Measurement of vibration of the top of the suspension in a cryogenic interferometer with operating cryocoolers

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Abstract. In the LCGT and CLIO projects for the interferometric gravitational wave detectors of Japan, the mirrors and a part of the suspension systems are cooled by cryocoolers to reduce the thermal noise. For the CLIO, extremely small vibration cryocoolers were specially developed by improving a commercial Gifford-McMahon type pulse tube cryocooler. We measured the vibration at the top of the suspension base in the CLIO interferometer while operating these cryocoolers. Although the seismic motion of $10^{-9}(1\ Hz/f)^2\ m/Hz^{1/2}$ at the site of the CLIO and LCGT in the Kamioka mine is 100-times smaller than that around Tokyo, these cryocoolers did not seriously increase the vibration. Consequently, a reduction of thermal noise by the cooled mirrors and suspension fibers using these cryocoolers is expected to be observed without any additional fluctuation disturbance due to the cryocoolers.

1. Introduction

The LCGT (Large-scale Cryogenic Gravitational wave Telescope; 3 km baseline) [1] and the CLIO (Cryogenic Laser Interferometer Observatory; 100 m baseline) [2] are future and current projects of the interferometric gravitational wave detectors in Japan, respectively. Their sites were selected to be in the Kamioka mine because its seismic motion is extremely small [3]. In both projects, the mirrors and a part of the suspension systems are cooled by cryocoolers at about 20 K to reduce the thermal noise [4]. Since commercial cryocoolers generally cause large vibration, extremely small vibration cryocoolers were specially developed [5, 6, 7] for the CLIO project. We measured the vibration caused by these cryocoolers.

Figure 1 is a schematic view of the cryogenic apparatus of the LCGT and the CLIO [8]. The mirror of the gravitational wave detector is suspended for vibration isolation. Since the actual suspension is complex, the suspension is treated here as a double pendulum for simplicity. The
Figure 1. Schematic view of the cryogenic apparatus of the LCGT and the CLIO [8]. The mirror of the gravitational wave detector is suspended for vibration isolation. The cooled parts of the suspension are surrounded by double radiation shields. The inner shield, cooled by a 4 K cryocooler, is connected to an intermediate mass by heat links. The heat due to optical absorption in the mirror flows to the 4 K cryocooler through the wires that hold the mirror, the intermediate mass, the heat links, and the inner shield. There are two external vibration paths to the mirror. In the first path, the fluctuation motion passes through the top of the suspension and the intermediate mass. In the second one, the vibration travels through the inner shield, the heat links, and the intermediate mass.

Although the mirror (20 K) and the intermediate mass (10 K) are cooled, the total suspension system is suspended from a room-temperature stage. The cooled parts of the suspension are surrounded by double radiation shields (inner (8 K) and outer (80 K) shields). All parts of the suspension and the cryostat are in a vacuum chamber (300 K). The inner shield, cooled by a 4 K cryocooler, is connected to an intermediate mass by heat links, pure aluminum wires. The heat due to optical absorption in the mirror flows to the 4 K cryocooler through the wires that hold the mirror, the intermediate mass, the heat links, and the inner shield. There are two external vibration paths to the mirror. In the first path, the fluctuation motion passes through the top of the suspension and the intermediate mass. In the second one, the vibration travels through the inner shield, the heat links, and the intermediate mass. Thus, in order to evaluate any mirror fluctuation caused by external vibration, we must measure both the vibrations at the top of the suspension and the inner shield. This article describes the measurement at the suspension top.

2. Experiment

We measured the vibration of the top of the suspension in the CLIO cryostats. These cryostats have already been installed in the Kamioka mine. Kamioka mine is in Hida city, located on the north side of Gifu prefecture, Japan. It is 220 km west of the TAMA300, which is an interferometric gravitational wave detector in Mitaka city, Tokyo [9].

Figure 2 shows a bird’s-eye view of the cryostat for an end mirror of the CLIO [8]. The mirror is surrounded by radiation shields. In the vacuum duct, a 5 m length radiation shield is also set so as to prevent residual gas molecules from contaminating the mirror. These shields are cooled by a 4 K and a 80 K pulse tube cryocooler, respectively. These cryocoolers, specially developed by High Energy Accelerator Research Organization and Sumitomo Heavy Industries Ltd. for the CLIO interferometer by improving a commercial Gifford-McMahon type pulse tube...
cryocooler, have extremely small vibration [5, 6, 7]. In order to shorten the cooling time, a commercial Gifford-McMahon cryocooler (Sumitomo Heavy Industries Ltd.) has been set up. However, it was removed because the cooling time was sufficiently short (3.5 and 4.5 days), even without this cryocooler. The measured point, the suspension top in the vacuum chamber, is supported by four legs, like a table. These poles are the only path of vibration from outside of the vacuum chamber to the suspension top. The suspension top is 1.9 m away from the floor. Even when the cryocoolers work, the suspension top is at room temperature.

In order to measure the vibration of the suspension top, we made a Michelson interferometer as an accelerometer [3]. A schematic view is shown in figure 3. The relative motion between a phosphor bronze oscillator and a reference mirror fixed on the suspension top was measured. The signal of this measurement (outputs of two photo detectors) was sent to a coil-magnet actuator through a differential amplifier and a filter in order to make the oscillator follow the suspension top. The suspension top motion was derived from this feedback signal (the filter output in figure 3). All parts of the interferometer, except for the differential amplifier and filter, were located on the suspension top in the vacuum tank. Sound did not disturb the measurement directly. The light source was a laser diode. Its wavelength and power were 635 nm and 5 mW, respectively. The resonant frequency of the oscillator was about 20 Hz. Both sides of the center mass of this oscillator were supported by horizontal thin beams. Two kinds of the oscillators were prepared for horizontal and vertical measurements. In the vertical measurement, a mirror was inserted between the beam splitter and the oscillator to steer the laser beam from the horizontal to the
Figure 3. Schematic view of a Michelson interferometer as an accelerometer [3]. The relative motion between a phosphor bronze oscillator and a reference mirror fixed on the suspension top was measured. The signal of this measurement (outputs of two photo detectors) was sent to a coil-magnet actuator through a differential amplifier and a filter in order to make the oscillator follow the suspension top. The suspension top motion was derived from this feedback signal (the filter output). All parts of the interferometer, except for the differential amplifier and filter, were located on the suspension top in the vacuum tank.

3. Results

Figure 4 shows the measured power spectrum densities of the suspension top vibration. Graphs (a) and (b) present the horizontal (optical axis of the CLIO interferometer) and vertical motions, respectively. The black thick and the grey thin lines are the vibration with and without operation of the pulse tube cryocoolers and the vacuum pump. In the results concerning the vertical motion, the vacuum pump was stopped even when the cryocoolers worked. Below 200 Hz, the cryocoolers did not seriously increase the vibration. The floor level of the power spectrum between 1 Hz and about 100 Hz was $10^{-9}/f^2$ m/Hz$^{1/2}$, where $f$ is the frequency in Hz [3]. This was about 100-times smaller than the seismic motion at Kashiwa city near Tokyo (the grey thick lines in figure 4). The noise of the accelerometer, the output when the oscillator was replaced by a fixed mirror [3] (the thin dashed lines in figure 4), did not disturb the measurement below 100 Hz.

The spectra of the horizontal measurement above 100 Hz are shown in figure 5. The results of the vertical motion were similar. Graphs (a) and (b) show the measured values when the cryocoolers and the vacuum pump worked and were stopped, respectively. Obviously, the output of the accelerometer, the black lines in figure 5, increased between 200 Hz and 20 kHz when the cryocoolers and the pump were running. However, it must be mentioned that these black lines above 400 Hz imply only the upper limit of the suspension top motion. The grey lines in figure 5 represent the results when the oscillator was replaced by the fixed mirror, and agree with the black ones above 400 Hz whether the cryocoolers and the pump worked or not. The difference between the black lines in the graphs (a) and (b) of figure 5 is the vibration of the parts, except for the oscillator, for example, the reference mirror and the beam splitter. The motion of these parts with working cryocoolers was at least 50-times larger than that without
Figure 4. Measured power spectrum densities of the suspension top vibration. Graphs (a) and (b) present the horizontal (optical axis of the CLIO interferometer) and vertical motions, respectively. The black thick and the grey thin lines are the vibration with and without operation of the pulse tube cryocoolers and the vacuum pump. In the results concerning the vertical motion, the vacuum pump was stopped even when the cryocoolers worked. The grey thick line represents the seismic motion at Kashiwa city near Tokyo. The thin dashed line shows the result when the oscillator was replaced by a fixed mirror [3] (The results of the fixed mirror above 100 Hz are in figure 5).

Before the Gifford-McMahon cryocooler was removed, we measured the horizontal vibration. The results are shown in figure 6. The black thick and grey thin lines are the vibration with the operation of the Gifford-McMahon cryocooler (vacuum pump was stopped) and the pulse running cryocoolers around 1 kHz. In any case, this loudness is not a serious problem because the isolation system works well in this frequency region.

Before the Gifford-McMahon cryocooler was removed, we measured the horizontal vibration. The results are shown in figure 6. The black thick and grey thin lines are the vibration with the operation of the Gifford-McMahon cryocooler (vacuum pump was stopped) and the pulse

Figure 5. Spectra of the horizontal motion above 100 Hz. Graphs (a) and (b) show the vibration when the cryocoolers and the vacuum pump worked and were stopped, respectively. The black lines are the accelerometer outputs with the oscillator (normal operation). The grey lines represent the results when the oscillator was replaced by the fixed mirror [3].
tube cryocoolers (vacuum pump was running), respectively. The grey thick line represents the seismic motion at Kashiwa. The Gifford-McMahon cryocooler increased the vibration. Below 10 Hz, there were high peaks. Between 30 Hz and 400 Hz, the spectrum was as large as that at Kashiwa. Although the Gifford-McMahon cryocooler is a popular commercial product, it is impossible to be used for the CLIO and the LCGT.

4. Summary
In the LCGT and CLIO projects, to decrease the thermal fluctuation, the mirror and the suspension are cooled by cryocoolers. In order to evaluate the vibration caused by the pulse tube cryocoolers specially developed for the CLIO, we measured the motion of the suspension top of the CLIO interferometer with the operating cryocoolers in the Kamioka mine, which is the site of the LCGT and the CLIO. These pulse tube cryocoolers did not seriously increase the vibration. Consequently, the thermal noise suppression using these cryocoolers is suspected to be observed without any additional disturbance, even at an extremely silent site, Kamioka mine. The floor level of the measured horizontal and vertical motion was $10^{-9}(1 \text{ Hz}/f)^2 \text{ m/Hz}^{1/2}$ between 1 Hz and about 100 Hz. This was 100-times smaller than that around Tokyo. The popular commercial Gifford-McMahon cryocooler is not useful because it causes a large vibration. Our future work is to measure the vibration at the inner shield of the CLIO interferometer.

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