ET suspension concept

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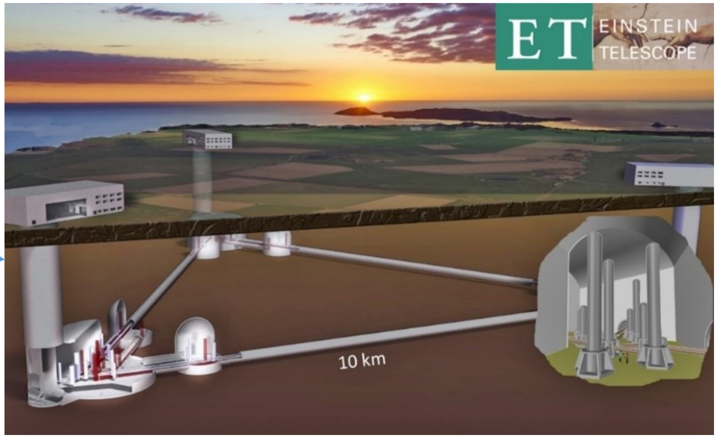
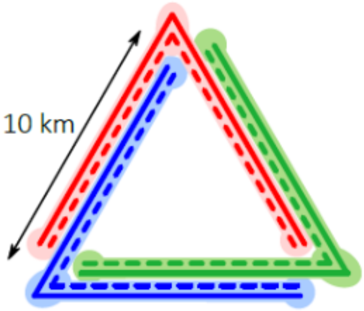
Talk summary

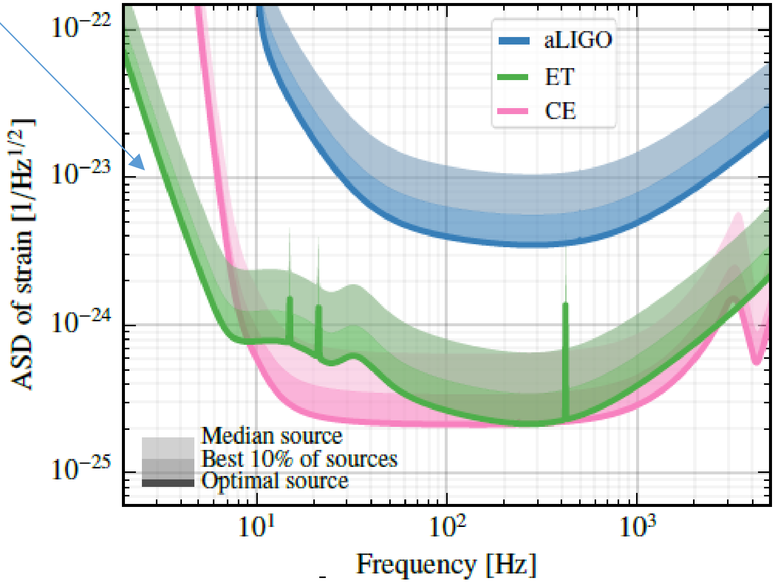
- Introduction
- Challenges for reaching ET requirements at low frequency
- Strategies for improving seismic isolation
- Reference solution → evolution of AdV seismic isolation system
- One example of R&D for further improvement → nested inverted pendulum
- Conclusions

Einstein Telescope (ET)

- ET is a project for a 3rd generation GW antenna
- The general approach is quite different from the one of CE
- ET is an underground, cryogenic detector in a triangular configuration and 3 interferometers with 10 km long arms.
- The target is improving the sensitivity by more than one order of magnitude and extending the detection band in low frequency down to 2-3 Hz.
- The antenna is designed in a xylophone configuration with two parallel interferometers, one optimized for low frequency and the other optimized for hi frequency







ET layout

- 3 Michelson interferometers. with 60° angled arms, sharing the same tunnels

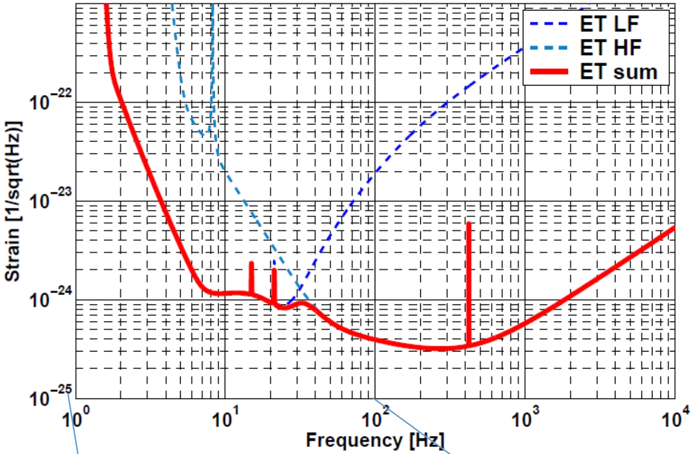
- Each Michelson is composed by two independent interferometers, one optimized for low frequency and the other for high frequency

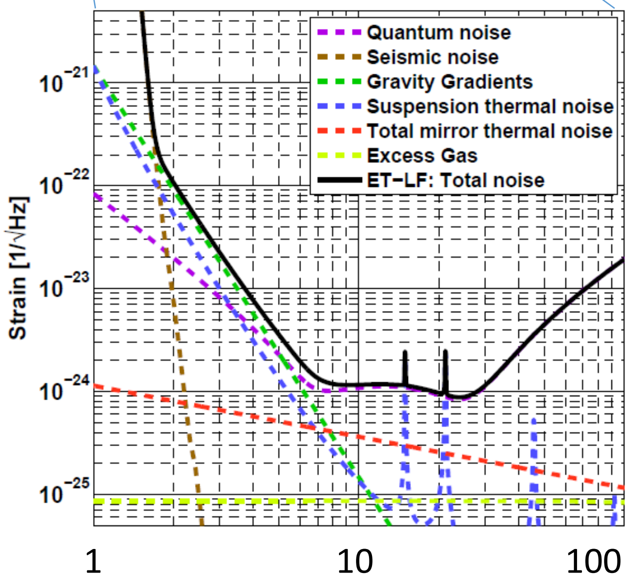
Limiting noise for ET-LF:

- Quantum noise → Squeezing
- Thermal noise → mirror, coating and wire materials and cryogenic operation
- Gravity Gradients → Newtonian Noise Cancellation
- Seismic noise → underground operation and improved seismic isolation

Role of the seismic isolation system is to reduce seismic noise at a level that doesn't spoils the design sensitivity

We will concentrate on ET_LF suspension system for cavity mirrors, that outs the most challenging reuirements





Seismic isolation

Reaching the ET design sensitivity is an ambitious task requiring enormous technological development on all the aspect of the detector

For seismic isolation we started from the Virgo heritage:

The Virgo/Adv Virgo Super-Attenuator has been used successfully for more than 20 years, ensuring that the Virgo interferometer sensitivity has never been directly limited by transmitted seismic noise.

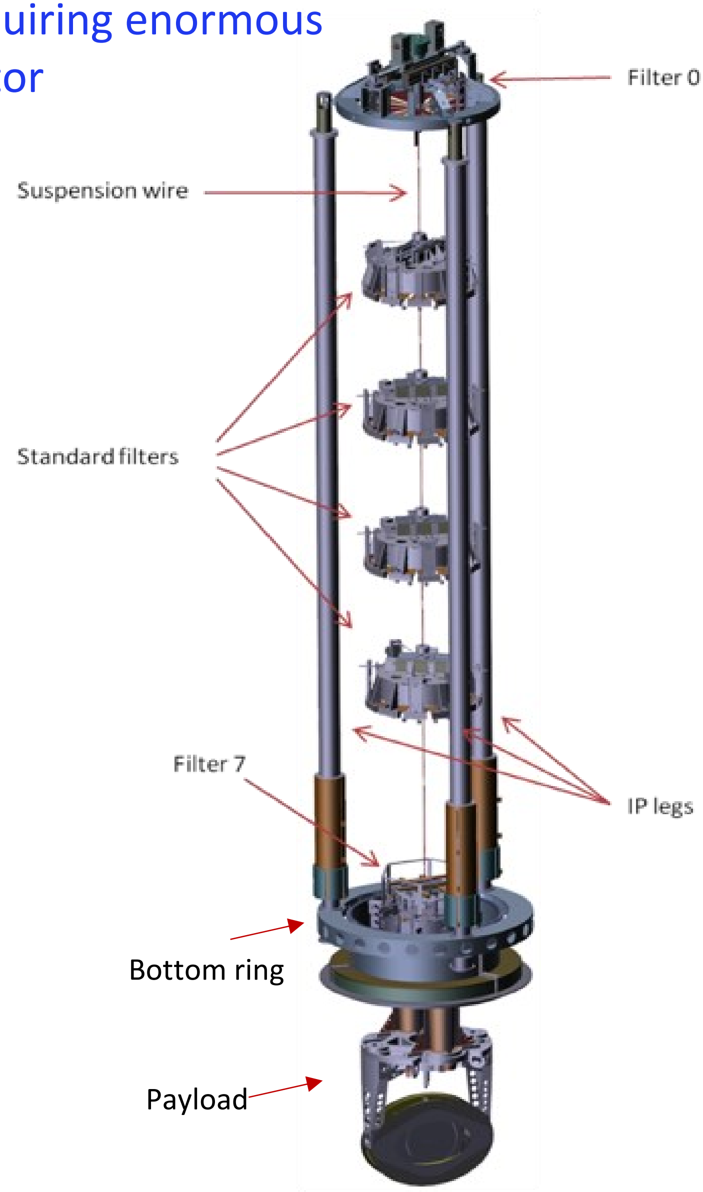
The SA is made by:

- A bottom ring equipped wit 3 PZT for angular control
- A pre-isolator inverted-pendulum (IP)
- A passive filter chain
- A Payload (mirror and control elements).

The total length is about 9 m.

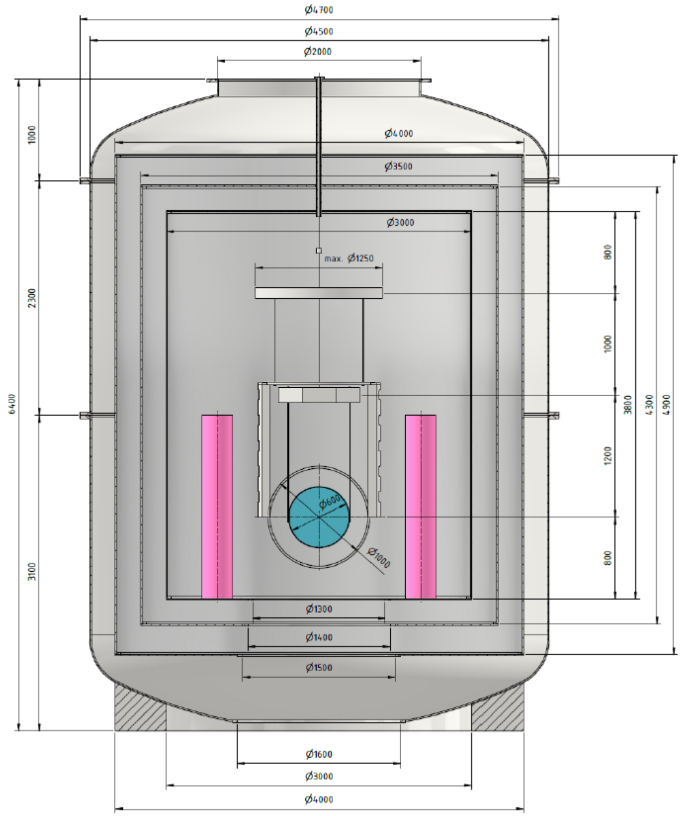
Total mass ~ 900 kg
Mirror mass 40 kg
Payload total mass ~ 200 kg

The SA is equipped with a complex system of sensors and actuators at different stages, with a hierarchical control system using local and global sensors



Challenges for reaching the ET_LF seismic noise requirements

- Target ~ 10^{-19} m/Hz$^{1/2}$ @ 2/3 Hz → more than 10^{-5} with respect to 2nd generation
- Underground operation → suspension length determines minimum cavern height
- All filter chain normal modes < 2 Hz
- There is a large and heavy payload hosted in a large cryostat → Their parameters are under definition; choices are driven by heat transfer and thermal noise
- the seismic isolation system should stay at room temperature and must be adapted Cryostat/payload parameters



Current payload parameters → mirror mass 180 kg, total mass 850 kg

AdV payload parameters → mirror mass 40 kg, 200 kg

How can we improve seismic isolation with the AdV technology ?

1) Increasing seismic isolation system length

2) Increasing total seismic isolation mass (or better Total mass/Payload mass)

3) Improving passive filter chain by

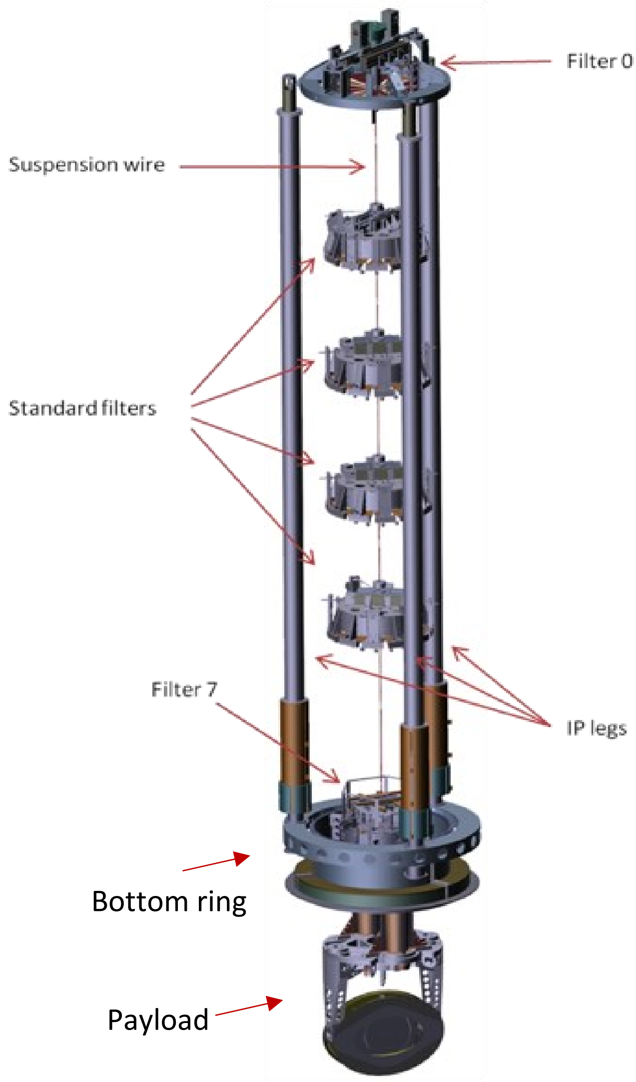
- Optimization of filter chain masses and length distribution
- Improved Anti-Spring for vertical isolation

4) Improving pre-isolation

- Active seism reduction
- New pre-isolator concepts

To keep in mind:

- Tilt and vertical to longitudinal Cross talk
- Noise of control systems

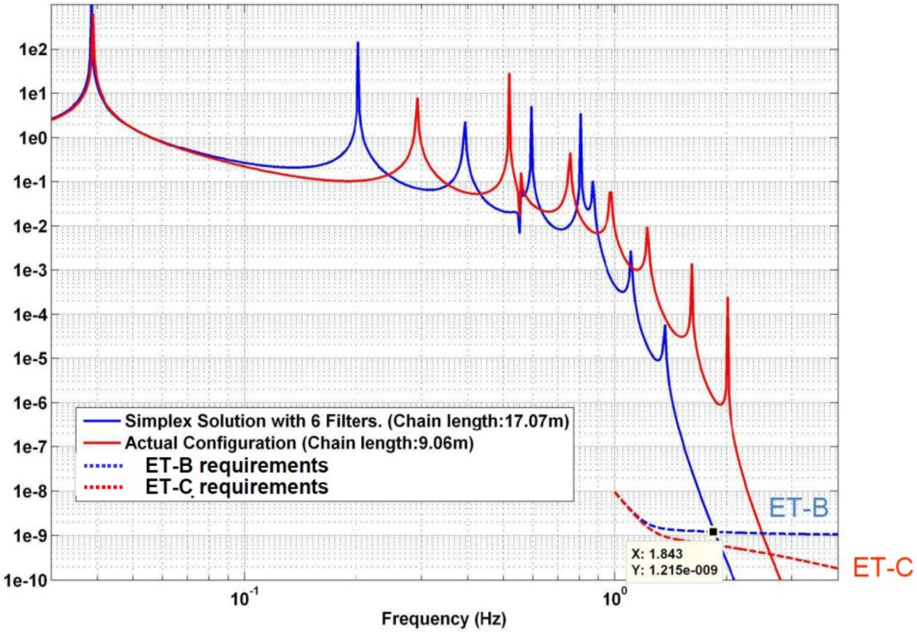


The ET_LF reference solution

In the “Einstein gravitational wave Telescope conceptual design study” only the first option was considered (increasing total length) this turned out in a Virgo-like super-attenuator with a total length of 17 m (starting from the 9 m of AdV)

We are aware that this is not an optimal solution, furthermore, this was studied for a payload that is not like the present design

Now there are several efforts in the suspension division to design an updated and optimized solution that can fulfill the requirements staying somewhere in between 9 and 17 m :

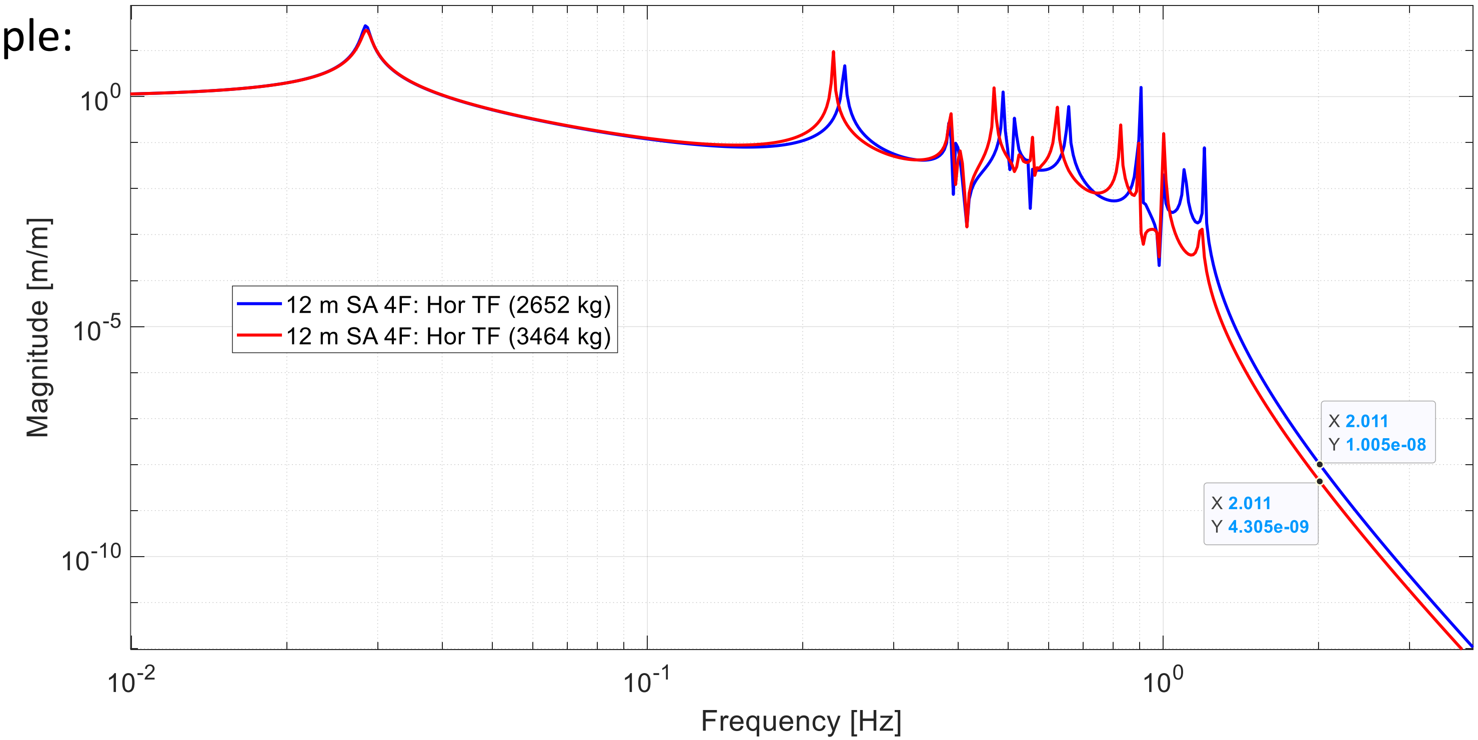


Improvement strategies: total mass

A relevant aspect is the ratio of the total suspension mass M over the payload mass m

For Virgo the M/m was ~ 4 → for an 850 kg payload, we should use M > 3000 kg

One example:



We can gain a factor ~ 2.5 in attenuation by increasing M/m from 3 to 4

Improvement strategies: Optimization of filter chain

Optimization:

- A seismic isolation chain with equal masses is not optimal → seismic isolation can be improved by optimizing mass distribution along the chain.

The concept is described, with a simplified analytical model, in an old paper:
The starting point is a quite old paper based on an analytical approach with a simplified model (point-like masses):

"Optimization of multipendular seismic suspensions for interferometric gravitational-wave detectors",
A. Bove, L. Di Fiore, E. Calloni and A. Grado, ***Europhys. Lett., 40*** *(6), pp. 601-606 (1997)*

In the following I will report the main results, referring to the paper for datails

Optimization of filter chain

Simple model: point-like masses, *N* stage seismic isolation

Assumptions:

Pendulum total length $L = \sum_{i=1}^{N} l_i$, payload mass $m_N = m$ and total mass $M = \sum_{i=1}^{N} m_i$

The loads on each stage is: $M_i = \sum_{n=i}^{N} m_i$

The TF can be approximated as $\mathrm{TF}\,(\omega > \Omega_N) \cong \frac{\prod_{i=1}^{N} \Omega_i^2}{\omega^{2N}}$

It can be shown that:

For horizontal motion:

$$\prod_{n=1}^{N} \Omega_n^2 = \left(\prod_{i=1}^{N} \frac{g}{l_i}\right) \left(\prod_{j=1}^{N} \frac{\sum_{h=j}^{N} m_h}{m_j}\right) = a(l_1 \dots l_N) b(m_1 \dots m_N)$$

It can be shown that:

The minimum of *a*(l_i) is for: $l_i = \frac{L}{N}$ ➔ **All the wires have the same length**

The minimum of *b*(l_i) is for: $\frac{M_i}{M_{i-1}} = \frac{M_{i+1}}{M_i} = q \qquad (i = 2, \dots, N-1)$ ➔ **M_i in a geometrical progression**

with $q = \left(\frac{M}{m}\right)^{\frac{1}{1-N}}$ ⇨ $m_i = m \left(\frac{M}{m}\right)^{\frac{N-i}{N-1}} \left[1 - \left(\frac{M}{m}\right)^{\frac{1}{1-N}}\right] \qquad (i = 1, \dots, N-1)$

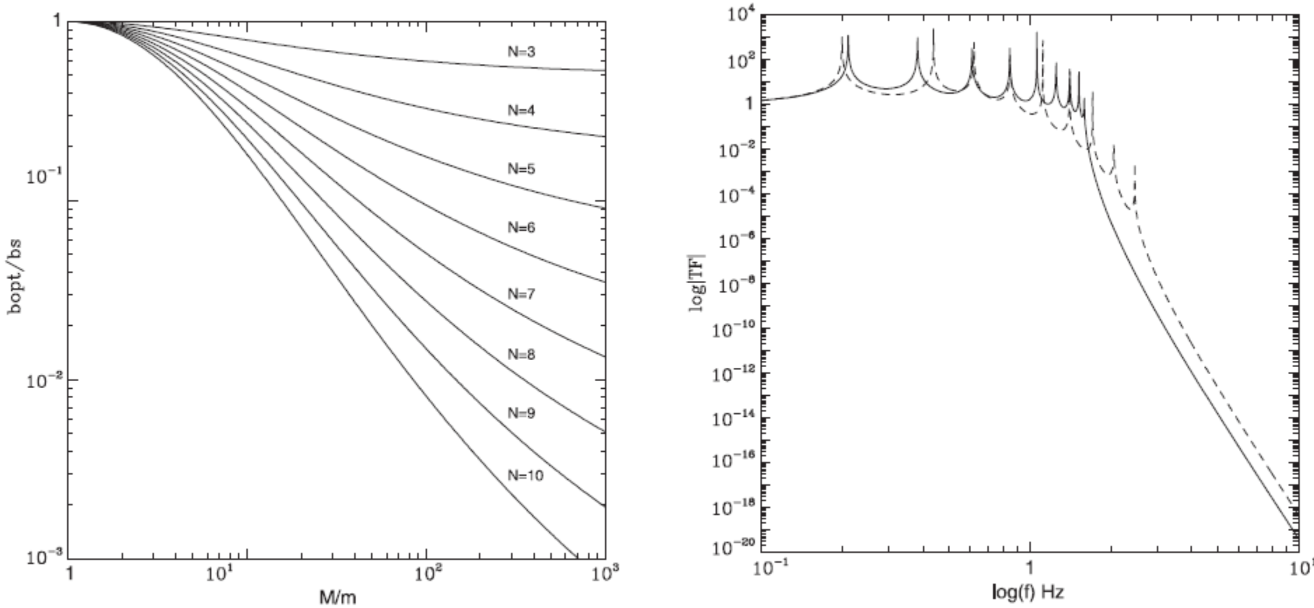


Fig. 1

Fig. 2

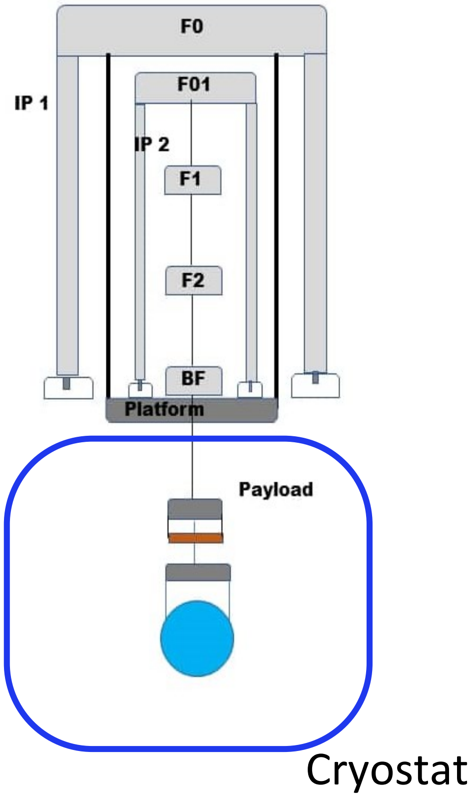
Fig. 1. – Plot of b_{opt}/b_S, the ratio of the optimum b over the standard one, as a function of M/m, for a SA with a number of stages ranging from 3 to 10. This ratio gives directly the increase in attenuation obtained by using the optimized configuration.

Fig. 2. – Comparison of the horizontal TF of a 9-fold SA similar to the one designed for the VIRGO antenna, computed for the optimized (solid line) and standard (dashed line) mass distribution.

- The analytic optimal mass distribution gives a starting point for the design
- A complete 6 DOF model (Octopus) is then used for a complete design considering extended bodies and cross-talks

Improving pre-isolator → two-fold inverted pendulum

- An old idea proposed several years ago: No experimental test so far
- There is an ongoing R&D activity (NGSA: new generation Super-Attenuator) funded by INFN (Pisa, Napoli and Univ. Sassari/Cagliari units) for developing and testing a Nested Inverted Pendulum pre-isolator



- Complex, heavy cryogenic payload (~ 850 kg) will be surrounded by a big cryostat
- The legs of the inverted pendulums must start above the cryostat

↓

- Shorter IPs legs (~ 4 m)
- Larger SA total mass

We performed preliminary simulation of three different configurations

CASE A:
I.Total length:8 m
II.Total mass: 2650 Kg

CASE B:
I.Total length:10 m
II.Total mass: 2650 Kg

CASE C:
I.Total length:10 m
II.Total mass: 3250 Kg

In all cases:

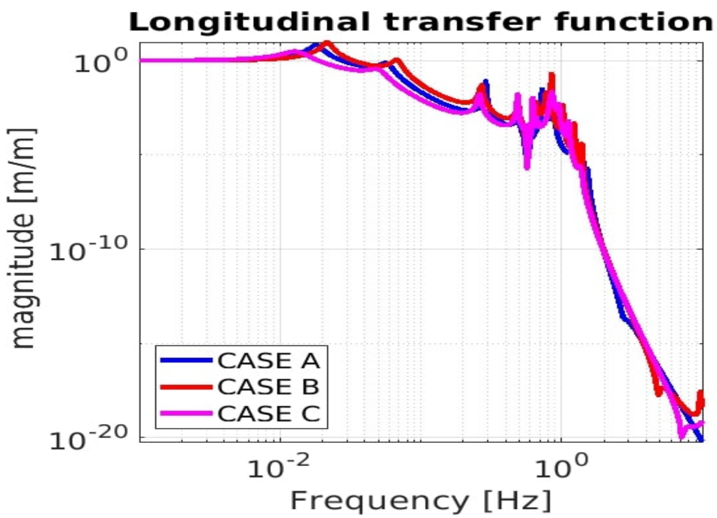
- Payload mass is 600 kg
- Filter MASs are based on the AdV technology (ferrite magnets)
- The mass distribution is optimized

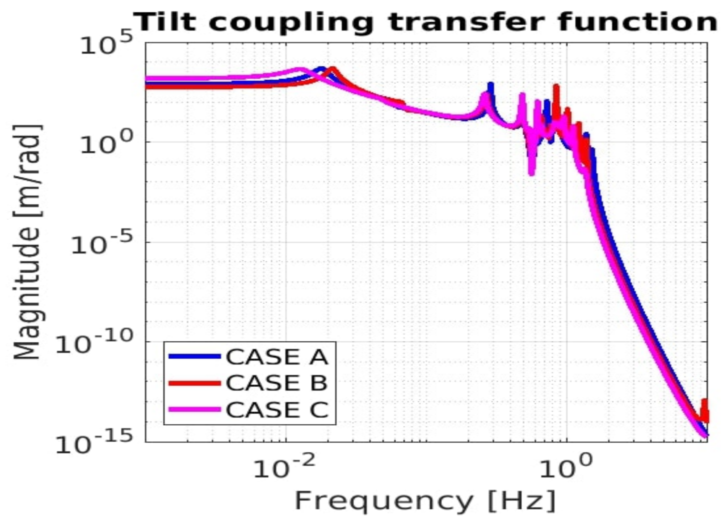
A → B Length: 8 → 10 m

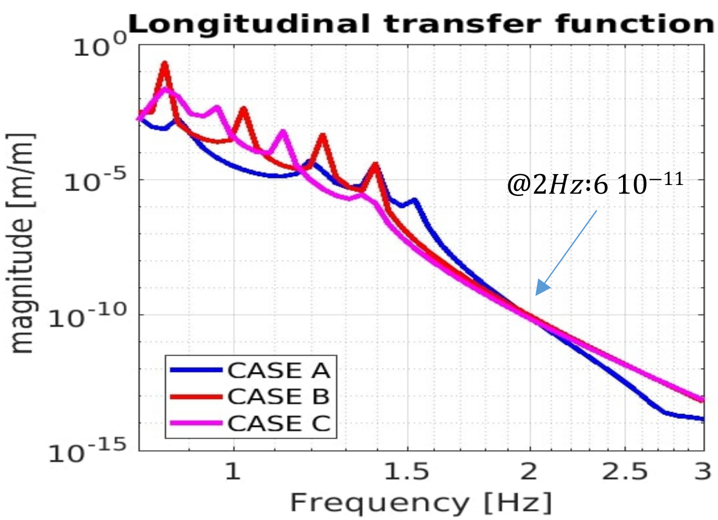
B → C Mass : 2650 → 3250 kg

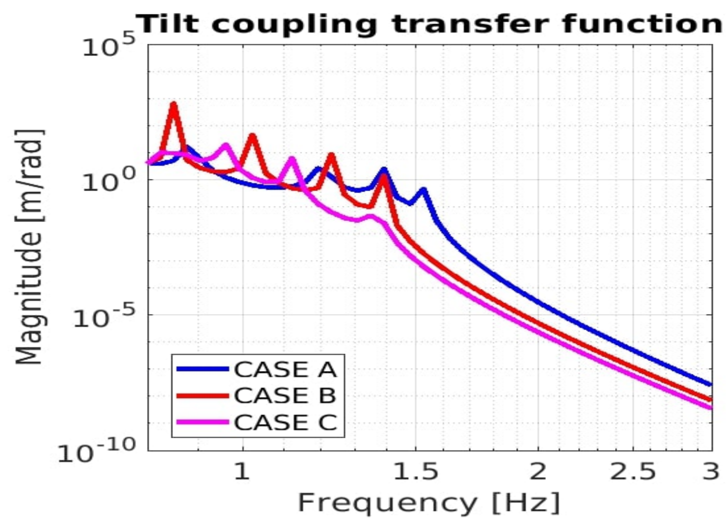
For more details see:
Bertocco et al, 2024, Class. Quantum Grav. 41 117004

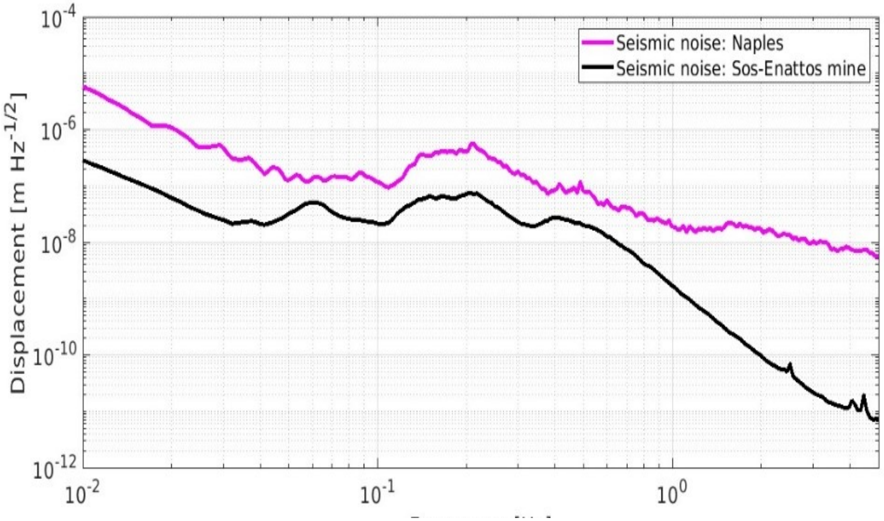
Evaluation of Longitudinal and Tilt coupling transfer functions

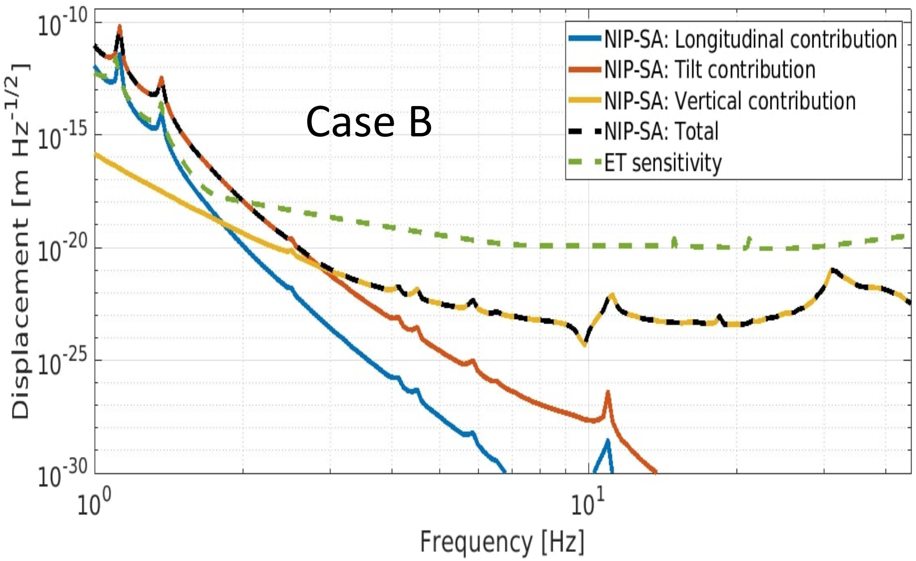












Tilt estimation $\alpha_0 = \frac{\omega}{v} x_0$

Assuming the values of υ (seismic wave speed) and x_0(longitudinal ground motion) to be about

3000 m/s and $8 \cdot 10^{-11}\, m/Hz^{\frac{1}{2}}$ respectively,

the estimated value of is

$\alpha_0 \sim 3 \cdot 10^{-13} \frac{rad}{Hz^{1/2}}$ @ 2 Hz

Horizontal seismic noise on the mirror il limited by

Tilt to longitudinal noise < 3 Hz
Vertical to horizontal noise > 3Hz

Note that from the submission of the paper one year ago the payload parameters have changed….

Development and test of a Nested Inverted Pendulum (NIP) prototype to be tested in PlaNET laboratory at Naples INFN.

Pisa, Napoli and Univ. Sassari/Cagliari

The goal is to built and test a NIP prototype in 1:2 scale, to be tested in the PLaNET Laboratory at INFN-Napoli

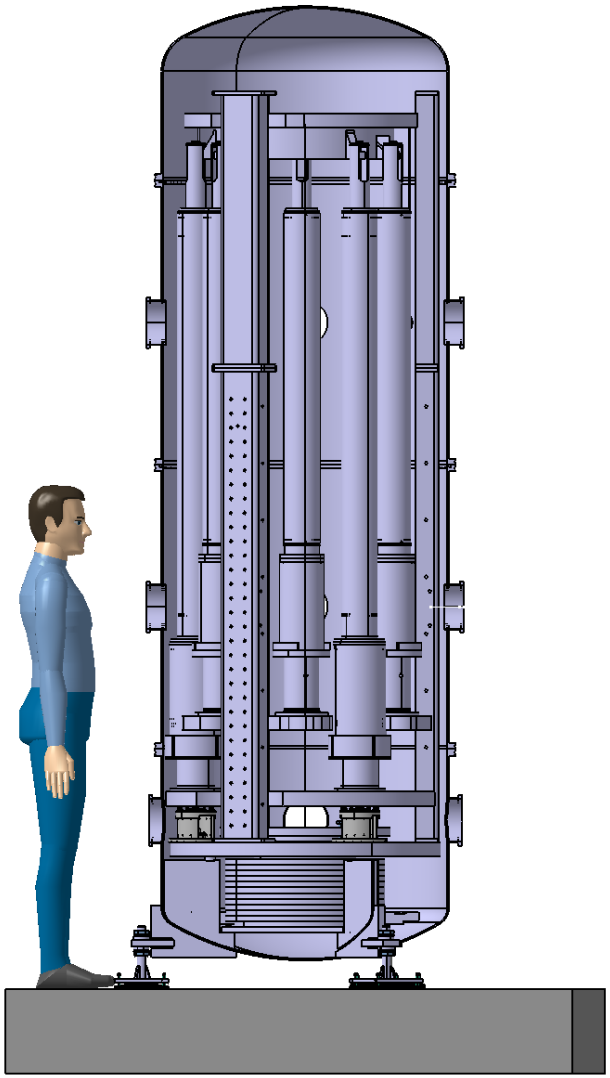
Total mass 1200 kg

Legs of about 1.7 and 1.4 m (excluding flex joints)

Dummy mass = 600 kg

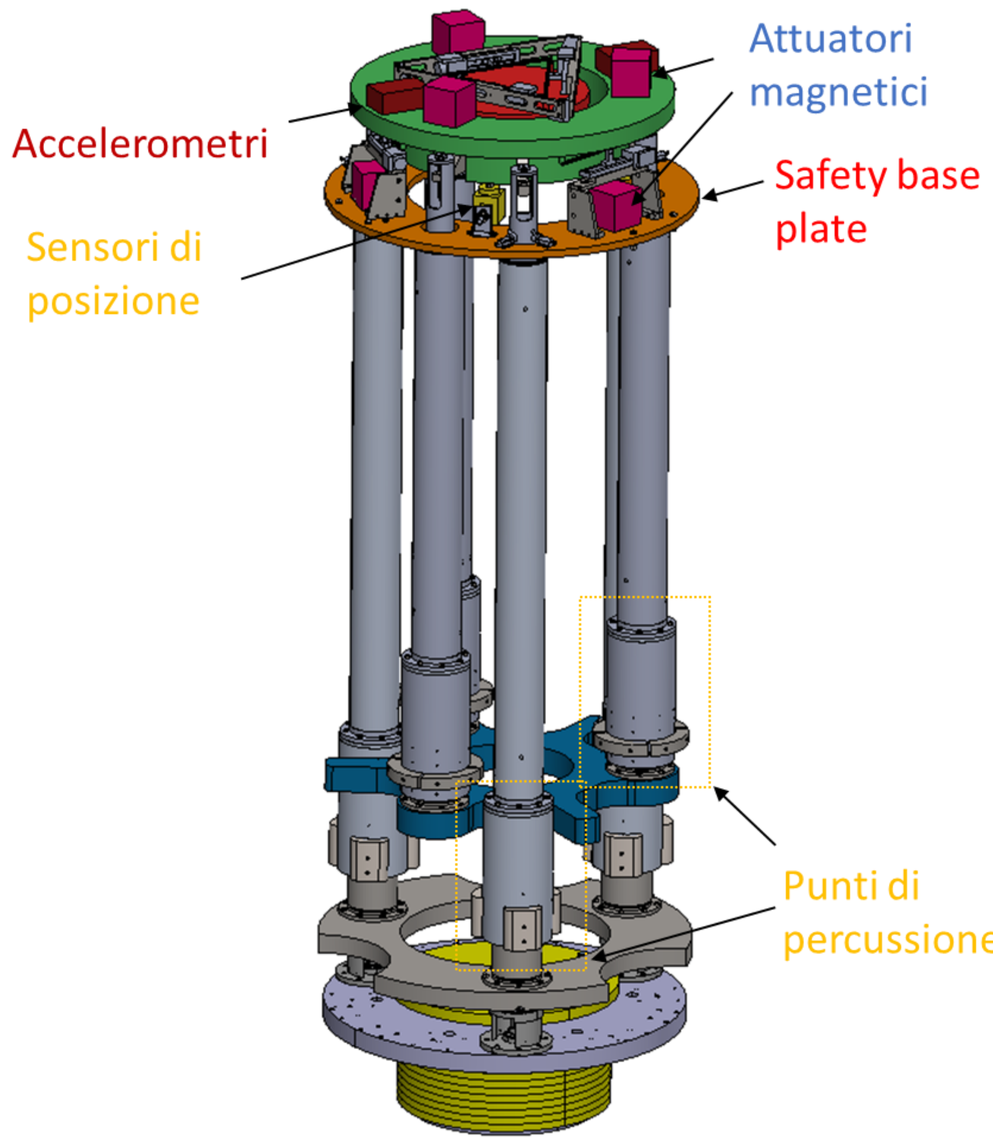
The design is based on preliminary studies with Octopus

The mechanical design is quite advanced
(it is supported by Octopus and FEM simulations



- Mechanical design is complete
- Building and procurement is quite advanced
- Assembling and integration will start at the beginning of 2025
- We expect first result by the end of 2025

If the test will be successful, this will be an interesting possible upgrade in seismic isolation systems.



Conclusions

- The Concept of the ET_LF seismic isolation system is based on the heritage of Virgo and Advanced Virgo

- The reference solution assumes a 17 m high Seismic-Attenuator

- There is room for further improvement and optimization with the aim to fulfill requirements while reducing SA height

- Various studies and R&Ds are ongoing for defining and testing new possible concepts and configurations for the ET_LF seismic isolator

Any proposed solution should address not only horizontal attenuation but also vertical and tilt cross-talks

Next talk by Paolo Ruggi will give some more insight on the effect of ground tilt

Thank you for your attention

GROUND ROTATION

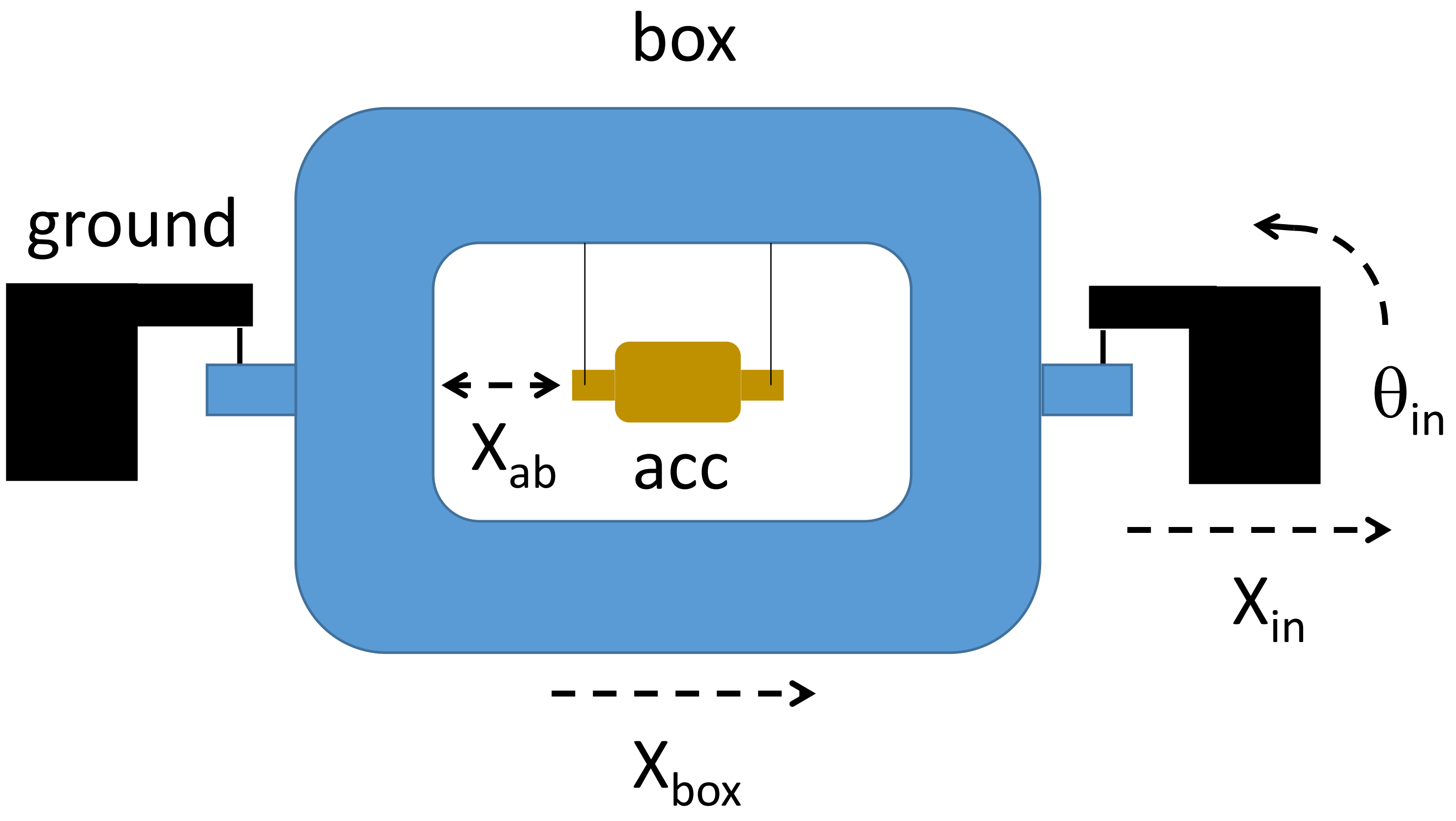
How it is transmitted to a suspended mass displacement

OCTOPUS MODELS

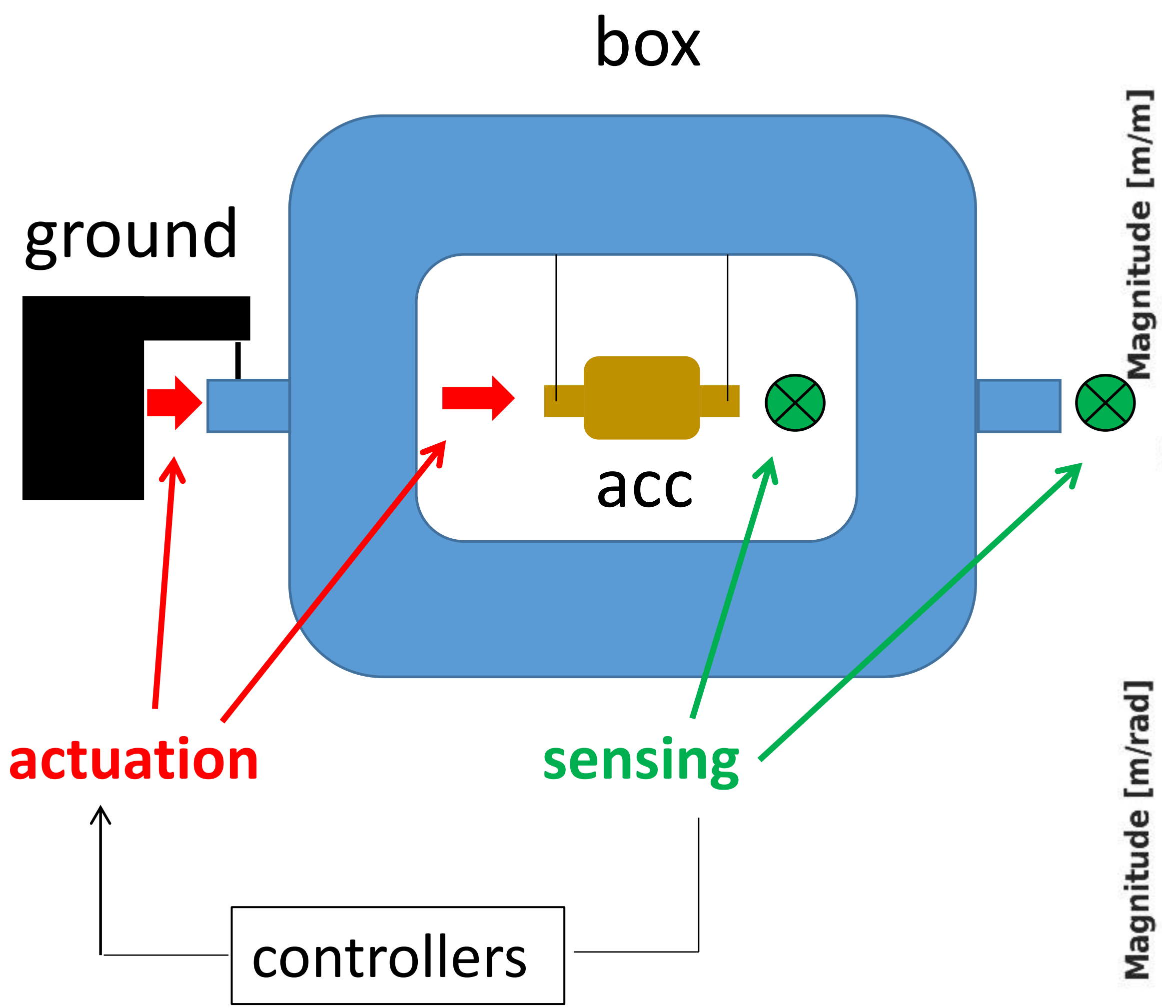
Transmission of vibrations through nets of rigid bodies interconnected by elastic/massive elements.

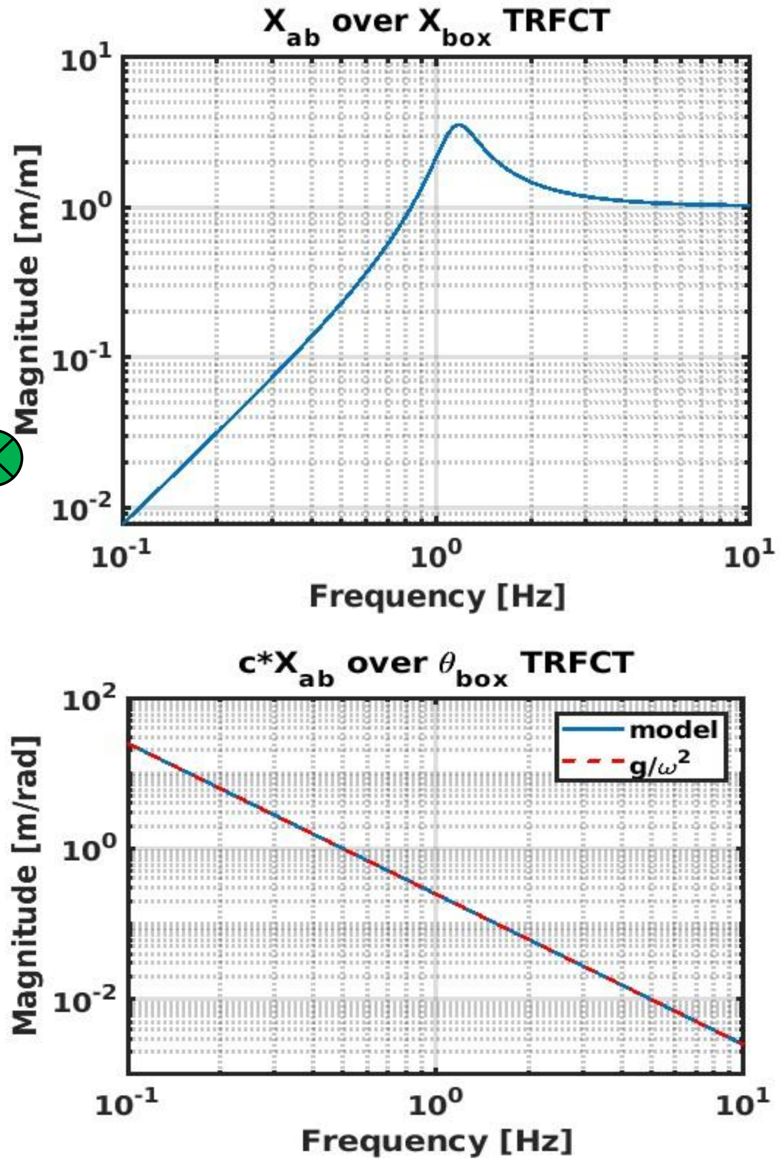
- Each body occupies a node, described by variables displacement and rotation in the space.
- Forces and torques can be applied in each node.
- Each element, rigid or elastic, is represented by a linear operator (impedance) in frequency domain, computed from the physical quantities associated to the element.
- Control loops can be implemented, defining a ‘spring-like’ impedance for each controller and linking two nodes by that element.
- The code provide the transfer function from any disturbance applied in an INPUT node to the vibration of any d.o.f. in any OUTPUT node.

Inertial control is limited by ground rotation



A model of inertial control made in OCTOPUS



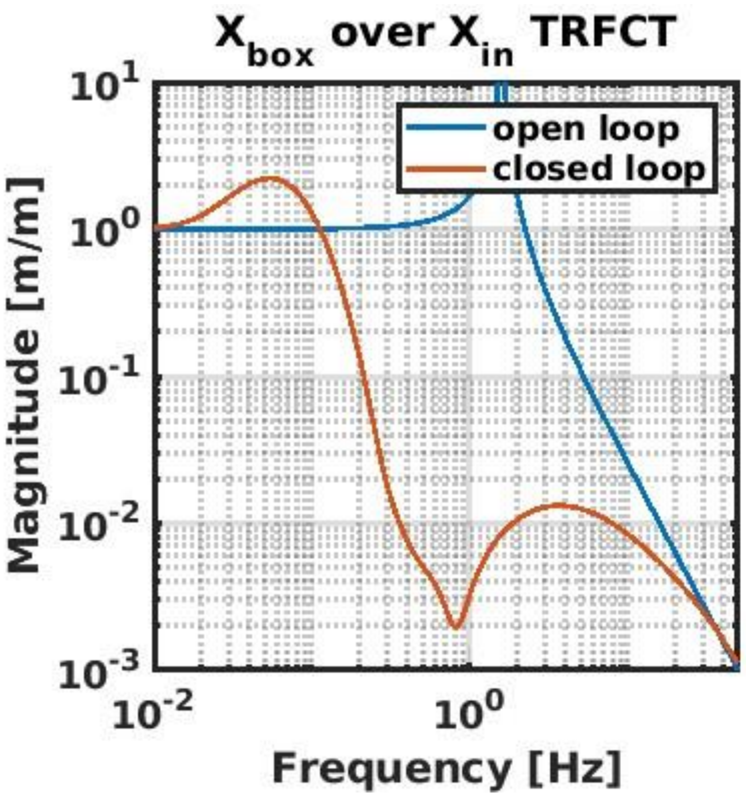


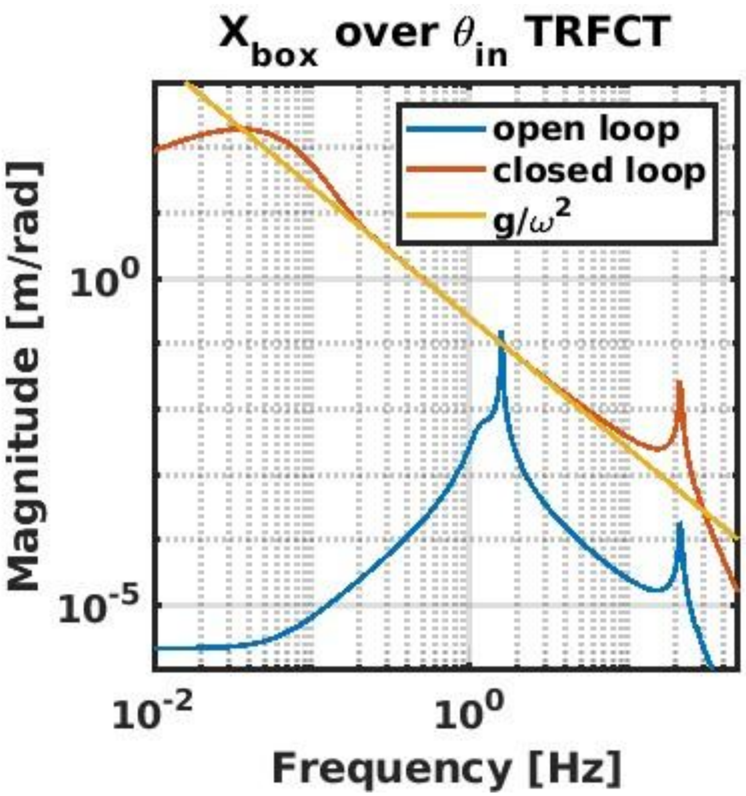
The internal loop is closed in order to damp the resonance.

The inverse of this curve is the calibration of the sensor response.

The calibrated response of the sensor to the box rotation is: **g/ω^2 m/rad**

A model of inertial control made in OCTOPUS



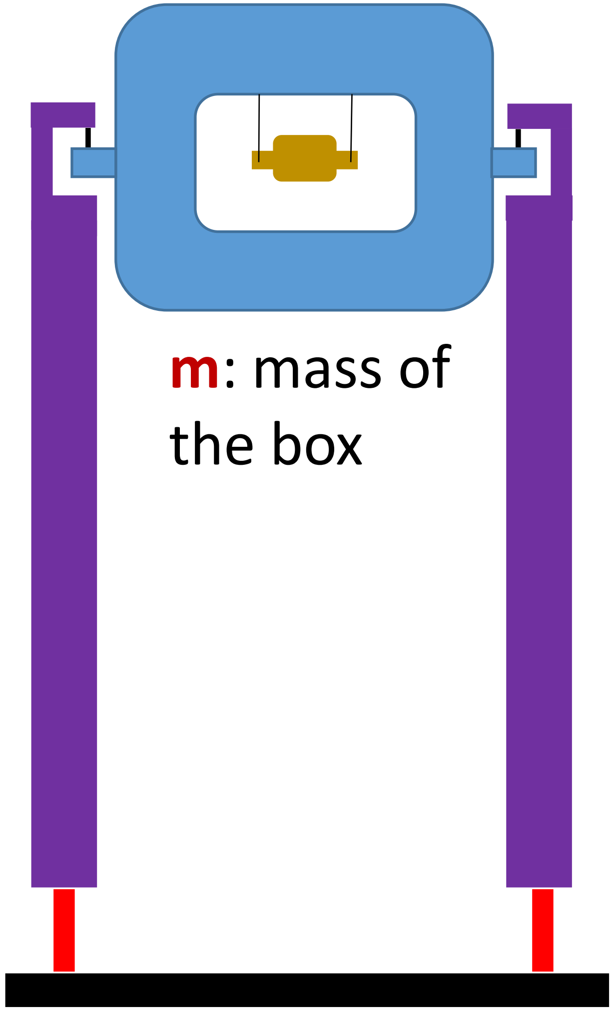


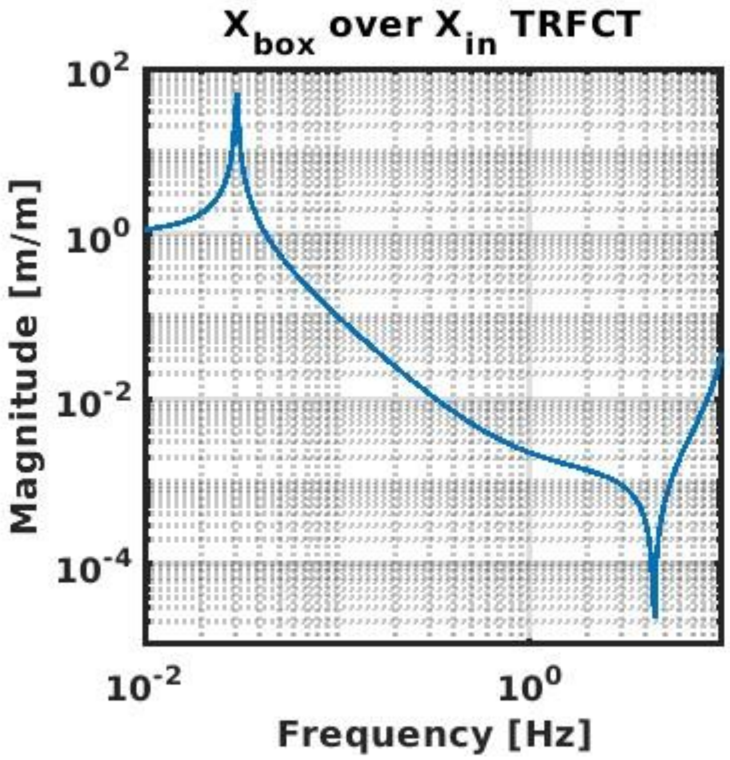
The accelerometer can be used in feedback in order to put the box in an inertial state above a certain frequency.

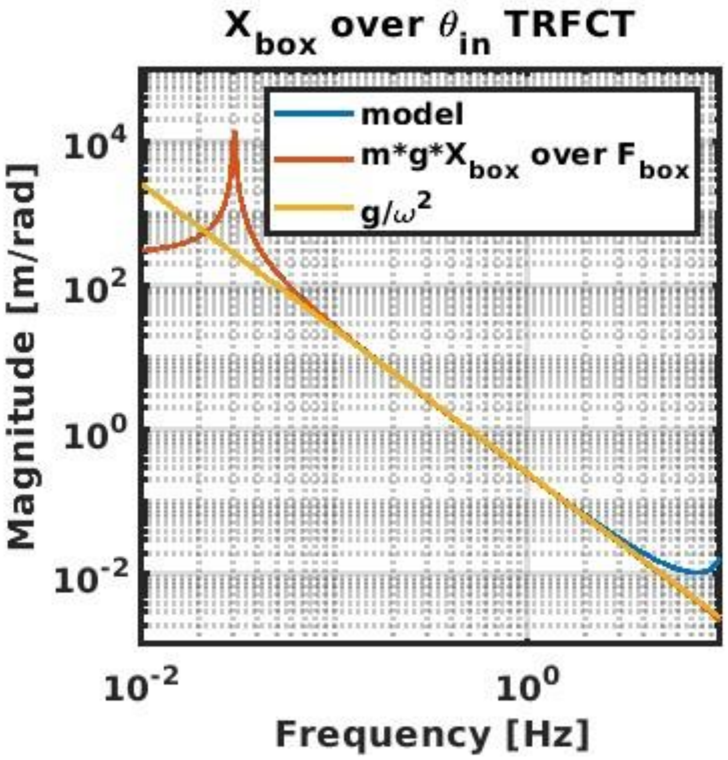
g/ω^2 spurious sensitivity of the accelerometer to rotations is passed to the box when the loop is closed.

The model is not externally informed about that: it knows by itself.

IP mechanical isolation is limited by ground rotation

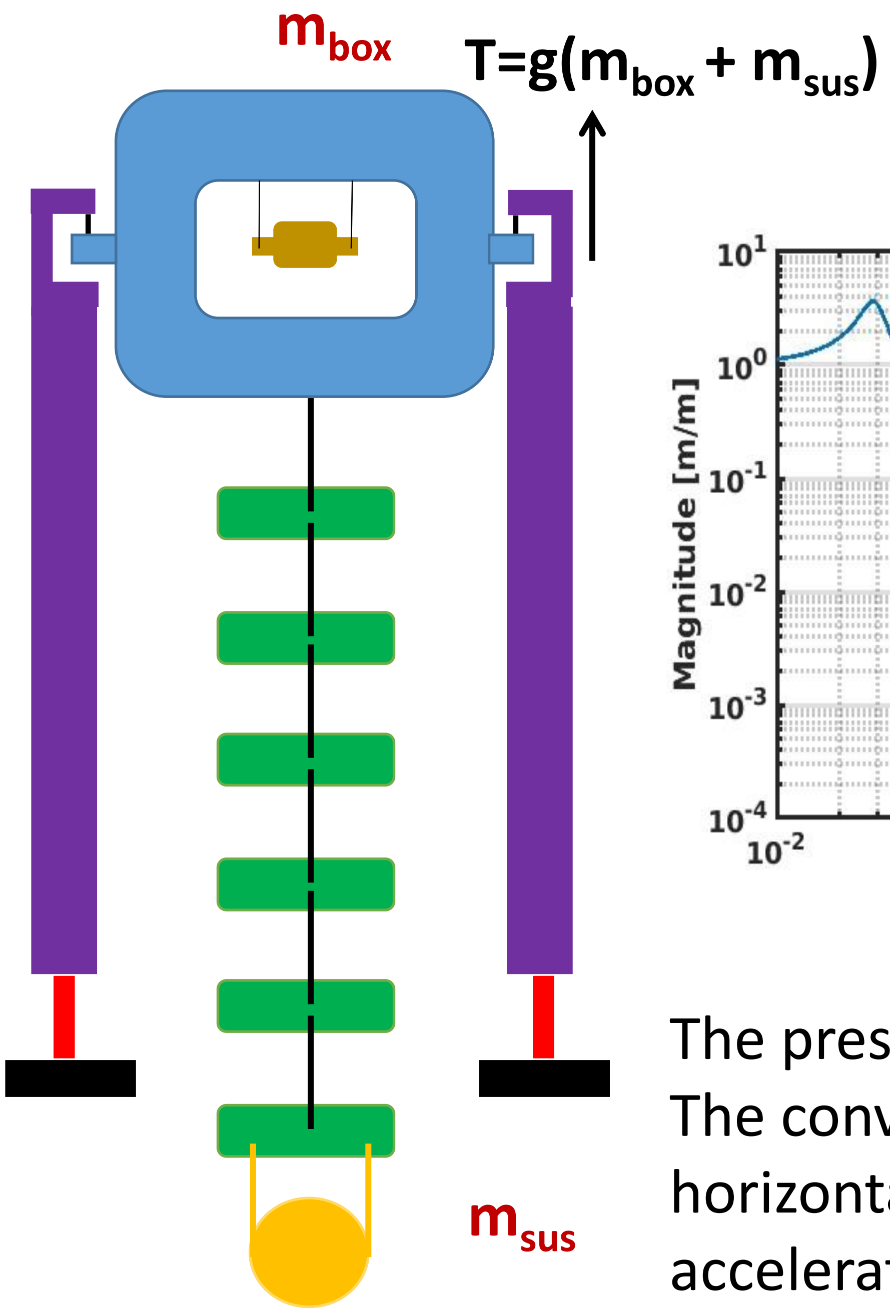


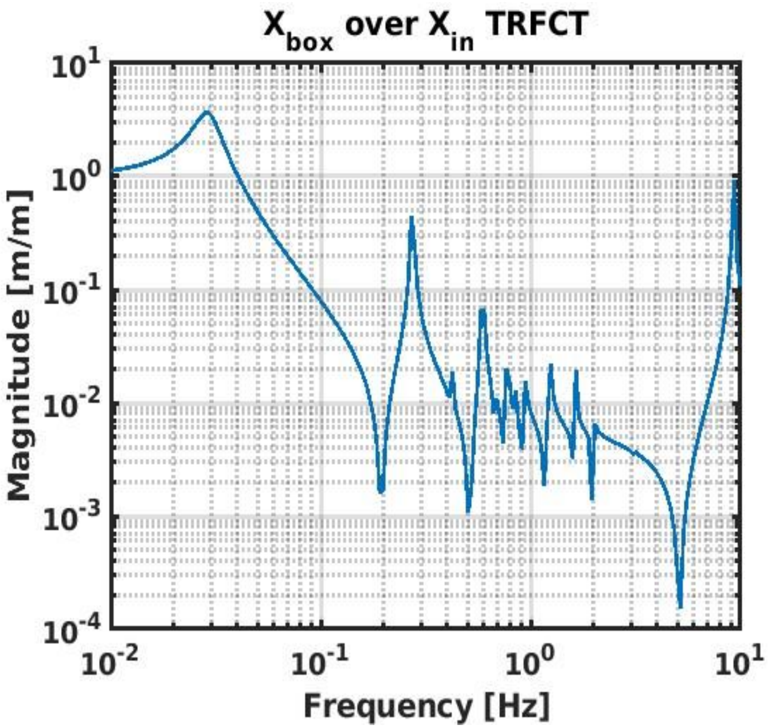


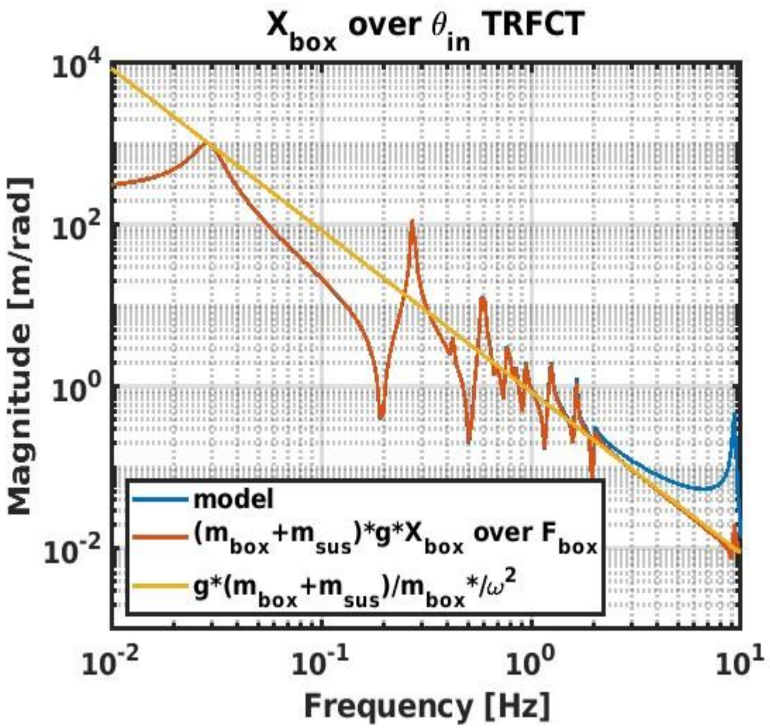


the ratio between output displacement and input rotation is $\mathbf{g/\omega^2}$. A force $\mathbf{mg\theta_{in}}$ applied to the box makes the same effect.

SUPERATTENUATOR







The presence of the seismic chain increases the load on the box. The conversion of rotation to force looks the same: it is the horizontal component of the rotated load. Out of the modes, the acceleration transmitted to the box is: $g\theta_{in}(m_{box} + m_{sus})/ m_{box}$

CONCLUSIONS

- The pre-isolator of a seismic suspension is normally subjected to a rotation $\theta_{box} = \theta_{in}$ This is inevitably a source a horizontal disturbance, which can be basically quantified as an acceleration $g\theta_{box}$, indipendent on the mechanics
- Just to give some numbers: at 2-3 Hz, a possible residual rotation 10^{-12} rad/sqrt(Hz) would determine a residual motion ~ 10^{-14} m/sqrt(Hz).
- A horizontal ground noise $X_{in} = 10^{-11}$ m/sqrt(Hz) would require an attenuation ~ 10^3, to achieve the same residual motion. This is almost feasible through a simple IP.
- An improvement of the horizontal attenuation at the level of the pre-isolator (AP+IP, nested IP, ...) become useful if the residual rotation is lower, or it is compensated by means of a very performing rotation sensor.
- If a residual rotation θ_{box} can be observed on an 'inertial box', the associated horizontal force $F_x = mg\theta_{box}$ would be observed as well. Adding a counter-force through the box control system could be an alternative method of disturbance reduction, instead of a feedback on a tilting platform.