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Seismic isolation for Advanced LIGO

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Abstract

The baseline design concept for a seismic isolation component of the proposed 'Advanced LIGO' detector upgrade has been developed with proof-of-principle experiments and computer models. It consists of a two-stage in-vacuum active isolation platform that is supported by an external hydraulic actuation stage. Construction is underway for prototype testing of a full-scale preliminary design.

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1. Introduction

The laser interferometer gravitational-wave observatory (LIGO) first-generation detectors (LIGO-1) are being commissioned and tested at the time of this writing. Members of the LIGO Scientific Collaboration and LIGO Laboratory have also been carrying out R&D towards a to-be-proposed Advanced LIGO detector upgrade, with a goal of installation in about five years.

With the notable exception of the vacuum envelope, nearly every aspect of the detector is planned to be improved or replaced, in order to reduce the strain-equivalent noise floor by about a factor of 10 over much of the detection frequency band, as well as to extend the detection band down to 10 Hz. This should have the effect of extending the detector's range

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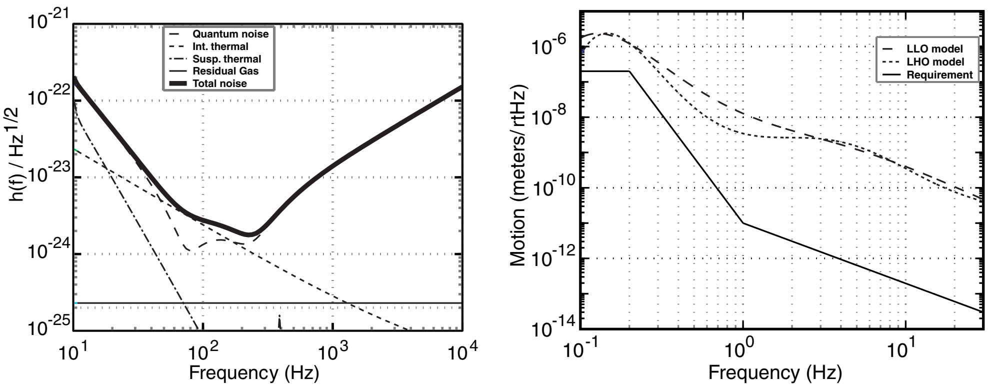

Figure 1. Current estimates of the contributions of various detector noise sources to the Advanced LIGO strain (h) sensitivity level (left), and the resulting requirement on displacement noise (right) where the seismic isolation system supports the test mass suspension, together with approximate displacement noise spectral densities at the two LIGO sites.

for binary neutron star inspiral sources by a factor of 10 and multiplying the detection rate by 1000. Figure 1 (left) shows the advanced LIGO team's preliminary strain noise estimates of the detector noise levels [1].

The general mechanical structure of advanced LIGO is planned to be similar to that of LIGO-1; a seismic isolation system supports and isolates an in-vacuum optics table on which test mass suspensions and other components are attached [2]. The solid trace in the right plot of figure 1 is the amplitude spectral density (ASD) of the part of Advanced LIGO's noise budget allocated to vibrational noise on the optical table. This includes transmitted ground vibration as well as internally generated noise. In comparing this requirement with the other two traces, which are the typical LIGO ground noise ASDs, one can see that the seismic isolation system has to reduce noise at the ≈0.15 Hz microseismic peak by about a factor of 10, and must reduce noise in the 1–10 Hz band by about a factor of 1000. The remainder of this paper describes how this may be achieved.

2. System description

Isolation from seismic noise is provided by an external actuation stage, a two-stage active isolation platform (supporting the optics table) and by the test mass suspension itself (see figure 2).

2.1. Structure and performance

The external stage provides ±1 mm of actuation in the three displacement degrees of freedom (DOFs) and ±0.5 mrad in the angular DOFs by the use of laminar-flow, low-pressure hydraulic fluid to compress and expand steel bellows. The large weight of the external stage and all of the in-vacuum payload is supported by stiff steel springs. We expect that 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 hertz) motion as measured by nearby seismometers. The expected motion levels on this stage are indicated in figure 2; the microseismic peak ASD should be below 2×10^{-7} m Hz$^{-1/2}$ there.

Inside the vacuum tanks, the next element in the design is a two-stage active isolation platform that supports the optics table. Each stage contains relative position sensors and

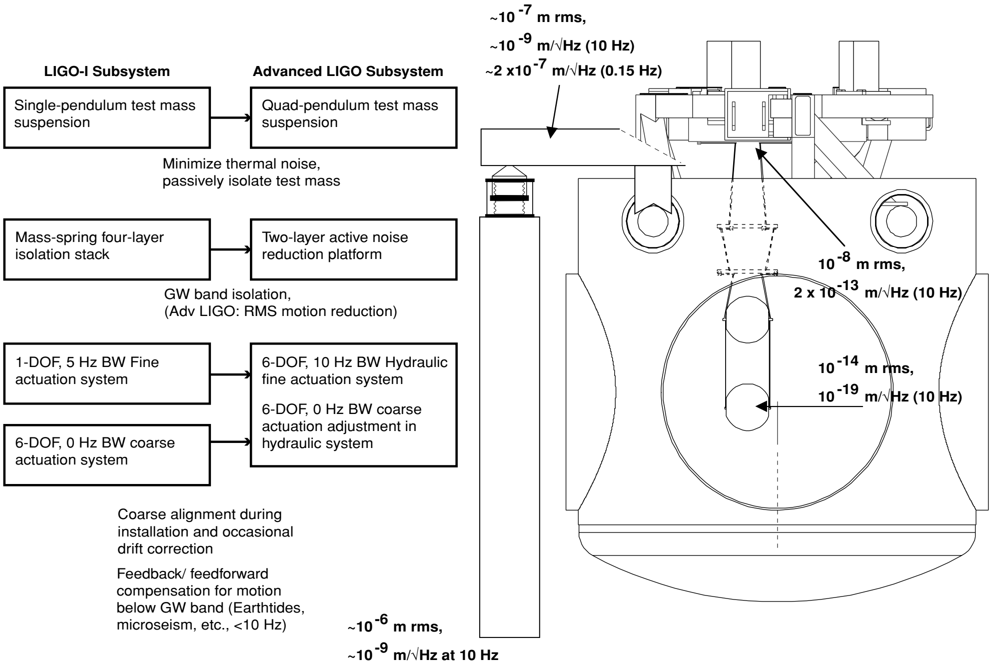

Figure 2. Overview of mechanical support and isolation of Advanced LIGO optics.

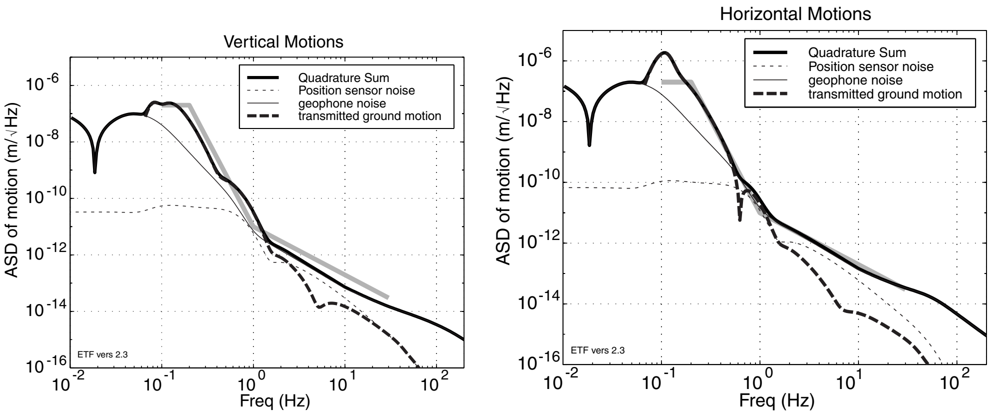

Figure 3. Modelled optics table motion due to transmitted ground motion (thick dashed), displacement sensor noise (thin dashed), seismometer noise (thin solid) and total (thick solid) noise of the two-stage active isolation platform. Also shown is a grey line indicating our goal.

seismometers, which measure motion in six DOFs; signals from these are filtered and applied to non-contacting voicecoil/magnet force actuators, quieting the stage [3, 4]. The active isolation platform has been modelled in detail using a `matlab` state-space representation, including all free-body DOFs [5]. The main contributions to its expected displacement noise are plotted in figure 3.

In the horizontal control loops, there is a low-frequency cross-over between a sensor that measures the relative displacement between the moving platform and its support structure and

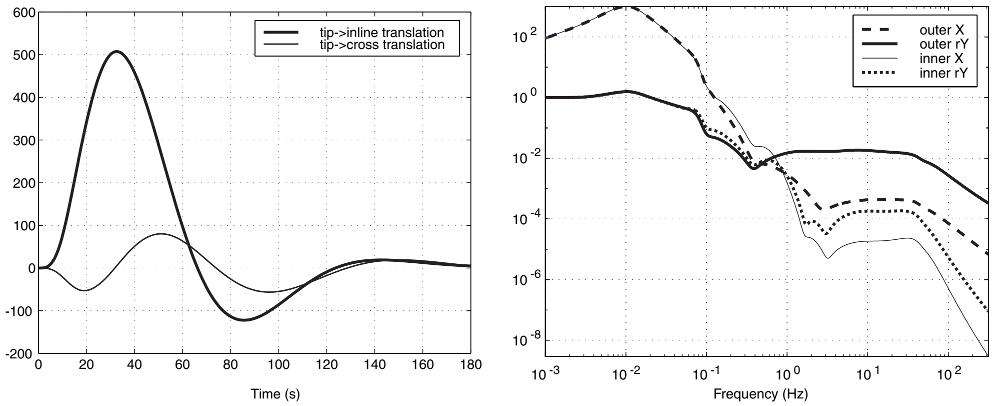

Figure 4. Response of the two-stage active isolation platform to a unit step function of rotation about the horizontal axis transverse to x (left), and the system transfer functions from this rotation (right).

a long-period seismometer. Also, horizontal seismometers measure both tilt and horizontal motion, so if the floor is suddenly tilted, the horizontal servos attempt to make a horizontal correction, which results in a peak excursion of approximately 20 μm for a 0.04 μrad floor tilt step function before the slow correction from the displacement sensor can prevail. In a complete interferometer with global length control, the beam-direction horizontal excursion would be servoed to near zero. This magnitude of tilt is approximately what would result on LIGO's slab if five curious scientists walked right up to a floor-mounted sensor, and is orders of magnitude larger than most environmental tilt motion. Since vertical seismometers do not have a first-order response to tilt, this effect does not occur in the vertical loops. This system performance (see figure 4) is probably acceptable for advanced LIGO, if we are careful to control human-generated tilt noise on the experimental slab.

3. Research and development

3.1. Proof-of-principle experiments

A series of experimental tests have been carried out to verify the basic techniques we require for this system to perform as needed. These include a two-stage active platform, which has been tested at MIT and Stanford, and has reached its major goal of robust operation with 12 DOFs under control. The Stanford group built a test stand and two full-scale hydraulic actuators, and has demonstrated adequate noise performance and actuation bandwidth [6].

Two other tests are described here in somewhat more detail. There are two key techniques to decrease the transmission of environmental vibration to the optics table, feed-forward correction based on measured environmental motion, and feedback servo loops that try to null motion measured on the payload. Feed-forward can be effective when (as an example) one can find a filtered combination of ground or floor-mounted seismometer signals that has a high coherence with the motion that the interferometer measures. The broad grey trace in figure 5 is about 2 min of data from a test run at the LIGO Livingston Observatory (LLO), of a channel that for the low-frequency signals seen here represents the measured difference between the lengths of LLO's two 4 km arms. The black trace is the output of a filter that takes as input four seismometer signals, representing motion along the axes x and y from the

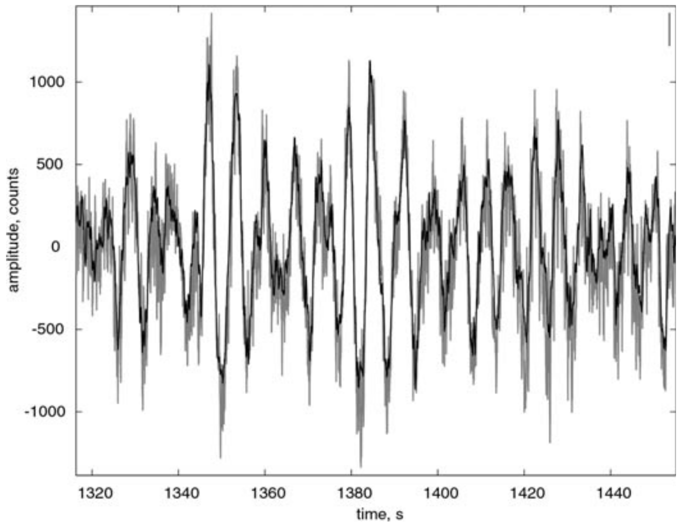

Figure 5. Prediction of the differential arm length in 4 km Fabry–Perot Michelson interferometer at the LIGO Livingston Observatory. The grey measurement trace is closely predicted by the black output of a filter that takes four seismometer channels as input. The vertical scale is in ADC counts; 1000 counts is approximately 1 μm.

LLO corner station, x from the x-end station and y from the y-end station. By applying this signal to actuators in the end stations we expect to reduce the microseismic peak height by a factor of 10. In Advanced LIGO, this technique can be further refined by actuating in all six DOFs and deriving local predictor signals for each seismic isolation platform, allowing this sort of feed-forward at higher frequencies for which the payload cross-couples motion between different DOFs.

Data from a demonstration that feedback and feed-forward can coexist are shown in figure 6. This graph shows the transmission of ground motion through a single-stage active isolation platform at Stanford under three control arrangements: no control, just feedback and feedback with 'sensor correction'. Sensor correction is a close cousin to feed-forward; a ground-mounted seismometer is used to predict and correct for the ground motion's coupling to the sensors that measure platform position relative to the ground-mounted support frame. This technique has an effect similar to out-of-the-loop feed-forward, and noise-reduction occurs well below the effective frequency band of the small feedback seismometers used here. Note that this experiment was conducted in air, not vacuum, so the transmission and noise seen at tens of hertz are due to acoustic coupling.

3.2. Prototype plans

Most of the authors are presently engaged in preparations for a full scale in-vacuum test of a two-stage active isolation platform at Stanford's Engineering Test Facility (ETF). This unit should allow tests of both the goal isolation performance, the noise floor, and the practical operation and control issues. We are using the same low-noise sensors, and very similar control laws to what would be used in Advanced LIGO. Figure 7 shows the mechanical design that is currently in the hands of the machine shops. The broad round-top cylinders are Streckeisen STS-2 seismometers, which measure motion from 8 mHz to 20 Hz. The longer cylinders are Geotech GS-13 geophones, used at higher frequencies. There are also small capacitive bridge

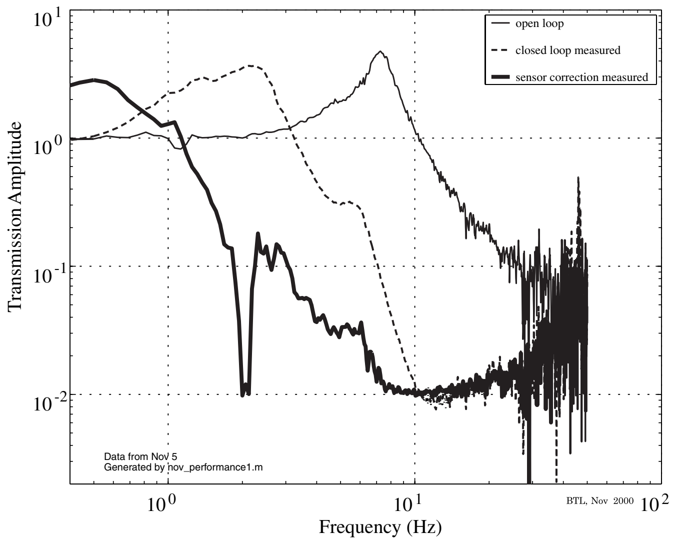

Figure 6. Measured transmission amplitudes from Stanford's single-stage active isolation platform. The upper thin solid trace is the uncontrolled transfer function through its natural resonance. Below, the dashed trace shows the noise reduction with feedback from seismometer signals. The thick lowest trace is the performance with both feedback and sensor correction.

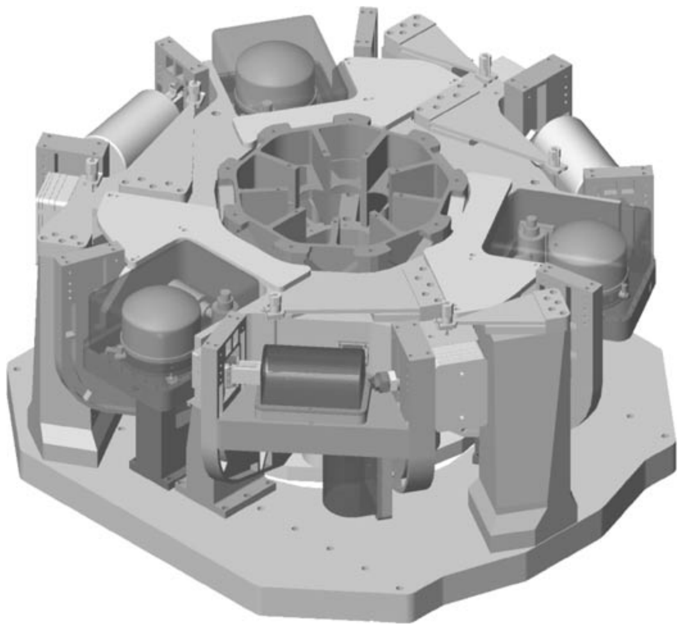

Figure 7. A computer rendering of a full-sized two-stage active isolation platform currently under production for in-vacuum testing at Stanford's Engineering Test Facility. Not shown is an optical table plate that bridges across the top. The overall width is approximately 1.5 m and a 600 kg payload can be supported.

sensors to measure the relative displacement of the two stages and ground. Noise performance should be similar to that in figure 3, except that on campus the ground noise is higher than at the LIGO sites. We are also preparing for a full-scale test of the hydraulic external stage in LIGO vacuum tanks at MIT.

Acknowledgments

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