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Seismic isolation enhancements for initial and Advanced LIGO

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Abstract

A seismic isolation system for the proposed 'Advanced LIGO' detector upgrade is under development. It consists of a two-stage in-vacuum active isolation platform that is supported by an external hydraulic actuation stage. A full-scale preliminary-design technology demonstrator of the in-vacuum platform has been assembled and is being tested at Stanford's engineering test facility. Unanticipated excess ground motion from local human activity at LIGO Livingston has prompted accelerated development of the external stage for installation and use in the initial Livingston detector. As an interim measure, active external isolation in the laser beam direction is implemented using existing PZT external actuators.

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1. Introduction

As reported elsewhere in this issue, the first scientifically interesting data from the initial LIGO gravitational wave (GW) detectors have been taken and analysed. At the same time, an 'Advanced LIGO' upgrade to the detectors has been proposed [1], leading to an installation

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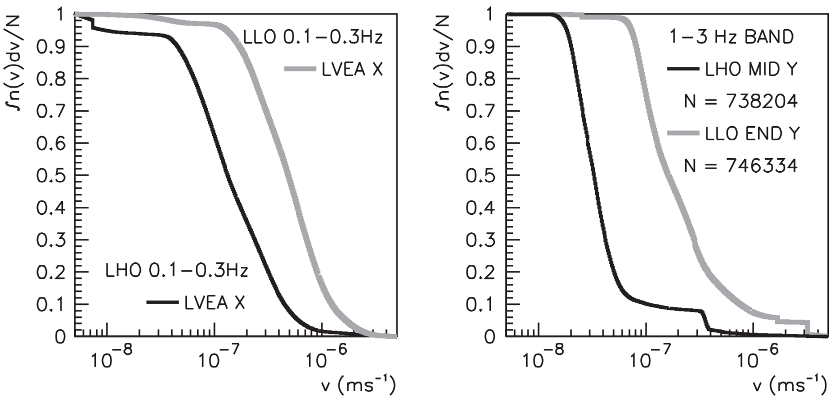

Figure 1. Cumulative histograms of the band-limited technical slab root-mean-squared velocity at LIGO sites, for the frequency bands 0.1–0.3 Hz (left) and 1–3 Hz (right), each shown for LIGO Hanford (black) and LIGO Livingston (grey). The ordinate represents the fraction of minute-long segments in which the ground motion was less than the abscissa.

in approximately 5 years, with the goal of decreasing the detector noise minimum by about a factor of 10, and moving the low-frequency edge of the detector band to ≈10 Hz.

Among the technical challenges facing both detector generations is the reduction of ground-motion-induced vibration that can prevent interferometer length control and can add noise in the GW band. The ground moves with root-mean-squared (rms) displacements of order 1 μm, but LIGO's 4 km arms must be held to an rms length error of 10^{-13} m for initial LIGO, or 10^{-14} m for the advanced detector. Much of the spectral contribution to the rms comes at low frequencies around the microseismic peak [2] in the 0.1–0.5 Hz band, which is due to surface waves on the solid Earth that are excited by ocean water waves. Another troublesome source of noise is human activity, which contributes largely between 1 and 10 Hz. Figure 1 shows cumulative histograms for rms ground velocity, band-limited to 0.1–0.3 Hz, which emphasizes the microseismic peak, and 1–3 Hz, which captures most of the human activity. It is easily seen that the LIGO Livingston site suffers in both bands.

These and other vibration sources below the GW detector band, which begins at about 40 Hz (initial) or 10 Hz (advanced), can directly prevent the interferometer length control systems from holding the positions of the optics accurately enough. As a result, the interferometer's detector noise in the GW band may also increase.

The seismic isolation system used in initial LIGO test mass chambers is a stack of passive mass-spring layers [3] inside the vacuum, which has resonances in the 1–3 Hz band that can amplify the ambient noise, causing some difficulty at the Livingston site. The stack is supported by an external fine actuation system that can translate ±90 μm in the laser beam direction, and, as will be described below, can be used to reduce the effects of the low-frequency ground noise on the detector using active techniques.

The general design strategy for Advanced LIGO seismic isolation was introduced in [4]. The proposed seismic isolation upgrade would replace the stack with a two-stage active isolation platform, and replace the external beam-direction actuation stage with a six-degrees-of-freedom hydraulic actuation stage. The Advanced LIGO design [5, 6] requires that these two systems together reduce noise at the microseismic peak by about a factor of 10, and reduce noise in the 1–10 Hz band by about a factor of 1000.

Active seismic isolation is a set of vibration-reduction techniques that use measurements of ground and payload motion to determine forces that act on the payload, reducing its

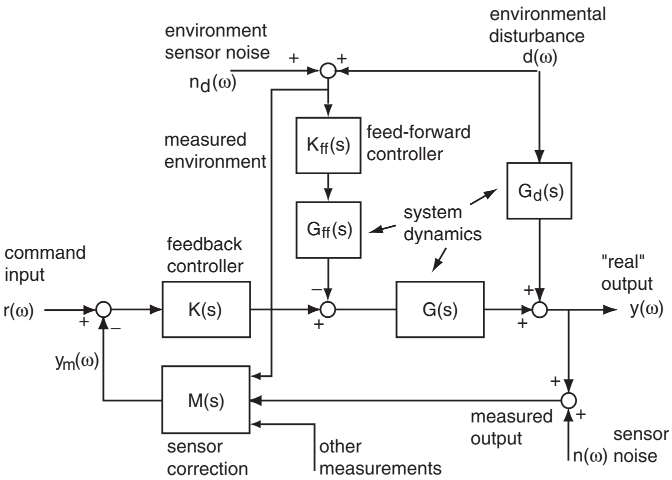

Figure 2. Active noise-reduction block diagram. The output, y, represents the real motion that is to be reduced. A feedback loop reduces a measured y by multiplying it by the controller function K and acting through the system dynamics G. The feedback loop can be made more effective by correcting, for example, the displacement measurements for ground motion using M. Finally, the disturbance d that couples to the system through G_d can be cancelled outside of the loop through the feedforward path $K_{ff}G_{ff}$.

undesired motion. Figure 2 outlines some possible signal paths. These include force *feedback* to the payload based on payload-mounted inertial sensors and *feedforward* to the payload based on sensors at the disturbance source, which is often the floor. Also, sensors that measure the payload displacement with respect to the ground can be corrected for the motion of the grounded side, and used in local feedback loops in a technique called *sensor correction*.

2. Active platform development

Development of the various aspects of Advanced LIGO seismic isolation continues, including the in-vacuum two-stage active isolation platform that supports an optics table surface on which test mass suspensions are to be mounted. Each platform stage contains relative position sensors and seismometers, which measure motion in six degrees of freedom (DOFs); signals from these are filtered and applied as feedback to non-contacting voicecoil/magnet force actuators, quieting the stage. Each stage is suspended from above through vertical rod flexures that are attached to the ends of triangular blade springs, which provide horizontal and vertical compliance, respectively. A full-sized technology demonstrator platform has been constructed and installed in Stanford's Engineering Test Facility (see figure 3). Previous laboratory experience with active platforms suggests that two figures of merit are most important to the seismic isolation performance after all the servo loops are designed and closed. One of these is the internal resonant frequencies in the stage structures, which in this case is approximately 200 Hz, which exceeds the 150 Hz that we require.

The other figure of merit, shown in figure 4, is the degree to which a suspended platform stage tilts when horizontally actuated. Consider a horizontal seismometer as a mass-spring oscillator with a natural frequency ω_0. The instrument's readout is sensitive to the relative displacement, Δx, between its inner test mass and the stage on which it rests. At frequencies well below ω_0, the instrument magnitude response to horizontal stage motion, x_0, at

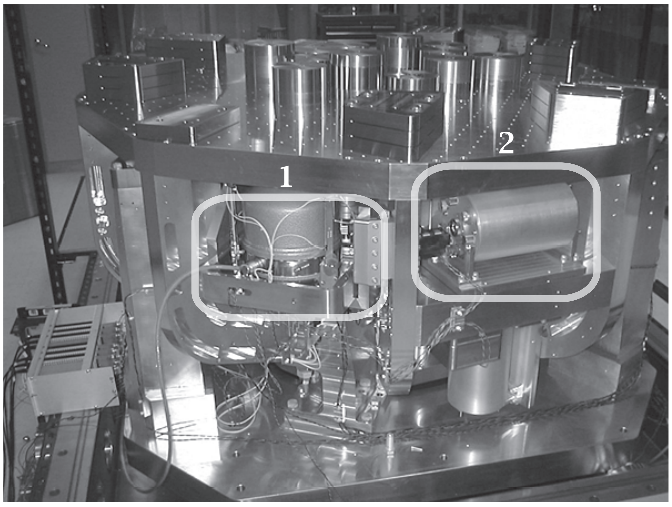

Figure 3. Photo of the Advanced LIGO seismic isolation technology demonstrator two-stage active platform, installed in a vacuum chamber. The two stages are structurally interleaved to correctly position the centres of gravity. Each corner of the outer stage (stage 1) is sensed by a 3-axis STS-2 broadband seismometer, two L-4C geophones and two displacement sensors, and is actuated by a vertical and tangential voice-coil/magnet actuator. Inner-stage (stage 2) corners contain a pair of GS-13 geophones instead of the STS-2 and L-4C. The overall width is approximately 1.5 m.

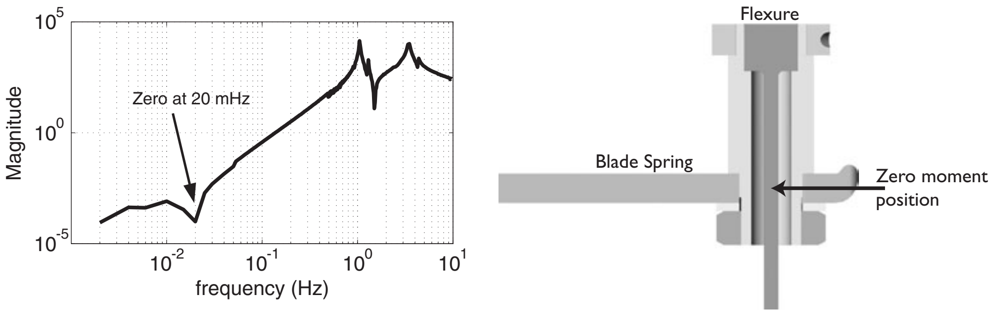

Figure 4. Left: measured stage-mounted seismometer response to horizontal actuation in the active isolation technology demonstrator. The tilt resulting from horizontal force actuation of a stage dominates the pure horizontal motion in sensed by a horizontal seismometer below 20 mHz. Right: each stage is supported from above through three vertical metal flexure rods from the ends of blade springs.

frequency ω, is $|\Delta x/x_0| \simeq \omega^2 \big/ \omega_0^2$. If horizontal motion also causes the stage to *tilt* slightly as though it were pivoting from a distance, R, away, then gravity pulls the seismometer mass against its restoring force, and the instrument responds with an additional term: $|\Delta x/x_0| \simeq g \big/ R\omega_0^2$. These two terms are equal and can cause a zero in the overall response when $\omega \simeq (g/R)^{1/2}$. In the outer stage of our platform, we see a crossover zero at $\omega = 20\,\mathrm{mHz}$, which implies $R \simeq 620$ m, considerably longer than that we have seen before, and more than adequate for use with 6-DOF active isolation servos. The key design detail leading to this performance is the shape of the rod flexure and its location with respect to the supporting blade above it and the stage's horizontal actuators below it. For example, the drawing in figure 4 shows the vertical zero moment position along the flexure. When the flexure assembly is held

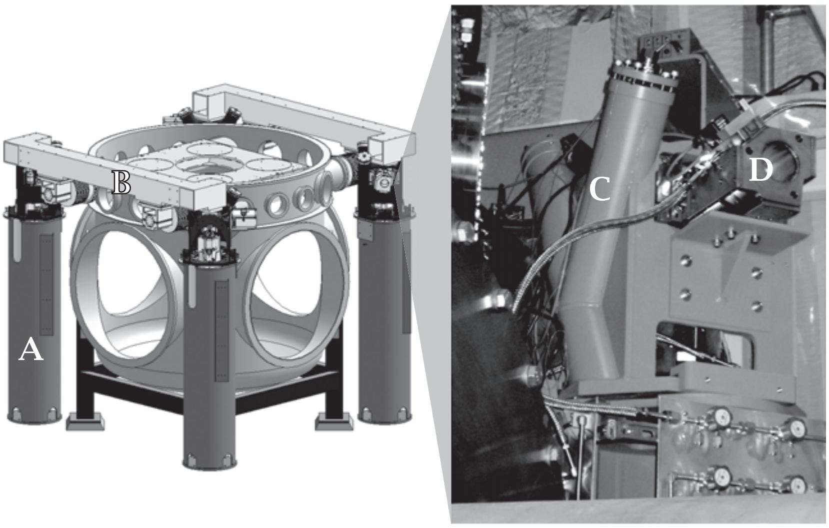

Figure 5. External pre-isolation stage using hydraulic bridge actuators. At each corner, a steel pier (A) supports a housing (C) from which large crossbeams (B) are suspended using two coil springs in a 'V' configuration. The internal seismic isolation system is held through support tubes that are clamped to the cross beams. Hydraulic bridge actuators push the supported payload vertically and horizontally (D) at each corner.

there (through the cylindrical assembly shown), a horizontal displacement of the suspended stage exerts no net torque on the blade spring, so that the blade does not flex and tilt the stage.

3. External pre-isolation development

The Advanced LIGO external stage provides ± 1 mm of actuation in the three displacement DOFs and ± 0.5 mrad in the angular DOFs by use of laminar-flow, low-pressure hydraulic fluid to compress and expand steel bellows. The large weight of the external stage and all the in-vacuum payload is supported by stiff steel springs. Actuation of this outermost stage can be used to track the Earth's tides, as well as to correct at each vacuum tank for large amplitude low-frequency (0.1 Hz to several hertzs) motion as measured by nearby seismometers, using sensor correction of actuator-mounted displacement sensors to which the stage's position is servo-controlled.

Over the past year, we have accelerated development of this stage, for installation at LIGO Livingston in Spring 2004, in order to allow reliable detector operation during high-noise periods, such as the daylight hours of weekdays. A prototype, shown in figure 5, is operating in a LIGO-design vacuum tank supporting a stack payload at MIT. The eight actuators are used to control the stage's 6 DOFs, using feedback from displacement sensors and geophones located next to the actuators. Then, a floor-mounted Streckeisen STS-2's signals are used to sensor-correct the position sensor signals in the three displacement DOFs, reducing the platform's motion between several tenths of a hertz and several hertz. Data from this experiment are shown in figure 6. Noise reduction of about an order of magnitude is seen in the critical 1–3 Hz band.

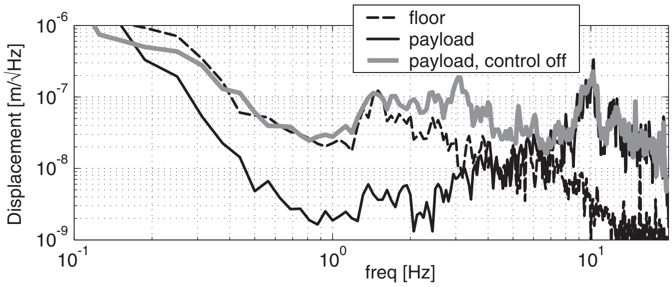

Figure 6. Prototype performance of the hydraulic external pre-isolation (HEPI) stage. The thin black and thick grey lines are the horizontal (beam direction) motion at the payload, with and without the noise-reduction system. About a factor of 10 noise reduction is seen over the critical frequencies 0.5–2 Hz. The dashed line is the motion of the floor near the system.

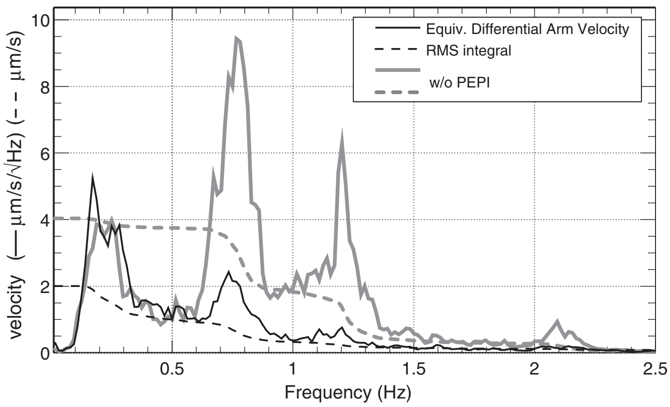

Figure 7. Piezoelectric pre-isolation (PEPI) noise reduction. Shown is this system's effect on the feedback signal used to control the differential length of LIGO's 4 km arms, calibrated as an equivalent mirror velocity, together with its right-to-left rms integration. The large peaks in the grey trace at the suspension and stack resonances are significantly reduced.

4. Interim external active isolation

Because several scientific data-taking runs have been held or are planned before the external pre-isolation stage can be installed at Livingston, the existing PZT actuators have been employed in an external single-direction active isolation system in the four test-mass chambers. Two Teledyne Geotech GS-13 seismometers are placed on the crossbeams of each tank. Then each GS-13 is used as the sensor in a servo control with the pair of actuators on its side of the tank, with unity-gain frequencies of approximately 0.5 and 5 Hz. The control laws contain resonant gain at the lowest two passive stack resonant frequencies, and the lowest test mass suspension frequency, in order to preferentially reduce excitation to these modes. Figure 7 shows the performance of this system, as used in LIGO's 'S2' run. Here, the important figure of merit is how the system reduces the relative test-mass velocity, since high velocities make it more difficult to obtain interferometer lock. This system, called piezoelectric pre-isolation (PEPI), although not as effective as we expect the hydraulic 6-DOF retrofit to be, can significantly reduce the payload velocity in its critical band.

5. Status and plans

Based on the external pre-isolation prototype performance at 1–3 Hz as shown in figure 6, we anticipate that the upcoming seismic retrofit will allow LIGO Livingston to operate round the clock, as the Hanford detectors can. Progress has also been made in reducing the effects of the sub-hertz microseism by using STS-2 signals from LIGO's three buildings to derive a feed-forward signal that is applied in the end stations [7]. Together, these improvements should largely eliminate Livingston's environmental disadvantage that is shown in figure 1.

The remaining Advanced LIGO seismic isolation component, the two-stage in-vacuum platform, which had been in less active development due to the group's effort on the retrofit, is now being tested, and we expect performance measurements during the coming year.

Acknowledgments

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