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Proposal for the SAS-SUS Active Control for the LIGO Advanced Configurations (LIGO2)

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1 Introduction

This report has been written with the aim to give an introductory description of a possible seismic attenuation system active control for the IFO core optics and to show its potentialities.

The simulations reported here have been done considering the mechanical system described on the document [1] i.e. the short SAS.

The seismic noise model used for the simulation is the measured ground motion of the LIGO Livingston site and is shown in figure 1.

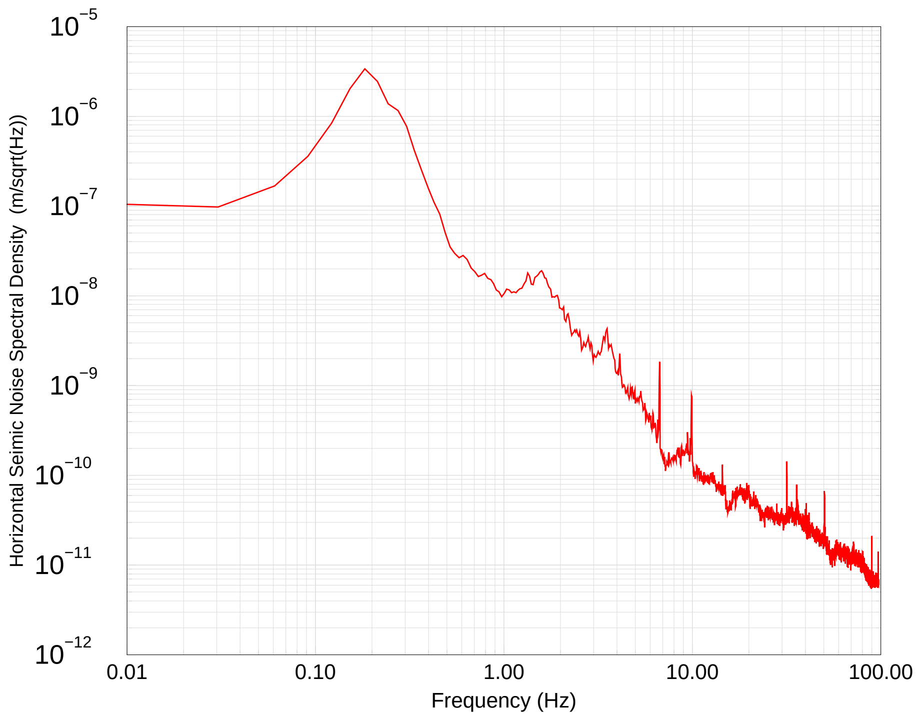

Figure 1: Horizontal seismic spectral density measured at the LIGO Livingston Observatory in a quiet moment.

2 Suspension Control Overview

The control and the required performances of the entire suspension (alias SAS-SUS) reflects the different stages of operating mode of the interferometer (IFO), which are essentially the initial alignment, the locking acquisition and finally the last one, the longitudinal locking and fine alignment (LSC and ASC) .

To be able to control the SAS-SUS and attain the minimum RMS value for the DOF of the mirrors, the inertial damping of the rigid body modes (at least those ones that mostly contribute to the RMS motion) is needed during all the IFO stages.

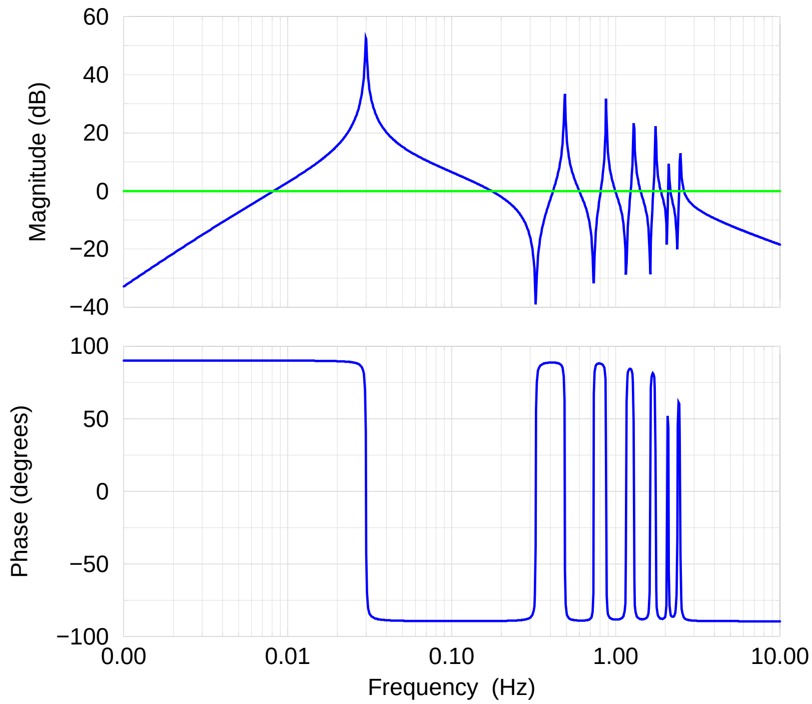

Figure 2: Open loop transfer function for inverted pendulum feedback.

Furthermore, to maintain the suspended mirrors position fixed with respect to a reference frame (local or global) a DC control on the SAS-SUS is needed.

The SAS-SUS DC control has to stay on also during all possible operating mode of the interferometer. In this case, the sensing scheme depends on the operation mode.

To perform these different tasks, the SAS-SUS has an active control system which can be divided into two main parts:

- The upper stages (the IP table) with inertial damping, the local and global positioning (LSC and ASC for essentially the tidal control, and long term drift compensations).
- The bottom part (the GEO triple pendulum) with a local positioning (initial alignment) and the global positioning (LSC and ASC).

A third part, already available, is the stepper motors installed onto the BSC piers and it can be integrated on the DC control architecture to improve the reliability and the performance of the overall system.

Due to the large complexity of the LIGO interferometer , the SAS-SUS needs to be really robust and reliable; without considering exceptional events, the average running time has to be of the order of months.

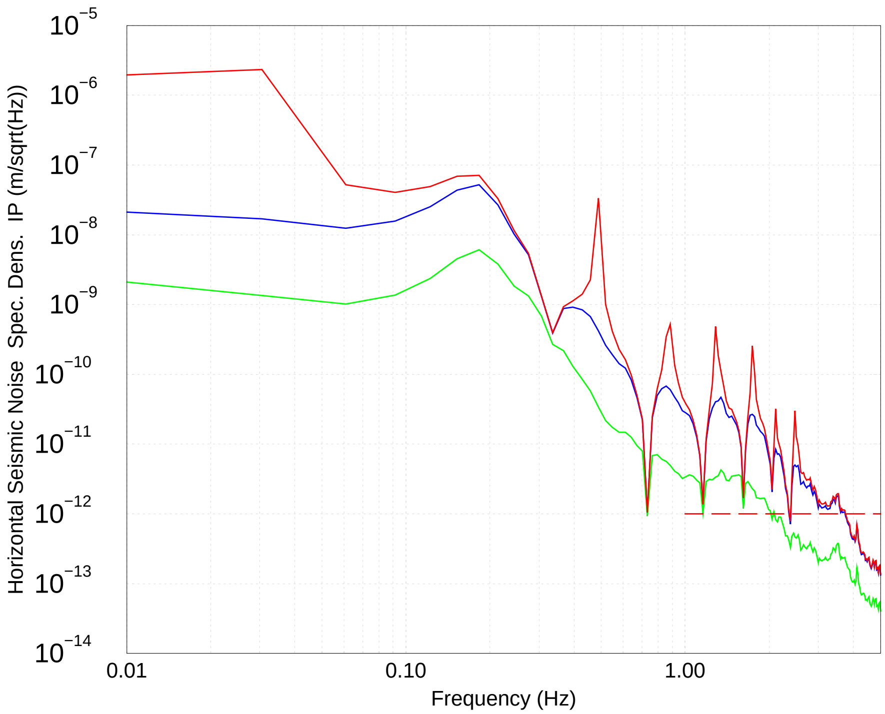

Figure 3: Horizontal seismic noise spectral densities for the IP with the feedback off (red curve) and on for two different open loop gain values of 40 (blue curve) and 500 (green curve). The red dashed curve is the displacement spectral density of the accelerometers.

2.1 The SAS Inertial Damping

The inertial damping is achieved using accelerometers placed on the inverted pendulum table precisely, on the top of the body of the geometric anti-sprint filter (F0). The controlled degrees of freedom are the three translations and the yaw.

The control topology is multiple input multiple output (MIMO) but the compensation is done considering an equivalent diagonalized system which is related by the physical system by two linear transformations. This kind of approach requires the use of a real time digital control system[1].

The horizontal and the yaw DOF's are sensed by 3 horizontal accelerometers placed at 120° onto the IP table. The vertical DOF is sensed using an accelerometer sitting on the safety disk of the F0.

The bandpass of this control is in principle defined by the spectral sensitivity of the accelerometers and the position of the resonances in the transfer function

For a digital control, the maximum feedback loop cutoff frequency is fixed by the ADC resolution (for an imposed dynamic range) and by the complexity of the filtering related to the cpu performance.

[1] The use of a digital system is also foreseen because of its versatility and especially for the need of interfacing the SAS-SUS system, to the LIGO data acquisition system

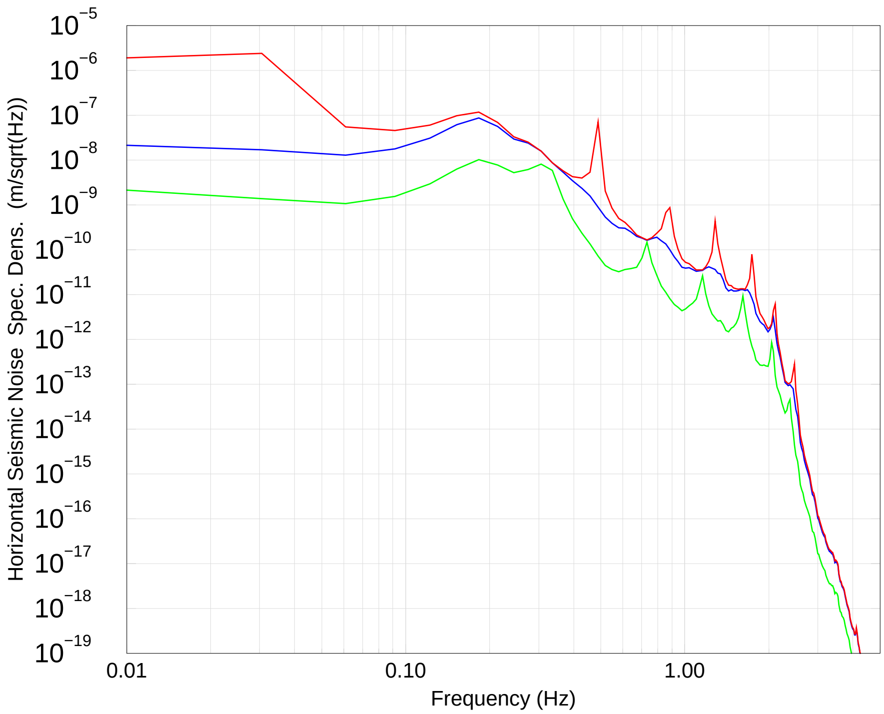

Figure 4: Horizontal seismic noise spectral densities for the mirror with the feedback off (red curve) and on for two open loop gain values of 40 ((blue curve) and 500(green curve).

The high pass frequency is limited by the tilt noise injected by the system (SAS + accelerometer) into the accelerometer.

Anyway this factors are not limiting the damping of the resonances of the chain and a further seismic noise reduction.

The simulation plots are for the so called inertial viscous damping of the chain resonances, excited by the horizontal seismic noise The unity gain bandpass is from 10 mHz to $3 - 4$ Hz with an open loop gain of 40 and 500 (see figure 2). The high open loop gain, which is unrealistic, is reported just to show the particular behavior of the closed loop mechanical system whose internal modes are changed by the feedback force. A more complex compensator can avoid this resonances and gives a plateau in the control bandwidth.

Figure 2.1 shows the seismic noise spectral densities of the mirror with the feedback on and off.

The RMS noise integrated from left to right in figure 2.1 for feedback on and off, shows that the main contribution on the residual motion of the mirror at closed loop, comes from the frequency band from about 0.2 to 1 Hz.

The residual longitudinal displacement, integrated from 100 Hz to 10 mHz for the two cases are[2]

[2]At low frequency the number of measured points of the seismic noise spectral density are very small, but the contribution to the RMS noise is expected to be small because of the required flatness and smoothness

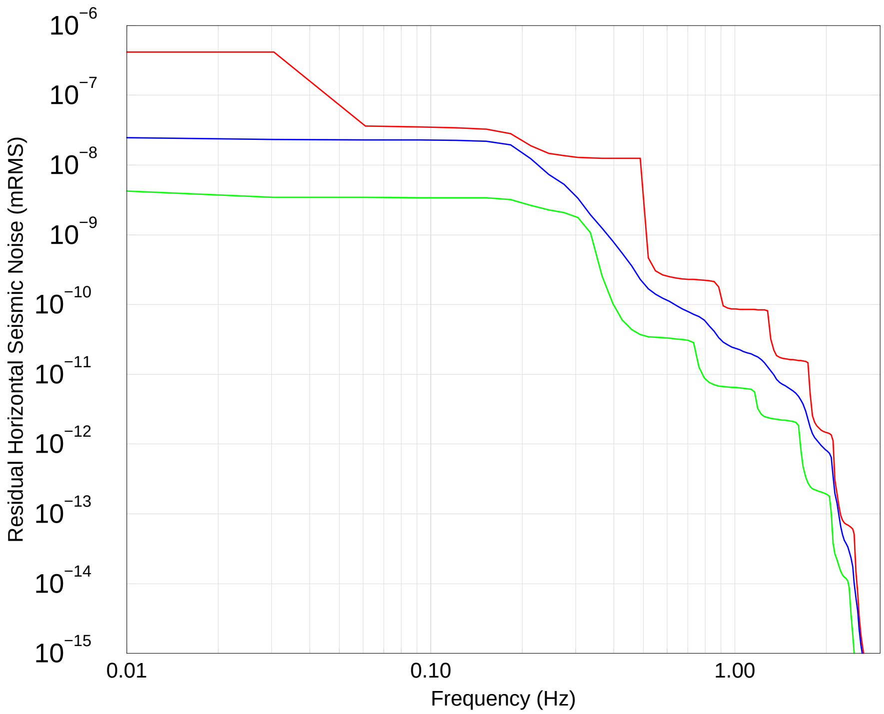

Figure 5: Horizontal residual RMS displacement for the mirror with the feedback off (red curve) and on with two open loop gain values of 40(blue curve) and 500(green curve).

$$\langle \tilde{x} \rangle_{RMS} \simeq 0.4\ \mu\mathrm{m}_{\mathrm{RMS}}, \qquad (\text{ feedback off}), \tag{1}$$
$$\langle \tilde{x} \rangle_{RMS} \simeq 0.04\ \mu\mathrm{m}_{\mathrm{RMS}}, \qquad (\text{ feedback on}). \tag{2}$$

A more aggressive active control in the previously mentioned band, done with higher complexity of the compensators, could improve significantly the overall performance of the SAS-SUS.

In the last plot, Figure 6, are the residual mirror velocity integrated from right to left. The main contribution still comes from band range from 0.2 to 1 Hz. The total RMS values are

$$\langle \tilde{v} \rangle_{RMS} \simeq 3\ \mu\mathrm{m/s}_{\mathrm{RMS}}, \qquad (\text{ feedback off}), \tag{3}$$
$$\langle \tilde{v} \rangle_{RMS} \simeq 0.3\ \mu\mathrm{m/s}_{\mathrm{RMS}}, \qquad (\text{ feedback on}). \tag{4}$$

The residual RMS velocity is ?? of magnitude ?? than the LIGO-I requirement [10].

of the seismic spectrum at frequency below about 10 mHz.

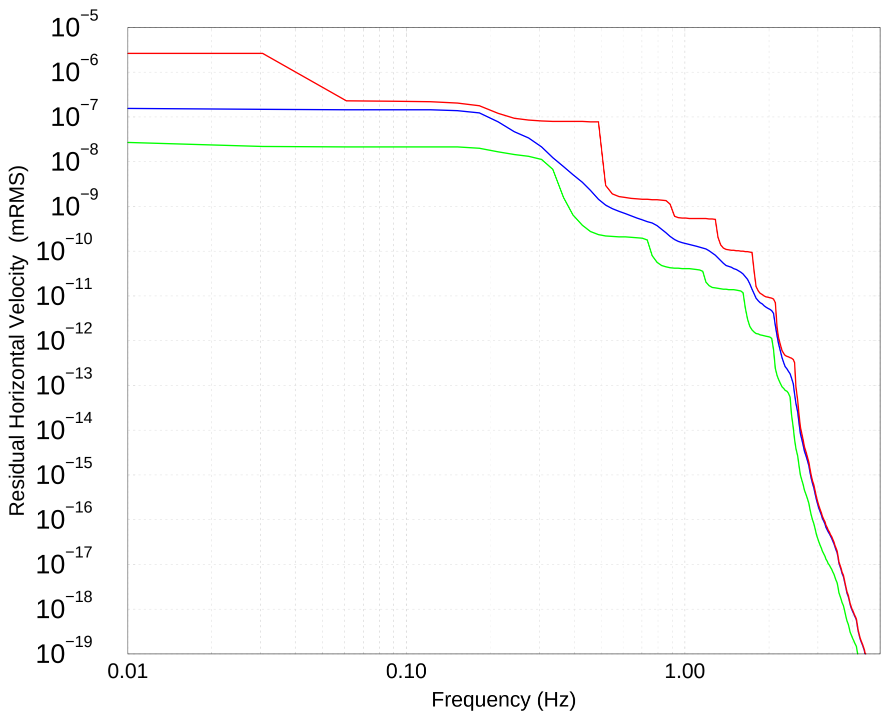

Figure 6: Horizontal residual RMS velocity for the suspended mirror with feedback off (red curve) and off with two open loop gain values of 40 (blue curve) and 500(green curve).

2.2 The SAS DC Control

The SAS DC Control has to perform essentially the two following tasks:

- Maintain the SAS aligned and positioned with respect to a local reference frame.
- LSC ASC.

The actuators for the DC control are the same ones used the IP inertial damping. The horizontal and yaw sensors are the 3 LVDT's radially placed at 120° with respect to the IP vertical axis and between the safety reference structure and the IP table. In the actual F0 prototype, the 3 vertical LVDT's sensors have the same topology but they sit onto the F0 safety disk and measure the displacement between this plate and the F0 body. In principle, these 3 sensors are able to measure the recoiling effect of the pitch and the roll onto the F0. In a more final version one LVDT axially mounted is envisaged.

Considering the sensitivity of the horizontal accelerometers, the DC bandwidth cutoff is set at $10-30$ mHz. Due to the flatness of the response of the system from DC to $10-30$ mHz no particular problems are envisaged on the control.

The dynamic range and the relative static force and the power needed are reported in the following table:

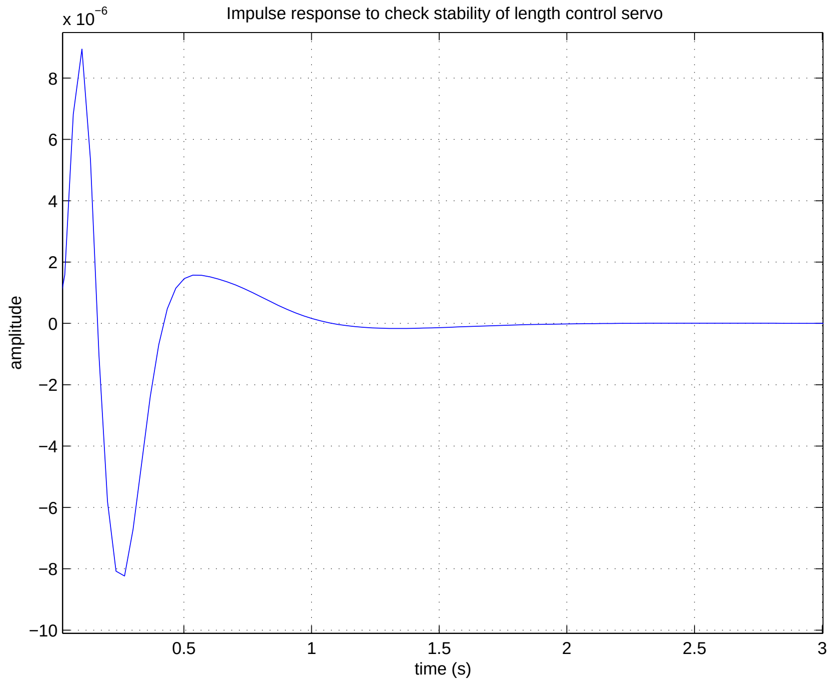

Figure 7: Impulse response of the SAS-SUS with the interferometer locked. The plot gives only a visual information about the stability of the loops.

DOF	Dynamic Range	Static Force(mN)	Power (W)
vertical :	± 5 mm	600	0.4
longitudinal a transversal :	± 10 mm	150	0.03
yaw :	± 20 mrad	150	0.03

To reduce the in vacuum heating produced by the actuators, one can avoid driving a DC current to the voice coil by introducing 3 stepper motors placed on the IP reference frame and connected to the IP by soft springs and in the same configuration as the voice coils. They can be used to remove the DC current sent to the actuators with a nonlinear control (triggered by a threshold for example).

A better solution can be instead to use the actuators already present on the top of the BSC's piers. The main advantage in this case is the recovering of the voice coils working point.

2.3 Initial Alignment

The initial alignment is done using the position sensors and voice coils located on the SAS-SUS, with the control split in the following way:

- x, y, z and θ_z (the yaw) controlled from the IP to the reference frame, using the SAS DC control .
- All the 6 DOF of the reference mass and the mirror controlled on the upper stages of the GEO triple pendulum with respect to its suspension point.

The GEO triple pendulum local control strategy is basically different from the SAS-SUS one. The GEO suspension local sensors (shadows sensors between the suspension point and the two upper masses) are used for the damping of the chain modes [5] which are very far from the GEO sensitivity bandwidth. The possibility of this kind of topology to damp the modes seems to be an important issue [5] for 10 Hz interferometer sensitivity, and has to be demonstrated.

In the SAS-SUS GEO the actuators will be used to perform the difficult task of the IFO initial alignment (also for the LSC-ASC).

for the x, y, z and θ_z DOF's, the cross frequency between the control on the IP and that one on the GEO upper masses and can be $10 - 30$mHz to avoid instability problems.

The sensors for the local controls for the GEO upper masses have to be defined (optical lever, CCD cameras, etc...).

3 Interferometer LSC-ASC

The LSC-ASC is done acting on the IP and on the GEO suspension splitting the bandwidth essentially in the same way envisaged for the initial alignment.

Using the GEO model for the triple pendulum [6] we have found a possible set of crossover points for the three control of the GEO suspension, which are (starting from the GEO upper stage down to the mirror), 4, 10 and 100-200Hz and with open loop gains of 4, 10, 200.

The estimation of performance of any kind of SEI-SUS for the locked operating mode of the interferometer is a huge task. Anyway, an indicative parameter of the performance can come out from a simple longitudinal unidimensional model of the system.

For example, using the GEO model for the triple pendulum , one can have a rough estimate of the residual RMS noise mirror motion for the locked interferometer when the only noise source is the ground motion[3]

The simulation has been done considering the spectral density of the expected seismic noise of the SAS on the suspension point of the GEO triple pendulum.

Due to the suspension topology, the longitudinal forces for the locking, acting on the three suspension stages, are considered as internal forces. In a real system, a recoiling effect of the longitudinal modes onto the upper stages of the SAS are expected to be chilled by the inertial damping.

Figure 7, which shows the impulse response of the triple pendulum on the mirror, gives a visual idea of the stability of the control [4].

[3]For the length sensing and control, using the GEO triple pendulum simulation, one assumes a perfect

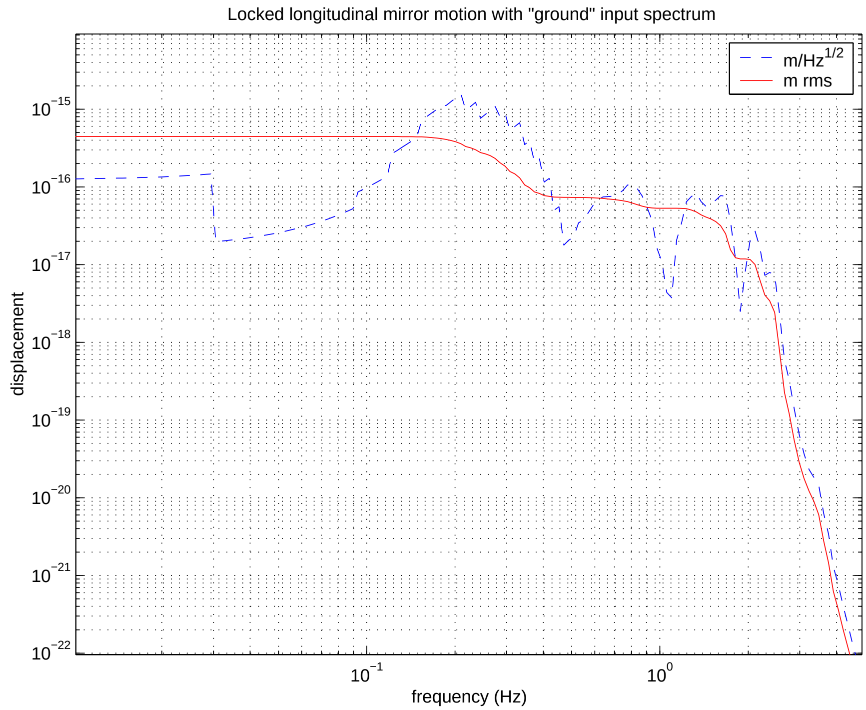

Figure 8: Spectral density and RMS residual displacement of the the suspended mirror.

Figure 8 shows the seismic noise spectral density and the RMS noise at the mirror when the interferometer is locked. The residual seismic noise on the mirror is

$$\langle \tilde{x} \rangle_{RMS} \simeq 5 \cdot 10^{-16} \ \mathrm{m_{RMS}}, \qquad \text{(LSC feedback on)},$$

which is particularly low, and it gives an optimistic point for the reliability of the system. A more detailed simulation which takes into account the IFO dynamic response is needed [9].

4 Sensors and Actuators

In this last section are reported some of the main characteristics of the sensor and the actuators proposed for the control of the DC control and the inertial damping of the SAS suspension.

correction signal unaffected by any noise sources or coupling between IFO DOF's.

[4]The longitudinal dynamical behavior of the IFO is not included in the GEO simulation. Indeed no information about the capability to acquire locking can be obtained.

4.1 Position Sensors (LVDT)

The LVDT (Linear Variable Differential Transformer) is a position sensor device composed of a primary winding nested in and coaxial to a secondary winding split into two coils. Their relative displacement is proportional to an induced voltage on the secondary winding.

This induced signal is extracted using the heterodyne technique to avoid electronic excess noise at low frequency (modulation frequency of the primary winding around 10 kHz).

A common mode rejection is obtained by the geometry of the secondary winding i.e. splitting the secondary winding into two coils with opposite winding. This geometry improves also the linear response of the sensor.

A typical noise spectral density δx obtainable for a range of $\Delta x = 20$ mm is [2]

$$\delta x_{LVDT} = 0.1 \ \mu\mathrm{m}/\sqrt{(\mathrm{Hz})}.$$

4.2 Inertial Sensor (Accelerometer)

The accelerometers proposed for the inertial damping, for the vertical and horizontal degree of freedoms, have a LVDT readout and work in a closed loop configuration to receive the benefit of the null instruments advantages. The typical displacement sensitivity at 1 Hz is [7]

$$\delta x \simeq 1 \ \mathrm{pm}/\sqrt{(\mathrm{Hz})},$$

with a dynamical range of about $100\mu m$. A capacitive transducer can theoretically improve the sensitivity by one or two order of magnitude [4].

4.3 Voice Coil (AC/DC Actuator)

The actuator geometry is that of the Maxwell pair voice coils to improve the smoothness of the magnetic field gradient. The achievable relative variation of the applied force is about 2% in a range of about 20 mm. Typical resistivity is 15 Ω with a response of 3 N/A.

4.4 Voice Coil Driver

The proposed voltage to current controlled coil driver, developed by the INFN of Pisa, has the following main features:

- Typical output noise : 10 nV/$\sqrt{(\mathrm{Hz})}$
- Bandwidth : DC to $>$ 1 kHz
- Maximum output current : 3 A

4.5 Stepper motor (DC Actuator)

A candidate as DC actuator is the UHV AML B14.1 stepper motor[8] rotating a threaded rod, which drives a very soft helical spring, connected to the body that has to be controlled (the IP table). The dynamic range is several centimeters. It is bakeable up to 200°.

Proposal of a seismic attenuation system SAS for the LIGO advanced configuration (LIGO2):

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