LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

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Seismic Attenuation Systems (SAS)

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Abstract

We have designed, tested and implemented a UHV-compatible, low-noise, non-contacting force actuator for DC positioning and inertial damping of the rigid body resonances of the Seismic Attenuation System designed for the TAMA Gravitational Wave Interferometer. The actuator fully satisfies the stringent zero-force-gradient requirements necessary not to re-inject seismic noise in the chain. Its closed magnetic field design makes for particularly low power requirements and low susceptibility to external perturbations. It retains enough strength to be able to absorb seismic perturbations even in case of small earthquakes.

Keywords: Gravitational Wave Interferometers, Seismic Isolation, Inertial Mode Damping

1. INTRODUCTION

Interferometric Gravitational Wave (GW) Detectors need to be isolated from the seismic motion disturbances in order to become sensitive to the GW signals whose predicted amplitude is less than 10^{-18} m/Hz$^{1/2}$ @ 10 Hz. The required isolation will be obtained by means of a passive mechanical Seismic Attenuation System (SAS) [1,2,3,4,5] made of an Inverted Pendulum[6] (IP) followed by a chain of passive mechanical oscillators (filters)[7,8,9,10,11,12]. The IP and the filter chain adequately isolate each interferometer mirror above 4 to 6 Hz by means of mechanical resonances carefully positioned between few tens of mHz and 3 to 4 Hz. These resonances, excited by seismic motion, can reach large excursions, causing the mirror payload to move by microns at low frequency. This residual motion would require large mirror control authority to keep the resonant cavities of the interferometer phase locked[13]. Since the noise of an amplifier is typically a fraction of its maximum output, large authority on the mirror translates into large actuation noise. To suppress the unwanted residual motion (and eliminate the mirror actuation noise problem), we use an active resonance damping system composed of LVDT (Linear Variable Differential Transformer[14]) position sensors and horizontal accelerometers[15] that detect the movement of the IP as it recoils from the low frequency chain oscillations and to generate feedback signals for damping actuators. The LVDT position sensors are also used for positioning the mirror suspension point.

The object of the damping actuator's design is to provide the forces necessary for both these functions.

Any force provided by the actuators would re-introduce seismic noise if the exerted force was dependent on the relative movements of the IP table. If the actuator force had any dependence on position, seismic vibrations applied to the actuator support would partially re-inject onto the IP table. For the same reason, it is also obvious that the actuator must be non-contacting. Any parts of the actuator making contact between its support and the IP table would, to some degree, short circuit seismic noise onto it.

It is then necessary to design a linear contact-free actuator that produces a force independent of its position in all three directions in space. The very good IP passive attenuation performance and its large positioning dynamic range require that the constant force actuator must operate over at least 10 mm in the horizontal plane, and 1mm in the vertical direction, with less than 1% force variation over this full range.

In the Virgo seismic isolation system this same problem was solved by using two large coils in a Maxwell pair configuration and a small permanent dipole magnet in the central volume of constant field gradient[16]. In a Maxwell pair, the two coils are positioned in a way that the increasing field gradient of one coil is cancelled by a corresponding decrease in the other coil. Sufficient gradient uniformity is obtained in a volume typically 5% of the coil dimension. The main disadvantage of this configuration is that in order to obtain a reasonable movement range, it requires large coils with a corresponding large dissipation of power in vacuum. To alleviate this problem a relatively large permanent magnet dipole is used. A disadvantage is that the absence of a magnetic field return yoke makes for large open magnetic fields which can either perturb or be perturbed by external fields. Additionally, relatively large currents (and power dissipation) are necessary to produce the required forces.

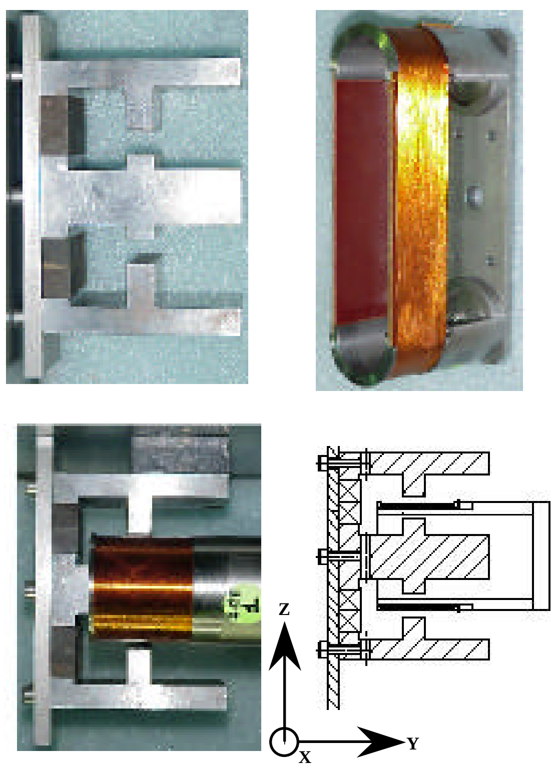

Figure 1:
Exploded (top) and assembled (bottom) view of the actuator. The two prong magnetic yoke (top left) has three arms protruding beyond the twin magnetic gaps to compensate the leakage field. The coil (top right, for convenience shown with its X axis in the vertical direction) is much longer than the magnet yoke to insure the force stability against longitudinal movements. The sketch on the bottom shows how the coil fits into the yoke when the actuator is fully assembled.

We have designed a solution (Figure 1) that solves both problems and fully satisfies the requirements. The actuator that we designed and implemented is made of a racetrack coil mounted on the IP table floating in the confined magnetic field of a twin-gap magnetic yoke. The yoke is attached to the external reference structure and energized by two permanent magnets. A current passing through the coil will generate a force proportional to the integral of the yoke's magnetic field combined with the distributed current in the coil as in the vector equation 1. This arrangement does not generally produce a force that is independent of the relative position of the coil and the yoke. A careful design of both the coil and yoke solved this problem.

2. Conceptual design

We started from the "voice coil" idea because the magnetic yoke allows large confined magnetic fields and thus large forces with small currents, power consumption, and exposure to perturbations. Normal voice coils have cylindrical symmetry and allow only unidirectional movement, while an IP allows free movement in the two horizontal directions.

A wire in a magnetic field will be subject to a force:

$$d\vec{F} = -i\,\vec{B} \times d\vec{l} \qquad (1)$$

The Constant Force Actuator we devised (figure 1) replaces the voice coil cylindrical permanent magnet with two separated linear yoke gaps with opposite field directions. The coil is stretched in one direction to a form a "racetrack", and fits in the 2 yoke gaps as shown in Figure 1, bottom. Figure 1 also shows the Cartesian axis convention.

In our case, B is parallel to the z direction and the coil wire runs in the x direction, in the flat surface where the force is exerted. The force F is therefore in the y direction. If the spires are evenly distributed on the coil, we can write the force exerted on the actuator coil as:

$$F_y = -\int_z \int_x B_z \sigma_x \, dx\, dz \qquad (2)$$

Here $B_z = B_z(x, y, z)$

$\sigma_x = \sigma_x(y)$ the current density in the plane xy which is in good approximation constant over the width and length of the coil.

1) Optimization of $\partial F/\partial x=0$

The coil is much longer than the magnet yoke and its wires are straight along axis x, straddling the yoke's gap. Consequently any movement along axis x will not change the force defined in (2).

2) Optimization of $\partial F/\partial z=0$

The coils, which are much wider than the magnetic yoke gap and mounted at the center of the gap, integrate the same fraction of the vertical component of the magnetic flux for small variations in z. Additionally, the symmetry of the two gaps cancels out any force variation related to z movements. Therefore the force F will not be modulated by vibrations in the z direction.

3) Optimization of ∂F/∂y=0

In the y direction the coil enters and exits the yoke's gap and can generate the largest variations of Force. The voice coil force would be independent of the y position if the magnetic field were completely confined in the yoke's gap volume. Unfortunately this confinement is far from complete. The leakage magnetic field between the two arms of the yoke can be as much as 30% of the field in the gap itself (see Figure 2). The permanent magnet's fringe field adds to this perturbation. As the coils move into the yoke, they intercept a growing fraction of this leakage field and the total generated force will increase. This unwanted growth could be compensated by shaping the leakage field in the outer part of the yoke.

In order to achieve ∂F/∂y=0, we have to compensate the leakage field around the coil so that the field gained on one side equals the field lost on the other side. This adjustment can be made by making B 'quasi-periodic' with respect to y and choosing the width of the coil equal to the period of B(y).

This was done in four steps:

1) We added protrusions of the yoke beyond its gaps to generate a leakage field equal in shape and strength on both sides. The shape and length of the protrusion was chosen to optimize this effect.
2) We measured the vertical magnetic field intensity as a function of y and obtained the graph of Figure 2.
3) We numerically integrated the measured magnetic field over the lengths of different coils and all possible positions to find the force applied to each coil.
4) We adjusted the length of the coil and the shape of the yoke to make the force constant.

3. Actuator Construction and Optimization

Examining Figure 2, which shows the field of an optimized yoke, we observe that the magnetic field profile on the left of the peak is similar to that on its right. The field shape locally mimics a periodic function with a period of about 43 mm. By making a 43 mm wide coil, we can get a constant force over a region of more than 10 mm of length. Figure 3 illustrates the steps used to optimize the coil width for the yoke of Figure 2. Of course, if the yoke is not well designed, no coil width will generate a constant force.

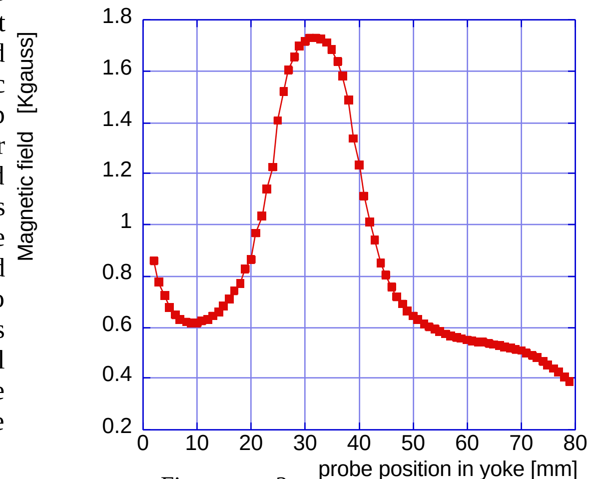

Figure 2: Magnetic field profile as a function of the y position.

Table 1

Position [mm]	0	20	40	60	80
Force [g]	193	193	192.5	192	192.5

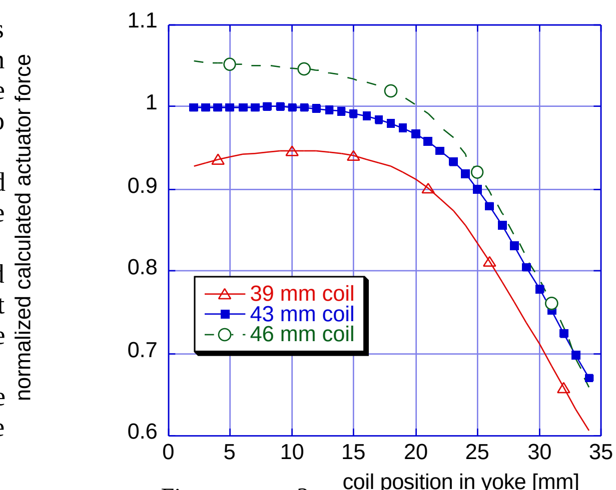

Figure 3: Calculated Y force amplitude for coils of different widths moving inside the yoke field of figure 2.

4. Prototype measurements

After building the optimized coil and magnet's yoke, we placed the coil on a precision scale and suspended the magnet over it. We measured, at constant current, the change of the weight of the coil while moving the magnet along all three axis. Table 1 shows the measured magnetic force exerted on the coil for varying positions of the magnet along the Y axis. The standard deviation is only 0.4% over 80 mm.

Similarly, the force did not show any measurable change for movements in the Z direction.

Finally, Figure 4 shows the force measurement for the coil moving in the Y direction, in and out of the yoke's gap. The result agrees perfectly with the calculations of Figure 3. The standard deviation is less than 0.2% within the resolution of the measuring apparatus in the first 10mm, and 0.4% within the first 15mm.

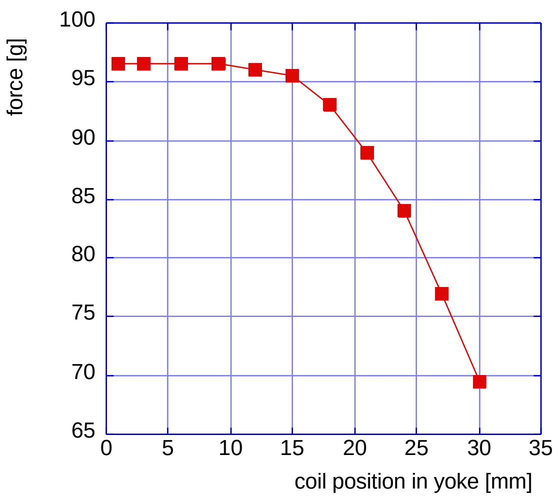

Figure 4: Force measured on a scale as the coil is moved micrometrically outside the yoke's gap.

Three additional points have been addressed in the design:

A. To avoid induced eddy currents in any moving conductor generating uncontrolled damping forces, the coil was built without metal parts in the magnetic field with the exception of the coil wire itself. The coil wire is very thin and uniformly wound, so the magnetic field variation integrated over it is vanishingly small. The damping generated by the coil as a whole is null if the coil is driven by a high impedance current generator circuit.

B. The actuator is completely built with vacuum compatible materials, and can be baked at high temperature to satisfy ultra high vacuum requirements.

C. The actuator provides a force per unit current of 1 Newton/Ampere and, with our coil driver, a peak force of 1 N (with a peak dissipation of 40 W). In normal working conditions, the actuator only dissipates a few mW.

5. Implementation in the SAS towers.

The actuators described above have been installed on the SAS Inverted pendulum prototype and successfully used in a Multiple In Multiple Out configuration to damp the attenuation chain modes.

The large force capabilities of the instrument have come in handy to shake the SAS chain during the characterization of its attenuation performance. The force versus position stability was completely satisfactory, and did not produce any additional noise. No attention was paid at the time to the electronics noise.

During the SAS system commissioning in the 3 meter Fabry Perot prototype for TAMA at the University of Hongo, it was noted that the actuator was much stronger than necessary. As a consequence, the electrical noise of the coil driver, coupled to the large force per unit current of the actuator, would inject too much electro-mechanical noise which would spoil the performance of the IP as illustrated in Figure 5. In order to reduce the actuator's electrical noise below all other sources, its force per unit current had to be reduced by a factor of at least one hundred. The actuator efficiency was reduced by a factor of 30 by replacing the original permanent magnets with much weaker ones. The remaining fraction of the required force per unit current reduction is obtained by reducing the driver electrical gain.

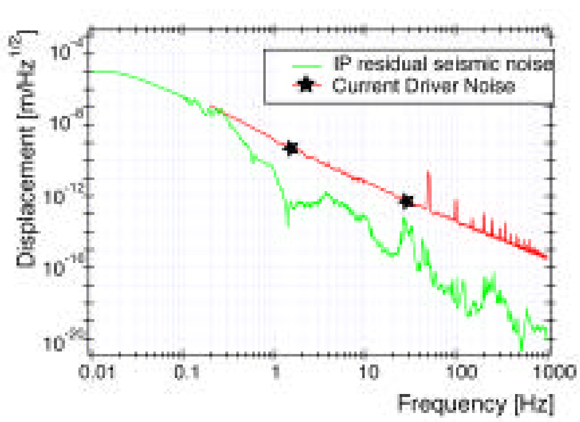

Figure 5: Comparison of the residual seismic noise on the passive IP platform and of the driver's electrical noise feeding into the actuator. The actuator gain would be low pass filtered below 3 to 5 Hz but it would still dominate over the IP mechanical noise. The actuator force per unit current has to be reduced by at least a factor of 100.

Replacing the magnets changed the saturation level of the yoke, and introduced an unacceptable 0.5%/mm force gradient, see figure 6, circles. This slope, coupled to the seismic noise at the actuator base, would have re-injected noise at the level of $2.5\ 10^{-10}$ m/Hz$^{-1/2}$ at 1 Hz (assuming 1 micron r.m.s. seismic noise and 5 mN standing force operation). This noise would be ten times higher than the IP performance. The force versus position slope was nulled again by adding 7 mm shims on the outer horns of the actuator's yoke. The corrector shims reduced the force slope by more than one order of magnitude, thus bringing the seismic noise re-injection level below the IP noise floor.

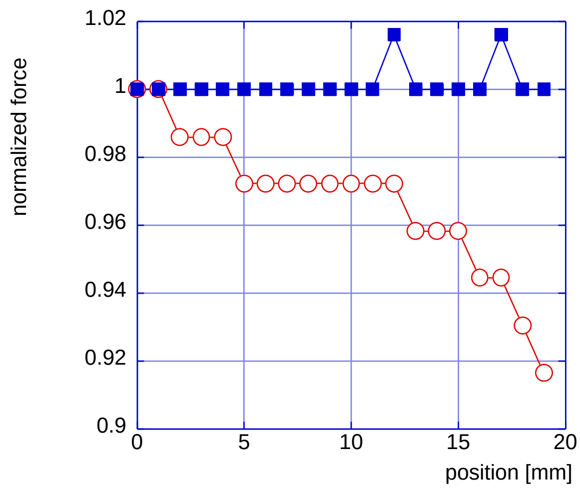

Figure 6: Actuator force versus y position after replacing the magnets (circles) and after re-shimming the yoke. The 0.5%/mm slope was eliminated by the shims (squares). The quantized jumps in the plot correspond to the scale digitalization noise (10 mg). The force drops rapidly (2%/mm) above 20 mm.

Even with the reduced force per unit current, it is expected that the actuator will operate below 50 mW of dissipated power in vacuum (10 mW necessary for full tidal corrections, the rest of the forces being picked up by tuneable parasitic springs).

The maximum force ever needed during operation is the force that is required during an earthquake to maintain the damping of the suspended chain.

Of course, chain damping can be maintained only as long as the ground does not shake the surrounding safety structures over distances larger than the mechanical end stops of the IP (10 to 12 mm in all directions). Below this excursion level, the maximum force required to maintain full damping is the static force required to move the IP to its end stops. The IP is designed for working below 30 mHz, which sets the maximum earthquake return force requirement between 30 and 50 mN. This force level can be achieved by the current drivers, even after the force per unit current degradation described above.

The Olympia earthquake, that damaged the Hanford Gravitational Wave Interferometer, shook the ground by plus and minus 5 mm. This excursion would not have brought the IP to touch its end stops. Therefore, we expect that the SAS chains would have maintained full damping and would not have been affected. If the earthquake had been stronger, the actuator yoke itself might have acted as an undesired end stop, limiting the IP range to 7-8 mm in one direction. To avoid this, future yokes will be designed 50% wider to allow the full IP swing dynamic range. Of course, during earthquake damping the actuator would dissipate several watts and warm up.

6. Conclusions

A low power, high linearity non-contacting force actuator has been developed to control the LIGO IP motions, and to damp the SAS rigid body resonances. The force it generates is constant within 0.5% in the entire IP dynamic range in all degrees of freedom and thus does not re-introduce seismic noise above the level of all other residual noise sources. The actuator current to force ratio was so high that it had to be reduced to keep its electronics noise contribution below the other noise sources. Even with the reduced strength, the actuator and its driver are capable of providing the forces necessary to maintain full chain damping during sizeable earthquakes.

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