Residual Gas Noise in the Test-mass Module for DECIGO Pathfinder

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Abstract. DECIGO Pathfinder is the first milestone mission for DECIGO, a future gravitational wave antenna. In DPF, residual gas noise acting on the test mass is estimated to increase and exceed the requirement for force noise of $1 \times 10^{-15} \text{N}/\sqrt{\text{Hz}}$ due to geometry of the test-mass module. We performed a Monte Carlo simulation to calculate the residual gas noise and found that the engineering model of the test-mass module cannot satisfy the requirement. To reduce the gas noise, we present revised geometry of the test-mass module using comb-like electrodes.

1. Introduction

DECIGO is a future space gravitational-wave detector which aims to detect gravitational waves around 0.1 Hz [1]. DECIGO has Fabry-Perot cavities between space crafts with a baseline of 1,000 km. As the first step toward DECIGO, a small satellite called DECIGO Pathfinder (DPF) is planned to verify some of the key technologies required for DECIGO [2]. DPF has a 30-cm Fabry-Perot interferometer with free-falling test masses.

In these space missions, force noise acting on the test masses is estimated to be the largest noise source to limit the sensitivity of the detector. To achieve the strain noise of less than $2 \times 10^{-24} \text{Hz}^{-1/2}$ around 0.1 Hz, DECIGO has stringent requirement for force noise of $4 \times 10^{-17} \text{N}/\sqrt{\text{Hz}}$ in deci-hertz band, which is 1/50 of LISA’s requirement. In the DPF mission, the force noise is required to be below $1 \times 10^{-15} \text{N}/\sqrt{\text{Hz}}$. However, force noise from residual gas molecules is found to increase and exceed the requirement for DPF. This increase is caused by narrow gaps between the test masses and surrounding modules.

The DPF test masses are placed in each test-mass modules, housings with electrodes and mechanical systems for precise control of a position of the test mass. The electrodes make units of capacitive sensor and electrostatic actuator mounted on the inner surfaces of the housing, developed with reference to the LISA Pathfinder Gravity Reference Sensor. For an engineering model of the test-mass module, each inner surface faces on a surface of the test mass with a
distance of 3 mm. This gap is smaller than 1/10 of a scale of the cubic test mass 50 mm on a side. Such a narrow gap causes increasing of force noise from molecular impacts, as investigated in the case of LISA Pathfinder [3] and ground detectors [4].

To reduce the residual gas noise, we studied geometry of the test-mass module with a Monte-Carlo simulation. In this paper, a test-mass module with comb-like electrodes is presented to mitigate increasing gas noise. Involving the change of the geometry, we also discussed actuation force with different shapes of the electrodes.

2. Residual Gas Noise in the Test-mass Module
Residual gas is one of force noise sources acting directly on the test mass. The test mass is disturbed by random molecular collisions and behaves like Brownian motion. If we regard the collisions as independent impulses, force noise from gas molecules has a frequency independent spectrum.

In DPF, gas force noise in the test-mass module is considered to be larger than the requirement of $1 \times 10^{-15} \text{ N/Hz}$. This problem comes from an increasing effect of fluctuation force with limited space around the test mass.

The cubic test masses are located in each housing called test-mass module. This module provides a local control system of the test mass. Figure 1 shows an assemble diagram of the housing. Electrodes mounted on the inner surfaces of the housing make capacitive sensors and electrostatic actuators which can monitor/control a position of the test mass without any mechanical contact to the test mass. When the test mass is floating at the center of the housing, the gap between the surfaces of the test mass and the inner walls of the housing is 3 mm.

The geometry with such narrow gaps around the test-mass raises additional gas force noise. We can attribute the increasing of gas noise to correlated collision impulses from molecules in the narrow gaps. A molecule which entered into the gap repeats collisions with the test mass and walls until it escapes from the gap. There is an interaction time $\tau$, the typical time during which a molecule stays in the gap and generates correlated collisions. Force noise on the test mass is known to increases proportionally with the interaction time $\tau$ [4].

We performed a Monte Carlo simulation to estimate the residual gas noise with the engineering model of the housing. This simulation traces the trajectory of gas molecules in a $20\times20\times20$ cm cubic volume containing the test mass and the housing: the electrodes and the guard rings shown in Figure 1. The size of the volume is chosen as a typical scale of a space around the test-mass module in the satellite. The electrodes and the guard rings enclose the test
Figure 2. Simulated force noise spectrum from residual gas molecules for the housing with the engineering model (blue) and the housing with comb-like electrodes (red), calculated for $10^{-6}$ Pa of H$_2$ at room temperature. A force noise spectrum with a test mass (TM) in infinite gas volume (green) is also plotted for comparison.

mass at a distance of 3 mm. This calculation model doesn’t include the frame and the covers (see Figure 1).

In this simulation, molecules are distributed uniformly and randomly in the volume with random velocities following a Maxwell-Boltzmann distribution. Collisions of the molecules with the walls are completely inelastic; once molecules are absorbed, then subsequently reemitted following a cosine angular distribution, independent of the incoming velocity. At each collision with the test mass, time and transferred momentum vector are recorded. We have run 1,000 molecules simultaneous simulation for 10 seconds. After that, we converted obtained power spectrum density of applied force noise on the test mass into that in the pressure of $10^{-6}$ Pa using the equation of state. Here we assumed the temperature as a room temperature and species of molecule as H$_2$. We ignored molecular sticking time on the surface and collisions of molecules with each other. This simulation methods are similar to those of the numerical study in [4].

The calculated power spectrum density of the gas force noise in the housing for the engineering model is described as a blue spectrum in Figure 2. We have confirmed that the used code is valid with comparing the result of the infinite gas volume case and an analytical calculation using equation (11) in [5]. Comparing the green and the blue spectrum, there is about increase in the result of the bread board model below a cut-off frequency $f \approx 1$ kHz. This cut-off frequency corresponds to a typical interaction time $\tau \approx \omega^{-1}$, a time scale that molecules repeat correlated collision impulses in a narrow gap [4]. Assuming that the gas noise has a flat spectrum at lower frequencies, calculated acceleration noise is about by a factor of 2 larger than the requirement.

There are several strategies to mitigate the increased gas noise. One is to lower residual gas pressure because the force brought from gas molecules to the test mass is proportional to the
pressure, however it’s difficult. Another is to expand the gap between the test mass and the housing. In this time, we have to consider a trade off between reducing the gas noise and the performance of the electrostatic instruments of the test-mass module. In particular, a wider gap between the test mass and the electrodes makes electrostatic actuators less powerful so that it cannot apply enough force to control the test mass. In the next section, we will present an alternative way to reduce the residual gas noise.

3. Mitigation of Gas Noise with Comb-like Electrodes

We designed comb-like electrodes for the housing to reduce the gas force noise. Figure 3 shows the configuration of the comb-like electrodes. This configuration is designed to reduce the gas noise by expanding the space around the test mass. The comb-like electrodes have slits through which gas molecules can escape from the gap. Because the gas-noise increase is proportional to the typical interaction time $\tau$, the slits can reduce the gas noise by shortening the time $\tau$.

The result of residual gas noise simulation with comb-like electrodes is plotted as a red curve in Figure 2. It shows that comb-like electrodes has about half as large noise as the engineering model. A higher cut-off frequency and less noise level are supposed to reflect the effects of the slits. Thus the model with comb-like electrodes satisfies the force noise requirement of $1 \times 10^{-15} \text{ N/}\sqrt{\text{Hz}}$. One concern is that other heavier species of molecule than H$_2$ we assumed here are highly likely to appear in the orbit, e.g. N$_2$ and H$_2$O. Because the force from gas molecules is proportional to their mass, the force noise will be larger by a factor of a square root of the molecular mass ratio. Moreover, other concern is deterioration in electrostatic shielding of the test mass by the electrodes. More slits would increase the sensitivity to any stray fields outside the housing and consequently spoil the force noise to some extent. Therefore, further optimization of the comb configuration may be necessary.

In addition, we have to take the trade off of loss of the area of electrodes into account. Making slits cannot avoid to decrease the area of the electrodes. Because electrostatic force applied by an electrode is proportional to its area, we estimated how much loss we can allow to the area of the electrodes by finite element analysis. In this analysis, we modeled the test mass housing (except for the frame and the covers) using COMSOL. As the first step of the study, we used an injection voltage of DC 300V to estimate the actuation force reduction. This voltage was applied to the two electrodes in $+x$ direction to calculate the resulting electrostatic force. Then the electrostatic force applied on the test mass is calculated. We assumed that other electrodes, guard rings and a plane at infinite distance are grounded.

Table 1 shows estimated maximum actuation force. With comb-like electrodes, there can be a drop in actuation force involved to decreasing their area. However the force per area is increased from the simple electrodes. This implies a possibility of satisfying the required actuation efficiency while reducing the gas noise by the use of comb-like electrodes. Comparison of this result to a case with simple electrodes and expanded gap will be done in future study. Based on this result, we will proceed to perform more thorough calculations with AC voltage
Table 1. Maximum actuation force with different shapes of electrode simulated with COMSOL.

| Electrode Type       | Net actuation force [μN] | Force/area [μN/cm²] |
|----------------------|--------------------------|---------------------|
| Simple electrode     | 45.9                     | 6.8                 |
| Comb-like electrode  | 22.5                     | 8.3                 |

injections, which will be used in the actual satellite.

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