Preliminary results on the cryogenic payload for the 3rd generation g.w. interferometers.

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Abstract. Thermal Noise is one of the limiting factor in the low and intermediate frequency range of the interferometric Gravitational Wave (GW) detectors. For beating this limit, a full scale last stage suspension (payload) prototype has been designed and built. Together with a mirror made of silicon, it has been cooled down at low temperature. Suspending the mirror from a cradle system, identical to that one used in the present VIRGO payload, the cooling strategy, the thermal behavior as well as the system mechanical response have been deeply studied. In this paper, the results obtained during the first cooling of the tested prototype are reported.

1. Introduction

Current GW antennas are designed to achieve the first direct detections and their proposed upgrades will look at typical GW sources distant of up to 100 $Mpc$. For effective Gravitational Wave Astronomy the sensitivity of future advanced detectors must increase ten-fold. The main noise limitation to the current and upgraded detectors is the Brownian thermal noise of the test masses. This limit can be overcome by cooling at cryogenic temperature the suspended mirror [1].

The use of the cryo-techniques have several other advantages:

- the thermo-elastic and thermo-refractive noises of the coated mirror decrease;
- the thermal expansion rate decreases at low temperature reducing drastically the thermal lensing effect induced by the high light power stored in the optical cavities of the interferometer;
- the mechanical loss of the payload will decrease significantly at low temperature if suitable materials are chosen.

On the other hand, for an effective use of low temperature in a GW detector we need to design the last stage suspension system in such a way

- to transmit the refrigeration power to the mirror without worsening its position control performance;
- to keep the residual vibration of the mirror due to the cryo system well below the noise sensitivity curve of the detector;
In the following sections we present a first attempt to design a cryogenic payload and the preliminary results obtained during its first cooling up to \(\sim 25\,\text{K}\).

2. The payload and its cooling system

The payload prototype we tested (figure 1) is composed by four main elements: a fake mirror, its reaction mass, the marionette and a fourth element, the marionette reaction mass (MRM). The marionette is hung to the aluminum flange of the inner vacuum chamber of the cryostat by means of the main Ti-6Al-4V suspension rod having a diameter of 4 mm. The MRM is suspended by three Ti-6Al-4V wires (1.5 mm in diameter) inclined by an angle of 58°, which are connected, to the main suspension rod by means of a junction box. This last element, having the shape of a Chinese hat, is conceived to rotate the MRM holding the actuation coils in front of the permanent magnets attached to the marionette wings.

The mirror is suspended to the marionette by means of two copper-beryllium ribbons wrapped around it. The 23 kg mirror is a silicon crystal plate, 350 mm diameter and 100 mm thick. We choose this material because of its high thermal conductivity, extremely low mechanical loss at low temperature and very low thermal expansion (zero below 17 K).

The reaction mass (RM) is suspended to the marionette by two steel wires (0.6 mm) wrapped around it. The thermal links are made by electrolytic copper bundles 3 mm thick and 30 mm large. They are attached from one end to the aluminum flange of the inner vacuum chamber of the cryostat and on the other end to copper plates of the marionette where the clamps of the mirror ribbons are located. The cryogenic payload temperature has been monitored on different point within the experimental chamber by using calibrated diode sensors from Lake Shore.
total mass \(~\sim\)300 kg of the payload is hosted in the inner vacuum chamber of a cryostat. The cooling system is a large cryostat installed at the European Gravitational Observatory (EGO) in Cascina. The dewar is equipped with two pulse-tube (PT) refrigerator. The pulse-tube is a closed loop cryo cooler invented by Alexander Mikulin in 1984. He modified a device known as the ”basic pulse tube” and created a new class of cryo-cooler, the Orifice Pulse Tube cryocooler. In our case the two refrigerators are commercial devices made by the CRYOMECH Company: the first one is a double stage PT410 while the second one is a single stage PT60. The cold head of the PT410 is attached to the external side of the aluminum vacuum flange of the inner chamber of the cryostat, while the PT60 cold head is connected to the intermediate thermal shield of the cryostat. In the figure 2 we show the plot of temperature versus time during the cooling. We notice the abrupt change of the temperature of the PT410 cold head due to failures of the cooling water system of the PT compressor experienced during the first 16\textsuperscript{th} days of the run. Moreover the sharp temperature decrease of the all the payload elements the 46\textsuperscript{th} day of the cooling is due to the payload vacuum chamber He gas ling, operated to speed-up the cooling. Once a stationary condition was achieved, the 51\textsuperscript{st} day we removed the gas exchange to perform the vibration measurements. The final mirror temperature was 30 \textit{K} while the cold head is at 15 \textit{K}. In the stationary condition the heat transfer through the suspension of the payload element results to be low: along the four CuBe\textsubscript{2} wires of the mirror the heat power transmission was 1.9 m\textit{W}, while along the four Steel c70 wires of the recoil sassy we have 1 m\textit{W}. During the test most of the thermal power (more than 10\textit{W} at \(~\sim\) 20 \textit{K}) was lost in the cooling process of the whole cryostat and this implies that a significant improvement of the thermal super insulation of the EGO cryostat is needed.

\textbf{Figure 2.} The temperature of the mirror, MRM, RM and marionette vs. time.
Table 1.

| Frequency at room temperature | Frequency at cryogenic temperature | Finite element simulation (no thermal links) | Mode identification |
|-------------------------------|-----------------------------------|--------------------------------------------|---------------------|
| 93.75 mHz                    | 71.00 mHz                        | 87.00 mHz                                  | $\theta_y$          |
| 0.460 Hz                     | 0.495 Hz                         | 0.467 Hz                                   | $\theta_y$          |
| 0.470 Hz                     | 0.510 Hz                         | 0.477 Hz                                   | $\theta_y$          |
| 0.560 Hz                     | 0.580 Hz                         | 0.590 Hz                                   | $\theta_z$          |
| 0.554 Hz                     | 0.643 Hz                         | 0.653 Hz                                   | $\theta_z$          |
| 0.600 Hz                     | 0.754 Hz                         | 0.680 Hz                                   | $\theta_z$          |
| 0.750 Hz                     | 0.763 Hz                         | 0.710 Hz                                   | $\theta_z$          |
| 0.924 Hz                     | 0.974 Hz                         | 0.740 Hz                                   | $\theta_z$          |
| 1.050 Hz                     | 1.021 Hz                         | 0.893 Hz                                   | $\theta_x$          |
| 1.087 Hz                     | 1.092 Hz                         | 0.995 Hz                                   | $\theta_x$          |
| 1.126 Hz                     | 1.122 Hz                         | 1.013 Hz                                   | $\theta_x$          |
| 1.485 Hz                     | 1.163 Hz                         | 1.024 Hz                                   | $\theta_y$          |
| 1.650 Hz                     | 1.228 Hz                         | 1.455 Hz                                   | $\theta_y$          |
| 1.724 Hz                     | 2.230 Hz                         | 2.136 Hz                                   | $\theta_z$          |
| 1.850 Hz                     | 2.288 Hz                         | 2.271 Hz                                   | $\theta_z$          |
| 2.040 Hz                     | 2.323 Hz                         | 3.972 Hz                                   | $\theta_z$          |

3. The payload characterization at room and low temperature

We measured the mechanical response of the system at room and cryogenic temperature using two optical fiber bundle sensors set in front of the reaction mass and of the marionette. Moreover, we had the possibility to use as a velocity sensor also the e.m. actuators of the mirror. They are made by a 1 T magnet set on the mirror border and a 250 turns coil mounted in front of it on the reaction mass. In this case, we amplified the output signal of the coil by means of the low noise amplifier PAR 51133 set in cascade to a select amplifier PAR 189. We measured the low frequency Fast Fourier spectra (FFT) of the ber-bundle sensor output set in front the reaction mass with the payload at room temperature and, then, once the stationary condition was achieved, at cryogenic temperature. In the low temperature spectra we noticed stray peaks at 1.4 Hz, 2.8 Hz and 2 Hz, which are due to the standing wave of the two PT cryo cooler vibration. The other frequencies of the peaks measured during this first cooling have been compared with the output of the finite element mechanical simulation of the complete payload based on the ANSYS software. The simulation permits us to identify for each frequency the main degree of freedom associated to the corresponding normal mode. In the table we report the frequencies measured at room and low temperature and its mode identification. The d.o.f. in the mode identification column are referred to the reference framework drawn in figure 1. These results contribute to highlight the design strategy of the cryo suspension and they provide the crucial framework to start the study of the related control issues. Thanks to the good agreement between the simulation and the experimental results, we are confident to be able to optimize the payload parameters for maximizing the thermal contacts with the mirror and minimizing the thermal noise budget.
4. Conclusions
We have designed the first prototype of the last stage suspension system for mirrors of the 3\textsuperscript{rd} generation of gravitational wave antennas with the aim to study the cooling and control strategy for the optical elements of interferometer. The system was cooled for the first time at low temperature. The preliminary results have been compared with the finite element simulation. Useful information concerning the change with temperature of the system dynamic behavior have been derived. The results will impact on mirror suspension control and, also, will reasonably require specific attenuation techniques of pulse-tube vibration.

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