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Gas Damping in Advanced LIGO Suspensions

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1 Introduction

The Advanced LIGO suspension design for the test masses involves the use of electrostatic drive between the test mass and a reaction mass hanging parallel to it. The baseline design for the gap between these masses is 5 mm. The question of enhanced gas damping due to the small gap has been raised in the past by an NSF review committee. This topic was addressed in a LIGO technical note T050241-00-R [1]. It was concluded in that document, with reference to papers on the topic at that time, that gas damping was not a serious noise concern. However since that document was written, new experimental evidence on enhanced gas damping due to small gaps has been produced by the Trento LISA group [2,3]. We reassess the impact of gas damping in small gaps using this new information and draw conclusions for Advanced LIGO noise performance.

2 Gas damping in Advanced LIGO

In T050241 we used Christian's model [4] for the quality factor of a plate oscillating in a low pressure. The quality factor is given by

$$Q = \left(\frac{\pi}{2}\right)^{3/2} \rho H f_0 \sqrt{\frac{RT}{M_m}} \frac{1}{P} \qquad (1)$$

where ρ is the specific mass of the plate, H is the thickness of the plate, R is the gas constant, T is the temperature, f_0 is the oscillating frequency of the plate, M_m is the molar weight of the gas and P is the pressure.

We note that in [3] the Trento group has carried out a calculation for a cubic test mass, arriving at a slightly different formula with an extra factor $(1+\pi/8)$. Since the test mass is more plate-like than cubic we will continue to use equation (1).

We calculated in [1] a limiting Q of ~ 4.7×10^{11}, with parameters $f_0 = 0.644$ Hz, $\rho = 2200$ kg m^{-3}, H = 0.2 m, T = 300 K, molar mass of 2×10^{-3} kg (H_2), and a conservative pressure for Advanced LIGO of 10^{-8} torr of H_2 (1.33×10^{-6} N m^{-2}). Solving for the thermal noise motion due to gas damping at this level using the relationship for viscous damping above resonance, as below,

$$x^2 = \frac{4kT\omega_0}{mQ\omega^4} \qquad (2)$$

we found $x \sim 1.5 \times 10^{-20}$ m/√Hz at 10 Hz, using m = 40 kg.

2.1 Pressure in Advanced LIGO

We note that the facilities limit pressure for Advanced LIGO is quoted as 10^{-9} torr (see for example M060056-v1 figure 1 caption). We understand that at present in LIGO a pressure of 2×10^{-9} torr can be achieved in the end station tanks, with the corner stations higher, up to 10^{-8} torr (ref emails from Dennis Coyne and John Worden). However we also note that residual pressure may be limited by outgassing from viton which will not be present in Advanced LIGO. As we shall see in our conclusions, we suggest that effort be made to reach 10^{-9} torr when running Advanced LIGO to minimise gas damping effects.

2.2 Relationship governing Increased gas damping due to small gaps

The Trento group [3] has carried out measurements of residual gas damping for their torsional pendulums developed to investigate noise forces for LISA. They found the damping coefficient increased significantly when the distance between their test mass and surrounding walls was smaller than the mass itself. They carried out a numerical simulation whose predictions are in good agreement with their results. They concluded that the increased damping approaches a power law $(d/s)^{-2}$ where d is the gap size and s is the test mass side length, for vanishing gap. This quadratic power law differs from previous modeling presented in Bao [5] and considered in [1], where a linear relationship was derived. The difference(s) between the two analyses have not been addressed by the Trento group. However the Trento model fits well with their experimental data and is taken down to lower pressure (4×10^{-6} Pa) than the data in Bao The Trento group also present a simple argument why the relationship should be quadratic.

2.3 Application of the Trento model to the Advanced LIGO suspension

From [3] figure 5 we conclude that for a gap size to length ratio of 1.5×10^{-2} (corresponding to gap size d = 5 mm and s = 340 mm, the diameter of the test mass), the gas damping is enhanced over the “infinite volume” value by a factor of ~ 250 for translational motion. Thus the Q will be decreased by the same factor.

Using this value we find the following quality factor and thermal noise motion for the test mass at 10 Hz.

i) Pressure = 10^{-8} torr (1.3×10^{-6} Pa), Q = 1.87×10^{9}, x ~ 2.4×10^{-19} m/√Hz

ii) Pressure = 2×10^{-9} torr (1.3×10^{-6} Pa), Q = 9.34×10^{9}, x ~ 1.1×10^{-19} m/√Hz

ii) Pressure = 10^{-9} torr (1.3×10^{-7} Pa), Q = 1.87×10^{10}, x ~ 7.6×10^{-20} m/√Hz

We note that the requirement for total suspension thermal noise motion of the test mass is 1×10^{-19} m/√Hz at 10 Hz. We see that this enhanced gas damping causes the motion to exceed this value at a pressure of 10^{-8} torr. With 10^{-9} torr we are below 10^{-19} m/√Hz for this contribution to the thermal noise. Note that since the damping is viscous the thermal noise due to gas damping falls off only as $1/f^2$ unlike the effect of structural damping within the silica suspension which falls off faster, as $1/f^{2.5}$.

3 Conclusions

Using the model developed by the Trento group for enhanced damping in small gaps we conclude that this noise source could be significant for Advanced LIGO depending on what gas pressure can be achieved. If a pressure of 10^{-9} torr can be obtained, it appears that the noise due to gas damping will not significantly impinge on the overall noise level. However if the pressure is 10 times higher, this noise source is significant. We have briefly considered what steps might be taken to reduce it. Increasing the gap is one option. However this would reduce the strength of the ESD and so some analysis would be needed to see if that is workable. In addition how to incorporate an increased gap into the existing suspension design would need to be addressed. Another possibility in the case of the ETM would be to add a large hole to the centre of its reaction mass, thus considerably decreasing the area over which there is a small gap. This would have a knock-on effect on the design of the reaction chain, requiring more mass at the penultimate reaction mass to compensate. Also it would not be feasible for the compensator plate behind the ITM to have a central hole.

In conclusion, this effect could be significant, and attention should be given to minimising its impact in Advanced LIGO. The simplest approach will be to work on achieving the facilities limiting gas pressure when the detectors are running. We note that the Advanced LIGO suspension design is well advanced, and that major changes to it at present would be difficult to implement without significant extra resources. We propose that the existing design goes ahead but that some background research should be undertaken to look at other options such as the ones suggested above, which could be incorporated in a future enhancement to Advanced LIGO.

4 References

[1] "Some Notes on Gas Damping in Small Gaps as a Potential Noise Source for Advanced LIGO Suspensions", Norna A Robertson, T050241-00-R

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[4] "The theory of oscillating-vane vacuum gauges", R G Christian, Vacuum, **16**, 175-178, (1966).

[5] "Energy transfer model for squeeze film air damping in low vacuum", M Bao et al, Journal of Micromechanics and Microengineering **12**, 341-346, (2002).