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The VIRGO suspensions

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Abstract
The VIRGO suspensions are chains of passive mechanical filters designed to isolate the interferometer mirrors from seismic noise starting from a few Hz. In order to reduce the low-frequency swing of the mirror along the beam, an active control system, acting at the level of the suspension point, damps the main resonant modes of the system (all below 2.5 Hz). Another control loop, at the level of the optical payload, makes use of a digital camera monitoring the mirror position in all six degrees of freedom. Its main goal is to decrease the rms angular displacements of the mirror, on a time scale of several minutes, down to less than 1 μrad. All the seven suspensions of the VIRGO central interferometer are presently in operation, while the assembly of the last two, for the terminal mirrors, is in progress. The design and performance of the system are described in this paper.

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(Some figures in this article are in colour only in the electronic version)

1. Specifications

1.1. Passive isolation

The linear spectral density of ground seismic displacement measured at the VIRGO site turns out to be well approximated in all directions above 1 Hz by the function $10^{-7}/f^2$ m $\mathrm{Hz}^{-1/2}$. The VIRGO suspension chains (figure 1) have been designed to suppress the transmission of ground vibrations to the suspended mirror. The goal is to make mirror residual seismic vibrations along the beam negligible with respect to other noise sources limiting the antenna sensitivity. This result is achieved from about 4 Hz. Indeed, below this frequency, the detection is prevented by *gravitational Newtonian noise* [1]. Between 4 Hz and a few tens of Hz, the VIRGO displacement sensitivity is limited by thermal noise to about 10^{-17}–10^{-18} m $\mathrm{Hz}^{-1/2}$ [2]. As a consequence, in this frequency range, where seismic vibrations are large, the VIRGO suspensions have to attenuate horizontal seismic

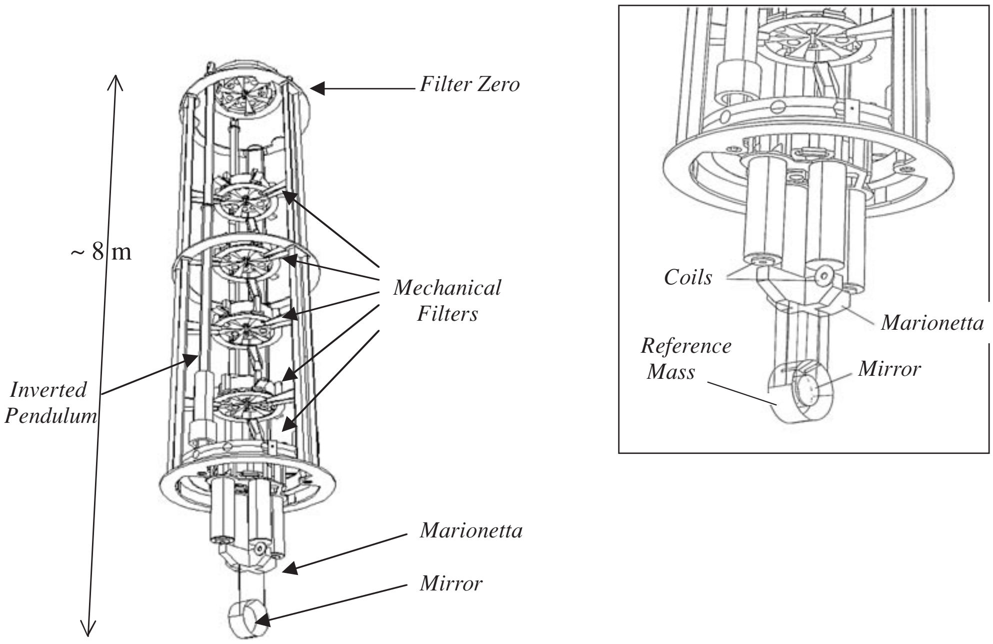

Figure 1. View of a VIRGO suspension chain. The suspension wires connecting the filters are not displayed. An enlarged view of the last stage is provided in the box.

noise by 7–9 orders of magnitude. Due to unavoidable mechanical couplings, vertical vibrations of the mirrors are partially transmitted to the beam axis, affecting the interference signal. An attenuation of vertical seismic noise comparable with the horizontal one is thus necessary.

1.2. Inertial damping

The suspended mirrors oscillate at low frequency (well below the detection band) along the beam direction with amplitudes of tens of microns. This oscillation is maintained by seismic noise injected at the suspension point. Its amplitude is mainly determined by quality factors of the fundamental horizontal modes of the system (located from about 100 mHz to 2.5 Hz). In order to keep the interferometer optical cavities at the resonance without injecting a considerable noise in the apparatus, the rms relative displacement of the mirrors along the beam has to be reduced down to about 10^{-12} m. This result is achieved by a digital servo loop that uses eight coil–magnet systems acting on the mirror and on the stage above as actuators. A limit on the maximum force one can apply in the proximity of the mirror is fixed by the finite dynamics of the digital electronic system; in particular by the DAC card used to convert the digital correction signal to the analog one, sent to the coil drivers. Compensation forces corresponding to displacements of the mirror along the beam larger than 1 μm cannot be applied by the eight payload actuators. Indeed larger forces, even if in quasi-DC, would induce an electronic noise floor in the detection band that is too large. This noise floor manifests itself in the currents of the actuator coils, causing mechanical vibrations of the item on which the force is applied. If the force is performed too close to the mirror (i.e. by the payload actuators), these vibrations are not filtered enough. They are almost entirely transmitted at the mirror level, limiting antenna sensitivity. It is for this reason that the large drifts of the mirror (in the very long term) are compensated from the suspension top stage. In this case the wide electro-mechanical vibrations induced by the large compensation force are filtered by the entire chain below. The *inertial damping* loop [3], discussed in [4], acts on the suspension point to damp the oscillation modes of the system. This allows a reduction of the rms mirror swing along the beam, in the band of horizontal resonances, down to fractions of a micron. The residual small mirror swing induced by damped horizontal chain modes can be further compensated at the level of the optical payload. Indeed, the residual compensation force is small enough that the noise injected in the band does not affect the antenna sensitivity. In conclusion, the inertial damping makes possible the noiseless fine control of the mirror position.

1.3. Mirror angular control

As shown below, the four coil–magnet systems acting on the stage above the mirrors can be used to control their angular positions about the horizontal axis perpendicular to the beam and around the vertical axis. They are used as actuators in a digital control loop that takes the error signals using a digital camera, monitoring the mirror position in all six degrees of freedom [5]. The goal is to keep the interferometer beams aligned and thus make the interference pattern stable enough during the locking acquisition. When the loop is open, the amplitude of the angular swings of the mirror (with the inertial damping active) is of a few tens of microradians about the vertical axis and slightly less around the horizontal axis. These wide swings can be ascribed to modes of the chain involving angular displacements of the mirror. They range from 12 mHz to a few tenths of a Hz. The VIRGO specification is that the rms values of these swings have to be reduced on both angles down to less than 1 μrad on time scales of several tens of seconds [5].

2. Design

2.1. Passive isolation

The mechanical chain suspending the optical payload is essentially a five-stage pendulum (figure 1). In an *N*-stage pendulum, well above the resonant frequencies of the system, the displacement noise of the suspension point is transmitted to the lowest mass with a transfer function of $\sim C/f^{2N}$, where C is the product of the square of the N resonant frequencies. All the main horizontal modes of the chain are below 2.5 Hz and the required attenuation is reached from about 4 Hz. Conceptually, the vertical attenuation can be achieved by replacing each suspension wire by a spring to make a chain of vertical oscillators. For this reason, each mass of the pendulum has been replaced by a drum-shaped metallic structure (70 cm diameter and 18.5 cm height). This item, weighing about 100 kg, is named a *mechanical filter* [6]. A set of triangular cantilever blade springs clamped onto the outer circumference of the bottom part of the filter provides the vertical elasticity. Despite the use of very thin blades (with a large stress inside), the highest vertical mode of the chain was around 7 Hz, well above the designed frequency threshold. In order to displace all vertical modes of the chain below 2 Hz, a system of magnetic anti-springs [6, 7] was assembled on each filter to reduce its vertical stiffness. In this way the required attenuation is achieved from about 4 Hz, also in the vertical direction. A detailed description of the chain of filters can be found in [8].

2.2. Top stage and inertial damping

The top stage of the chain is formed by another mechanical filter (*filter zero*) rigidly connected to a ring. This ring, and thus the entire chain, is attached to a three-legs-elastic structure. Each 6 m long leg is based on a flexural joint that provides the required elasticity to the system. The structure acts as an *inverted pendulum* and the top stage oscillates along the two directions of the horizontal modes with frequencies of 30–40 mHz [9]. This ultra-low frequency oscillator provides a remarkable attenuation in the horizontal directions above 100 mHz, where the main resonances of the chain below are located. In addition, this softness allows control of the position of the chain suspension point by low forces. Three coil–magnet actuators are employed in the inertial damping loop to suppress the main resonances of the suspension. This is done by actively damping the displacements of the top stage (horizontal translations and rotations about the vertical axis) due to the resonant modes of the system. As discussed in [4], these displacements are measured by a set of three high-sensitivity accelerometers and three linear variable differential transformers (LVDT) position sensors assembled on the top ring.

2.3. Payload and mirror control

A special component, named the *marionetta*, is suspended to the last filter of the chain (figure 1). This item has been designed to steer the suspended mirror in three degrees of freedom: the translation along the beam and the rotations around the horizontal axis perpendicular to the beam and around the vertical axis [10]. The marionetta supports the mirror in a cradle formed by a couple of 1.9 m long thin wires. The mirror steering is performed by four coils each placed at the end of a 1 m long cylinder, extending from the last filter of the chain (see exploded view in figure 1). The coils are thus isolated from seismic noise so as to avoid the injection of seismic vibrations during the action. They act on permanent magnets mounted on the four wings of the marionetta, allowing the displacements mentioned above. The displacements of the marionetta are transmitted to the mirror by the cradle wires. The fine control of the mirror position along the beam direction (above 1 Hz, with typical corrections of fractions of nanometers) is obtained by four coils acting on magnets glued directly on the back of the mirror. The coils are supported by a *reference mass*, located behind the mirror and suspended to the marionetta by another couple of thin wires.

3. Performances

3.1. Passive isolation

Above a few Hz, the attenuation is so strong that it is not possible to perform a direct measurement of the transfer functions connecting the displacements of the floor to the mirror displacements. No commercial instrument is sensitive enough to detect the small residual displacements of the mirror. However, combining the measurements of the transfer functions of the single filters, an evaluation of the transfer functions of the entire chain was recently provided. This experimental analysis, discussed in [8], was performed on a suspension prototype. This demonstrates that the total transmission of horizontal ground vibrations, at least above a few Hz, is many orders of magnitude smaller than the transmission of vertical

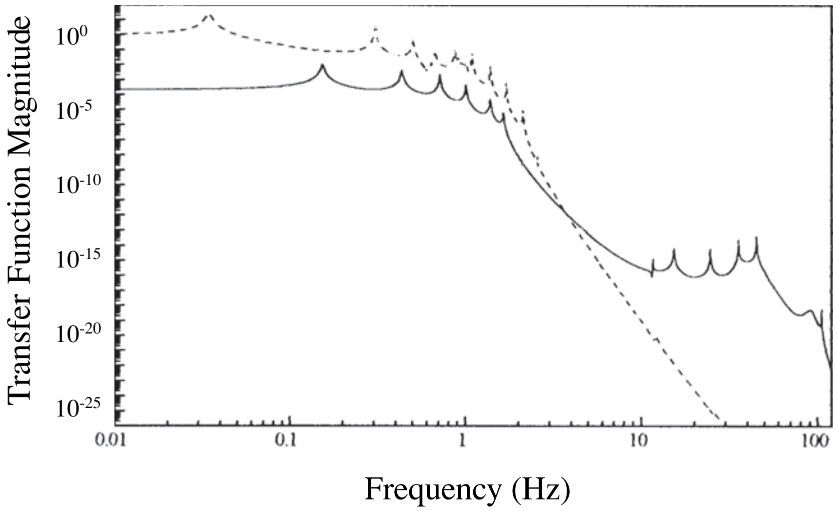

Figure 2. Magnitude of the vertical transfer function multiplied by the geometrical coupling factor (continuous line) and of the horizontal transfer function (dotted line). The measurements have been obtained by combining 'stage-by-stage' measurements. Multiplying the two curves by the linear spectral density of the input seismic noise (similar in the two directions) one can obtain the displacement noise induced in the interferometer by vertical and horizontal ground seismic vibrations.

vibrations. This is due to the better attenuation performance of each mechanical filter in the horizontal plane. As a consequence, the residual vertical vibrations of the mirror in the band are much higher than the horizontal vibrations. As mentioned above, vertical vibrations are partially transmitted to the horizontal beam directions because of coupling mechanisms. An unavoidable vertical–horizontal coupling is due to the Earth curvature. The 3 km far end mirrors have to be inclined by about 3×10^{-4} rad with respect to the local plumb line to keep a position perpendicular to the incoming beam (i.e. parallel to the other mirrors). As a result, a fraction of the displacement of the mirror along the local plumb line is transmitted to the beam direction. As shown in figure 2, even considering only this small coupling mechanism (neglecting the larger ones due, for instance, to mechanics), the largest spurious contribution induced by seismic noise in the band is due to residual vertical vibrations of the mirror projected to the beam direction. However, at the same time, from the continuous line of figure 2, one can see that the transmission of ground vertical seismic vibrations along the beam through the entire suspension chain is not so large. A suppression by more than 12 orders of magnitude occurs from about 4 Hz. Taking into account the values of the ground vertical seismic noise reported at the beginning of the paper, this corresponds to a residual mirror seismic displacement along the beam less than 10^{-20} m $\mathrm{Hz}^{-1/2}$. This value is well below (2–3 orders of magnitude) the mirror displacement induced by thermal noise. This represents a good safety margin. Even considering vertical–horizontal coupling factors much larger than the geometrical factors, the seismic noise should not affect the antenna sensitivity curve.

3.2. Inertial damping

The absolute velocity of the suspension point in the horizontal plane has been monitored for a long period on the seven chains already in operation at the VIRGO site. The measurements

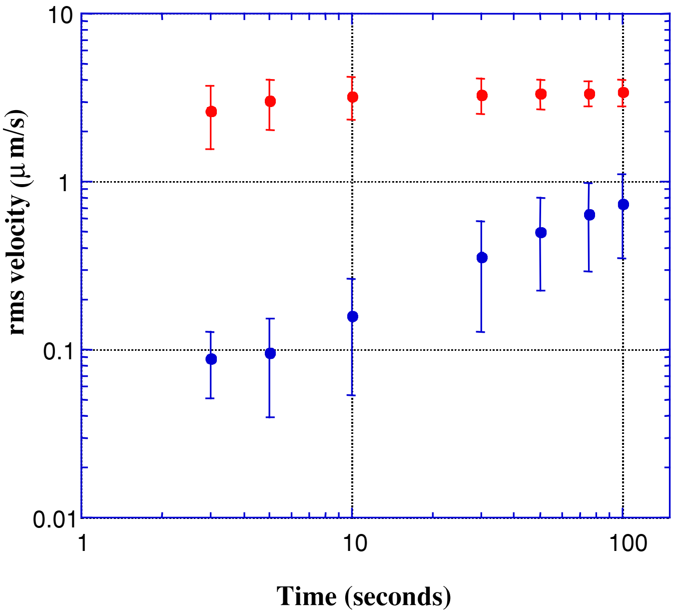

Figure 3. rms velocity of the beam splitter suspension point along a given horizontal direction as a function of the different time scales on which it is computed, open loop (grey points) and closed loop (black points).

were made by using the three top-stage accelerometers. The rms values of the horizontal components of the velocity turn out to be very similar for all suspensions and for all horizontal directions. The rms values were computed several times taking into account data files for consecutive intervals of a few days. The two curves in figure 3 display the statistical mean of the rms velocity of the suspension point along a given horizontal direction, open loop (upper curve) and closed loop (lower curve). They are plotted as a function of the different time scales on which the rms is computed. The variances are reported as bar errors. Comparing the two curves one can see that the inertial damping provides a strong reduction of the top-stage horizontal rms velocity on time scales of several seconds and more. As shown in [4], this performance is enough to reduce, on the same time scales, the rms displacement of the mirror along the beam down to less than 1 μm, as required by our specifications.

3.3. Mirror angular control

The rms displacements of the mirrors along the two angular coordinates mentioned above were monitored by means of the digital cameras used in the control loops. The curves in figure 4 display the statistical mean (and the variance, given by the error bar) of the mirror rms angular displacements when the loop is closed. The values, similar for all mirrors, are plotted as a function of the different periods in which the rms is computed. The statistics have been obtained by analysing consecutive time intervals of 2 day data files. One can see that up to several hundreds of seconds, the residual rms angular displacements of the mirror with respect to the camera, are less than 1 μrad, as required by our specifications.

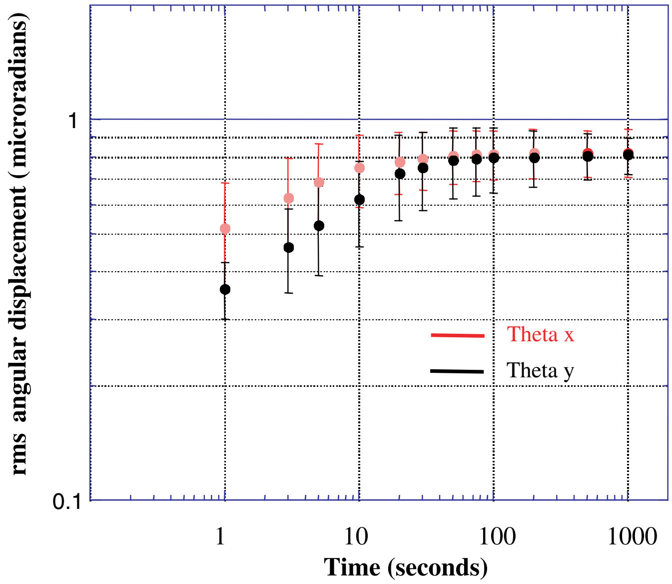

Figure 4. rms angular displacements as a function of different time scales. The measurements, taken when the angular control loop is closed, concern the input mirror of the VIRGO North cavity. *Theta x* (light points) denotes the rotation around the horizontal axis perpendicular to the beam, while *Theta y* (black points) is the rotation around the vertical axis.

4. Conclusions

The results discussed in this paper show that the VIRGO suspensions meet the specifications concerning the passive seismic attenuation, the active reduction of the low-frequency horizontal swings of the mirror and the local control of its angular position.

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