Global control using a laser strainmeter for KAGRA

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Abstract. The KAGRA is a large-scale laser interferometric gravitational wave (GW) telescope that is has been constructed in Japan’s underground. Underground telescopes such as KAGRA and the proposed Einstein Telescope have the advantage of substantially reduced seismic noise above 1 Hz relative to GW telescopes on the surface. However, even in underground, seismic motion at low frequencies such as microseisms (< 1 Hz) and earthquakes (< 10 mHz), could severely degrade GW telescopes’ stability. In the current design of the KAGRA, these disturbances are suppressed by feedback controls using inertial sensors such as seismometers and geophones. Nevertheless, suppression with this control method is limited by the insufficient sensitivity and tilt-horizontal coupling of the sensors at low frequencies. In this paper, we have developed a new control method based on a laser strainmeter named the Geophysics Interferometer (GIF) to resolve this problem. This was installed in the KAGRA tunnel and has a superior sensitivity of less than 100 mHz and no problems with tilt coupling. This new method will achieve improved stability for the operation of an interferometer. Also presented in the paper is the design of the control system and an experimental result.

1. Introduction

For gravitational wave (GW) astronomy, which requires simultaneous observation with multiple GW telescopes, maintaining a high duty cycle of the each telescope is important issue. All the existing GW telescopes are essentially Michelson interferometers implemented in each arm with high finesse Fabry-Perot resonant cavities. The optical components of these arm cavities are suspended by the multiple-stage pendulums to attenuate the seismic noise. While disturbances above the eigenfrequency of the pendulums can be attenuated, those below this frequency cannot. The typical eigenfrequency of these pendulums is a few hundreds of mHz, but the the root-mean-square (RMS) motion of suspended mirrors is dominated by lower-frequency seismic noises. Examples of these seismic noise include microseisms of a few m RMS amplitude around 200 mHz, the atmospheric pressure responses of rocks, which is a few mHz, and earth tides of a few 100 μm RMS amplitude around 10^{-5} Hz. Since the RMS amplitude of these seismic noises is larger than the linewidth of the arm cavities by two or more orders of magnitude, some controls to keep the cavities locked are required. This disturbance severely degrades the stability of the GW telescopes, if not mitigated adequately.

To attenuate the low-frequency seismic noise, active vibration isolation systems for the arm cavities have been developed. An example is an active vibration isolation system using the feedback control implemented with a suspension point interferometer (SPI). This is an additional optical cavity installed at the suspension point of the main cavity [1]. Although the SPI can measure the length change of the arm cavity directly, it requires additional facilities,
and complicated controls to keep it operational. The other approach is an active vibration isolation system in which seismometers are used to monitor the displacement of the suspension points of the pendulums. The displacement of the suspension point (i.e., the length change of the arm cavity) is reduced by feedback controls using the seismometer signals [2]. However, this method is expected to provide only minor improvement to GW telescopes’ duty cycle because its effect is limited for seismic motions at low frequencies. This is typically below 100 mHz. This implies that seismometers cannot measure the ground motion accurately because of insufficient sensitivity and inevitable tilt-horizontal coupling. Therefore, to avoid these issues, the active vibration isolation system requires some other control strategy [3].

To overcome these limitations, we have developed a new active vibration isolation technique using a laser strainmeter, which directly monitors baseline length change. In the KAGRA tunnel, we have built a 1.5-km laser strainmeter named the Geophysics Interferometer (GIF), designed to measure the crustal deformations [5]. The GIF does not need any alignment control, unlike the SPI, and it has a high dynamic range with better sensitivity than seismometers at low frequencies.

2. GIF

2.1. Features of GIF

The GIF is a laser strainmeter, which is installed along the X-arm of the KAGRA as shown in Fig. 1. It is an asymmetric Michelson interferometer that observes the length change of a main arm (1.5-km baseline length) with reference to a stable short arm (0.5 m). Displayed in Figure 2 is the optical layout of the interferometer. Both retroreflectors in the main and reference arms are fixed on the granite blocks, which are mounted on the bedrock directly, in order to observe the geophysical phenomena. The retroreflectors are used to eliminate alignment control for achieving the robust operation of the instrument.

The displacement of the main arm reflector, including its direction, is observed by the quadrature phase detection technique [4]. The optical phase change, which is proportional to the length change of the main baseline, is obtained by fitting an elliptic curve to the Lissajous curve drawn by these quadrature signals. It takes less than 61 sec for the phase signal to be fitted. The range of the strainmeter is unlimited as long as the fringe signal is tracked by the data acquisition system without losses.

Fundamentally, the noise level of the GIF is limited by the stability of the laser frequency because of its asymmetric optical configuration. The resolution of the strain measurement is estimated to be order $10^{-12}$, based on the evaluation of the laser frequency stability.
2.2. Comparison with Seismometer Array

Figure 3 shows a comparison of spectra of the change in baseline length as measured by the two seismometers in the KAGRA against that of GIF signal. The seismometers were installed at the two ends of the 3 km baseline (X-arm) of the KAGRA, while the baseline length fluctuation was obtained from the differential component of these two seismometer outputs. The length change of the 1.5-km arm measured by the GIF was doubled for comparison. Above 1 Hz, noise is greater for the GIF than for the seismometers because of the GIF laser frequency fluctuation, whereas below 50 mHz, noise is greater for seismometers than for the GIF because of the instrumental noise. For this reason, we propose the strainmeter as a global sensor for our low-frequency control system.

![Figure 3. Comparison of the baseline length fluctuation measured by two seismometers (black) and GIF (green). Dashed lines represent the sensor noise.](image1)

3. Global Control using the GIF

3.1. Control Method

As shown in Figure 4, the GIF signal is feedforwarded to the end mirror suspension of the arm cavity in conjunction with the local feedback control, which uses a displacement sensor. This feedforward control system contains two paths: i) a sensor correction path, in which the strainmeter signal is injected to the actuation point and ii) a simple feedforward path, in which the signal is injected to the error point (see block diagram in Fig. 5). In the diagram, \( X_{\text{GND}} \), \( X_{\text{STG}} \), and \( X_{\text{TM}} \) denote the motions of the ground, of the stage that houses the test mass pendulum, and of the test mass, respectively. \( H_{\text{TM}} \), \( P_a \), and \( H_s \) denote the transfer functions, respectively, from the stage to the test mass, from the actuator to the stage, and from the ground to the stage. Moreover, \( S_{\text{fb}} \) and \( S_{\text{ff}} \) denote the frequency response of the displacement sensor and of the GIF, respectively. The terms \( C_{\text{fb}} \), \( C_{\text{ff}} \) and \( C_{\text{sc}} \) denote the control filters of the local feedback, of the simple feedforward, and of the sensor correction, respectively. The end stage motion is given as

\[
X_{\text{STG(Ex)}} = \frac{G}{1 + G} \left( 1 - C_{\text{sc}} \frac{S_{\text{ff}}}{S_{\text{fb}}} \right) X_{\text{GND(Ex)}} + \frac{1}{1 + G} \left( H_s - P_a C_{\text{ff}} S_{\text{ff}} \right) X_{\text{GND(Ex)}} + \frac{G}{1 + G} C_{\text{sc}} \frac{S_{\text{ff}}}{S_{\text{fb}}} X_{\text{GND(IX)}} + \frac{1}{1 + G} P_a C_{\text{ff}} S_{\text{ff}} X_{\text{GND(IX)}},
\]

where \( G = P_a S_{\text{fb}} C_{\text{fb}} \). The last two terms in this equation indicate that the end stage responds not only to the local ground motion but also to the seismic input to the front stage. In other words, the entire cavity can be seen as a single object whose length fluctuation will be suppressed by designing adequate parameters as detailed below. This integration is one of the main features qualifying our method as a global active vibration isolation method.
3.2. Experimental Demonstration
We have implemented a digital control system in real time and conducted a test experiment. To reduce the length change of the arm cavity, in the above equation, we designed the control filters to be $C_{sc} = 1$, $C_{ff} = 0$, and $G \gg 1$. As a result, only the third term in Eq. (1) remains, indicating that the input suspension motion determines the motion of the end suspension motion. This result follows logically, since the transfer functions are unity gain in the frequency region below the eigenfrequencies of the suspensions. Therefore the end test mass motion follows the input test mass motion, while the length change of the arm cavity is reduced.

In the test experiment, the X-arm cavity of the KAGRA was locked by controlling the main infrared laser frequency through an acousto-optic modulator (AOM). The length change of the arm cavity was obtained from the feedback signal to the AOM.

![Figure 5. Block diagram of the central system shown in Fig. 4. The GIF signal is the differential motion of the each local ground, and it is sent to the actuator using two filters: $C_{sc}$ and $C_{ff}$.](image)

![Figure 6. Result. The GIF strain signal (top) and the change of the arm cavity length (bottom) for 30 minutes. The control was turned on at 14 minutes.](image)

3.3. Result
As shown in Figure 6, the feedforward control was turned on at 14 minutes. While the X-arm was disturbed by earth tides before the control was applied, this slow disturbance was reduced by the control. On the other hand, the reduction was not so clear at shorter periods, below several tens of seconds. For these periods, we interpret the motion of the stages to be influenced by the other degrees of freedom, especially the transverse and yaw directions, as high coherence was observed between them. The local feedback control applied to keep the cavity in resonant status may have introduced these couplings with X-arm length.

3.4. Conclusion And Future Prospects
In this paper, we described, and showed the demonstration results of, KAGRA’s new vibration isolation control system, which uses a laser strainmeter installed parallel to the X-arm. By applying the new control, X-arm displacement was substantially reduced in the tidal frequency band, while higher-frequency motions remained. Those higher-frequency motions may have been excited by the couplings from other degrees of freedom. Thus, the coupling problem should be resolved by other means. Further commissioning effort will be spent on for the coming O3 run and future constant GW observations.

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