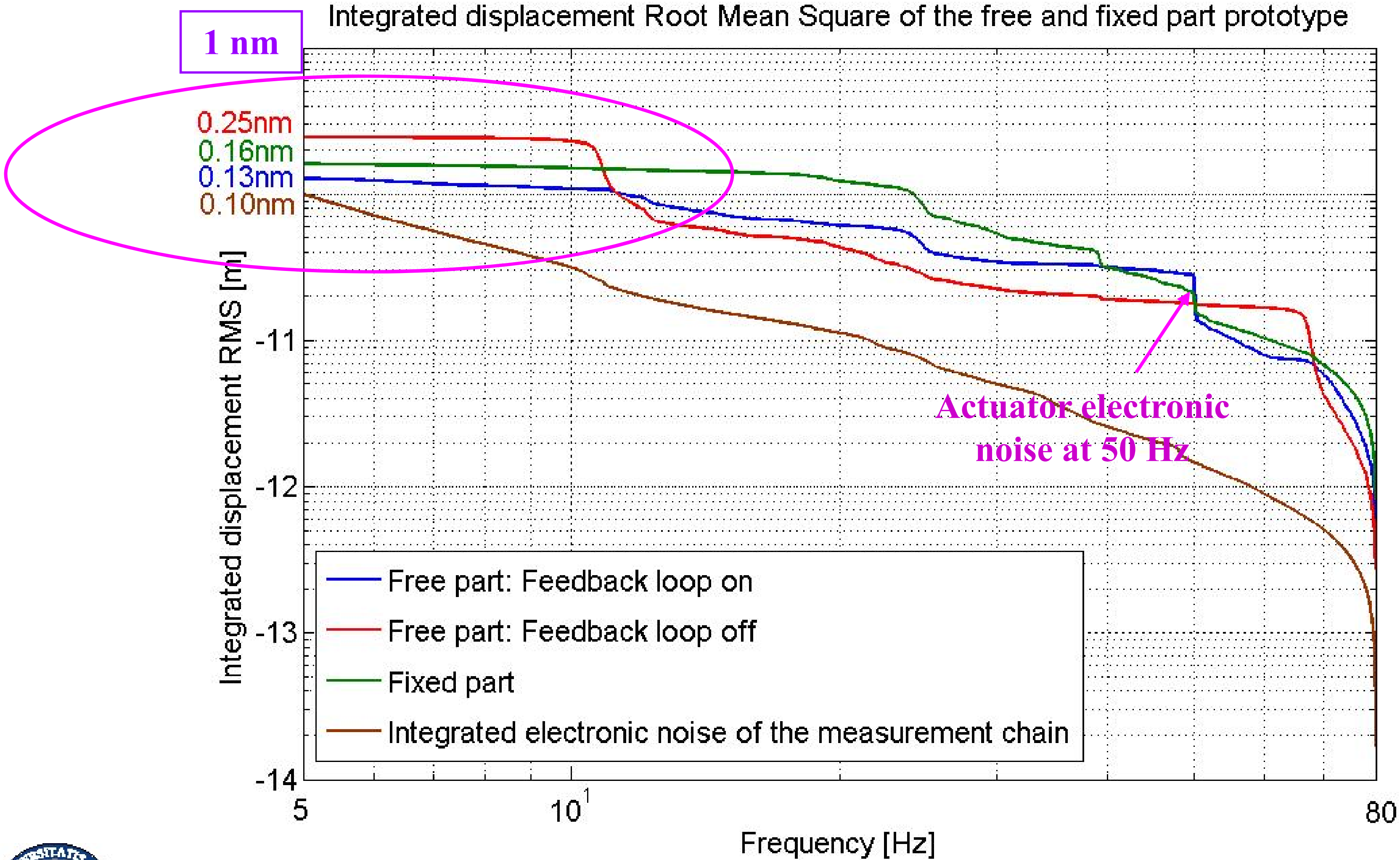
Tests with the large prototype

✓ **Results : Power spectral density (with active table ON)**



Tests with the large prototype

✓ **Results : integrated displacement RMS (with active table ON)**



Tests with the large prototype

✓ **Current state :**

- This method is efficient and easily adaptive to a mechanical structure

✓ **Current and future works :**

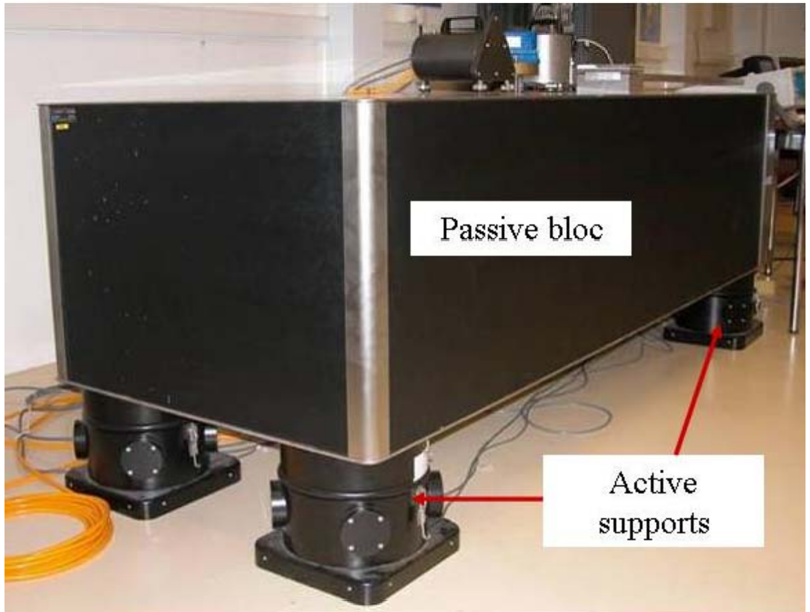
- **Minimize the influence of a bandwidth rejection on the neighbour frequencies.**
- Finish the robustness tests.
- Parallelize a second real time setup for increasing the number of rejected disturbances (with mixed types of algorithms), in order to obtain an optimal RMS.
- Combine with active isolation.

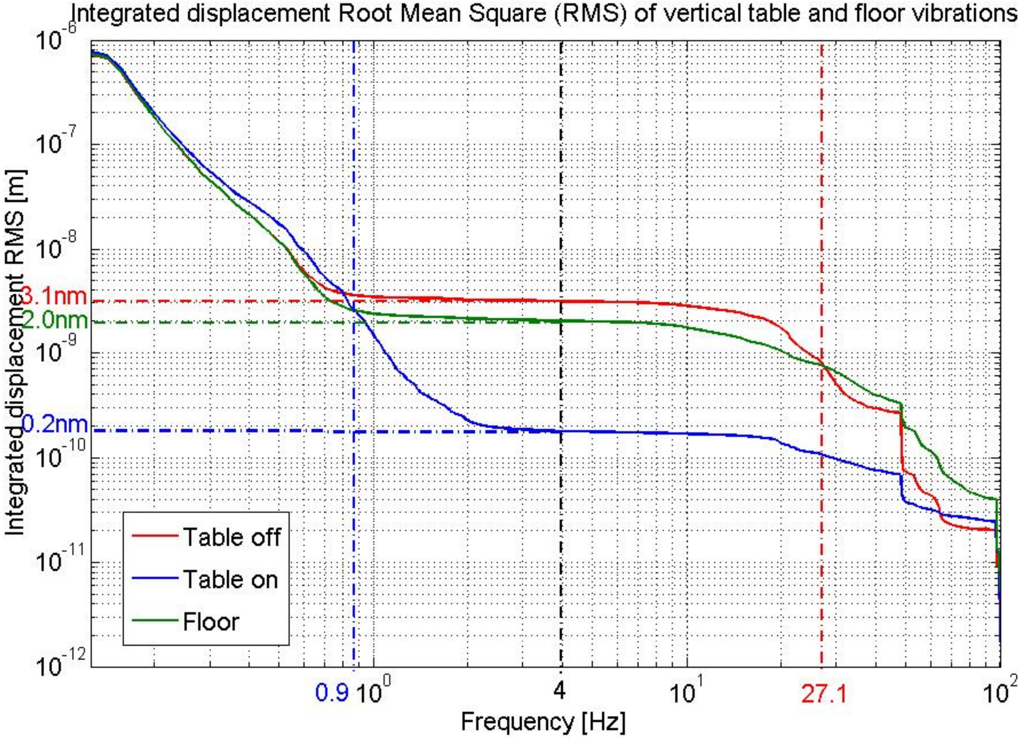
➢ Obtain these last results but in a critical configuration (for example when the motion of the beam is without rejection about 30 to 100 nm)

➢ Obtain these results all along the beam

The industrial solution

✓ **Test of industrial solutions : the TMC table of CERN.**





✓ Composed of a passive bloc, placed on 4 active feet (STACIS).

✓ Principle and all characteristics are known but the process is unknown.

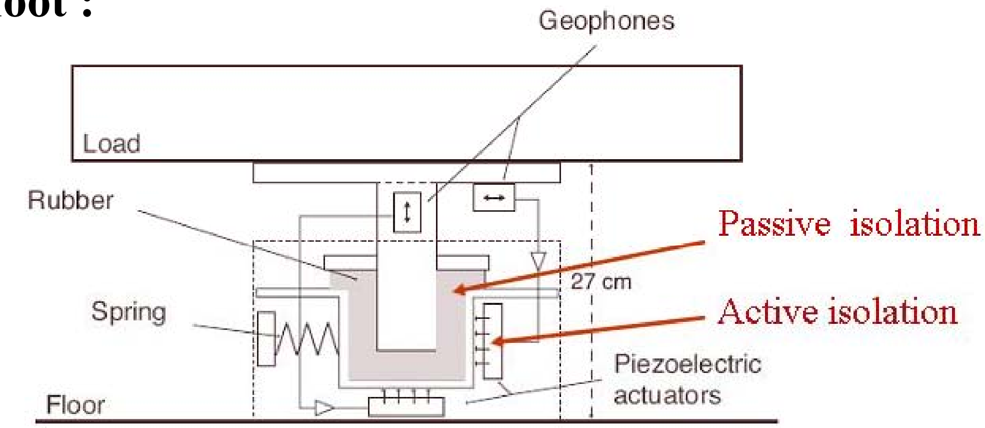
➢ Efficient but partially a “black box”…

Reasons of this study and the STACIS feet

✓ In the case of a possible partnership, we have no competence about active isolation.

✓ In the case of the development of a low cost table (this one is very expensive), we have no information about the mechanism (mainly the feedback loop).

✓ **STACIS foot :**



(Thesis of S. Redealli)

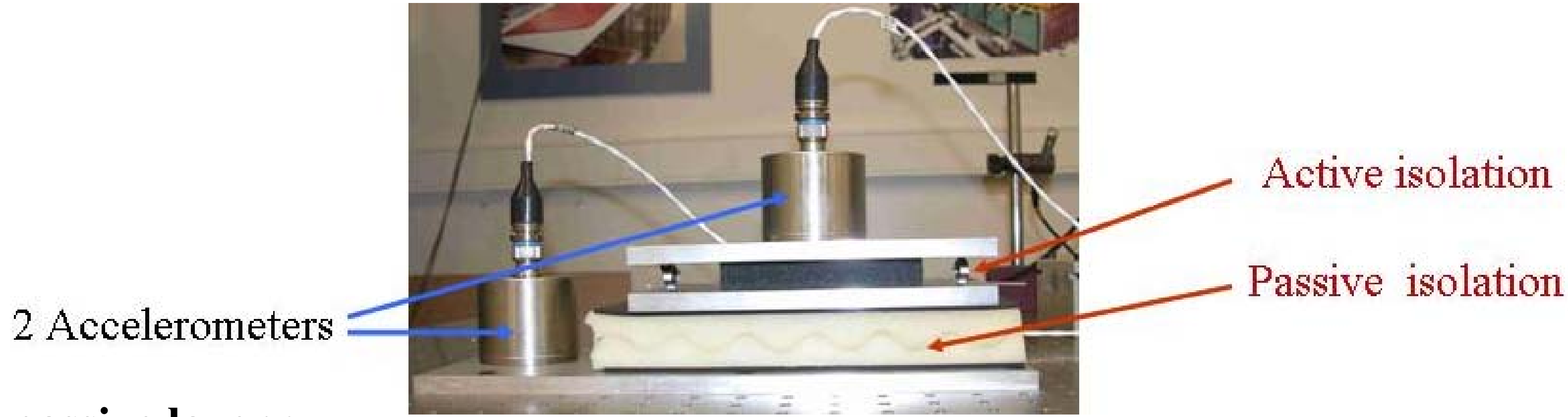
- <u>Passive isolation :</u> attenuates all the high frequency disturbances but amplifies the low frequency disturbances (like a resonant filter).

- <u>Active isolation :</u> attenuates the disturbance amplified by the passive isolation (low frequencies disturbances).

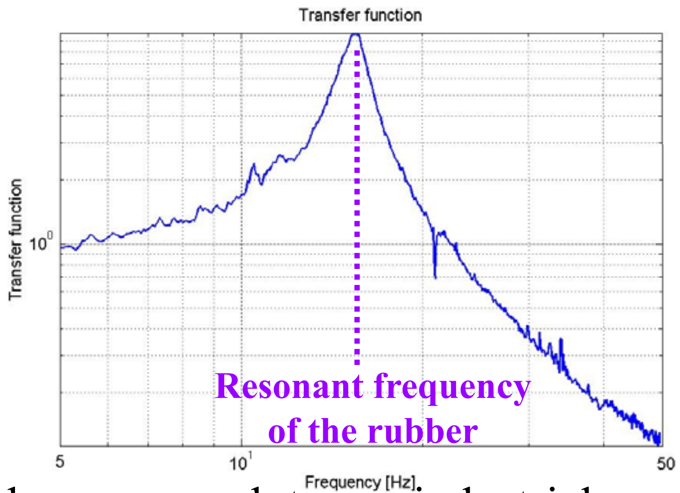
➢ **Test of active isolation on a small mock-up…**

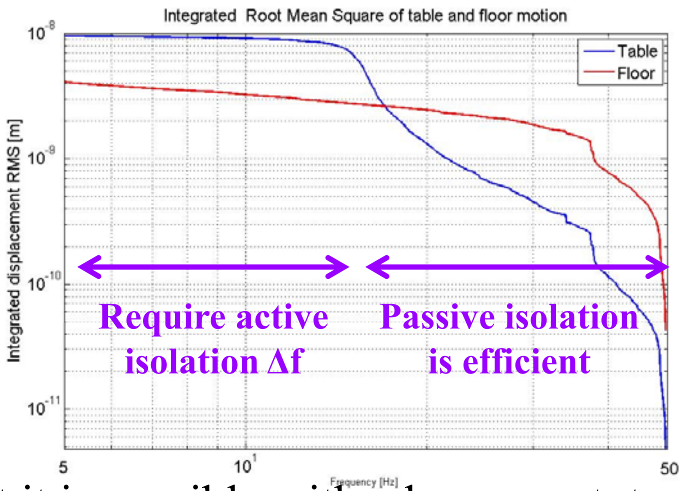
The small and elementary mock-up

✓ **Association of active and passive isolation :**



✓ **The passive layer :**





→ Not heavy enough to use industrial products, but it is possible with a larger prototype.

The active part

✓ **Algorithm : test with the LQG command (Linear Quadratic Gaussian)**

- The Model is definable, so a classical algorithm based on a model is appropriate.
- This type of algorithm is adapted for noisy system, so for the seismic domain.

✓ Simulation under Matlab - Simulink in state space representation :

- Test of a mass - spring system excited by a measured sequence of the ground motion

✓ Test in real time with the small built mock-up :

➢ Future works : expected results at the next meeting!!

→ Depending on the quality of the results, possible transposition to support the large mock-up with industrial rubber, in order to have a complete solution with the active compensation.

Conclusions

✓ **Hardware :**

- Acquisition chain able to measure at a nanometer scale
- Actuators to create nanometer displacements
- A real time solution to run automatics algorithm

✓ **Control :**

- 2 types of algorithms for active compensation
- A beginning of study for active isolation

➢ We have succeeded in stabilizing an elementary structure at a nanometer scale with a natural environment.

✓ **Future prospects :**

- The purpose now is to obtain the best possible stabilization all along the elementary mechanical structure (lower or equal to the imposed tolerance)

ANNEXES

Command with internal model

✓ **Similarities of tuning between the initial algorithm (state space for punctual disturbances) and this one (CIM for large peaks) :**

State space	Command with internal model
▪ Amplification in open loop. ▪ Difference of phase in open loop. ▪ Setting time.	▪ Determinate a model which corresponds to the process for the selected bandwidth with the same : - Amplification in open loop. - Difference of phase in open loop. - Damping of the selected eigenfrequency. ▪ Build a corrector from this model, which is stable, meaning respects the rules of automatic.

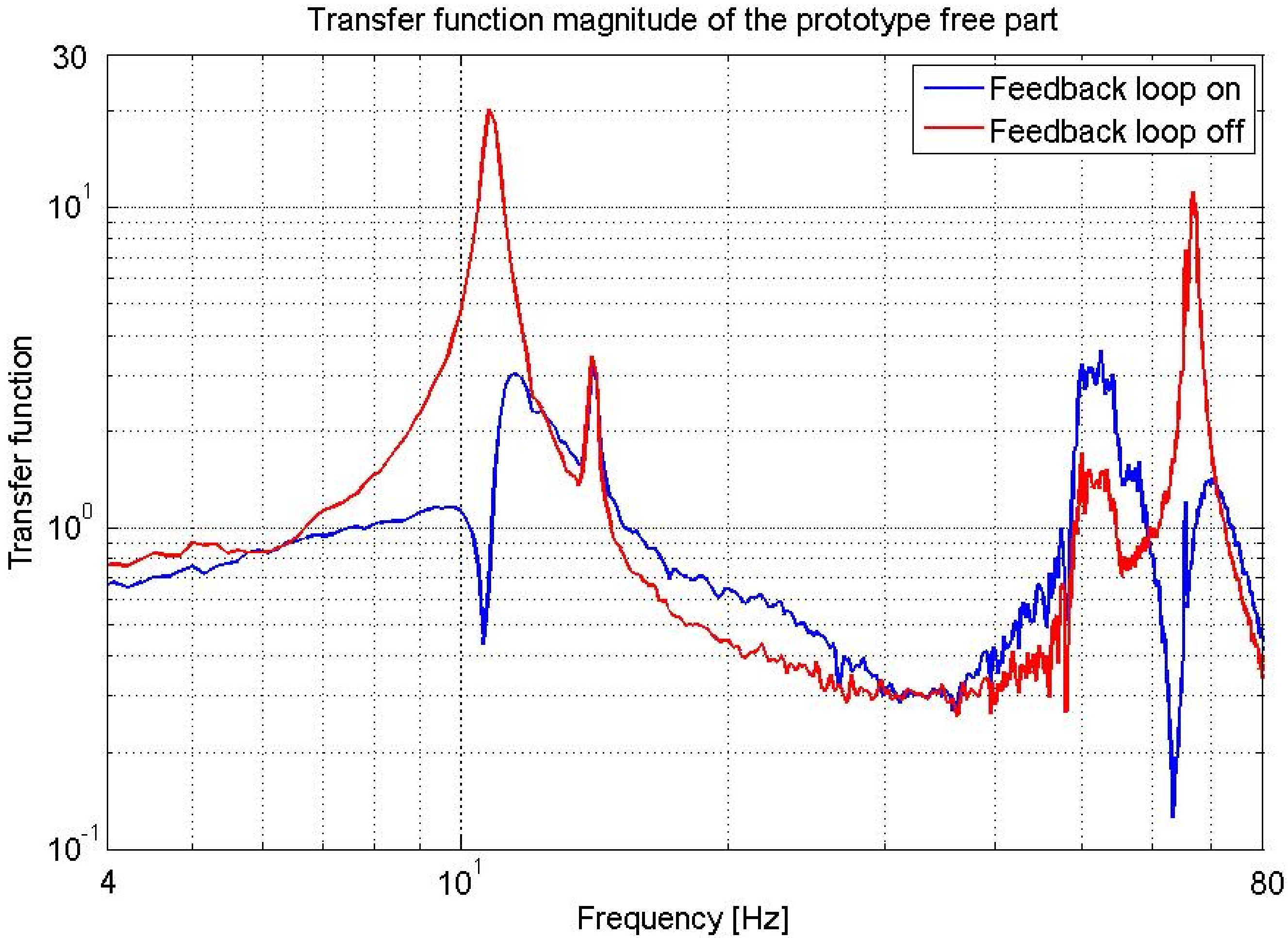
✓ To determinate the damping values, there are different methods :

- Theoretical : modelling…
- Experimental : hammer test, in function of the amplification…

→ **The requirements of this algorithm are a bit more complex but still basic, so realistic !!**

Tests with the large prototype

✓ **Results : transfer function between the displacement at the clamping and at the end of the beam :**



Sensors noise measurement at LAPP

✓ **Sensors noise estimation (Corrected difference calculation):**

→ Two sensors of the same model put side-by-side (2 SP500 sensors)

$$PSD_c(f) = 2(1 - C(f))\sqrt{PSD_1(f) PSD_2(f)}$$

✓ **Environmental conditions:**

1. Very low ground motion (coherence as low as possible: best estimation)
2. Low-frequency noise: No fast temperature and pressure change in time

1. Sensors on the CLIC active table / Measurements done the night / Shutdown of all computers / Acquisition system outside the room

2. Ventilation cut / Doors closed: 10 hours before measurements