LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Gas Damping Monte Carlo

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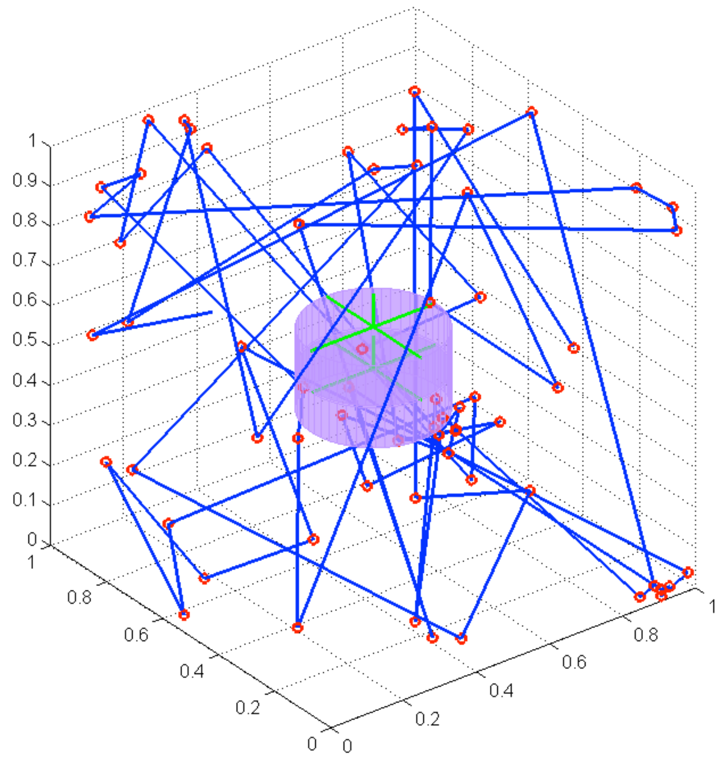
1 Introduction

Gas damping noise, or force noise on the aLIGO test-masses due to residual gas in the vacuum chambers was recently explored analytically in T0900509, “Gas Damping of the Final Stage in the Advanced LIGO Suspensions”, Rai Weiss. Here we present a numerical Monte Carlo simulation of the aLIGO geometry.

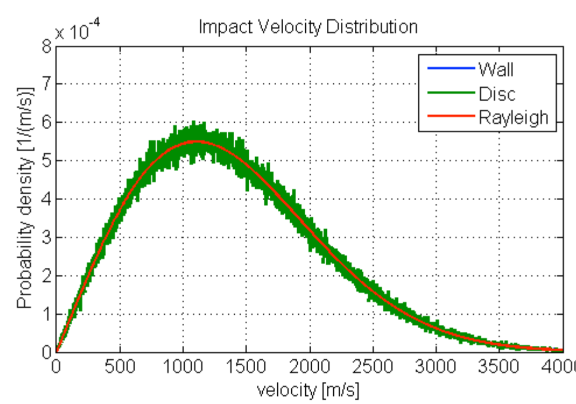
2 The simulation



The simulation is a brute-force approach to the problem of computing force noise due to residual gas in which gas particles move about in a 1m cubic volume. In the volume there are 2 cylinders 34cm in diameter (see figure at right). The separation between the cylinders is varied to produce various levels of force noise (see next section).

The mean-free-path at vacuum levels of interest (around 1e-8 torr) is much larger than the size of the box, so gas particle collisions are ignored.

Each time a particle encounters a surface (box wall or cylinder surface), it immediately leaves the surface with a random velocity. This models complete accommodation with no residence time. After accommodation on a surface, particles are emitted with a Rayleigh distribution of velocities in the normal direction, and Maxwell-Boltzman distributions in the directions tangential to the surface. This is the same as was used in a recent publication on the topic [1].



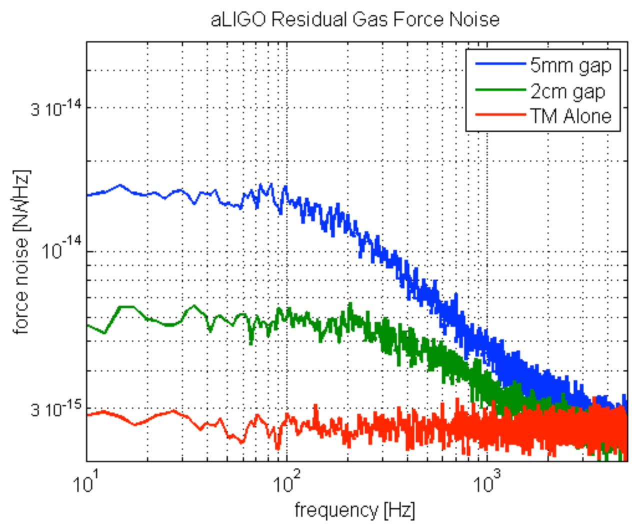
A number of checks were performed to establish that the simulation was working properly. After debugging, it was found that the pressure was equal on all surfaces and had the expected value given the particle number density and the temperature. The distribution of impact normal velocities on all surfaces was found to be the Rayleigh distribution (see figure at right).

Each impact of a particle on a surface is recorded, along with each departure of a particle from a surface. These are collected in to 100us bins and multiplied by the mass of each particle to produce a time series of the net force on each surface.

3 Force Noise

To compute the force noise associated with residual gas, simulations used in this note follow each of 20 thousand particles for 10 seconds. The molecular mass of the gas used was 2amu (hydrogen), and the temperature considered was 293K, giving a characteristic velocity of 1.4km/s. The results were then scaled to a density of 3.3×10^{14} particles / cubic meter to produce a pressure of 10^{-8} torr.

Comparing the result for a test-mass alone in a 2 meter cubic volume gives 2.6×10^{-15}N/rtHz, which matchs [2] for a cylinder in an infinite volume of gas.



Comparing the same result to the approximate calculation in T0900509, we find that the force noise on the TM similar to the "unconstrained noise" given in that document, scaled to the area of the TM,

```
force_noise_free = sqrt(8 * pi * rho * 0.17^2*
kBT * sqrt(kBT * mass)) = 1.9e-15 N/rtHz
```

where rho is the number density and kBT is the Boltzman constant multiplied by temperature.

Taking the blue curve, which has the nominal aLIGO gap of 5mm between the TM and the CP or ERM, each aLIGO test mass is subject to a force noise of

```
force_noise_5mm = 1.53e-14 N/rtHz, force_noise_2cm = 5.9e-15 N/rtHz,
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We show below that this is about a factor of 2 lower than the force amplitude noise found in T0900509.

4 Diffusion time

The diffusion time apparent in the above plot, again using the 5mm gap case, is about

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tau = 1/(2*pi*200Hz) = 800us
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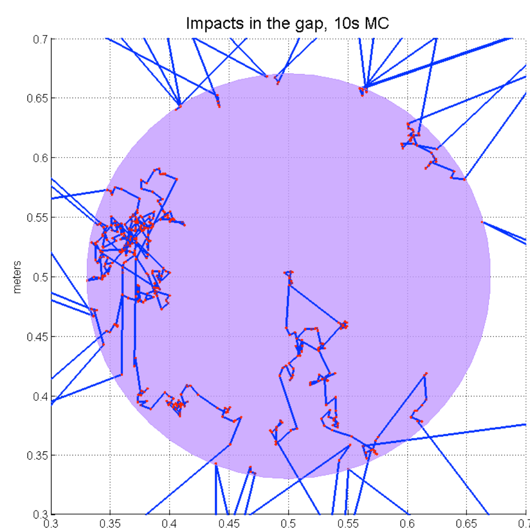


which is about a factor of 6 less than the value computed in T0900509 (tau = 5 ms) using the simple analytical model where tau = $r^2/ d_{gap} v_{th}$ (r is the test mass radius, d_{gap} the gap length, and v_{th} the molecular thermal velocity). Since the noise in the analytical model scales with the square-root of the diffusion time at low frequency, the noise predictions of the analytical model and this simulation, for a given diffusion time, are fairly close, though not quite equal (i.e., the difference between sqrt(6) and 2). It is worth noting that in other Monte Carlo simulations a shorter than expected diffusion time was also found [1].

5 Impact on interferometer sensitivity

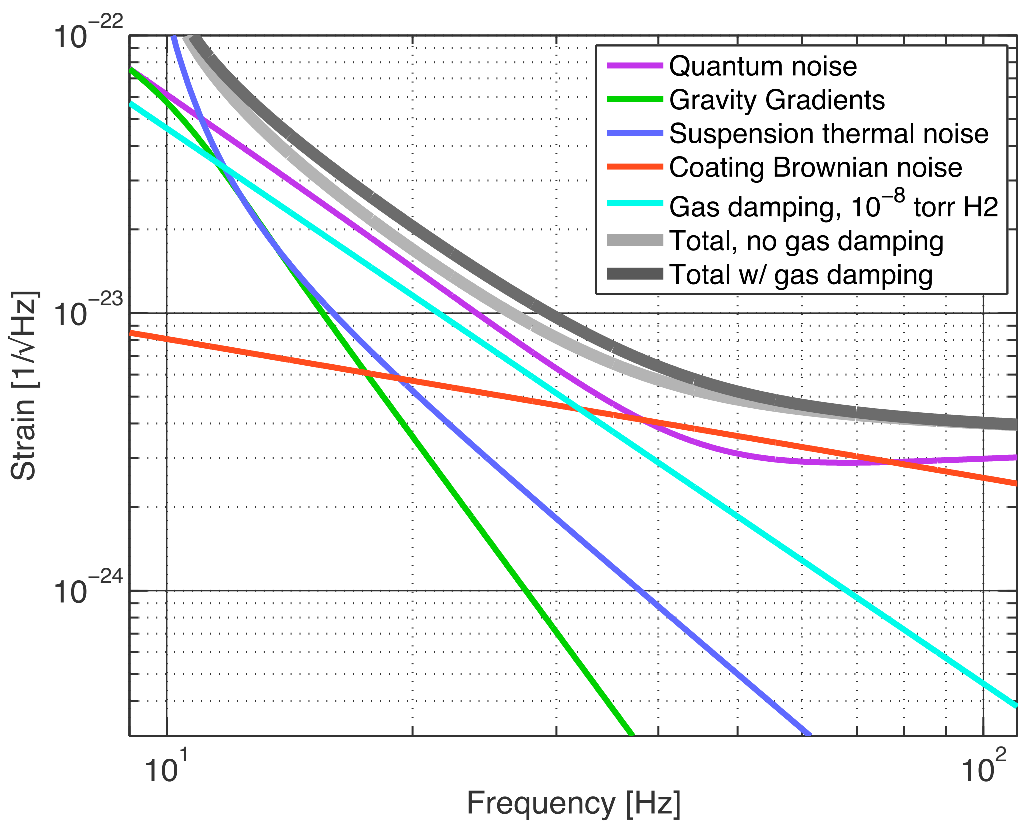
We will assume a residual pressure in the gap of 1e-8 torr of molecular hydrogen. To within a factor of 2-3, this is a reasonable estimate for what we will have in the test mass chambers without adding more pumps to the vacuum system.

Using the result for 5mm gap from simulation given above of 1.53e-14 N/rtHz, and converting this to a strain noise at 20Hz gives,

```
h(20Hz) = 2 * 1.53e-14 / (L * M * (2*pi*20)^2) = 1.21e-023
```

where L = 4000m and M = 40kg are the arm length and TM mass. This is about a factor of 2 below the value presented in figure 1 of T0900509.

The impact of gas damping on the interferometer strain noise budget is shown in the figure below (the suspension thermal noise is for the current tapered-circular geometry). For the assumed pressure of 10^{-8} torr of hydrogen, this noise term is just below the radiation pressure (quantum) noise, where the latter is calculated for full laser power and non-detuned signal recycling (mode 1b in the Systems Design, T010075-v2). With this gas damping noise, the NS-NS inspiral range is reduced from 190 Mpc to 178 Mpc; the range for 30 solar-mass BH binaries is reduced from 1.85 Gpc to 1.65 Gpc.

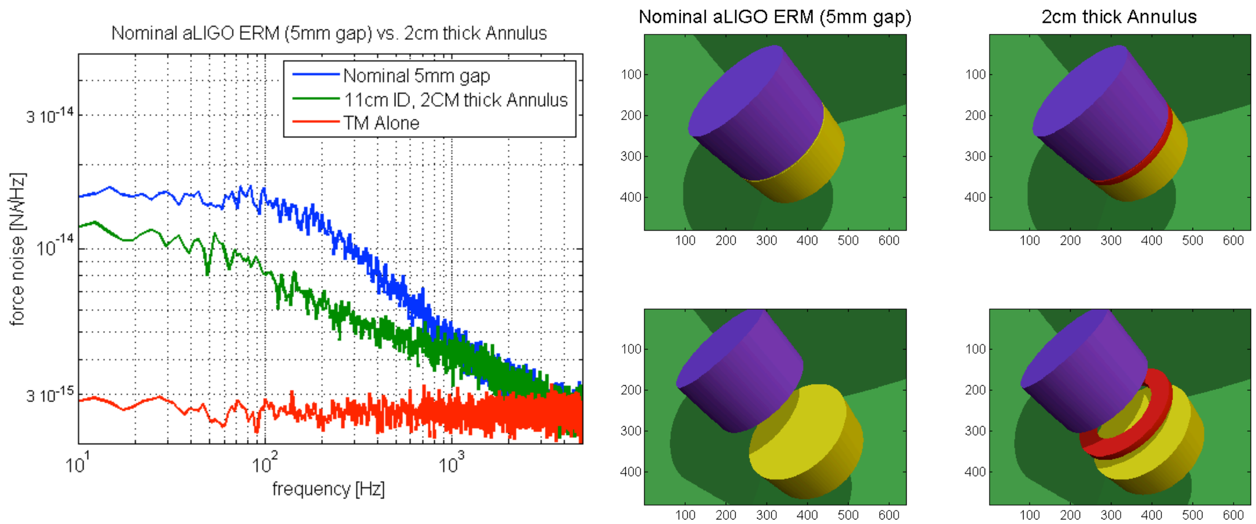


6 Comparison of Various Mitigation Approaches

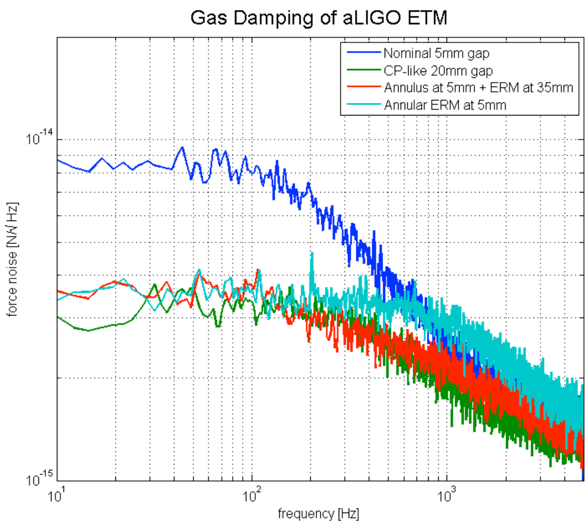
Given the non-trivial impact of this noise source on the aLIGO sensitivity we consider a few options for mitigation. The primary motivation for not simply increasing the gap is the consequent reduction in ESD range (see T1000119). The input test-mass (ITM) and compensation plate (CP) combination house an ESD which is not currently planned to be used for locking, which is the major driver behind our ESD range requirement. As such, we can mitigate gas damping noise from the ITM+CP by increasing the gap between them from 5mm to 20mm (accomplished by thinning the CP by 30mm while keeping its center-of-mass fixed). The result is a factor of 2.6 reduction in gas damping noise (see figure in section 3, above).

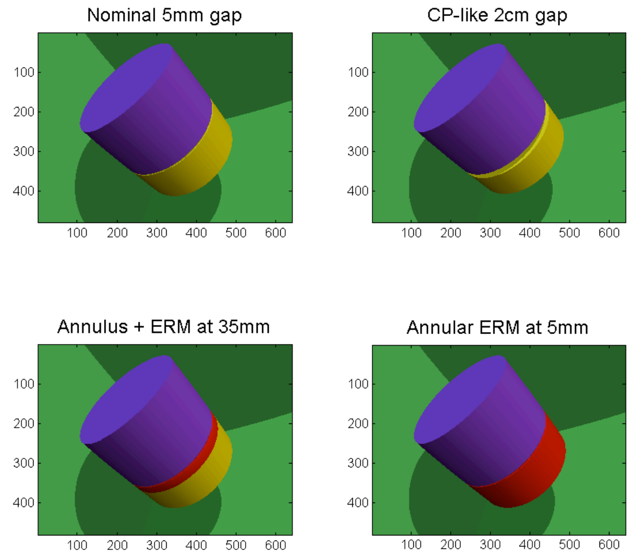
For the end test-mass + end reaction-mass combination (ETM+ERM), the problem is more difficult in that increasing the gap may compromise our ability to acquire lock. On the other hand, the ERM is not located in a resonant cavity and does not act as a thermal compensation plate, and thus there is considerably more flexibility its design. The designs considered here involve replacing some or all of the ERM with a dielectric annulus with an OD of 34cm (same as ERM) and ID of 22cm (sufficient to support the ESD).

The following figure shows the nominal configuration, which has no annulus and an ETM-ERM gap of 5mm (upper left, lower left is exploded view). One of the proposed configurations, which replaces 2cm of the ERM with an annulus is also shown (upper right, exploded in lower right). The ETM is purple, the ERM yellow, and the annulus is red. The bounding box provides the green backdrop. The noise curves associated with these configurations are also shown.



Continuing along the same lines, we considered a 3cm annulus, and the extreme case in which the ERM is simply replaced by the ESD supporting annulus. Some of these results are redundant to those presented in section 3. This was done to confirm that the new simulation code produces the same results as the old one, and to have all of the relevant results in the same format.

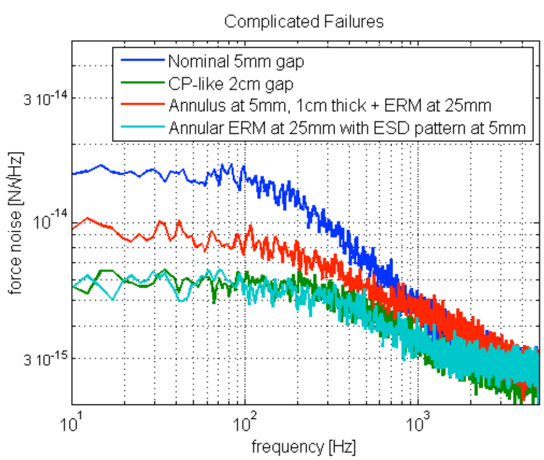


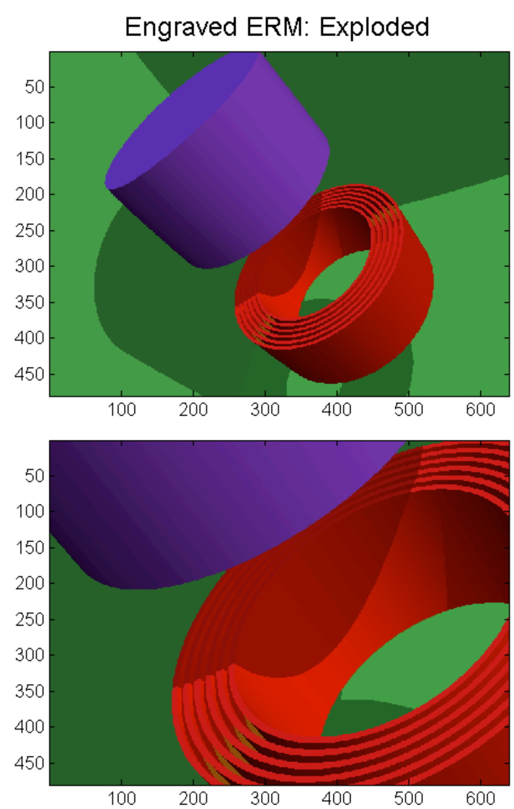


The conclusion is that the area of the ESD supporting annulus results in a noise level which approximately matches that of the ITM-CP with a 2cm gap, and that this level dominates the total for annular designs 3cm thick or more.

6.1 Complicated Failures

Here are the results for a couple of more complicated designs that seemed promising, but turned out not to give good results. The "vented" ERM has the ESD supported by a 1cm thick annulus which is held 1cm away from the 11cm thick ERM by some kind of stand off, leaving the ERM at 25mm from the TM. Another is the "engraved" annular ERM in which the gaps in the ESD pattern are cut out to a depth of 2cm, thus minimizing the surface area which is close to the TM.





7 Reference

(1) M.A.G. Suijlen, J.J. Koning, M.A.J. van Gils, H.C.W. Beijerinck, "Squeeze film damping in the free molecular flow regime with full thermal accommodation", Sensors and Actuators A: Physical, In Press, Corrected Proof, Available online 10 April 2009, ISSN 0924-4247, DOI: 10.1016/j.sna.2009.03.025. (http://www.sciencedirect.com/science/article/B6THG-4W1SRNG-C/2/c1827853917e1df128b5724db3e45170)

(2) A. Cavalleri, G. Ciani, R. Dolesi, M. Hueller, D. Nicolodi, D. Tombolato, S. Vitale, P. J. Wass, W. J. Weber, "Gas damping force noise on a macroscopic test body in an infinite gas reservoir" (arXiv:0907.5375)

(3) A. Cavalleri, G. Ciani, R. Dolesi, M. Hueller, D. Nicolodi, D. Tombolato, S. Vitale, P. J. Wass, W. J. Weber, "Increased Brownian Force Noise from Molecular Impacts in a Constrained Volume", Phys. Rev. Lett. 103, 140601 (2009)