



Piezo-Electric Actuator Initial Performance Tests

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Abstract

This report briefly describes the setup and results from a series of tests performed on a commercially available piezo-electric stack actuator. The tests address dynamic characterization (bandwidth, gain, etc...) as well as mechanical noise under constant commanded deflection of the actuator.

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LIGO  PROJECT

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1. Equipment tested

The piezoelectric actuator system that was subjected to the tests described below is commercially available from Polytec PI, Inc., 3152 Redhill Ave, Suite 110, Costa Mesa, CA. The hardware is manufactured in Germany by Physik Instrumente, a well-established company in the micro-positioning arena.

The system consists of a long stroke actuator stack with internal preload, instrumented with an internal strain gage bridge to measure actual stack expansion and eliminate hysteresis through closed loop control. The stack is driven by a high voltage amplifier and a closed loop controller mounted in a benchtop rack. All equipment are standard PI catalog items.

Actuator	P239.97 + P177.10	180 micron High voltage PZT + strain gage sensor
Controller	E509.S1	Closed loop controller for strain gage sensor
Amplifier	E507.00	High voltage amplifier (0-1000 V)
Rack	E501.00	9 ½ " rack with power supply
Extension Cables	P209.10 & P892.10	10 meter extension cables for high voltage & strain gage

Table 1: list of PI equipment tested.

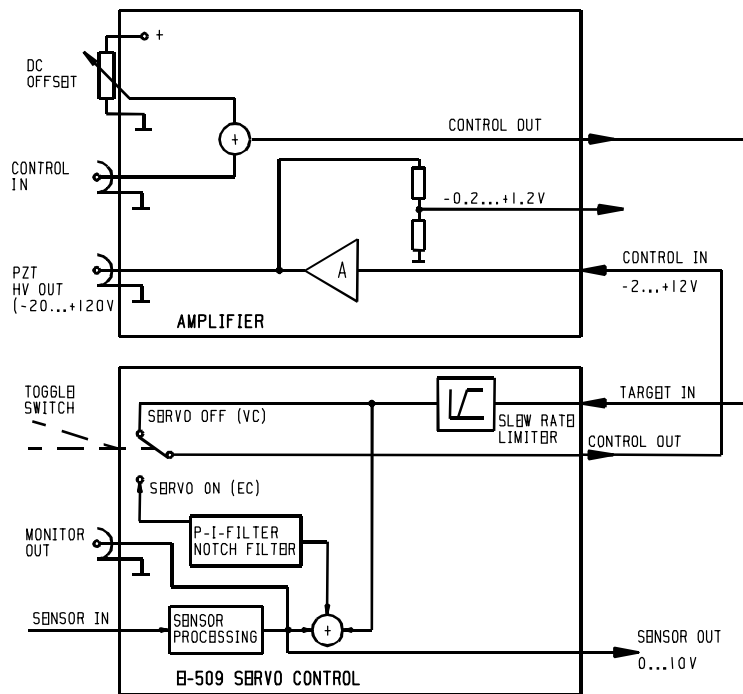


Figure 1: Overall schematics of PI controller and amplifier electronics^[1].

Figures 1 and 2 show schematics of the PI controller and amplifier setup. The command signal (0-10V analog) is supplied to the amplifier module through a BNC connection on the front panel. A multi-turn potentiometer provides an adjustable DC offset of that signal. The resulting control voltage is fed to the servo control module through the bus of the rack. That control module, comprises an adjustable slew rate

limiter, an analog closed loop control with PI compensation, and a notch filter. The control signal is sent back to the amplifier module through the Bus of the rack. A switch on the controller module allows enabling and disabling the closed loop control.

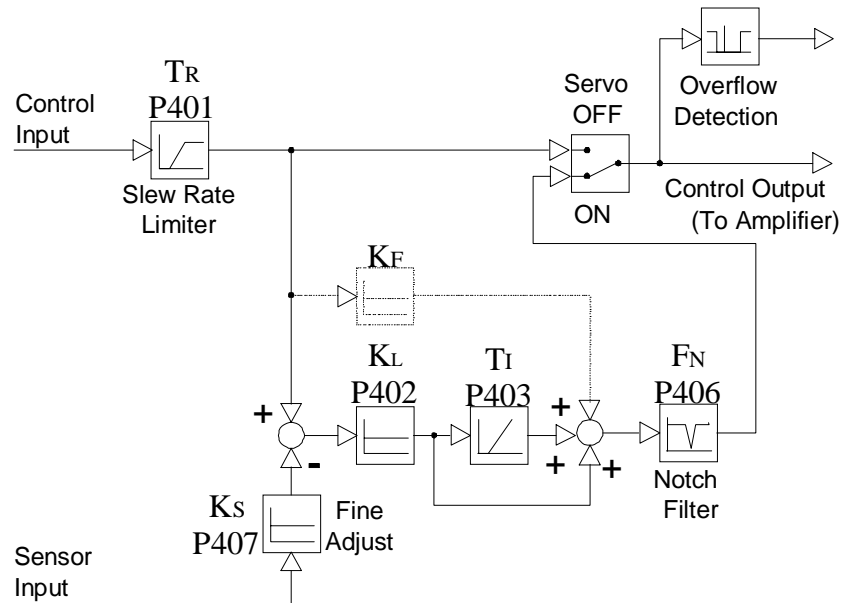


Figure 2: Schematics of PI linearizing controller^[1].

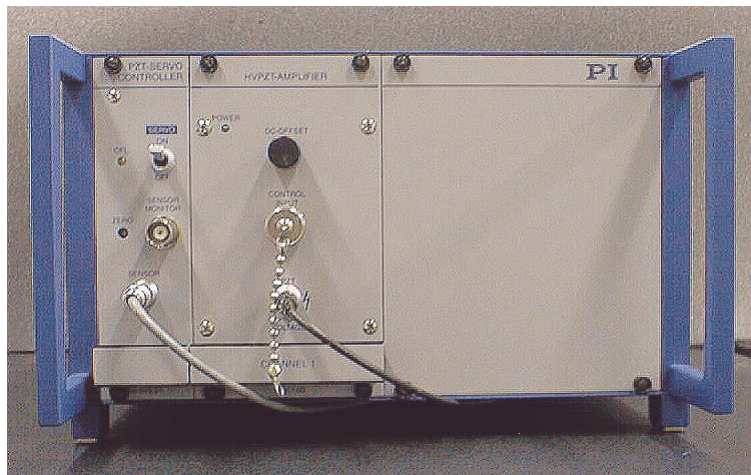


Figure 3: PI control rack.

A number of adjustments to the PI controller are available via multi-turn potentiometers. The adjustments relevant to response and noise are:

- slew rate (T_R)
- overall control loop gain (K_L)
- Integral (I) gain of compensator (K_I)
- notch filter frequency (F_N) (the notch filter is used to avoid control instability at a primary resonance of the driven system; it was adjusted at the factory based on *rough*

stiffness and mass information provided by Hytec). The Q of that filter is adjustable with an optional potentiometer (not installed on tested hardware).

- strain gage signal low pass filter (enabled or disabled via jumper); the cutoff frequency of that filter is factory set to 100Hz and is not adjustable. We requested and obtained instructions for component replacements to bring this cutoff point down to 15 Hz.

2. Preliminary Requirements

Approximate requirements for the LIGO fine actuation system were derived in Reference ^[2]. They are briefly summarized in Table 2 and Figure 4 below.

Range	> 150 microns
Bandwidth	0 to 5±1 Hz (-3 dB), -20dB/dec min. rolloff
Broadband Noise	< 40 nm RMS, wideband spectrum limit shown in Fig. 4
Rack-actuator distance	~ 10 meter maximum
Drift	< 1.5 micron / day
Operating Temperature	72 ± 3.5 °F (22 ± 2 °C)
Humidity	20 to 70% RH, non condensing

Table 2: preliminary requirements for fine stage actuators.

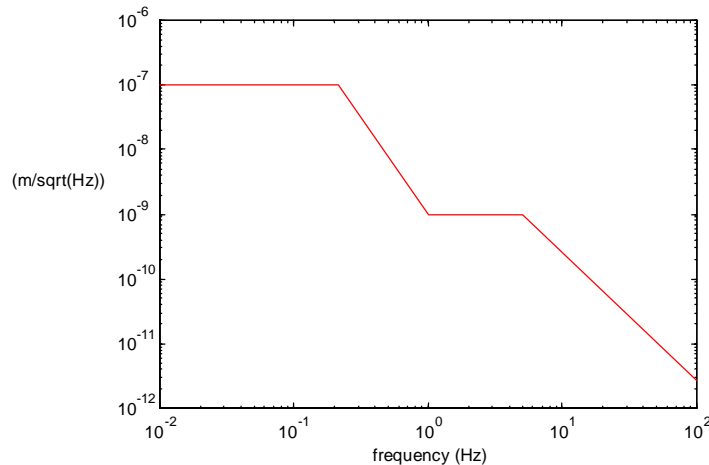


Figure 4: broadband displacement noise amplitude spectral density - preliminary requirements^[2].

3. Description of Test Setup

3.1 For response and transfer function measurements

The Piezo-electric stack is mounted in a V-shaped cradle and held in place with 2 clamps. The cradle is mounted on a heavy and stiff steel base. A Newport translation table with differential micrometer drive is mounted on the same base, facing the moving end of the PZT. A non-contact eddy current probe (Kaman, SMU9000-15N) is mounted on the translation table and measures the displacement of an aluminum target attached to the moving end of the PZT. The probe has a range of 200µm and a noise floor (HYTEC

measurement) around $10^{-3} \mu\text{m}/\sqrt{\text{Hz}}$. All measurements are performed using a DSP Technology data acquisition and FFT analysis system (SigLab 20-42). That system also provides a number of outputs with programmable signal generators.

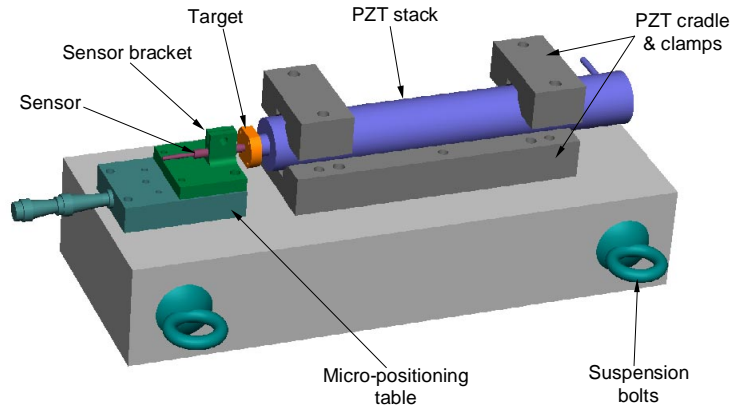


Figure 5: PZT test setup.

3.2 For mechanical noise measurements

Because of the very small motions to be detected (picometer level), a very sensitive capacitive displacement probe (Queensgate NS2000-S series, $20\mu\text{m}$ range) is mounted at the moving end of the PZT as shown in Figure 6. The output sensitivity of the probe is 2V/micron. The broadband noise level from that probe is about $10^{-12} \text{ m}/\sqrt{\text{Hz}}$, which allows detection of mechanical noise at the requirement level up to about 100 Hz. See Section 4.3 for the measured noise floor of that probe.

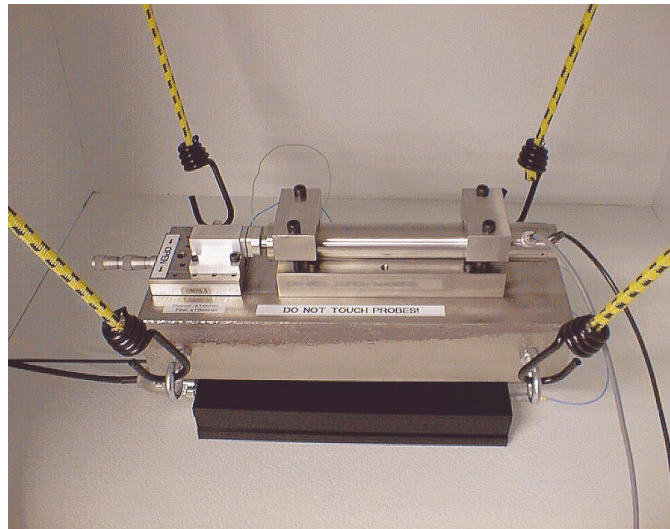


Figure 6: close-up on the test fixture itself, showing the PZT stack, and the capacitive probe mounted on the micrometric translator.

To minimize perturbations of the measurements from extraneous noise (acoustic and seismic), the test fixture is suspended from soft bungee cords (about 1 to 3 Hz suspension frequencies) inside an acoustically isolated enclosure (wooden box with

acoustic foam barrier). The enclosure itself is sitting on a layer of foam on top of a single stage isolation platform.

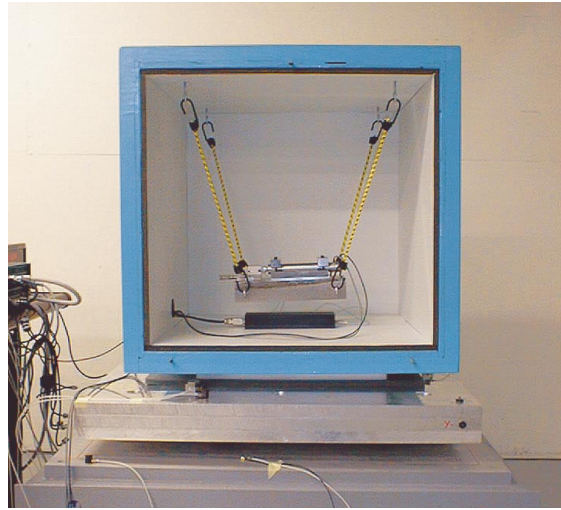


Figure 7: the test fixture suspended from bungee cords inside the acoustic enclosure; the black box underneath the fixture is the electronics for the capacitive probe.

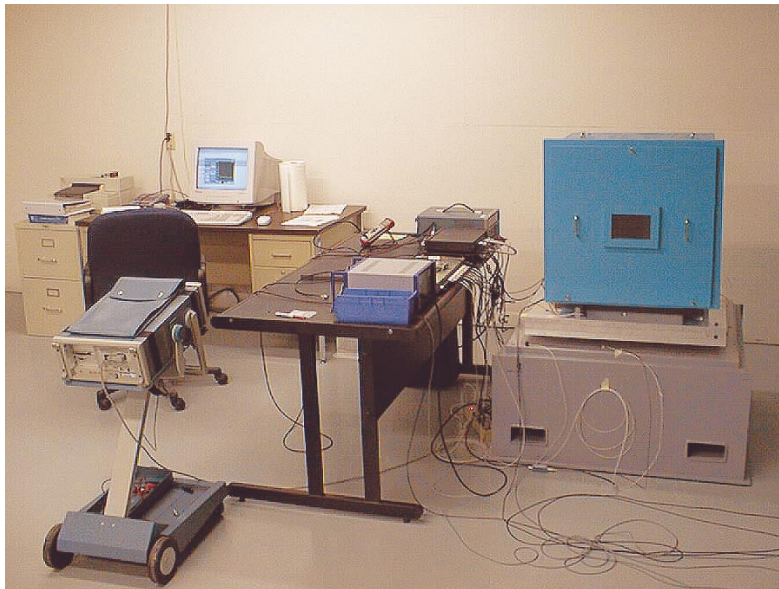


Figure 8: overall lab setup, showing acoustic enclosure on isolation platform and data acquisition system.

For noise measurements, the setup is prepared as follows:

- the control input to the PI controller is shorted with a BNC termination cap.
- both the sensor cable and high voltage cable are extended with 10 meter extension cords (worse case EMI noise pickup).
- the actuator is held at a constant expansion of $90\ \mu\text{m}$ (50% of range) controlled via the offset potentiometer on the PI amplifier (see Figs. 1 and 3).

- the probe is set to its nominal mid range offset from the target (20 μm).
- the probe power supply is provided by a Tektronix linear power supply (+/- 15V, noise & ripple < 2.5mV RMS / 30 mV P-P).
- the probe signal is fed to an input channel of the DSP FFT analyzer, set to +/-20 mV sensitivity, DC coupled.

4. Test Results – Equipment as Received from PI.

4.1 Open-loop Response

4.1.1 Slew Rate

The control signal is band limited by a “slew rate limiter” (see Figure 2) whether the controller is enabled or disabled. We measured the actual slew rate of the PZT from the open loop step response to a large amplitude command step (4 Volts P-P or approximately 70 μm P-P). The measured response is shown in Fig 9; the slew rate is 2116 $\mu\text{m}/\text{second}$. Note that the high voltage supply to the PZT was also monitored and was found to have the same slow rise as the PZT deflection.

Note that the slew rate limiter is factory adjusted to avoid exceeding the current capacity of the high voltage amplifier. The current capacity of the E-507.00 amplifier is between 13 mA (continuous) and 50 mA (peak). The capacitance of the P-239.97 stack is about 3 μF and its expansion range 180 μm . This would lead to a maximum slew rate between 780 and 3000 $\mu\text{m}/\text{sec}$, consistent with the measured rate.

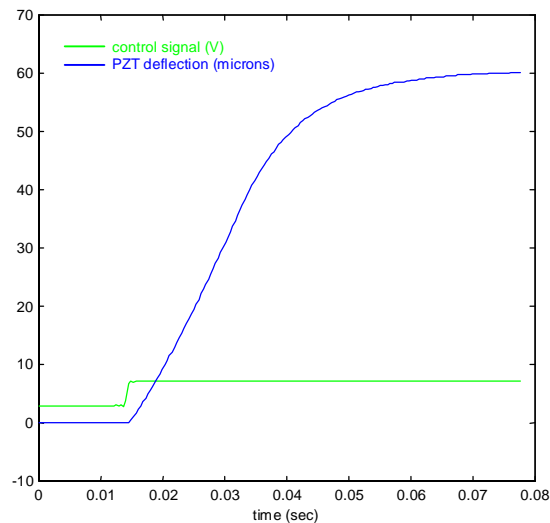


Figure 9: open-loop step response (with slew rate limiter active); the initial response rate is 2116 $\mu\text{m}/\text{sec}$.

4.1.2 Hysteresis

The hysteresis in open-loop control was not quantitatively recorded; however, PI’s calibration certificate shows about 13% hysteresis for full deflection cycles of the PZT. This is consistent with our observations.

4.1.3 Transfer Function

Note that since the open loop response is non-linear (both because of the hysteresis and the slew rate limitation), the open loop “transfer function” is not completely meaningful and probably amplitude dependent. The transfer function shown in Fig. 10 was obtained from white noise excitation between 0 and 500 Hz at 0.5V RMS.

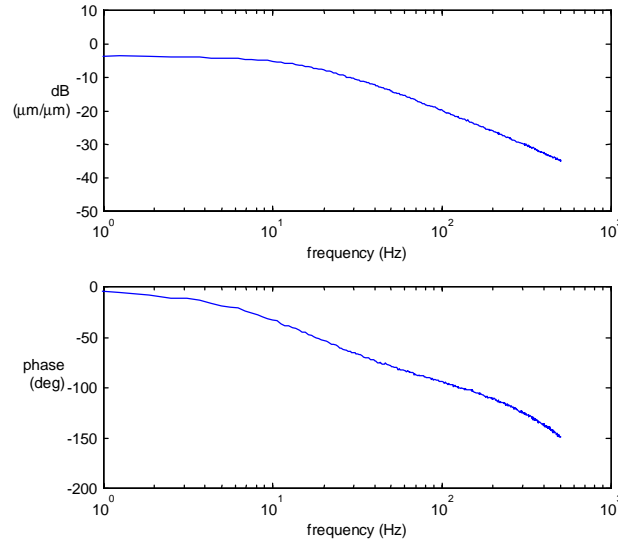


Figure 10: open-loop “transfer function” from control signal (normalized to microns @ 10V/180μm) to PZT expansion (in microns); command signal was white noise with 0.5V RMS (9μm RMS); for indication only since open-loop response is non linear.

4.2 Closed-Loop Response

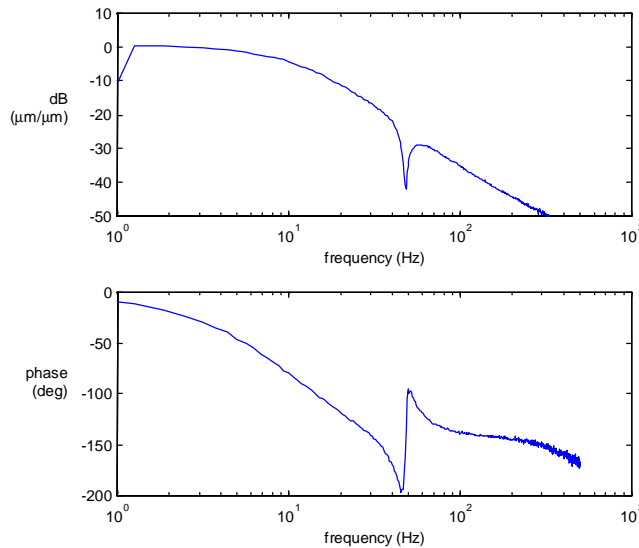


Figure 11: closed loop transfer function from control signal (normalized to microns @ 10V/180μm) to PZT expansion (in microns); command signal was white noise with 0.5V RMS (9μm RMS).

Figure 11 shows a Bode plot of the closed loop transfer function of the PZT actuator. The observed bandwidth is DC to 8 Hz @ -3dB, with a roll-off rate of approximately -30dB/decade above 10 Hz. This compares favorably with the requirement. A sharp anti-resonance is obvious at about 47 Hz and is due to the notch filter (factory adjusted, see Figure 2). The phase lag is about -40° at 5 Hz.

4.3 Broadband Mechanical Noise @ Factory Settings – Open and Closed Loop

Figure 12 shows amplitude spectral densities of the measured mechanical noise from the PZT. The four curves in the figure show the background noise from the probe (with open circuit PZT), the open-loop noise, the closed loop noise, and the preliminary requirement of Figure 4. All measurements were performed with all hardware as obtained from the factory (no readjustments or modifications).

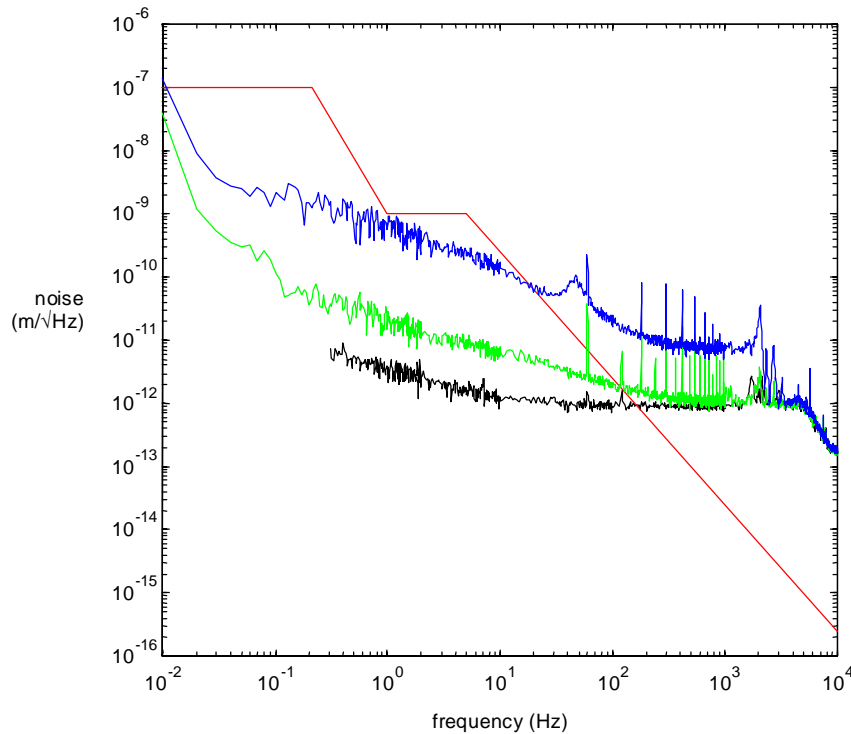


Figure 12: PZT noise levels measured with Queensgate capacitive probe: preliminary requirement (red), probe background (black), open loop PZT at mid range (green), and closed loop PZT at mid range (blue).

The following observations can be made:

- the background noise from the probe is at the expected level (approx. 1 picometer/ $\sqrt{\text{Hz}}$).
- the measured noise to background noise ratio is 10 or more up to about 2000 Hz in closed loop.
- the closed loop noise is about 30 times higher than the open loop noise (Dc to 100 Hz).

- a shallow peak ($Q \sim 3$) can be seen in the closed loop noise spectrum around 47 Hz. That peak is caused by the notch filter (adjustable, factory set to 47 Hz) as also evident in Figure 11.
- there is a significant amount of 60Hz noise and higher harmonics. That noise is likely a combination of power supply noise, direct pickup by the strain gage and extension cable, and other noise inputs inherent to the test setup and instruments. Substantial day to day variations were observed in the amplitude of those peaks, probably due to changes in the electrical noise environment of the lab. These peaks may not however be a concern as they are significantly attenuated by the isolation stacks (see Figure 14).
- the noise level is within preliminary requirement up to about 20 Hz in closed loop. Note that the preliminary requirement is unduly strict above 35 Hz, where thermal noise becomes the primary contributor to overall strain noise while PZT and seismic noise rolls off at a very steep -160dB/decade (see Figure 14).
- except for the 60 Hz and harmonics noise, the measured noise spectrum shown in the figure was found to be remarkably stable from one measurement session to the next.

5. Broadband Mechanical Noise – Effect of Additional Filtering and Controller Tuning

5.1 Effect of Low-Pass Filtering on Strain Gage Signal Conditioning Board

The strain gage signal conditioning board used by PI includes a low pass filter, factory set to 100Hz and intended to reduce noise in low frequency control applications. That filter can be enabled or disabled via a jumper on the board. The controller was received from PI with the filter disabled.

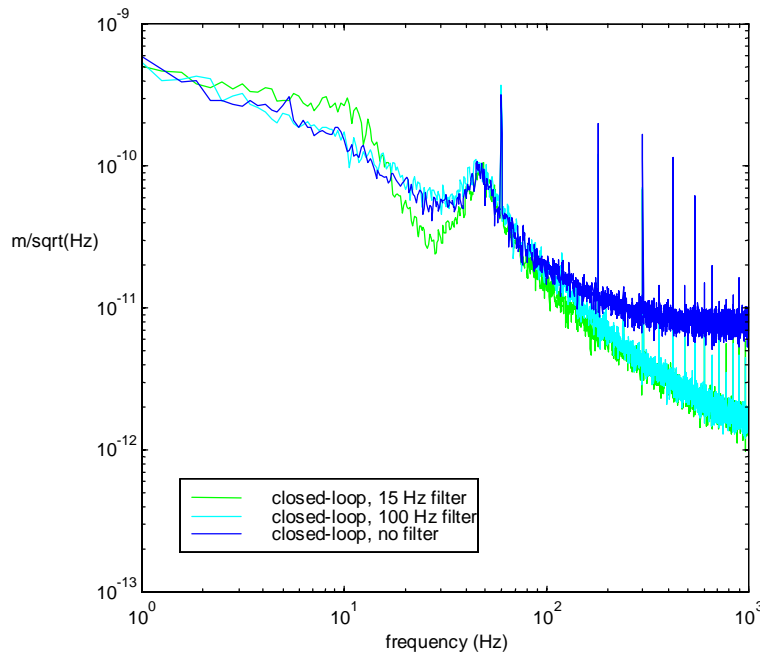


Figure 13: PZT noise levels showing the effect of the low pass filtering on the strain gage signal conditioning board.

We first measured the effect of the factory-set 100Hz filter (see Figure 13) and found that it effectively reduced noise above 100 Hz by an additional 14 dB/decade. This lead us to request information from the PI factory on component exchanges required to lower the roll-off frequency of that filter to about 15 Hz. The noise spectrum was re-measured after exchanging components per PI's instructions. Although the modified filter does attenuate noise by another -20dB/dec between 15 and 30 Hz, it causes a slight increase in the noise at lower frequencies. Also, above 50 Hz, the attenuation is no better than that obtained with the 100Hz filter. Note also that below 35 Hz, the attenuation is no better than about a factor 2, a very small gain when compared to the stack attenuation (about 1/100000 at 35 Hz) as seen in Figure 14.

5.2 Effects of Controller Tuning

We experimented with various adjustable parameters of the PI controller: primarily the overall control gain, the integral gain (I), and the notch filter frequency. The effects of those adjustments on step response, transfer function, and noise were qualitatively observed. However, definitive conclusions are hard to draw because of the inter-dependence of the various adjustments and the fact that all tests so far were performed without mass or stiffness loading on the stack. Any combination of adjustments judged optimal without loads are likely not optimal at all once the actuator is inserted in the system. Note that this is probably truer in this particular application than most other PZT applications, because of the extremely large mass driven by the PZT.

In Short, it has become clear that detailed analysis of the effect of those adjustments requires a test setup that simulates as closely as possible the actual mass and stiffness conditions that the actuator will experience in the LIGO detector. Such tests are being planned at time of writing.

6. Calculated Residual PZT Noise at Test Mass

The support system, isolation stack, and suspension system filter the largest part of the noise caused by the PZT stack. To evaluate the residual displacement noise at the test mass, we calculated the transfer function from unit deflection of the PZT actuator to U-motion of the optics table surface, using the Matlab models of the SEI. Combining those with approximate transfer functions of the SUS and the measured PZT noise spectrum, we derive the residual noise curves of Figs 14 and 15. Three curves are shown in the figures; they correspond to transmitted noise from closed loop PZT actuators without sensor signal filtering, with 100Hz low-pass filter, and with the modified 15Hz low-pass filter. The seismic residual noise requirement^[3] is also shown.

Note that the Matlab models use a single rigid body to represent the support tubes and support platform, so that the effects of differential noise inputs from the 4 PZTs cannot be accurately accounted for. The PZT-to-optics-table transfer function calculated with these models implicitly assumes that the inputs from the 4 PZT actuators are synchronized (common-mode transfer function). The noise inputs from the four PZTs are in reality uncorrelated (except probably for the 60Hz line power noise and harmonics). The residual noise at the test mass ($D_{testmass}$) was therefore calculated as

$$D_{testmass} = \frac{1}{\sqrt{4}} D_{PZT} T_{PZT-table} T_{table-testmass}$$

where D_{PZT} is the measured amplitude spectral density of the noise from a single PZT stack, $T_{PZT-table}$ is the transfer function from PZT expansion to optics table motion in the U direction, $T_{table-testmass}$ is the transfer function of the SUS system in the U direction, and the $\sqrt{4}$ factor is an attempt at accounting for uncorrelated inputs from the 4 PZTs. Note also that uncorrelated noise inputs would cause yaw motions of the support platform that are not included in this approximation.

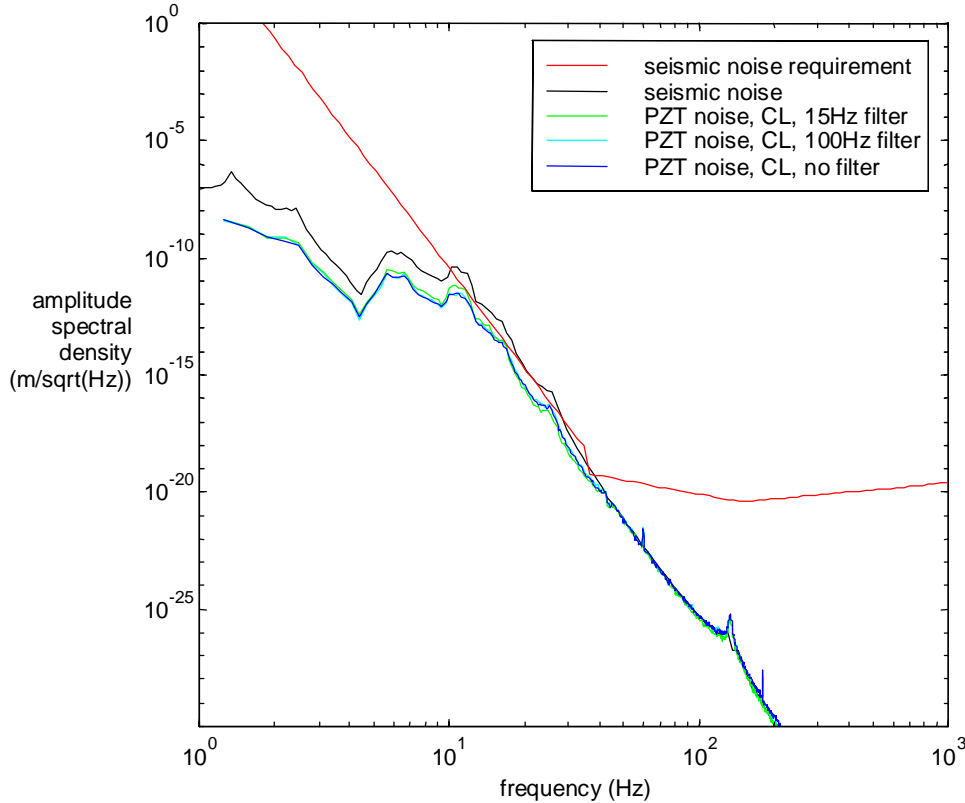


Figure 14: Residual noise from PZT at the test mass compared to residual seismic noise and LIGO requirement for seismic noise; the effect of the strain gage signal filtering is negligible at this scale.

A few observations can be made about those results:

- The amount of residual noise from the PZT at the test mass is very close to the amount of residual seismic noise.
- The preliminary requirement of Figure 4 is unnecessarily restrictive above 35 Hz where thermal noise becomes the primary noise source for LIGO.
- In the critical range from 10 to 35 Hz, the residual PZT noise is roughly 4 to 10 times less than the residual seismic noise (within the assumptions of this analysis).
- The relative effect of the strain gage filter on the residual test mass noise is small.

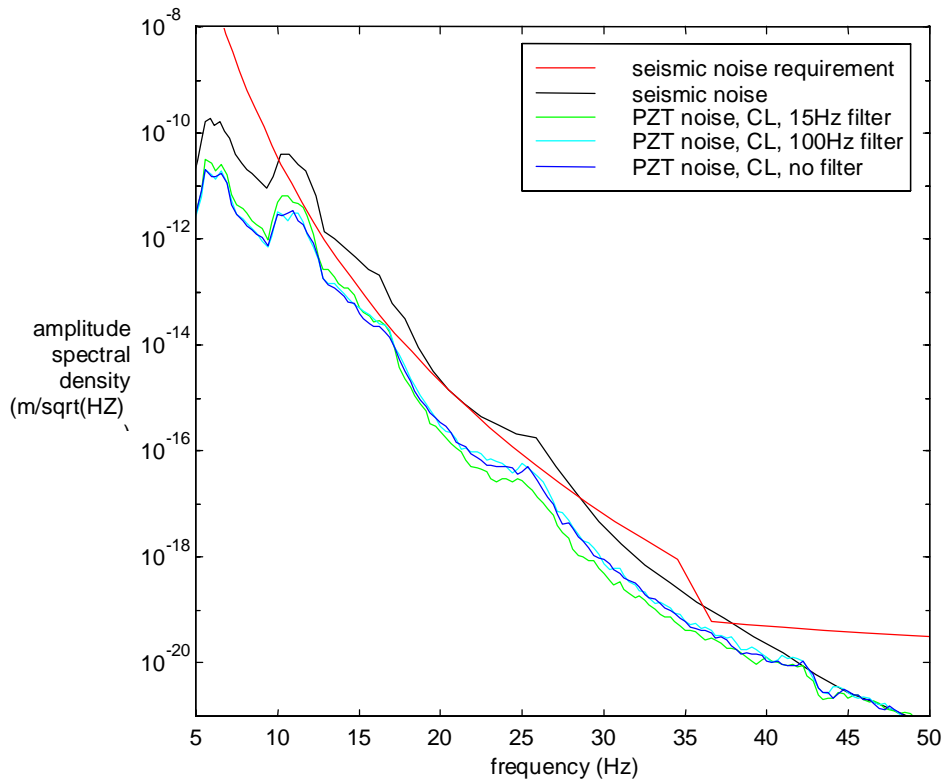


Figure 15: Enlarged view of the residual noise from the PZT at the test mass in the critical frequency range. Residual PZT noise is compared to residual seismic noise and LIGO requirement for seismic noise;

7. References

1. *Operating Manual PZ 77E, E-509 Position Servo Control Module*, Release 1.0, Physik Instrumente (PI) GmbH & Co., Waldbronn, Germany, July 25, 1997.
2. D. Coyne, *SEI Fine Actuation Subsystem Requirements*, LIGO-E970141-00-D (Draft), October 22, 1997.
3. F. Raab, N. Solomonson, and M. Fine, *Seismic Isolation Design Requirements Document*, LIGO-T960065-03-D, February 20, 1997.

Note 1, Linda Turner, 09/03/99 02:47:23 PM
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