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A control strategy for seismic noise reduction on advanced LIGO gravitational-wave detector

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Abstract
The differential seismic motion between the internal seismic isolation platforms on the advanced laser interferometer gravitational wave observatory, affects the sensitivity of the detector at lower frequencies (below 1 Hz), because each platform moves independently. This induces noise inside the cavities of the auxiliary optics placed on the platforms, which translates into a higher control effort to maintain stability and resonance. This paper shows that the differential motion between the platforms can be efficiently measured by the capacitive position sensors installed on each platform. We investigate how we can use these sensors to modify the seismic control configuration and help reduce the differential motion between the platforms, reduce the control efforts and help

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maintain the cavities in resonance. Reduced differential motion is expected to reduce control noise thereby improving sensitivity and improve detector duty cycle by preventing actuator saturation, resulting in loss of optical cavity resonance.

Keywords: LIGO, control, seismic, CPS

1. Introduction

The advanced laser interferometer gravitational wave observatory (aLIGO) are large scale Michelson interferometers combined with Fabry–Perot cavities in each arm, whose mirrors are placed near inertial test masses for them to act as indicators of space-time coordinates. Gravitational waves (GW) induce a strain in space-time, which modulates the separation of the mirrors in the detector arm, typically by less than 10^{-19} m around 100 Hz. To account for such minute displacements, the optical cavities are held on resonance with highly stabilized laser light in order to both build up laser power and to ensure a linear response to the GWs. aLIGO performance covers a wide range of frequencies, but it is affected by some noises which make them unable to detect waves from sources emitting in the low frequency window (below 1 Hz) [1].

It is important to open the lower frequency window because it can give access to the detection of GWs emitted by sources with unknown physical structure and astrophysical features. Moreover, it would broaden the study of the features of a wave in the earlier phases of the spiral [2–7] and to give a contribution to a more efficient multimessenger astronomy [8, 9].

The seismic noise is affecting the stability of the interferometer by injecting unwanted motion on the auxiliary optics inside the cavities. This induces instabilities in the resonant cavities, producing lock losses. When the detector loses resonance, the control systems of the optical cavities are under effort to restore stabilization. This means that during lock loss the interferometer is no longer able to be stable and the observing time is interrupted. After a lock loss, it takes a minimum of 30 min to reacquire the locked state of the detector, thus substantially impeding its duty cycle [10].

The efforts of the scientific collaboration to solve these issues are devoted to the development of new technologies for active control of the noise sources, responsible for the lack of sensitivity at lower frequencies and for detector instabilities [10, 11].

The strategy generally investigated is based on the subtraction of this noise source. In particular, modeling, controls and reduction of the noise of seismic platforms are currently under examination for increasing the sensitivity from below 30 Hz.

Amongst the major environmental noise sources contributing to lock loss incidents are earthquakes and microseismic events [12]. In particular, during O3 run, it was observed that the platforms in the corner station, hosting the beam splitter, the input test masses and the auxiliary optics, show a differential motion with respect to each other [13], because they move independently from each other with respect to ground. Due to constraints on the relative position and distance of optics, photo-detectors and other sensors, separate platforms host various sections of the optical systems [14]. Ideally, if a block of platforms close to each other could move synchronously, the whole block would follow the motion of one platform only. This, in turn, would help the cavities between those platforms to maintain stability and in cases of lock losses, allow regaining of lock state in shorter times [11].

Optics at aLIGO are suspended from pendula that are supported by actively isolated platforms. These platforms are actively controlled with feed-forward and feedback signals from sensors on the ground and on the platform respectively. The experiments described in the paper were performed on the aLIGO apparatus. Specifically, we focus on the differential motion between the tables that support recycling cavity optics and the beam splitter and input test masses. This choice is due to the fact that the hardware equipment is already present and installed, and the only required modifications would affect the aLIGO software, for subsequent less stressful and faster operations for test and implementation.

In this paper we describe the analysis developed on the HAM2 and HAM3 platforms, because these showed more correlated noise than others. Therefore it was supposed that the benefit of this scheme would be most apparent. The goal is to obtain a block of platforms moving as a single platform, following the average motion of the ground under the leading platform. Since large seismic events can induce saturation in the actuation, this strategy could reduce the actuation range required, and larger control gain can be applied to the differential degrees of freedom.

Section 2 of this paper illustrates the strategy adopted to perform simulations. Simulation results are shown in section 3, where also a preliminary experimental test is reported to validate the preliminary simulations. Conclusions follow in section 4, where further studies are described.

2. Control strategy

The devices dedicated to monitoring and providing feedback for the seismic motion are horizontal and vertical inertial sensors and displacement sensors. Actuators are paired to each sensor, for active isolation of the sensed noise. The vertical and horizontal inertial sensors with the dedicated actuators are placed on the platforms, underneath the optical tables, measuring the table motion in the horizontal and vertical directions. Amongst these sensors, the capacitive position sensors (CPS) measure the relative motion between two different stages of the isolation system [14]. The control design presented in this paper was motivated by studies of the O3 platform motion data [12]. These studies demonstrated that with the inertial isolation used in O3 there was a significant differential motion between the platforms. A model of the control system was developed that showed that if the CPS sensors were used to suppress differential motion, this motion could be suppressed at the expense of more common motion [15]. It was demonstrated that this control scheme was effective at making the interferometer more robust to earthquakes [15], but we expected that reducing differential motion would also reduce noise in the microseismic frequency band.

The plots in figure 1 show the differential motion measured by the CPSs between the basic symmetric chamber (BSC) and the horizontal access module (HAM) chambers along the arm in the x direction. The ISIs show a good common motion for our purpose. This can be confirmed by noting that the difference between two chambers is lower than for individual chambers. The sensors can then be used for monitoring the differential motion during the active control strategy proposed.

The CPSs are then reliable devices for sensing the differential motion, and they can be used to monitor the platform motion at lower frequencies. We then investigated if it is possible to use the CPSs to lock HAM2 and HAM3 together. This would make those platforms move in sync and possibly stabilize or significantly reduce their differential motion.

The strategy used was to control HAM2 with the configuration currently used on aLIGO [16–18], then to use the CPS signal of HAM2 to control HAM3 [13]. General notations used in the hereafter are listed in table 1. The methodology is based on computing the resulting platform motion solving the related block diagram illustrated in figure 2.

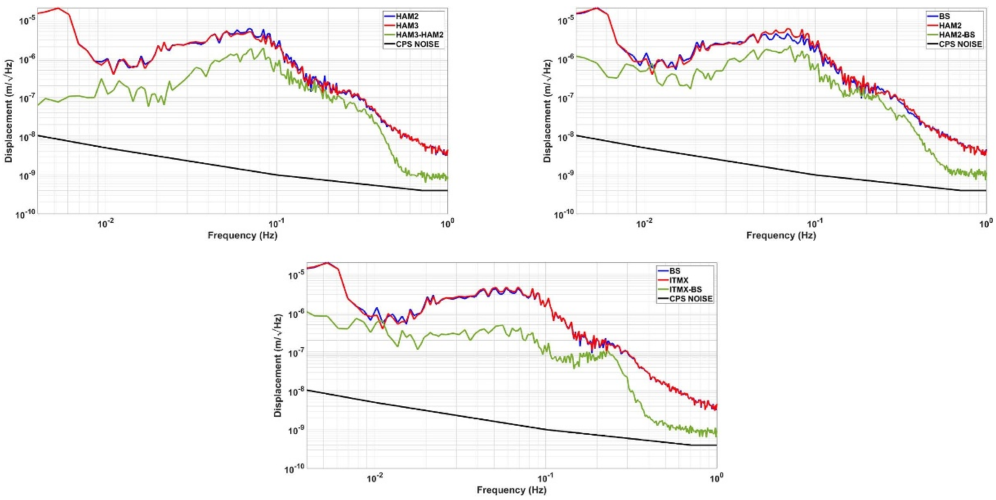

Figure 1. Differential motion sensed by the CPSs, between the chambers along the x axis. The sensors showed a slightly more correlated noise in the HAM chambers (top left), so this block was chosen for the present study. The same procedure can be applied to the BSC chambers hosting the beam splitter (BS, top right) and the input test mass (ITM, bottom).

Table 1. Notations used in the block diagrams and equations. All the variables are transfer functions: the notations in this paper were simplified from their usual frequency-dependent nomenclature. i.e. for example $C(j\omega)$ to C.

P	Plant	L	Low pass filter	N_i	Inertial noise
S	Sensor correction	H	High pass filter	x_g	Ground motion
C	Control	N_g	Ground noise	x_p	Plant motion

Our goal is to calculate the expected differential platforms motion between HAM2 and HAM3 once we use HAM2 signal to control HAM3, thus causing HAM3 to follow HAM2 platform motion, i.e. lock them. What we expect is that the two platforms should act as one platform, with a subsequent reduced differential motion (in the frequency band of interest). In the block diagrams, the sensor correction filter (S) takes the ground motion signal from an inertial instrument, filtering it before adding it to the relative sensor signal. This filter is present because the sum of the motions from the ground inertial and relative sensors can in principle provide a measurement of the absolute motion of the platform. However, the ground sensors are affected by low frequency noise and need to be suitably filtered. The sensor-corrected CPS signal is then low-pass filtered (L) and blended with the high-pass filtered (H) inertial sensors to fit the requirements and tuned to obtain the best performance combining the best results of both sensors. The frequency where the CPS and the inertial sensors contribute at their best is called the *blend frequency* and it is set to 1.14 Hz for optimized blending. The output of the blended sensor feeds the feedback loop, where the actuators close the loop.

In figure 2, P is the plant transfer function, describing how the platform reacts to the actuation. The control filter, C, is generally designed such that the open loop gain is unity at $\sim$30 Hz, and is very large at low frequencies. For a general standalone platform, the motion is as follows:

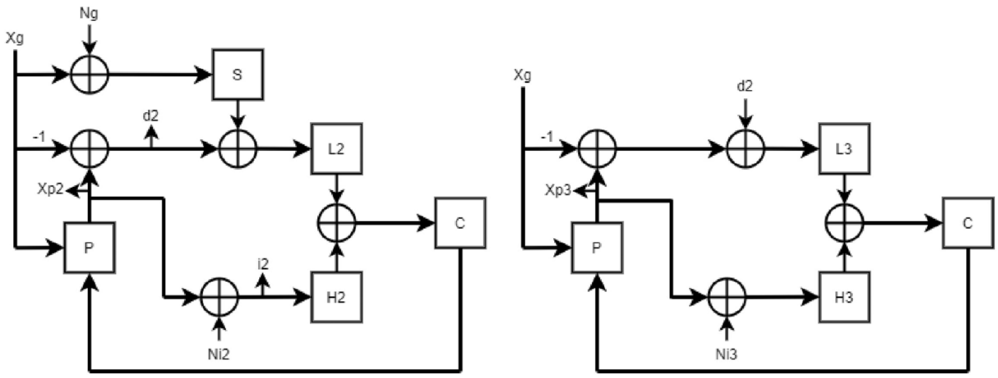

Figure 2. Scheme of the involved platforms. Simplified block diagram for HAM2 platform (left) as it is at present on aLIGO [13] and for HAM3 (right) in the new configuration where this platform is now connected to HAM2. The signals from d_2 represents the offset given by the CPS coming from HAM2. At low frequency the CPS noise is negligible because its contribution is about 10^3 times lower than the microseismic peak.

$$x_p = \frac{Px_g - (1-S)\cdot x_g \cdot L \cdot C \cdot P}{1 - C\cdot P} + \frac{(N_{i2}\cdot H + N_g \cdot S \cdot L)\cdot C \cdot P}{1 - C \cdot P}. \tag{1}$$

which can be simplified to,

$$x_p \approx x_g \cdot (1-\mathrm{S}) \cdot L - (N_{i2}\cdot H + N_g \cdot S \cdot L). \tag{2}$$

In presence of a very large gain ($||C\cdot P|| \gg 1$) at frequencies below 1 Hz. This derivation is valid for HAM2 and HAM3 before engaging the conjoined motion scheme.

Once we engage *Lock Mode*, between HAM2 and HAM3, we use equation (2) as a feedforward signal injected into HAM3 controls as shown in the block diagram 2 marked by point *d2*. Moreover, there is no sensor correction and ground noise on HAM3, since sensor correction is now being controlled by HAM2 feedback loop.

Solving the block diagram when *LockMode* is engaged [13], in very high gain and a low-pass dominating conditions ($||C\cdot P|| \gg 1$ and $H \to 0$), and including in the model of HAM's motion the contribution of ground tilt θ_g dominating in the microseismic frequency (<0.15 Hz) [12], we obtain a differential motion given by:

$$|x_{p_3} - x_{p_2}| = \left|\sqrt{(L^2 S\theta_g)^2 + (LS\theta_g)^2 + (x_g S L^2) + (x_g S L)}\right|, \tag{3}$$

where we also considered the low pass filters to be the same for both platforms ($L_3 = L_2$).

3. Results

The result computed above was used in a simulation of the effect of this strategy in figure 3. The plot shows a modeled motion of HAM2 in isolation, compared to HAM3 modeled motion and their differential motion when the *Lock Mode* is engaged. Below 10 mHz HAM3 motion

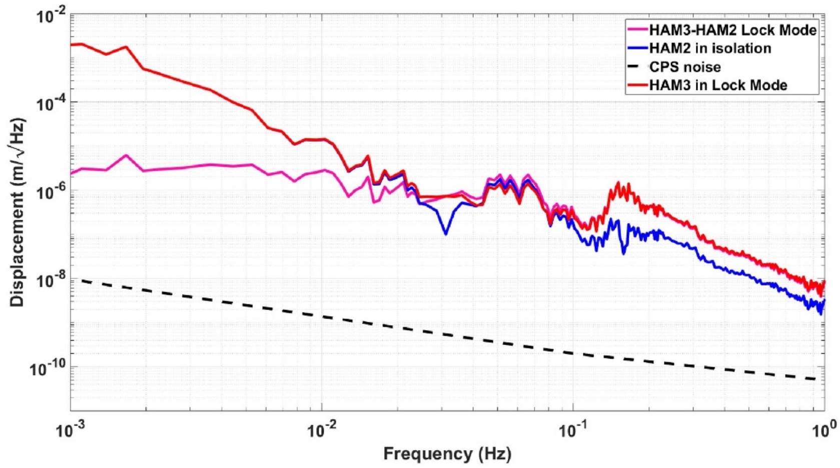

Figure 3. HAM chambers in *Lock Mode* condition. The plot shows the simulated motion of each platform, where HAM3 depends on HAM2, through CPS locking, and the differential motion between them. Below 10 mHz, HAM3 in *Lock Mode* (red) matches HAM2 motion (blue) as expected, maintaining a low differential motion, thanks to the fact that HAM3 and HAM2 are now considered as one platform (pink).

when in *Lock Mode* matches the motion of HAM2 in isolation, as expected, maintaining a low differential motion, but this is not valid above this frequency. We believe that this strategy, at its present stage, could be helpful only at frequency ranges below microseismic (around 10 mHz and below), due to the fact that the bandwidth of the filters was not changed, nor the structure of the sensor correction. Further studies are required to understand if it is possible to make such changes and what they would imply. Yet an experimental test involving the real systems is necessary to observe if the differential motion can be effectively reduced using this technique: the simulations consider the two HAM ISIs as identical, so a computed differential motion between HAM2 and HAM3 in isolation leads to zero, which is not possible to compare with the differential motion when in *Lock Mode*.

Preliminary validations of the coherence between differential motion of the platforms and the engagement of the *LockMode* can be seen in the input mode cleaner (IMC) cavity. The optics of the IMC lie entirely on HAM2 and HAM3 platforms. We projected the CPS signal to the IMC optical suspension points. Figure 4 shows that the curve is matching the differential motion of the platforms where the mode cleaner optics lie. This demonstrates that the IMC can be used as a witness for monitoring the differential motion of HAM2 and HAM3. When in *Lock Mode*, this cavity can be used to check that the variations of its motion were directly related to the platform motion and not to other external causes.

Moreover, it demonstrates that the CPS can be used as a sensor to monitor the motion of the optics of a cavity and discriminate whether the motion of the optics is due to the differential motion of the platforms they belong to. When this is the case, it would be possible to help stabilizing the cavity lengths using the differential motion between the platforms hosting the optics.

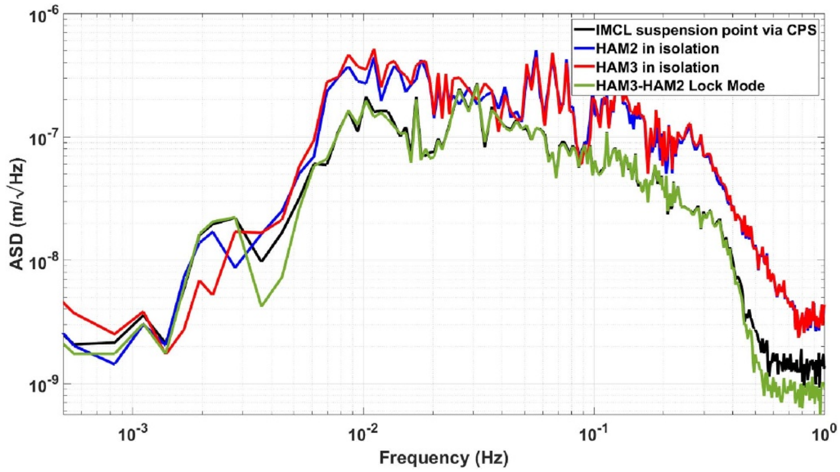

Figure 4. CPS projection to IMCL suspension point (suspoint). This plot shows that the motion of the optics seen by the CPSs matches the differential motion of the platforms hosting them. This is compared to the platform motion sensed by CPSs of individual chambers not engaged in *Lock Mode*. CPSs are then reliable sensors to monitor the motion of the optics at suspension points. Hence we can use these sensors to monitor the motion of the optics, additionally to the relative position between the platforms.

4. Conclusions

Maintaining the resonance inside the optical cavities of a gravitational-wave interferometer assures stable and long observation times, increasing the probability to detect the passage of a GW. A low differential motion between the platforms is demonstrated to be of crucial impact on the stability of the resonance inside the cavities. In this paper we studied a control strategy to help reduce the differential motion of the ISIs, through the use of the CPSs. The results show that the control strategy illustrated to implement the *CPS Lock Mode* could be helpful in locking two ISIs together, maintaining a low differential motion between the platforms in HAM2 and HAM3 chambers below 10 mHz, improving inertial isolation without increasing low frequency differential noise, and it could have a direct positive impact on the motion of the auxiliary optics. If the platforms move synchronously, the auxiliary optics could also benefit from a reduced motion and the resonance could be more stable. For this purpose, we demonstrated that the CPSs can be used to monitor the motion of the auxiliary optics caused by the motion of the platforms. aLIGO Livingston site has also actuated a similar process, following the progression at LHO during the work on site in 2019. Although the effective reduction of differential motion using this strategy needs to be experimentally demonstrated, it is currently under test because, at present stage, the idea is worthy of future developments and improvements for the stabilization of the optical cavities. A further investigation is ongoing to extend the procedure to connect the auxiliary optics of the other cavities to the CPS signals from their platforms. The final goal is to help understanding if it is possible to relate the motion of the optics to the one of the platforms, when the case occurs, and if it could be beneficial controlling them from the ISI itself [13].

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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