LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

LIGO-T030131-00-D *Advanced LIGO* 9 July 2003

Summary of Preliminary Dynamic Measurements Conducted on the Advanced LIGO Seismic Isolation System, Technology Demonstrator

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Distribution of this document:
LIGO Science Collaboration

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1 Introduction

A two stage active isolation system similar in size, shape, capacity and performance as that required for advanced LIGO in the HAM vacuum chamber, has been installed into the Engineering Test Facility (ETF) at Stanford University. This unit has been dubbed the "technology demonstrator" (Tech Demo) and is intended to serve as a dynamics and controls test bed for the advanced LIGO active isolation system development.

Two aspects of the Tech Demo unit have been tested to date; the stage modal frequencies and the tilt response of the stages in response to horizontal forces. These tests were carried out first because the experience of the team suggests that the ultimate system performance is most commonly limited by low-frequency resonances and tilt-horizontal cross coupling. The intent of this report is to convey the initial preliminary results from the dynamics testing of the Tech Demo unit.

Note that in the text below, the following terms are used interchangeably: "nearby", "collocated" and "common corner".

2 Requirements for the ETF Tech Demo unit

The requirements[1] for the tech demo unit were

1) Rigid Body Frequencies: The 12 coupled frequencies should lie between 1 and 10 Hz. Within this range, lower spring stiffness is preferred. The flexures shall be designed such that the upper zero moment point of each flexure shall lie on the neutral axis of its spring.
2) Actuation Alignment & Position: For each stage, the plane defined by the actuation centers of the 3 horizontal actuators shall be in the plane defined by the lower zero moment points (LZMPs) of the 3 flexures at that interface. Each horizontal actuator shall have its axis parallel to the plane defined by the LZMPs. Adjustability (+/- a few mm) shall be provided.
3) Sensing Alignment and Position: The tangential sensor axes shall coincide with the plane defined by the LZMPs of the flexures. The sensors for vertical displacement shall be perpendicular to the plane defined by the LZMPs of the flexures.
4) Center of Mass Position[2]: The center of mass (CM) of Stage 2 shall lie from 0-3.1” (0-8 cm) above the plane of the centers of the actuators at the stage 1-2 interface.
5) Stage Dynamics: The minimum elastic mode of each stage structure (with free boundary conditions) should be less than 150 Hz.

As indicated in the results sections, requirements (1) and (5) above have been met in the ETF Tech Demo system. The intent of requirements (2), (3) and (4) were to achieve a tilt-horizontal coupling frequency of no higher than ~30 mHz. This has been achieved, as indicated in the results sections below.

[1] G. Hammond, ETF Seismic Isolation System Requirements Document, LIGO-T010169-03, 23 May 2001

[2] B. Lantz, Location of the Center of Mass of the Inner Stage Relative to the Horizontal Actuator-Flexure Plane and the Table Top , LIGO-T030170-00, 1 June 2001

3 Requirements for the LASTI Prototype units

The requirements[3,4] for the advanced LIGO prototype units, to be installed in the LASTI facility at MIT, are summarized below:

1) Rigid Body Frequencies: The 12 coupled frequencies shall lie between 2 and 10 Hz. Within this range, lower spring stiffness is preferred. The flexures shall be designed such that the upper zero moment point of each flexure shall lie on the neutral axis of its spring[5].
2) Actuation Alignment & Position: For each stage, the plane defined by the actuation centers of the 3 horizontal actuators shall be within 0.040" (1 mm) of the plane defined by the lower zero moment points (LZMPs) of the 3 flexures at that interface. Each horizontal actuator shall have its axis parallel to the plane defined by the LZMPs to within 1 mrad.
3) Sensing Alignment and Position: The tangential sensor axes shall coincide with the plane defined by the LZMPs of the flexures to within 1 mm. The sensors for vertical displacement shall be perpendicular to the plane defined by the LZMPs of the flexures to better than 1 mrad.
4) Center of Mass Position: The center of mass (CM) of Stage 2 of the shall lie from 0-3.15" (0-8 cm) above (BSC), or below (HAM), the plane of the centers of the actuators at the stage 1-2 interface. The Stage 1 CM shall lie at +/- 1.6" (+/- 4 cm) vertically with regard to the Stage 2 CM.
5) Collocated Dynamics, all stages: For common-corner seismometer/actuator and displacement sensor/actuator pairs that share an axis direction on stages 1 and 2: the phase of the transfer function Xs/Xa shall be greater than -90 degrees for all frequencies below 500 Hz.
6) Non-Collocated Dynamics, Stages 1 & 2: For all other pairs of seismometer and actuator, and displacement sensor and actuator on stages 1 and 2: the phase of Xs/Xa shall be greater than -90 degrees for all frequencies below 150 Hz.
7) Non-Collocated, Stage 0: For all pairs of displacement sensor and actuator on stage 0: the phase of Xs/Xa shall be greater than -90 degrees for all frequencies below 100 Hz. If a mode that causes a phase excursion has only minimal amplitude in the | Xs/Xa | of all of the above pairs, and the phases return above -90 degrees above the resonance frequencies, and with Caltech's consensus, the modal frequency may not count against this requirement. (This sort of behavior may result from modes that primarily involve motion of the external structure.)

[3] Design Requirements for the In-Vacuum Mechanical Elements of the Advanced LIGO Seismic Isolation System for the BSC Chamber, LIGO-E030179-01

[4] Design Requirements for the In-Vacuum Mechanical Elements of the Advanced LIGO Seismic Isolation System for the HAM Chamber, LIGO-E030180-01

[5] The accuracy of this positional requirement is not yet stipulated in the requirements.

Although these requirements were not imposed on the tech demo unit, it is nonetheless of interest to know if they are satisfied by the tech demo design. As indicated in the results sections below:

- requirement (1) has been met,
- requirements (2), (3) and (4) have apparently been met, as measured indirectly by the tilt-horizontal coupling frequency,
- with regard to requirement (5):
  stage 1, horizontal: meets the requirement to 240 Hz, no test results yet > 240 Hz
  stage 1, vertical: meets the requirement to ~250 Hz (not 500 Hz)
  stage 2, horizontal meets the requirement to ~300 Hz
  stage 2, vertical: no test results yet
- measurements to address requirements (6) and (7) have not yet been reported.

4 Measurement of the transfer function zero associated with tilt-horizontal coupling:

When a suspended platform is driven with a force from one of its horizontal actuators, in general the platform both displaces horizontally and tilts. If the platform suspension is well designed, the tilt can be minimal. In the case, the crucial parameter is the position of the flexure zero moment positions with respect to the blade spring plane and the plane containing the horizontal actuator force vectors (see our requirements document for the details.) The velocity of the resulting horizontal stage motion is detected by a seismometer, and the resulting transfer function of velocity/force rises with one power of *f,* until the expected rigid-body resonant features of the double platform are encountered at about 1 Hz.

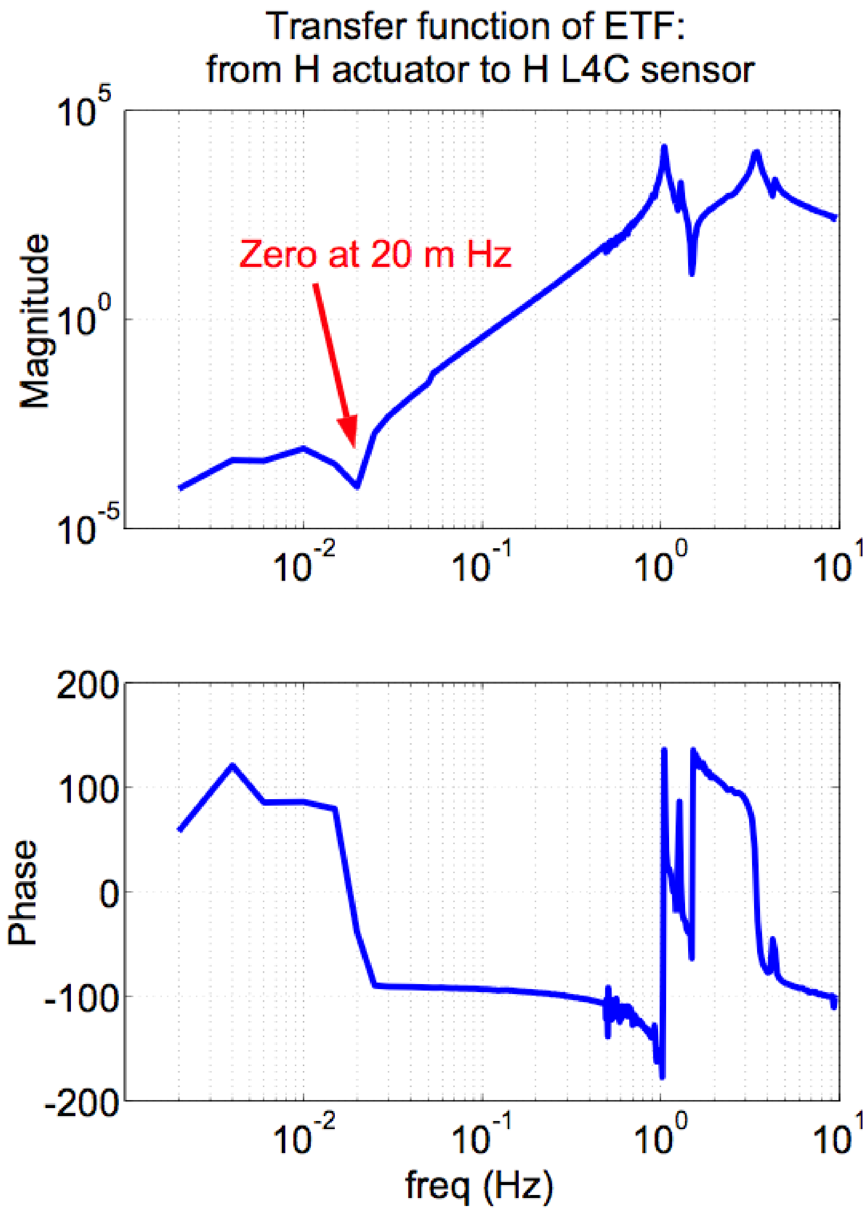

Figure 1. The transfer function from one horizontal actuator on the first stage to seismometer's horizontal output at the same corner.

Seismometers also directly sense tilt at all frequencies, and at extremely low frequencies where the stage velocity response is very low, this tilt dominates the transfer function. Our figure of merit for tilt-horizontal coupling is the frequency at which the tilt signal equals the translational velocity signal in the seismometers. Figure 1 shows this frequency to be approximately 20 mHz, which we expect will nicely meet our needs.

5 Stage modal frequency measurements:

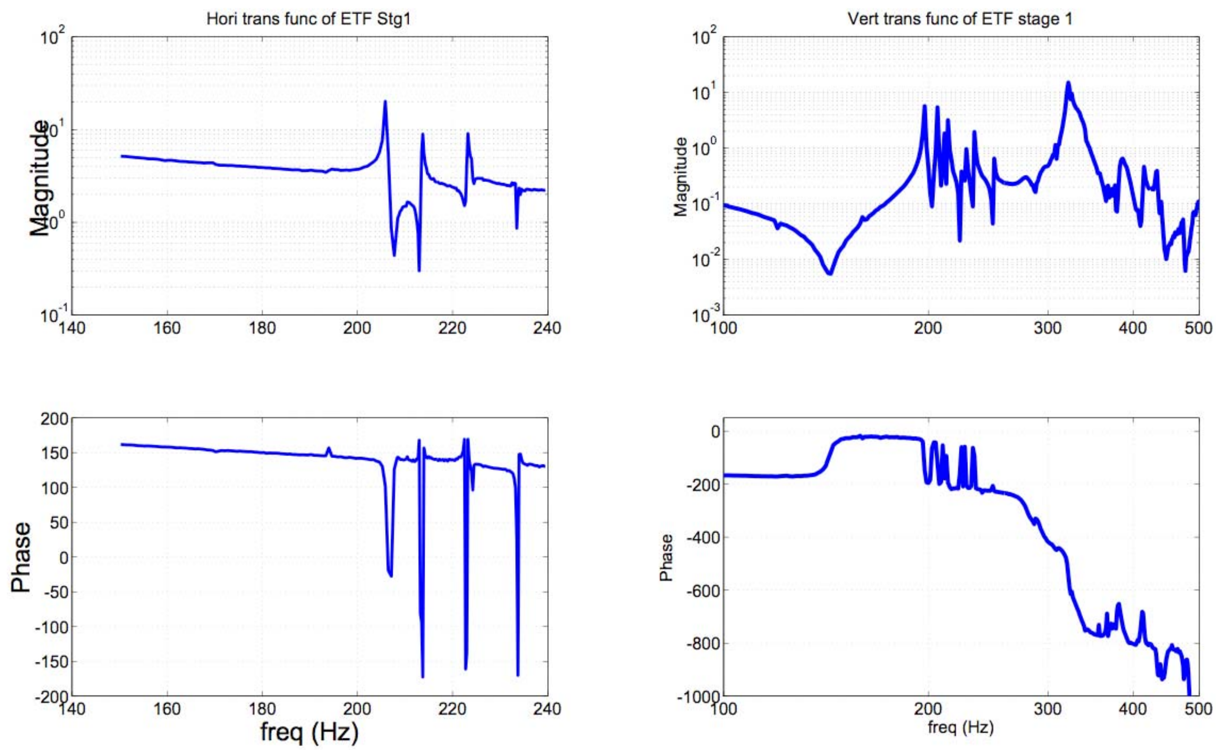

Figure 2. Transfer function between the horizontal (left) and vertical (right) stage 1 actuators and nearby geophone sensors.

At frequencies between the stage suspension resonances and the normal-mode frequencies of the rigid structures, the actuator force is essentially acting on a free rigid body, causing acceleration in both position and angle. Since we measure velocity, the response generally falls with f in this band. Figure 2 shows transfer functions measured between stage-1 actuators and nearby sensors. The stage modal frequencies can be seen to be at about 200 Hz and above, meeting our requirements.

Figure 3 shows similar plots for stage 2's horizontal response. Two types of geophone sensors were used. The slight differences between the sensors themselves, their locations, and the way that they were mounted causes slight differences in the TF's. This stage also had modal frequencies beginning at above 200 Hz. Once can discern this easily with either sensor's output.

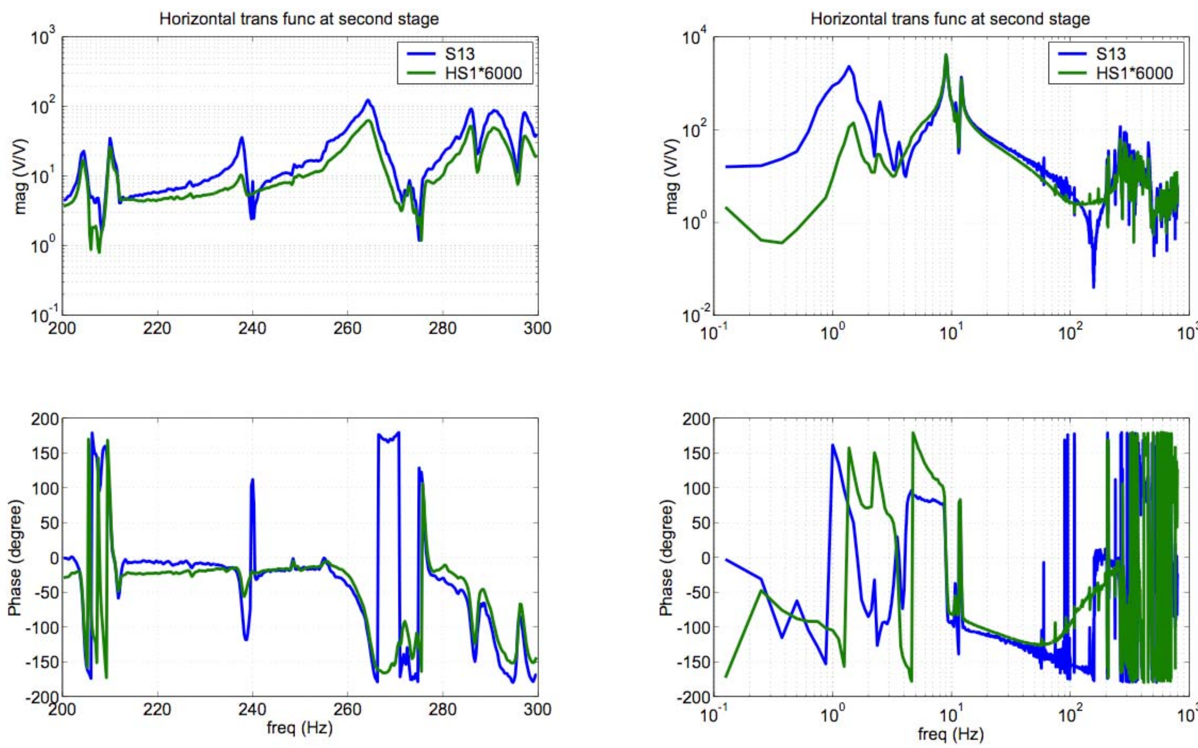

Figure 3. These plots show horizontal transfer functions between stage-2 actuators and two nearby geophone sensors, the HS1 and the S-13. The left and right graphs differ only in the range of frequencies shown.