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Thinner Compensation Plates for Reduced Squeeze Film
Damping

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1 Introduction

The test mass suspensions are currently designed to have a uniform gap between the test mass and its reaction mass of 5 mm. With this gap, the squeeze-film damping from the residual gas in the chambers is predicted to cause thermal displacement noise that is in excess of the thermal noise due to dissipation in the silica suspension fibers. Calculations of this effect and the resulting noise can be found in LIGO-T0900582-v5, *Gas Damping Monte Carlo*.

A fairly simple approach to reducing squeeze-film damping is to increase the gap, as the force noise goes approximately as the inverse of the gap. The suspension design, however, does not accommodate simply increasing the separation of the main and reaction chains by more than \sim a millimeter. But the gap can be increased by using a thinner reaction mass, and not changing the center-to-center separation of the chains. Uniformly increasing the gap in this fashion will of course reduce the force coefficient of the electro-static drive test mass actuation. We would not want to significantly decrease the actuation force available for the End Test Masses, as we rely on those for acquiring lock of the interferometer. For the ETMs, we are considering more complicated geometries, where the gap is small only for the ESD electrode annular area, but made large in the central region.

For the Input Test Masses, however, we do not expect to need such a high actuation force, and it makes sense to consider just making the Compensation Plates thinner. This note is an examination of the design and technical implications of thinner CPs.

2 Compensation Plate thickness

As shown in T0900582, the force noise from gas damping is reduced by a factor of 2.6 in going from a 5 mm to a 2 cm gap. Beyond that, the improvement levels off – a gap of 4 cm gives an additional factor of 1.4 noise reduction. Assuming 10^{-8} torr of hydrogen, a 2 cm gap puts the gas damping noise at essentially the same level as suspension thermal noise due to silica dissipation. Note though there is still a fair amount of uncertainty in the expected gas pressure, and we do not rule out the possibility of adding more pumping capacity to the vertex volume.

We consider 2 cm to be adequate for reducing gas damping, and we use that gap size from hereon. For integration into the suspension, we prefer to keep the CP mounting symmetric. That is, the 2 cm gap (increase of 1.5 cm) is achieved by reducing the thickness of the CP by 3 cm. Thus we are considering a 10 cm thick CP (34 cm diameter), with a gap of 2 cm between the CP and the ITM.

3 Gas Damping Noise Level

From T0900582, the force noise for a 2 cm gap is $1.5 \times 10^{-14} \text{ N}/\sqrt{\text{Hz}}$ per meter-squared of area, for 10^{-8} torr of H_2 ; the force noise is flat up to a pole frequency of about 50 Hz.

<i>Noise component</i>	<i>Displacement noise at 30 Hz</i>
Gas damping, ITM, 2 cm gap	$3.9 \times 10^{-21} \text{ m}/\sqrt{\text{Hz}}$
Gas damping, ETM, 5 mm gap	$1.1 \times 10^{-20} \text{ m}/\sqrt{\text{Hz}}$
Silica fiber dissipation, ITM or ETM	$3.7 \times 10^{-21} \text{ m}/\sqrt{\text{Hz}}$

Table 1. Test mass displacement noise at 30 Hz due to thermal noise loss mechanisms. The gas damping numbers are calculated for 1e-8 torr of molecular hydrogen.

The interferometer strain noise due to gas damping, with a 2 cm gap for the ITMs and a 5 mm gap for the ETMs, is $4 \times 10^{-24} / \sqrt{\text{Hz}}$ at 30 Hz. This can be compared to the quantum noise for the baseline configuration (mode 1b), $6.5 \times 10^{-24} / \sqrt{\text{Hz}}$; and to the coating Brownian noise, $4.5 \times 10^{-24} / \sqrt{\text{Hz}}$ (both at 30 Hz).

It should be noted that the pressure level of 10^{-8} torr of hydrogen used above is by no means a well established figure, but is rather a convenient level from which scalings can be made (currently at LHO the pressure in the vertex is about 10^{-8} torr, and is 3-4 times lower in the end station chambers). A very preliminary estimate of outgassing loads has been made by M Zucker (LIGO-E0900398), giving an estimated pressure of 2×10^{-8} torr in the end and vertex volumes.

4 Electro-Static Drive

Increasing the ITM-CP gap will of course decrease the force coefficient of the electro-static drive (ESD). This has been examined with a finite element analysis of the system, and this work is summarized in LIGO-T1000119. For a given ESD pattern, the force coefficient goes with the gap dimension d as $d^{-2.38}$. This means that increasing the gap from 5 mm to 2 cm decreases the force coefficient by about a factor of 30. The force coefficient for the 2 cm gap is calculated to be $7.5 \times 10^{-12} \text{ N/V}^2$.

Is this sufficient for actuation on the ITM? There are no global control forces that are planned to be applied directly to the ITMs. The LSC loop that needs a relatively wide-band—the DARM loop—will use the ETMs for the fast feedback path. The alignment control signals for the ITMs will be applied to the penultimate masses of the ITM suspensions. There are two instances where it might be required to apply force directly to the ITM: for calibration and for active damping of parametrically unstable acoustic modes. For calibration, the 2 cm gap would still afford an ITM displacement of a few tenths of a picometer at 100 Hz (with high voltage drive), which should be plenty.

The use of the ESD for damping parametric instabilities is investigated in John Miller’s Ph.D. thesis, LIGO-P1000032. He calculated how much ESD force would be required to damp any acoustic mode so that the parametric gain associated with that mode would be $R = 0.1$ or smaller ($R = 1$ is the threshold for parametric instability). He assumed the force coefficient for the 5 mm gap, and found that at most 0.3% of the full drive range (with 800 V of drive swing) was required. Specifically, the highest force needed was 148 nN, from one ESD quadrant (for a mode near 48kHz). With the 2 cm gap force coefficient, this would require a drive voltage of about 300 V.

A rule of thumb for designing the ESD pattern is that the electrode width and spacing should be equal to the gap for maximum force. So we also investigated an ESD pattern design that has wider electrodes; the details are in T1000119. The result is that with a wider electrode design, the force coefficient for a 2 cm gap could be increased by a factor of about 2.6. Given that the pattern and tooling for 5 mm wide electrodes is already designed, it does not seem worth changing the pattern for the wider electrode design.

5 Thermal Compensation

There is some radiative coupling between the ITM and CP, so it is worth looking at whether the thermal compensation would be affected by an increase in the ITM-CP gap. Thus, the thermal compensation analysis found in LIGO-T0900359, *TCS and the Golden Shield*, was repeated for the 2 cm gap. There was no discernable difference in the thermal compensation between the 5 mm and 2 cm gaps.

6 Suspension Implications

To accommodate a thinner CP, two aspects of the ITM quadruple suspension will need to be changed: the mass taken away from the CP will need to be added to the reaction chain penultimate mass; the earthquake stops for the CP will need to be adapted for to the thinner plate.

The CP mass is reduced by about 6 kg in changing from 13 cm to 10 cm thickness. This is fairly easily made up on the penultimate mass (PM) by increasing the shell thickness of the cylindrical stainless steel PM inserts that hold the PM coils (D080168).

On the non-ITM side of the CP, the earthquake stop screws are already long enough that they can be screwed in an additional 1.5 cm, so no change is required there. Between the CP and the ITM, currently there are four bumper stops that are attached to the CP; the CP has four recessed holes to accommodate the overall length of the bumper stop assembly. With thinner CPs, there are two options for these stops: keep the bumper stop concept but make them longer to span the larger gap; eliminate these bumper stops and instead mount stops to the suspension support structure. At this time the choice between these options has not been made. If bumper stops are retained, recessed holes would not be required because the 2 cm gap is large enough to fit them in without a recess. So for the thinner CPs we propose eliminating the recessed holes.

7 Layout implications

The removal of 3 cm of fused silica within the recycling cavities reduces the optical path length by $3\text{ cm} \cdot (n - 1) = 1.35\text{ cm}$. This will need to be accommodated in the positioning of the recycling cavity mirrors. The nominal approach would be to keep the cavity lengths the same so that RF frequencies remain the same, most likely by changing the position of PRM/SRM. Given that the radii of curvature of the recycling cavity optics would not change, this would slightly degrade the mode matching; M Arain has calculated that the mode matching would decrease by 2 ppm.