First measurements for test and characterization of the Pendulum Inverted Pendulum for ET suspensions

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Einstein Telescope and Low Frequencies

Einstein Telescope (ET) aims to detect gravitational waves in a range of frequencies from $\sim$ 3 Hz to 10^4 Hz. With the term **low frequencies** (LF) we mean the range between the lowest limit detectable to few tens of Hz. The benefit to detect the signal at LF are:

- early-warning localization;
- increase the bulk of Universe observable;
- improve S/N on continuous signal.

In order to work at the LF, several expedients have been taken in consideration in order to improve the sensitivity. Regarding seismic noise attenuation, the ET Design report [1] considers the construction of a 17 m height **Super Attenuator** (SA), on the model of the Virgo. A new and more compact solution is presented in this work.

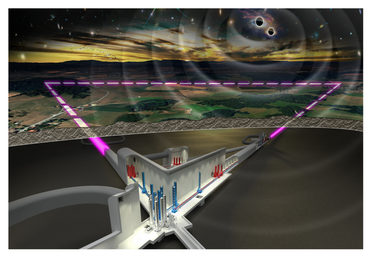

Fig. 1: An artistic imagine of ET from one of the three detector vertices [2]. In the picture it is possible to see the towers of the SAs which are high $\sim$ 17 m

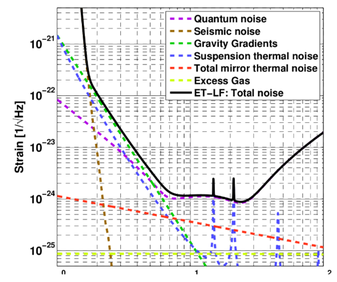

Fig. 2: The spectrum noise of the ET-LF. At low frequencies the seismic noise is dominant [1].

Pendulum Inverted Pendulum

Inside the project *" Black Holes for ET in Sardinia"* (BHETSA) a new concept of filter has been developed: the **Pendulum Inverted Pendulum** (PIP). In this new design, the SA chain is made up of a series of PIPs that replace the individual vertical filters. A chain of three PIP will be able to attenuate 1.9×10^{-5} at 2 Hz occupying 4 m. In this way it is possible to reduce the height of whole structure of the SA from $\sim$ 17 to 10 m.

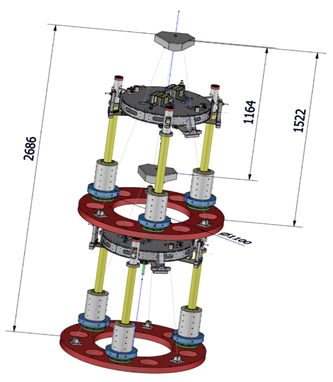

Fig. 3: Concept of two PIP linked each other.

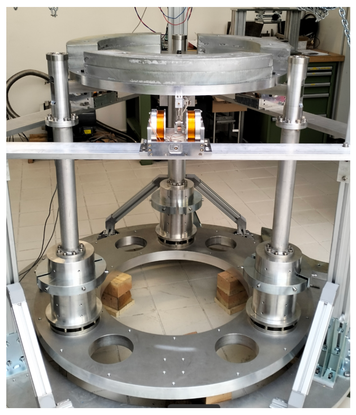

Fig. 4: The status of the PIP at the Laboratory of INFN Pisa. The horizontal bar in the middle-height supports the LVDT for displacement measurements.

Noise and stiffness of flexible joint

Position noise as measured contains the PIP attenuated seismic noise, as well as vibrations of the structure and safety frame. From Figure 6 it is possible to know the equation 1 and then compute the value of k of the flexible joint:

$$f_0^2 = \frac{1}{4\pi^2}\frac{k - (M_{load} - M_{leg}/2)\frac{g}{l}}{M_{load} - M_{leg}/3} \quad \text{, Stiffness is: } k_1 = (1775 \pm 61)\frac{N}{m} \tag{1}$$

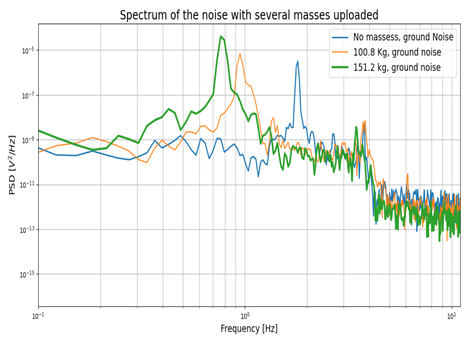

Fig. 5: Noise spectrum as measured by the LVDT of Figure 4

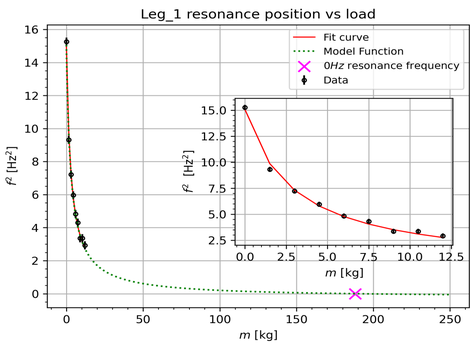

Fig. 6: From the data it is possible to compute the fit, finding the stiffness of the flexible joint.

Resonance peak

We have compared the real data with the data simulation of the PIP under stress. The simulation is made with Ansys and indicates that the two lower frequencies modes are degenerative. The values are reported in the table:

	Simulated		Data	
	mode 1 (Hz)	mode 2 (Hz)	peak 1 (Hz)	peak 2 (Hz)
No masses	2.24	2.24	1.80	2.65
50 kg	1.52	1.52	1.22	1.69
100 kg	1.12	1.12	0.97	1.28
150 kg	0.99	0.99	0.763	1.07

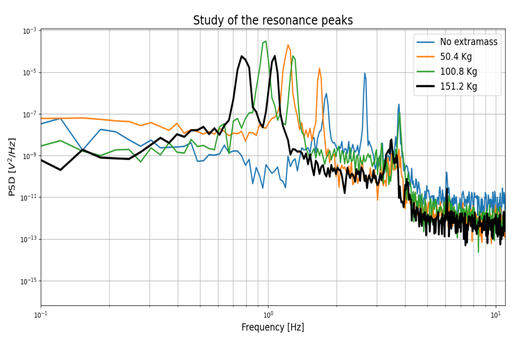

Fig. 7: Spectrum at the top legs varying the mass. As expected, the resonance peaks shift towards lower frequencies

Percussion Point

Using counterweight on each leg of inverted pendulum it is possible to modify the position of the percussion point reducing the motion at the top of the leg.

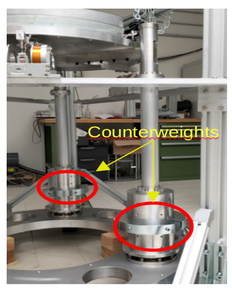

Fig. 8: The counterweigths are mounted on the IP legs

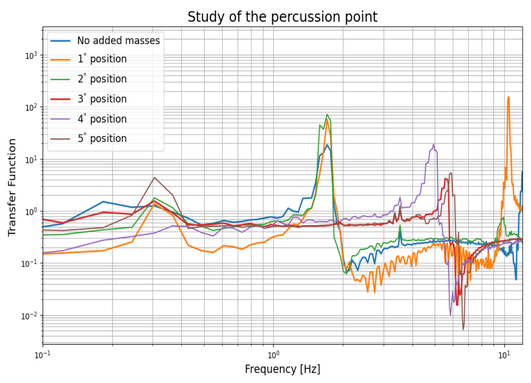

Fig. 9: Transfer function of the position of the counterweight on a single IP.

Future Works

We are currently conducting tests at the INFN laboratories in Pisa. The main objective is the characterization of the seismic attenuation of a single PIP. Until now we have studied the legs of inverted pendulums, characterized by the Linear Variable Differential Transformer (LVDT) and we are proceeding to the characterization of the ground-supported PIP.

In parallel with this process, we have developed a database to store and manage both data and components of the PIP (see **Michele Vacatello**'s poster).

References

[1] Harald Lück et al. "Et design report update 2020". In: *Design Report Update 2020 for the Einstein Telescope*. 2020.

[2] Sibilla Di Pace et al. "Research facilities for Europe's next generation gravitational-wave detector einstein telescope". In: *Galaxies* 10.3 (2022), p. 65.

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[5] Tariq et all. "The linear variable differential transformer (LVDT) position sensor for gravitational wave interferometer low-frequency controls". In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* (2002).