Compact vibration isolation and suspension for Australian International Gravitational Observatory: Local control system

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High performance vibration isolators are required for ground based gravitational wave detectors. To attain very high performance at low frequencies we have developed multistage isolators for the proposed Australian International Gravitational Observatory detector in Australia. New concepts in vibration isolation including self-damping, Euler springs, LaCoste springs, Roberts linkages, and double presiolation require novel sensors and actuators. Double preisolation enables internal feedback to be used to suppress low frequency seismic noise. Multidegree of freedom control systems are required to attain high performance. Here we describe the control components and control systems used to control all degrees of freedom. Feedback forces are injected at the presiolation stages and at the penultimate suspension stage. There is no direct actuation on test masses. A digital local control system hosted on a digital signal processor maintains alignment and position, corrects drifts, and damps the low frequency linear and torsional modes without exciting the very high Q-factor test mass suspension. The control system maintains an optical cavity locked to a laser with a high duty cycle even in the absence of an autoalignment system. An accompanying paper presents the mechanics of the system, and the optical cavity used to determine isolation performance. A feedback method is presented, which is expected to improve the residual motion at 1 Hz by more than one order of magnitude. © 2009 American Institute of Physics. [doi:10.1063/1.3250861]

I. INTRODUCTION

In a companion article we describe test mass vibration isolation and suspension systems developed for the proposed Australian International Gravitational Observatory (AIGO). The performance of an individual isolator system cannot be measured due to the lack of an inertial reference. For this reason a pair of isolators was configured to suspend mirrors for a 72 m optical cavity. The isolators were developed to satisfy the sensitivity requirements of advanced interferometric gravitational wave detectors, which require test masses to be isolated from seismic noise at frequencies down to a few hertz. For a target sensitivity of $10^{-20}$ m this typically requires a seismic attenuation of more than ten orders of magnitude. In addition to high performance isolation within the detection bandwidth, it is critical to interferometer operation that the isolator provides minimal residual motion at low frequencies. This facilitates cavity locking and minimizes noise injection through actuation forces. Pendulum systems inherently have large Q-factors, therefore, it is often necessary to damp the normal modes of the suspension system.

Such requirements can be addressed by a local control system. A feedback loop injects control forces at various actuation points on the isolator. These forces are derived by applying appropriate filters to error signals from local transducers such as position sensors. Typically the local control system is responsible for several tasks, each requiring different bandwidths and different filters. For example, in the frequency band dc to $\sim 10$ mHz the control system is responsible for drift correction, positioning, and alignment. In the frequency band up to $\sim 1$ Hz the control system is mainly needed for damping normal mode peaks. For higher frequencies (hertz–kilohertz) the control system may be required to suppress high frequency noise, in the form of active vibration isolation. Despite being conceptually simple, the operation of local control systems is complicated by resonant modes and mode interaction between isolation components and different degrees of freedom (DoFs). As a result, the feedback scheme often requires complex filter designs to avoid noise injection at critical eigenmodes that would interfere with the noise budget of the test mass.

In the gravitational wave community there have been two broad approaches to the vibration isolation problem. The first, and most widely adopted, including this work, has been to create mostly passive vibration isolators based on mass-spring systems. To stabilize them a local control system is used to control or damp certain normal modes. The second approach is to invest heavily in very sensitive seismometers to measure the seismic noise, and then to use active feedback in a rather stiff system to actively suppress the measured motion. In the first case, one allows the system itself to provide an inertial reference. In the second, the inertial reference is provided by the test mass of the seismometer. In the design presented here we extend the idea of the system itself being the inertial sensor, by using a pair of very low frequency stages that are designed specifically to allow relative sensing and feedback, to provide an additional means of active suppression of very low frequency seismic noise.
The VIRGO project\textsuperscript{2,3} and the TAMA project\textsuperscript{4,5} have used the first approach using multiple passive isolation stages, and relying on the control system mainly for damping and alignment. The GEO600 project\textsuperscript{6} uses a combination of an active layer and several passive stages. The LIGO project\textsuperscript{7,8} first implemented an active preisolation stage to overcome problems of excess seismic noise. For the Advanced LIGO project they have constructed a system, which combines stages of stiff active isolation with multiple pendulums.\textsuperscript{9}

The AIGO vibration isolator is conceptually similar to the VIRGO Superattenuator,\textsuperscript{10} but is more compact and has an extra stage of preisolation. The compactness is made possible through the use of novel isolation techniques with multiple preisolation stages.\textsuperscript{11} Pendulum normal modes are passively damped through self-damping.\textsuperscript{12} Feedback is applied to the preisolation stages and the penultimate suspension stage to steer the mirrors and maintain alignment and positioning, while correcting for various sources of drift such as temperature fluctuations. Low frequency control loops also damp fundamental modes of the preisolation stages and angular modes (Yaw) of the suspension chain to minimize low frequency residual noise dominated by the eigenmodes of the isolation chain. These low frequency resonances can otherwise have large amplitudes as they are located close to the microseismic peak of the seismic background. Therefore careful consideration has to be taken when designing the feedback loop in order to avoid exciting the test mass suspension fundamental mode, which by design has extremely low loss and hence low Brownian motion. To facilitate this, the Pitch and Yaw of the test mass are monitored directly through an optical lever. Control forces are applied indirectly to a control mass from which the test mass is suspended, in similar fashion to the VIRGO marionetta.\textsuperscript{13} In order to provide a flexible platform capable of satisfying the various control requirements, a digital control system was implemented on a Sheldon Instrument digital signal processor (DSP) board,\textsuperscript{14} running on a peripheral component interconnect (PCI) bus. Each vibration isolator is integrated with an independent digital control system. The two only differ in minor adjustments of gains and corner frequencies to match small differences in the mechanical modes of the isolation stack.

Two vibration isolators were installed at the AIGO test facility in Gingin, Western Australia. The systems were installed in the East arm of the vacuum envelope to form a 72 m suspended cavity. A neodymium-doped yttrium aluminum garnet laser was locked to the cavity using the Pound–Drever–Hall\textsuperscript{15} technique. In a companion article\textsuperscript{1} we discuss the vibration isolator design and the low frequency performance as determined from the error signal of the optical cavity.

This article presents the control architecture and systems to enable the potential performance of the isolators to be realized. In Sec. II we describe the integration of the isolator components with specially developed sensor and actuator components including high dynamic range shadow sensors, high force magnetic actuators, and Ohmic position control systems. The control scheme is presented in Sec. III, where we also show how the novel dual preisolation approach is expected to allow major improvements in performance through use of so called superspring techniques. Finally in Sec. IV we review cavity locking results, which confirm the performance of the control system, and demonstrate the capability of the system for use in interferometric gravitational wave detectors.

II. EXPERIMENTAL SETUP

A. Isolator components

The AIGO vibration isolation design is discussed in detail in the companion article,\textsuperscript{1} and only a brief review is presented here. It consists of nine cascaded stages as illustrated in Fig. 1, including three stages of preisolation in a compact nested structure from which is suspended a triple self-damped pendulum. A vertical stage based on Euler springs is colocated with each of the three pendulums. Anti-spring geometries are implemented into various stages to reduce fundamental mode frequencies.\textsuperscript{11,16,17}

The preisolator consists of several ultralow frequency (ULF) stages: the inverse pendulum, the LaCoste linkage,\textsuperscript{18} and the Roberts linkage,\textsuperscript{19} each with their resonant frequencies in the order of 100 mHz. The inverse pendulum stage can be tuned close to 0.05 Hz to provide low frequency horizontal preisolation. It has a large dynamic range with ±10 mm in all directions, which can be used to buffer temperature drifts and tidal effects. The inverse pendulum requires minimal force to displace it and is therefore well adapted to actuation.\textsuperscript{20} Vertical preisolation is provided by...
the LaCoste linkage, which is a combination of negative springs to null out flexure stiffness and zero length coil springs to support a 250 kg load. The LaCoste linkage, like the inverse pendulum, has a large dynamic range and can be tuned below 0.05 Hz. The Roberts linkage provides the second horizontal preisolation stage.11

The combination of coil and magnet provides the actuation for the positioning and damping for both the inverse pendulum and the LaCoste stages. Additional heating of the coil springs at the LaCoste stage provides a means of compensating for slow temperature drifts in the vertical direction as well as correcting for creep in the isolation chain. Position control at the Roberts linkage stage is done through heating of the individual wires. A low frequency isolation stack is suspended from the Roberts linkage consisting of three almost identical stages (see Fig. 1). A 40 kg mass load is suspended from each stage in a self-damped pendulum arrangement12 and each is combined with an Euler spring for vertical isolation.16

The test mass is suspended from a control mass, which can be actuated in Pitch, Yaw, and horizontal translation. The suspension design uses four niobium ribbons21 to form a low loss suspension with pendulum Q-factor \( \sim 10^6 \). The control mass itself is suspended from the isolation system by a single suspension wire. All optical cavity testing has been done without direct sensing or actuation on the final test mass of the system, beside the use of optical levers. An integrated electrostatic actuator/rf sensor has been developed22 as a final stage of low level control. This will be implemented when the vibration isolators are used in a full interferometer configuration.

B. Control hardware

1. Shadow sensors

The position of several stages of the isolation stack is monitored by the local control system through optical shadow sensors. A shadow sensor as illustrated in Fig. 2 is a simple device consisting of a light-emitting diode (LED) shining an infrared beam onto two photodiodes, and an intermediate shadow mask is attached to the part to be measured.

![FIG. 2. The shadow sensor is a simple device, where a LED shines a beam onto two photodiodes, and an intermediate shadow mask is attached to the part to be measured.](image)

2. Magnet-coil actuator

Magnetic-coil actuators are used to control several stages as described in Sec. II C. Each actuator consists of a pair of coils assembled together as illustrated in Fig. 3. Two designs of magnetic actuators are used in the isolator. Large actuators are used on the preisolation stage, for position control, drift correction, and damping ULF normal modes. This design uses coils with \( \sim 1600 \) turns of 0.25 mm wire to form a coil diameter 65–80 mm, with a resistance of \( \sim 115 \) \( \Omega \). A \( 20 \times 10 \) mm permanent neodymium boride magnet is used to result in a force of \( \sim 160 \) mN with a current of 100 mA driving the actuator (50 mA each coil, connected in parallel). A smaller actuator design is used at the control mass, with a coil diameter of 25–30 mm, made of \( \sim 600 \) turns of 0.25 mm wire. These coils have a resistance of \( \sim 37 \) \( \Omega \) and are paired with a \( 10 \times 10 \) mm magnet. The magnetic field within the actuator coils is nearly uniform within 1% in the central 10 mm of its range, allowing a large dynamic range in the control system.

3. Wire heating

In addition to the magnetic actuators, some stages are controlled by passing a current through particular suspension elements. The elements warm up and lengthen through thermal expansion. This control method is relatively effective when the system is under vacuum, as heat does not dissipate through convection, but only by the relatively slow processes of radiation and conduction. The advantage of this method is that it removes the complication of added parts, and in some cases provides much greater dynamic range. This is used to correct for large drifts caused by daily and seasonal ambient

![FIG. 3. (Color online) The magnet-coil actuator. A magnet mounted on an isolation stage is placed in the center of two coils that are mounted on the support frame.](image)
temperature changes. This actuation method responds with a quadratic relationship, but it is linearized in the digital feedback loop. The horizontal control of the Roberts linkage and the vertical control of the LaCoste linkage, both employ this strategy.

The four suspension wires of the Roberts linkage are individually wired to current power supplies, allowing the length control of each of them by thermal expansion as they warm up. Since the Roberts linkage is very sensitive to any change of tension in any of the wires due to its carefully tuned folded configuration, a relatively small change of length is enough to control the stage through its entire dynamic range ~10 mm. The position of the Roberts linkage is controlled via the circulating current, which in turn is controlled by the local control system through integral feedback to the current power supplies.

The LaCoste linkage has a large dynamic range and can be controlled through its entirety by magnetic actuators at a fixed ambient temperature. However, daily and seasonal temperature fluctuation cause drifts that would far exceed the capacity of the actuators. A 1 °C change will offset the balance point of the LaCoste linkage by its entire range of 10 mm. For this reason, wire heating is an essential part of the LaCoste control loop. The coil springs of the LaCoste linkage are electrically connected in series, and can be heated to change the spring constant of the springs, which greatly affects the vertical position or balance point of the stage. Low frequency control (dc–10 mHz) of this stage is achieved by regulating this current, while the magnetic actuators are used at higher frequencies (~100s mHz).

C. Control implementation and degrees of freedom

The inverse pendulum can be monitored and actuated in three DoFs, two in the horizontal plane (X and Y), and one angular (Yaw φ), i.e., the rotation about the vertical axis. These are sensed and actuated through four shadow sensors and four actuators that are collocated on the inverse pendulum frame as shown in Fig. 4. The four signals are diagonalized into the three DoF X, Y, and φ, and each is controlled independently as a single input single output (SISO) feedback loop.

The LaCoste stage is a purely one-dimensional vertical stage (DoF: Z). Two actuators are mounted on opposing sides as illustrated in Figs. 4 and 5. They are used to damp the ULF normal mode of the stage. In addition, the LaCoste linkage can be controlled by heating the coil springs on all four sides of the stage, which are all connected to a high current supply. A shadow sensor mounted on the side of the preisolation structure monitors the vertical position of the LaCoste linkage.

The Roberts linkage in Fig. 6 is controlled in two DoF, X and Y, by passing a current through its suspension wires. Each of the four suspension wires are electrically isolated from the rest of the vibration isolator structure and independently connected to a high current power supply. By controlling the circulating current on each wire it is possible to control its length, and therefore, the position. Since the suspension system is under vacuum the heat loss by convection is minimal. The X and Y signals from the control mass are converted to an orthogonal reference frame X, Y, Z, and φ by a sensing matrix.

FIG. 4. (Color online) The inverse pendulum is controlled through shadow sensors and magnetic actuators.

FIG. 5. (Color online) The LaCoste stage is controlled through a shadow sensor and magnetic actuator as well as the heating of the suspension coil spring.

FIG. 6. (Color online) The Roberts linkage is controlled through shadow sensors and the heating of the four suspension wires.

FIG. 7. (Color online) The control mass has three actuators and shadow sensors collocated on the horizontal plane, in a 120° arrangement. These three signals are converted to an orthogonal reference frame X, Y, Z, and φ by a sensing matrix.
actuation method. This control system provides a low frequency correction of any drift in the Roberts linkage and ultimately of the multistage pendulum and the test mass.

The control mass can be controlled in five DoF, three orthogonal translations \(X, Y, \text{ and } Z\), the rotation about the vertical axis, Yaw \((\phi)\) as shown in Fig. 7, and the rotation about the horizontal axis perpendicular to the laser axis, pitch \((\theta)\) shown in Fig. 8. Three horizontal actuators and shadow sensors are colocated in a 120° arrangement on the horizontal plane as seen in Fig. 7, while two vertical shadow sensors and actuators are colocated on opposing sides of control mass along the laser axis, as in Fig. 8. The signals are digitalized by a sensing matrix into five orthogonal DoF, \(X, Y, Z, \phi, \text{ and } \theta\). These are treated by five separate control loops as independent SISO systems, before the signals are recombined by a driving matrix into the appropriate actuator signals.

D. Optical lever

Due to poor coupling of the mirror suspension angular modes to the control mass, it is necessary to have a direct readout of the mirror angular orientation. This was achieved by a simple optical lever as illustrated in Fig. 9. A laser outside the vacuum envelope is reflected off the test mass and is measured by a quadrant photodiode, also outside the vacuum envelope. In addition to being a direct measurement from the mirror surface the optical lever provides better sensitivity to angular motion as it is placed further away from the center of rotation of the mirror, such that the same angular rotation corresponds to a much larger arc-length measured by the quadrant photodiode \(\approx 5\ m\) away from the mirror, than the shadow sensors, which is only 200 mm away. The drawback is the limited dynamic range, it provides \(\approx 1\ \text{mrad}\), which is greatly exceeded by the test mass suspension oscillation when it is excited. Therefore the shadow sensor feedback is used for initial damping of the angular modes, before the optical lever signal can be used for feedback, as discussed in Sec. III B.

E. The digital controller

The control system is hosted by a Sheldon Instrument DSP board, forming a flexible multidimensional digital control platform. The board is a SI-C33DSP on a PCI bus, based on a 150 MHz Texas Instruments TMS320VC33 DSP using a mezzanine board SI-MOD6800 to provide 32 input channels (16 bit ADC), 16 output channels [16 bit digital to analog converter (DAC)], and digital input/outputs. \(^{14}\) The input channels are used as described in Table I. Most input channels are used for the shadow sensors, which require two inputs each, one per photodiode. Two more inputs are used for the vertical and horizontal axis readout of the quadrant photodiode used with the optical lever, and two more are wired to auxiliary connectors to inject any arbitrary analog signal. The output channels are used for the control signals of actuators and current power supplies.

An intermediate analog system amplifies and filters the input and output channels between the DSP and the control components (shadow sensors, wire heating, and actuators) with the exception of the quadrant photodetector used in the optical lever, which is integrated on a board with preamplification. The analog electronics consists of 13 boards in a standard 6U rack, each board contains a dual photodetector circuit for the pair of photodiodes in one shadow sensor, and a control signal circuit to drive an actuator. The dual photodetector circuit contains a transimpedance amplifier, anti-aliasing filters, and an amplifier. The signal of both photodiodes is then distributed to two inputs on the DSP board. The control signal is distributed from one DSP output to the corresponding channel on the control circuit, which contains anti-aliasing filters and a high speed current amplifier before distribution to the actuator coils. An additional board in the 6U rack contains five filter circuits for the wire heating control signals. This five signals are then distributed to five external voltage controlled current supplies.

The control scheme, algorithms, and the user interface, are written and operated in LABVIEW\textsuperscript{®}. The built-in libraries provided by the DSP manufacturer allow for the control loops to run on the DSP board in real time including ADC and DAC at a 100 Hz sampling rate. The user interface is run on a host personal computer to monitor every stage of the isolation chain and adjust control parameters, such as filters and loop gains as necessary.

<table>
<thead>
<tr>
<th>Table I. I/O channel allocation usage of DSP.</th>
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<tr>
<td>Stage</td>
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<tr>
<td>-----------------</td>
</tr>
<tr>
<td>Inverse Pendulum</td>
</tr>
<tr>
<td>LaCoste Stage</td>
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<tr>
<td>Roberts Linkage</td>
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<tr>
<td>Control Mass</td>
</tr>
<tr>
<td>Optical Lever</td>
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<tr>
<td>Auxiliary</td>
</tr>
<tr>
<td>Total:</td>
</tr>
</tbody>
</table>

FIG. 8. (Color online) The Pitch of the control mass is actuated by two vertical magnetic actuators.

FIG. 9. (Color online) The optical lever setup, using a quadrant photodiode placed outside the vacuum envelope.
TABLE II. Stages and relevant DoFs in the control scheme.

<table>
<thead>
<tr>
<th>Stage</th>
<th>DoF</th>
</tr>
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<tbody>
<tr>
<td>Inverse Pendulum</td>
<td>X, Y, φ</td>
</tr>
<tr>
<td>LaCoste Stage</td>
<td>Z</td>
</tr>
<tr>
<td>Roberts Linkage</td>
<td>X, Y</td>
</tr>
<tr>
<td>Control Mass</td>
<td>X, Y, Z, φ, θ</td>
</tr>
<tr>
<td>Optical Lever</td>
<td>φ, θ</td>
</tr>
</tbody>
</table>

III. CONTROL SCHEME

The control scheme has three main purposes. One is to maintain alignment and positioning for all stages, against drifts such as caused by ambient temperature changes or tidal effects. These effects are extremely low frequency, with timescales from tens of minutes to days. Therefore the control strategy consists of low gain integration feedback. The control system has also to maintain the test mass alignment to obtain a resonant cavity. The alignment of the test mass is controlled indirectly via Pitch and Yaw of the control mass stage. However, sensing is done with the control mass shadow sensors and directly from the test mass through the optical lever. The control is achieved by both proportional and integration control while aligning the cavity, and integration only when maintaining the cavity locked.

While the isolation design relies on passive isolation, some active damping is required for some ULF resonant modes of the preisolation, as well as low frequency torsional modes (Yaw) of the entire chain. Additionally, the two normal modes of the test mass suspension (Pitch and Yaw) must be damped at least initially after any alignment or positioning offset. The extremely high Q-factor of the niobium suspension would otherwise result in several days of oscillations after any large perturbation. While controlling the alignment the control system must also avoid driving the suspension resonant modes, this is done through carefully placed filters in the feedback gain.

At each stage the sensor signals are converted into orthogonal DoF by a sensing matrix, such that the control system consists of independent SISO systems, which simplifies the control strategy and requirements over a multiple input multiple output system. The various DoF of each stage relevant to the control system, as discussed in Sec. II C, can be summarized in Table II. Figure 10 illustrates the physical location for sensing and actuation of the feedback loops.

A. Preisolation feedback

Damping of the Yaw (φ) mode of the inverse pendulum is done via velocity feedback \( [F(s) = \partial / \partial t (\phi - \phi_{ground})] \) in a bandpass filter 0.3 Hz < f < 0.7 Hz. However, the two horizontal modes require some consideration to maintain stability. Figure 11 shows the loop gain with feedback loop gain using a relatively high damping gain and a second order low pass filter at 0.7 Hz. Note that lowering the corner frequency of the low pass filter would lead to instability as can be seen from the small gain margin. In order to damp the large resonance at 70 mHz we apply a damping gain using the inverse pendulum shadow sensor output (which is a measurement of \( x_1 - x_p \), as illustrated in Fig. 14). This control method is being summarized in Table II. Figure 11 illustrates the physical location for sensing and actuation of the feedback loops.

![Figure 10](imageurl) Block diagram of the isolation local control system. The signals from shadow sensors and a quadrant photodiode are used to feedback to several stages using magnetic actuators or high current heating.

![Figure 11](imageurl) (Color online) Plant gain \( P(s) = A(s)IP(s)S(s) \), loop gain \( G(s) = P(s)C(s) \) and closed loop transfer function \( H(s) = P(s)/1 + G(s) \) of inverse pendulum horizontal DoF. The diagonalized signal from the inverse pendulum shadow sensors is feedback at the inverse pendulum actuators \( x_1 \) and \( F_1 \) in Fig. 14, respectively. The digital compensator \( C(s) \) with a low pass filter at 0.7 Hz.
replaced by the scheme described in Sec. III C but it was used for initial testing of the cavity. In principle it should also be possible to damp the second resonant mode (cause by the Roberts linkage) with phase compensation at the appropriate frequency, but this is difficult to implement effectively while maintaining stability due to the small frequency separation of the two preisolation stages. However, damping of the Roberts linkage can be done with the method described in Sec. III C.

The LaCoste stage feedback method in the vertical direction $Z$ is divided between the actuator and the coil heating. The shadow sensor signal is feedback to the actuator with a damping gain and a low pass filter at 0.7 Hz. The vertical signal from the control mass is also feedback to the coil heating supply with a low integration gain, after being linearized by taking the square root of the resulting control signal. The coil heating method allows to correct for a large range of ambient temperature, which would be impossible with the actuators alone, while the fast response of the magnetic coils is used to damp the ULF normal mode. It is possible to also use the control mass vertical signal for damping feedback to the LaCoste actuators, but this is not currently implemented to avoid coupling to the control mass Pitch, pending a thorough investigation of the sensing matrix digitalization and coupling of the DOFs.

The Roberts linkage control merely consists of position feedback to the heating current supplies, with a low gain integral loop, to the two axes, $X$ and $Y$, at frequencies below 10 mHz. Position sensing of the control mass is feedback to the position control of the Roberts linkage, to minimize forces injected at the control mass.

**B. Control mass feedback**

The control mass horizontal translation $X$ and $Y$ is feedback to the preisolation stages with a low integration gain, to minimize noise injection at the control mass. Pitch ($\theta$) and Yaw ($\phi$) are controlled to maintain alignment of the optical cavity, as well as to damp the Pitch and Yaw resonant modes of the control mass. The control mass is an order of magnitude heavier than the test mass, hence the suspension resonances are weakly coupled to the control mass. This results in a poor signal to noise ratio at the suspension resonances. An optical lever is therefore used to monitor the Pitch and Yaw directly from the mirror.

The Yaw resonance is damped with the shadow sensor control otherwise its amplitude is too large for the range of the optical lever $\sim 1$ mrad. Although the oscillation couples weakly to the control mass, there is sufficient signal to noise ratio to damp the test mass into a range where the optical lever becomes operable, then a much better level of control can be achieved ($\sim 10$ $\mu$rad). Low frequency resonances caused by the torsion of the suspension wires dominate the residual angular motion with either control method. The optical lever achieves better performance due to higher angular sensitivity and decoupling from translation motion ($X, Y, Z$).

If the optical lever goes out of range, either due to a large offset or a large amplitude in the suspension normal mode, the control system will damp the Pitch and Yaw modes with a strong velocity feedback gain. Integral and proportional feedback are used in the loop for cavity alignment, it also includes band-pass filters to damp the suspension modes. In particular, the phase of the control signal at the suspension resonances must be reversed, since the control mass coupled oscillation is out of phase to the test mass oscillation. Once the optical lever is in range, the damping feedback automatically changes the source of its error signal to the optical lever signal (quadrant photodiode). This process is automated by the control system through a set of Boolean operations to determine the state of the system according to threshold values on the range of the optical lever and shadow sensors. The transition from one loop to the other is “smooth” in the sense that the dc force resulting from integral and proportional set points are passed on from one loop to the other.

Since the Pitch and Yaw damping feedback operate at the highest bandwidth of the control scheme, they are the most affected by the phase lag due to the 100 Hz sampling rate. At the Pitch resonance of 3.3 Hz, the minimum possible phase lag due to the 100 Hz operation of the ADC/DAC is approximately $12^o$, at the Yaw resonance of 1.75 Hz it is $6^o$.

Figure 12 shows a comparison between the frequency...

![Control mass Pitch frequency response](image)

![Control Mass Yaw frequency response](image)
responses of the Pitch and Yaw modes with the optical lever control loop off (dotted line) and optical lever control loop on (continuous line). Optical lever control loop off means that only the shadow sensor readout and its corresponding control loop are being used for controlling the test mass position. The optical lever control loop on means that the shadow sensors control loop is turned off, but the level of the control signal at the time of switching the loop is used as an offset for the optical lever control loop. Figure 12 shows a Pitch mode reduction of 20 dB at 3.3 Hz when using the optical lever control loop. The reduction on the Yaw mode is more significant with about 40 dB at 1.75 Hz.

Figure 13 shows the Yaw angular motion of the test mass in time using either shadow sensors or optical lever feedback. The set point has been removed so as to center the curves on zero removing the offset introduce by the control loop set point. The total Yaw displacement is dominated by the torsional mode of the suspension wires, causing very low frequency Yaw oscillations at ∼20 mHz.

C. Optimized feedback for preisolation

A feedback scheme was devised based on the superspring concept, which takes advantage of the dual stage of horizontal preisolation in our design. This is an active control method consisting of feeding back the position of the loaded end of a mass-spring system to the spring suspension and keeping their relative distance constant in order to synthesize a very-low frequency system. The concept can be equally applied to pendulum systems. Shadow sensors mounted between the inverse pendulum frame and the Roberts linkage, as shown in Sec. II C, could be used for such a purpose. These sensors provide a signal \( z(x_2 - x_1) \) as illustrated in Fig. 14. Feedback to the inverse pendulum actuators would permit to lower the effective inverse pendulum resonance. In addition, velocity feedback \( \alpha \partial / \partial t (x_2 - x_1) \) would also allow effective damping of the Roberts linkage resonant mode and simplify stability considerations compared to feedback of the inverse pendulum position. Modeling of this control method shows that the low frequency isolation below a few hertz can be improved by an order of magnitude compared to that described in Sec. III A. A comparison of the theoretical performance with the initial setup is shown in Sec. IV.

IV. INITIAL CAVITY MEASUREMENTS

Preliminary performance results of the cavity displacement noise have been obtained from initial trials of cavity locking. The locking scheme employed in these runs was, as described in Sec. III, with simple damping feedback at the inverse pendulum stage and did not yet implement the superspring feedback concept in the preisolation stage. A standard Pound–Drever–Hall feedback system was implemented to keep the laser locked to the 72 m cavity. The companion paper1 describes the optical scheme and laser feedback in more details.

The integrated residual motion per test mass can be calculated from the control signal and it is shown in Fig. 15.
Here we see that above 1 Hz, the residual motion is ~3 nm per test mass. The measured curves compare closely with the predicted performance for the simple feedback at the inverse pendulum. Note that the theoretical performance without any control is an order of magnitude lower at the same frequency, however, the large resonance of the preisolation stage at ~70 mHz is too large to practically lock the optical cavity.

The inverse pendulum feedback loop permits to damp the normal mode, at the sacrifice of high frequency noise injection. This simple feedback is also ineffective in damping the second resonant mode of the two body system formed by the inverse pendulum and Roberts linkage. An optimized feedback system was devised using the superspring concept as discussed in Sec. III C, which could achieve an acceptable residual motion at low frequencies without compromising the isolation performance. This scheme, which requires additional sensors on the Roberts linkage stage, has been tested on a single isolator and will be implemented and tested in the cavity in the near future.

V. CONCLUSIONS

A local control system was implemented in a novel isolation and suspension design for laser interferometer gravitational wave detectors. The system provides feedback for position control, cavity alignment, and damping of normal modes. Three DoFs are controlled by Ohmic thermal tuning of the length of pendulum wires in the Roberts linkage and by thermal spring constant of the LaCoste linkage. Large dynamic range shadow sensors and actuators allow more than 20 cm mm three dimensional position control of the test mass. Two suspensions systems and their associated control systems were installed to form a 72 m optical cavity. Without using direct test mass control, it was possible to lock the cavity and maintain lock, with a residual motion of 3 nm per test mass above 1 Hz. Low frequency residual motion at microseismic frequencies is expected to improve by over an order of magnitude once the second horizontal preisolation stage is used for angular control. The feedback of the test mass is aided by an optical lever, with an automatic transition between local sensors and the optical lever. Additionally both sensing and direct actuation of the test mass will be possible by a capacitive plate mounted on the control cage. The cavity demonstrates long term stability, indicating that there are no unexpected noise sources or drifts in the system.

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