Structural design and analysis of test mass module for DECIGO Pathfinder

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Abstract. Deci-hertz Interferometer Gravitational-Wave Observatory: DECIGO is a project aimed at future detection of deci-hertz gravitational waves in space. DECIGO Pathfinder: DPF is a precursor mission to test the key technologies with one spacecraft. Our work in this article was to examine the strength of the DPF test mass module to ensure that it is sufficiently robust for launch with a launch vehicle. We designed the test mass module, and examined the structural strength of this model by structural analysis, Quasi-static acceleration analysis and Modal analysis using FEA (Finite Element Analysis). We found that the results of each analysis fulfilled all requirements. We are confident that the DPF test mass module will withstand Quasi-static acceleration or coupling with vibration of launch vehicle during launch, if the design matches the current design. For more detail, further analysis including Response analysis and Thermal analysis are recommended. In addition, it will be necessary to lighten the model in the next step.

1. Introduction
DECIGO (Deci-hertz Interferometer Gravitational-Wave Observatory)\textsuperscript{1}\textsuperscript{2} is the future Japanese space gravitational wave antenna. The purpose of DECIGO is to observe gravitational waves from astrophysically and cosmologically significant sources at the frequency band mainly between 0.1-10Hz, thus, to open a new window of observation for gravitational wave astronomy. DECIGO will be formed by three drag-free spacecraft which are separated from one another by 1000km. We will detect gravitational waves by measuring relative displacements between each spacecraft as a Fabry-Perot Michelson interferometer. For this magnificent mission to succeed, we will need to make use of some advanced techniques, for example drag-free control, precise measurement, etc. At present, we have a roadmap to launch two milestone missions before DECIGO, DECIGO Pathfinder (DPF) and Pre-DECIGO. DPF\textsuperscript{3} is the first milestone satellite currently being developed. The purposes of DPF are to verify each technique that will be used.
in DECIGO, to detect gravitational waves in our galaxy, and to monitor the Earth’s gravity. We will also use a Fabry-Perot Interferometer as a sensor for gravitation waves. The differences between DECIGO and DPF are that the arm length will be 30cm and we use only one Fabry-Perot cavity within one spacecraft. The Fabry-Perot Interferometer is formed by two mirrors adhering to the test masses, which act as free proof masses. Each test mass is held by the test mass module, whose functions are to hold the test mass inside floating on the geodesics in orbit, and to guard the test mass from the effects of launch.

This article describes the structural design and analysis of the test mass module. We designed the test mass module to satisfy certain requirements. As a first step in the design, we worked on the prototype (Bread-Board Model). In addition, we checked the rigidity of the model using FEA methods (Finite Element Analysis). Our work is very important in examining how the module functions without breaking down during launch and in orbit.

2. DPF / Test mass module

2.1. DPF

DPF will be the first precursory satellite for DECIGO. One of the purposes of DPF is the demonstration of each technique that will be used in DECIGO (Drag-free control, Precise measurement, Stabilized Laser, etc.). The other purposes are detection of gravitational waves in our galaxy at 0.1-1Hz frequency band and Earth gravity monitoring. DPF will be a small satellite weighing about 350kg. We assume that DPF will be launched by a next-generation solid propellant rocket from JAXA (Japan Aerospace Exploration Agency) as one of the ”small scientific satellite series.” The DPF orbit will be sun-synchronous (Altitude: 500km). The mission payload part of DPF (Figure 1) will be the size of 950 × 950 × 1100 mm. Included in the DPF are main units, Interferometer Module, Stabilized Laser, Mission Thrusters for drag-free control, and some Control Units. The Interferometer Module contains a Fabry-Perot cavity for detection of gravitational waves (Figure 2). The arm length will be 30cm. We can detect the gravitational wave signals by measuring the relative displacement of two mirrors in the Fabry-Perot Interferometer. The interferometer is formed by two mirrors bonded on the test mass which act as free proof mass. To act as free proof mass, each test mass will be drag-free controlled by S/C. In the next section, we will provide further details of the test mass module.

2.2. Test mass module

We will use a Fabry-Perot Interferometer as a sensor for gravitational wave (Figure 2). We will measure the relative displacement between two proof masses of Fabry-Perot Interferometer. The test masses will act as free proof masses. The proof mass has to freely float in space, so we...
will use drag-free control techniques to achieve free mass. This means that the test masses will be supported without contact in orbit. Therefore, the test masses must be stabilized with the satellite during launch. The test mass module controls the test mass without contact in orbit, and holds the test mass tight during launch. To achieve this, we will use certain mechanisms.

(1) Test mass (acts as proof mass including mirror for interferometer, metallic cube)
(2) Electrostatic sensor and actuator (to sense and actuate the position of test mass, some electrodes as capacitor with metallic test mass)
(3) Laser sensor unit (for Earth gravity monitor, sense the position of test mass with Michelson Interferometer, with arm length of about 23mm)
(4) Launch lock mechanism (to hold test mass during launch using motors)
(5) Clamp and release mechanism (for precise positioning and clamp-release of test mass in orbit using motors)
(6) Caging frame (to hold other components, metallic frame)
(7) UV-LED (discharge of test mass)

![Figure 3. Design of the test mass module (BBM)](image)

3. Structural design of DPF test mass module

We will have three steps of development for test mass module, Bread-Board Model (BBM), Engineering Model (EM) and Flight Model (FM). As a first step, we designed test mass module as BBM.

The module was designed to contain the components in the above section except UV-LED as seen in Figure 3. The required size is 200 × 200 × 300mm and weight is 5kg. The size of the test mass is 70mm cube (blue cube in Figure 3). The test mass has a hole at 15mm in diameter, which is the path for the laser of Fabry-Perot Interferometer, and there is a mirror for the Interferometer on one side of the hole. The test mass also has three pairs of corner cube mirrors for Laser Sensor Units. The test mass is inside the caging frame, which acts as a holder for the test mass and base of other components. The caging frame is a 110mm cube ((6) in Figure 3). On each surface, there are three electrodes ((2) in Figure 3), face to face with each surface of the test mass. The center electrode is an injection electrode for sensor (area: 18×40mm), and there are two electrodes for the sensor and actuator (area: 18×62mm) on the right and left sides of the injection electrode. The gap between the test mass and the electrode is 1mm. Three pairs of the laser sensor units are on the caging frame. The units surround three
surfaces of the test mass ((3) in Figure 3). The units for the X and Y surfaces are linear (size: 26 × 140 × 32mm), and those for the Z surface are L-shaped (size: 26 × 85 × 32 + 24 × 62 × 32mm). Each unit has optics for the Michelson Interferometer, which measure the displacement of the test mass with the corner cube mirrors on the test mass. We will use some kind of motor as a launch lock mechanism. Eight motors will push top and bottom of the test mass during launch ((4) in Figure 3). We will also employ motors for the clamp and release mechanism. Motors for clamp and release are on the right and left sides ((5) in Figure 3). They can move the test mass to the center of the caging frame and release it at very slow velocity. We have not yet installed a UV-LED unit in this model but we will include it in the next step.

4. Structural analysis of DPF test mass module
Every subsystem including the test mass module will experience extraordinary disturbance, mainly during launch, so we have to test the strength of each component to prepare for the disturbance. We have to perform some structural analyses that correspond to mechanical environmental tests and thermal vacuum tests. Mechanical environmental tests are run on quasi-static acceleration (Axis direction and Cross axle direction), modal analysis, random vibration, vibroacoustic, shock. The thermal vacuum test is on radiant heat. We performed the quasi-static acceleration analysis and modal analysis in this paper.

5. Quasi-static acceleration analysis
5.1. Method of analysis
The first procedure is modeling the test mass module using 3D CAD software (Autodesk Inventor Professional 2009) for optimized quasi-static acceleration analysis. All main components, except the optics for the laser sensor, are contained and each part is attached with a screw. The key points for analysis are that the mass, shape and position of each part match those of the design, and the physical properties of each part are the same as the FM (physical properties: test mass; Au-Pt, casing frame; aluminum, electrostatic sensor/actuator; sapphire, motor rod; steel). The next procedure is to build a Finite Elements Model (FE Model) and to apply certain conditions to the FE Model using CAE software (Autodesk Inventor Professional 2009 Advanced Simulation Technology Preview). The number of elements is about 50,000. We clamped the bottom. We applied quasi-static acceleration (Axis direction) 24G (235.4m/s^2) as Figure 4. As a final procedure, we used software to solve the model as linear statics analysis under the above conditions.

5.2. Results of analysis
Figure 5 shows the stress of the test mass module and electrode plate as an example of tested parts. Left of Figure 5 is the stress of the test mass module. The color bar shows stress value (red: high stress, blue: low stress). Because we used different materials for each part, the physical properties of each differ; so we verified each one. Right of Figure 5 is the stress of one part: electrostatic sensor and actuator. The maximum and minimum value of the maximum principal stress is +4.2MPa (tensile) and -0.2MPa (compressive). The minimum of Safety Factor of the part is 535.7 (tensile), because of each strength of sapphire is 2,250MPa (tensile) and 2,950MPa (compressive). Therefore, this part will not break. Results concerning the other parts also demonstrated them to be robust and unbreakable.

6. Modal analysis
Modal analysis yields resonant frequencies and mode shapes at the frequency. The requirement of the frequency of fundamental mode for axis direction is above 50Hz, and that for cross axle direction is above 30Hz. We used two methods of modal analysis for validation; (1)Spring-Mass Model, (2)Finite Element Analysis (FEA).
6.1. Spring-mass model
The spring-mass model was used to obtain a rough estimate of resonant frequency. We regard the test mass module as two mass systems for the spring-mass model. The first system is caging frame, electrode plate and launch lock motors. The total mass of the system is $m_1$, and the spring constant is $k_1$ (the upper right of Figure 6), which is given by the estimation by considering the first system to be a beam clamped on one side. The second system is the test mass and the rods of launch lock motors. The total mass of the system is $m_2$, and the spring constant is $k_2$ (the lower right of Figure 6), which is given by the estimation by considering the second system to also be a beam clamped on one side. We calculated each spring constant by considering each system to be a leaf spring. The equations of motion of this spring-mass system is given as follows.

$$m_1 \frac{d^2 x_1}{dt^2} = -k_1 x_1 - (x_1 - x_2)k_2$$
$$m_2 \frac{d^2 x_2}{dt^2} = -(x_2 - x_1)k_2$$

$x_1$ and $x_2$ are the displacements of the mass of each system. The analytic solution of these equations give the resonant frequency (angular frequency) of the system as follows.

$$\omega^2 = \frac{1}{2} \left( \omega_{11}^2 + (1 + \mu)\omega_{22}^2 \pm \sqrt{[\omega_{11}^2 + (1 + \mu)\omega_{22}^2]^2 - 4\omega_{11}^2\omega_{22}^2} \right)$$

$$\omega_{11} = \frac{k_1}{m_1}; \omega_{22} = \frac{k_2}{m_2}; \mu = \frac{m_2}{m_1}$$

$- : first mode, + : second mode$

$\omega$ is the angular frequency of the system.

According to the expression, the first mode resonant frequency of the system is 434Hz, which is high enough to fulfill requirements.

6.2. Finite element analysis
We used CAE software (NX I-DEAS 5) for FEA.
The model was optimized for modal analysis. We want to obtain the resonant frequency of the main structure, so there are no laser sensors or clamp and release mechanisms, which are outside of the caging frame and very light compared with the test mass and launch lock mechanism. Each part was bonded with the others, and the physical properties of each part match those of the flight model. The key feature is that the mass and stiffness of each part are correct. We based the FE Model on the model. The number of elements is about 20,000, which is optimum for the model. We clamped the bottom of the model to estimate most low frequency (Figure 7). We used software to solve the model using modal analysis under the above conditions. As a result, the resonant frequency of first mode is 764Hz (cross axle direction), and the lowest resonant frequency of the axis direction is 2.56kHz, which are high enough to satisfy requirements.

6.3. Conclusion of modal analysis
The resonant frequency of the test mass module of DPF is high enough according to the results of analysis; spring-mass model and FEA. Therefore, the module will not resonate with the launch vehicle.

7. Conclusions
The DPF test mass module was designed as BBM including most necessary components. According to the results of the structural analysis, the module will be strong enough for launch with the launch vehicle. It can be concluded that the structural design is so far successful. Further analysis, including Response analysis and Thermal analysis is recommended for more detail. We will lighten the model in the next step, EM, because the current design is still too heavy to satisfy requirements. In addition, we are now making a BBM test mass module, and we will demonstrate that the system and each component work as required.

References
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