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DESIGN CONSIDERATIONS FOR SEISMIC ATTENUATION SYSTEMS IN GRAVITATIONAL WAVE DETECTORS

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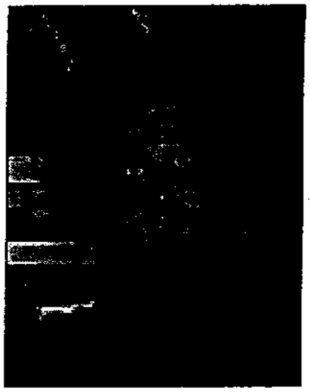

1 Introduction

To make a rational design of a seismic attenuation and mirror suspension system for interferometric gravitational wave detectors, it is necessary to first determine its requirements. The Seismic Attenuation System (SAS) must satisfy two main requirements. First, it must attenuate the seismic perturbation below the level of any other perturbation in the frequency band of interest, and second, it must keep the mirror steady within acceptable mirror actuation dynamic range at all frequencies. The most advanced seismic attenuation system being built is represented by the Virgo super attenuation chains, which were designed mainly around the first requirement. More focus is necessary on the second one.

The mirror actuation system on the mirror suspensions must keep the mirror on the dark fringe position at all times and well within the signal detection dynamic range. The 10^6 dynamic range of the Radio Frequency (RF) mixer that extracts the position information from the beam sidebands limits the signal detection performance. The mixed signal is required to have sensitivity below 10^{-18} m and, therefore, saturates above 10^{-12} m. At the same time, the mirror actuation system must not introduce noise above 10^{-18} m and leave the mirror free to respond to the gravitational wave signal within the desired frequency range. For a conservative safety margin, to keep the RF sensors safely out of saturation, it is required that the mirror actuation system keeps it on the dark fringe within 10^{-14} m.

The mirror actuators will then be required to have a dynamic range extending from 10^{-14} m up to the maximum excursion of the mirror residual motion. The amplitude of the residual motion is given by the seismic attenuation system resonances and by internally generated motions.

If, for example, the mirror residual resonant motion showed a 100 nm Gaussian distribution with 10 micron non-stochastic tails, the mirror actuation system will have to provide a 10^9 dynamic range to maintain lock, 10^7 only if the non-stochastic tails are eliminated.

From these considerations the following requirements of the seismic attenuation and suspension system are derived. It must generate the lowest possible residual motion, free from non-stochastic tails so as not to overload the mirror actuation system. The above hypothetical 10^9 (or even only 10^7) dynamic range is a prohibitive one for a single stage of actuation; therefore it is necessary to split its dynamic range into at least two hierarchically nested systems, requiring at least a double pendulum system.

It is also wise to remove the actuators from the mirror itself for two reasons. First, the actuators are likely to reduce the mirror mechanical quality factor, which is the interferometer sensitivity limit in most of the frequency band of interest, and second, the actuators themselves are liable to inject random forces on the mirror, which can easily mask the signal. To illustrate this point, it is sufficient to calculate that the energy necessary to move a 30 kg mirror suspended on a 1 m long pendulum to the sideband mixer saturation point (10^{-12} m) is only 10^{-3} eV. The mechanical noise generated by an actuator is proportional to the force that it delivers. It is therefore important that the finest attenuator is required to give the lowest possible force and that it is isolated from the mirror by at least an isolation stage. Removing the actuator from the mirror requires a triple pendulum configuration.

To avoid seismic motion re-injection through non-linearity of standing forces, the actuators must operate from recoil masses also hanging from the seismic motion attenuation system.

At this point we are ready to evaluate the payload required from a seismic isolation suspension system. A typical mirror will weight about 30 kg and will be accompanied by masses of similar magnitude for the other 2 bobs of the triple pendulum, the 3 recoil masses and the intermediate body that supports them.

The main requirements of a SAS are a) a payload of approximately 250 kg, b) a residual motion, integrated over all frequencies, measured in tens of nm, c) the residual resonant motion must be free of non-Gaussian tails, d) the seismic attenuation level must drive the seismic perturbations level below the sensitivity limit given by other effects in the frequency range of interest. A mix of active and passive techniques are necessary to meet the requirements.

Using low resonant frequency oscillators in 6 degrees of freedom, the attenuation requirements in the frequency band of interest (point d) can, in principle, be satisfied entirely with passive filtering techniques. Arbitrary attenuation factors can be obtained by simply chaining a sufficient number of filters.

The problem of purely passive attenuation is that the oscillators' resonances outside the frequency band of interest are excited by seismic motion to very large amplitudes, leading to excessive resonant residual motion to be handled by the mirror actuators. This problem in the past has been handled by either introducing passive dissipation in the oscillators (LIGO's and GEO's rubber loaded springs) or building oscillators with the highest possible mechanical quality factor and precede the passive attenuators by a layer of active attenuation charged to soak out the energy from the unwanted resonances (Virgo's technique). The active attenuation stage is also used to provide additional attenuation in the frequency band of interest and reduce the load (and the number) of following passive attenuation stages.

The first technique has the obvious limitation that damping by internal dissipation in plastic materials will introduce non-stochastic energy releases that will load the mirror actuation system which is part of the data flow and ultimately limit the sensitivity level of the interferometer. Also passive damping will not reduce the residual motion due to the ground motion integrated at and below the system lowest resonances. The active solution is more difficult to achieve but it has a much better potential. To best operate it, high mechanical quality factors are required in the passive portion of the chain.

Active attenuation cannot be used throughout the entire chain; it ultimately stops at the sensitivity level of the best available accelerometer, which is still many orders of magnitude above the gravity wave generated signal[1]. Beyond the sensitivity level of the best accelerometer the attenuation must proceed passively. The trade off decision of this technique is at what level to make the transition between active and passive attenuation.

Active attenuation in Virgo is obtained acting on a 'platform' of very low resonant frequency (30-50 mHz mechanical oscillators) supporting the passive portion of the attenuation chain. The action is made on feedback from accelerometers with low-end dynamic range starting substantially lower than the resonant mode of any other oscillator in the chain. On the high side the unitary gain point of the feedback loop can be extended until the passive attenuation power of the mechanical attenuation below crosses under the accelerometer sensitivity level. In this arrangement, as long as the actuators can feed more power than the injected seismic noise, the accelerometer feedback system freezes the platform to an inertial reference system within its own sensitivity. Any energy stored in the resonances of the mechanical oscillators below will recoil against the

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[1] *If an accelerometer of sufficient sensitivity existed it could be used to directly detect the gravitational waves instead of an interferometer.*

platform and shake it. The feed back system will then soak up this energy. The residual motion of the mirror suspension point will be minimized using the highest sensitivity accelerometers, low platform recoil mass, and the highest quality factors in the passive chain.

The performance of a Virgo-like active attenuation stage is limited by the wrong direction sensitivity of its accelerometers rather than by their sensitivity level. This drawback can be reduced with the use of Multiple In Multiple Out (MIMO) feedback, but eventually it is necessary to add a nested second active stage inside the first one as shown by the Jila group. Going to multiple stage active attenuation systems will strain the requirements of the accelerometers, requiring performances exceeding the present Virgo ones (which are limited by their position sensor noise and by thermal noise in the test mass flex joints) and an effective tilt meter to level the nested IP platform.

2 Design Guidelines

In the conceptual design of a new attenuation chain we assumed a maximum attenuation power of 10^2 per stage (10^3 for active stages) and kept any excess performance in reserve.

Given the difficulty of reducing modal cross talk below the percent level we assumed a 10^{-2} cross talk at all points along the chain, thus requiring uniform progression in attenuation level in all 6 degrees of freedom.

To build the above seismic attenuation system we started the following path. On one hand, we are pushing an aggressive simulation program, taking advantage of the LIGO end to end simulation package. On the other hand, we have singled out the existing and still missing components and are attacking them one by one either by incremental improvements or by radically new design.

The existing and tested components (mainly derived from the Virgo experience) are a) the suspended, chainable seismic attenuation filter (standard filter)1), b) the filter Zero geometry2), c) the inverted pendulum geometry3), d) the digital readout and control electronics, e) the active damping and attenuation technique in three degrees of freedom MIMO controls for the inverted pendulum, and f) the first-stage accelerometers.

Of the items being extensively redesigned, a prototype of the new Standard Filter based on Geometric Anti Springs (GAS)4) has been built and will be reported below.

The items that need to be developed from scratch are a) the nested inverted active stage configuration, b) a precision level meter to generate a dynamically flat platform for the nested inverted pendulum, c) wireless controls of the mirror and of the active attenuation instrumentation, d) high sensitivity second stage accelerometers.

3 Development Status

A first attenuation chain design has been sketched (Figure 1) and is being simulated. It is only a conceptual design and will evolves as the simulation and the construction of prototypes of the components progress. It is presently composed of the following:

a) A long inverted pendulum instrumented with first generation accelerometers to gain height, for horizontal low frequency attenuation (x, y, and ϕ) and to provide suitable soft platform for the first stage active attenuation stage.

b) A triplet of low frequency, vertical attenuation actuated GAS filter zeros providing suitable soft platform for the first stage active and tilt attenuation stage, instrumented with first generation accelerometers for vertical low frequency attenuation (z, θ_x, θ_y).

c) An intermediate platform hanging from wires 2-3 m below the filter triplet instrumented with a suitable level meter.

d) A short, inverted pendulum to provide suitably soft platform for the second stage active attenuation stage with high sensitivity accelerometers for additional horizontal low frequency attenuation (x, y, and ϕ).

e) A low frequency, vertical attenuation actuated GAS filter zero also instrumented with high sensitivity accelerometers for vertical low frequency attenuation (z).

f) A chain of four or five passive GAS attenuation filters to follow up below the sensitivity of the active stages

g) A triple pendulum mirror suspension configuration with independent recoil masses.

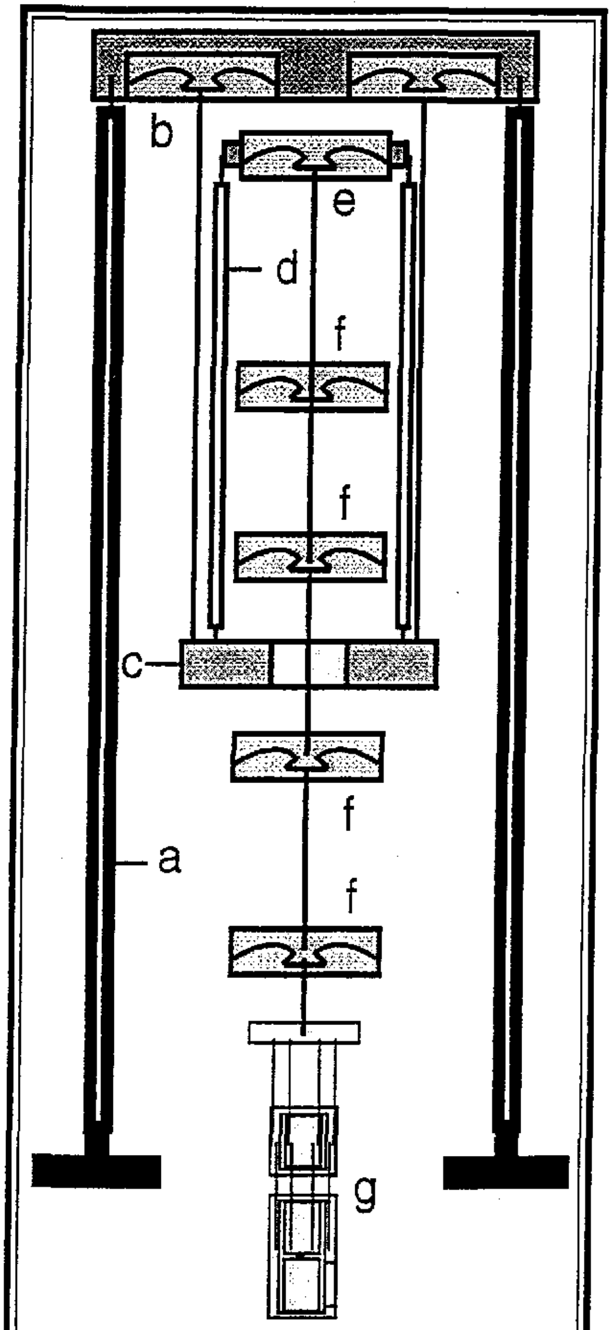

Figure 1. Attenuation chain, schematic design.

The entire chain will operate under wireless controls and can be baked to 100-150°C for Ultra High Vacuum (UHV) compatibility and creep noise elimination.

Development of 3 improved components has started already. The first is a prototype of accelerometer with improved sensors which is currently being tested. The second is a series of 2 consecutive prototypes of an improved standard filter, based on a new concept of anti springs, are being partially tested. The third is the design and manufacture of a filter zero prototype based on the standard filter design, and including Inverted Pendulum provisions.

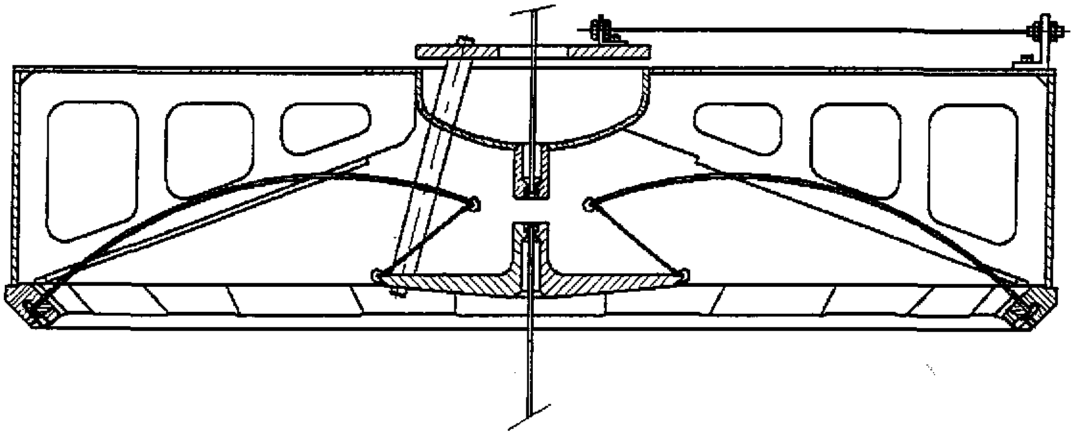

Figure 2. Prototype of GAS·filter.

The geometric anti springs of the new design are obtained with a crown of converging flat triangular blades, bent by the load. The blades are also stressed in the radial direction by inclined wire links hooked to a load disk. Changing the radius of the disk changes the anti spring force. A concept demonstrator prototype was built and tested as reported elsewhere. It completely validated the GAS idea [4)].

The second prototype is a real UHV compatible filter (Figure 2). All filter tuning mechanisms, both manual and remote, have been eliminated, taking advantage of the much better thermal stability and larger dynamic range (both more than 10 times wider) of GAS compared to the Virgo magnetic anti springs. The filter resonant frequency will be factory preset and the working point tuned by adding weight. All the mechanical

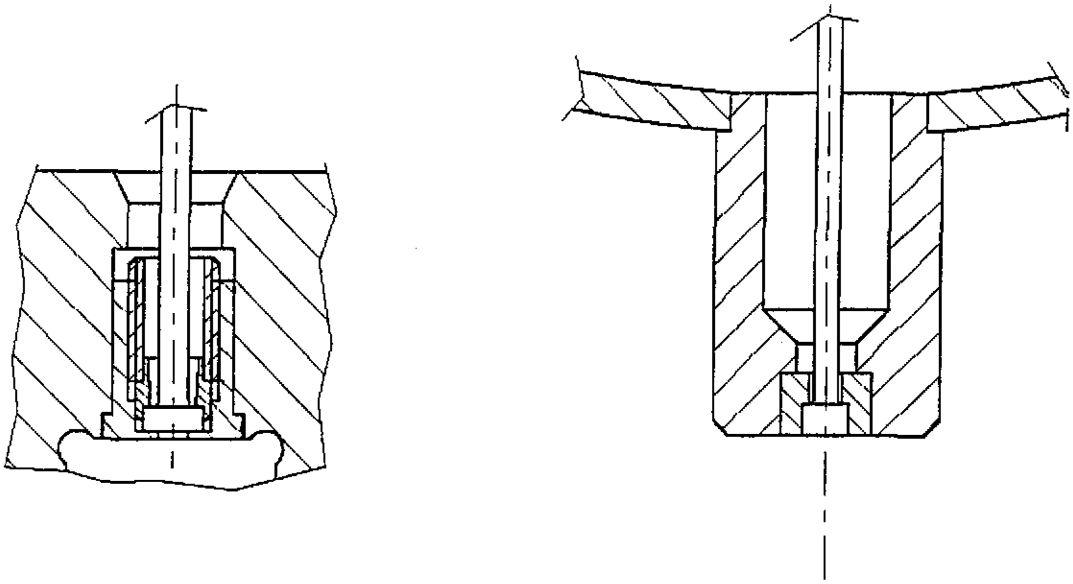

Figure 3. Suspension wire connection to the filter's body—old Virgo design on the left and new design on the right. A suspension wire with 2 "nail heads" at its extremity is machined from a maraging steel rod. The head is supported by a split cup housed in a cyclindrical hole turned directly in the filter body.

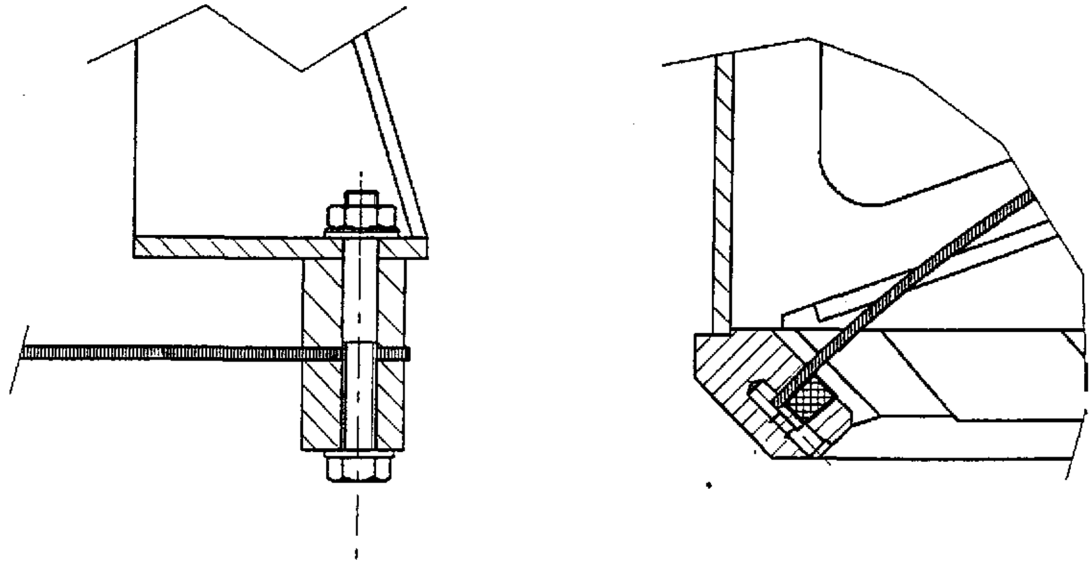

Figure 4. Connection of the cantilever blade's base to the filter body–Virgo design on the left, new design on the right. Orginally, 3 bolts under flexural stress were constraining the blade. In the new design, a wedge constrains the blade in position. The stress applied by the blade's load is almost completely compressional.

connections of the chain components that carry load present negligible or no shear stress in the contact surfaces. There are only 5 such points in each filter—the two connections to the suspension and the suspended wires; the connection of the spring blades to the filter body, and the 2 connections of the wire link to the blade's tip on one extremity and to the load disk on the other.

These points are dealt with as follows:

1. The connection of the suspension wires is made with the half-cup technique already tested in Virgo. The half-cup contact surfaces are flat and horizontal, perpendicular to the vertical load. The ill-defined thread contact points in the screw are eliminated (Figure 3).
2. The connection of the blades to the filter body is made by means of wedges in a suitable slot (Figure 4). Some shear is generated when pressing the wedge in its seat. When applying the blade's load the stress becomes mostly compressional and the shearing component can be neglected. This geometry replaces the clamps used in Virgo again eliminating the ill-defined contact points in the bolted structure.
3. Machining monolithic hooks on the wire extremities makes the connection of the wire link ends. The hooks present a contact surface perpendicular to the wire axis and sit in notches in the blade's tip and in the load disk. All screws are eliminated and the contact stress is purely compressional (Figure 5).

In addition, all the contact surfaces may be coated with low melting braze that will braze during bakeout and transform the entire chain in an essentially monolithic one. Bakeout under stress is expected to eliminate all creep noise generation problems. These precautions, together with the elimination of all cabling and connections bypassing the attenuation chain are expected to generate the best noise performance.

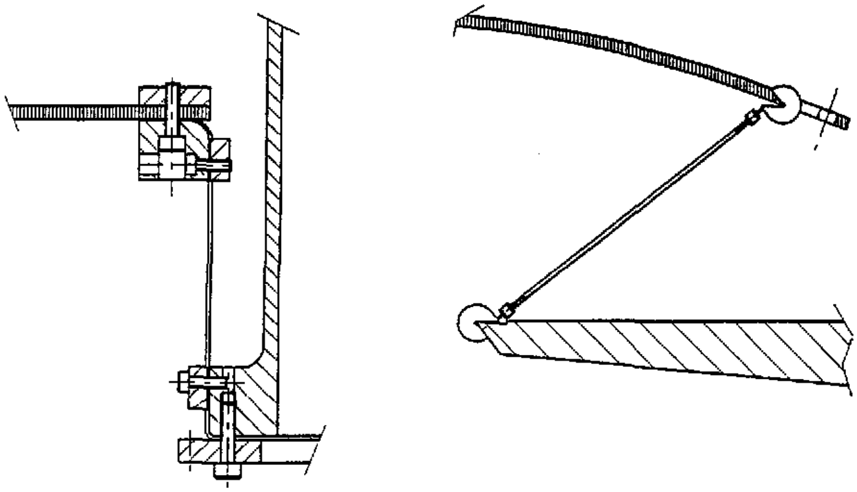

Figure 5. Connection of the blade's tip to the load disk–Virgo design on the left and new design on the right. The connection wire in the old design is clamped perpendicularly to the stress direction and is subject to microslippage. The new wire is provided with hoops having contact surfaces perpendicular to the load on purely compressional stress.

Acknowledgements

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