LIGO-T990126-A-D

HYTEC-TN-LIGO-35a
Rev a 08/24/99
06/22/99

BSC Fine Actuator Stages Assembly and Installation Procedures

Eric Ponslet

Revision *a*: August 24, 1999
June 22, 1999

Abstract

This note documents the recommended assembly procedures for the LIGO fine stage actuation systems. Preparation of individual components, assembly of the mechanical flexure stages, installation into the BSC SEI systems, and proper initialization of the PZT drives are covered.

Design Engineering
Advanced Composite Applications
Ultra-Stable Platforms

110 Eastgate Dr.
Los Alamos, NM 87544

Phone 505 661 3000
Fax 505 662 5179
www.hytecinc.com

LIGO PROJECT

Table of Contents

1. Scope

This technical note provides detailed instructions for assembling the BSC Fine Actuator Stages Assembly drawing number D972101 and installing it into the BSC System.

2. Special Tools Needed

- Tube wrenches
- Portable crane

3. Mechanical Assembly of Flexure Stages

1. install spring seats (D972101: Item 8) and fixed ball seat (D972101: Item 11) for PZT
   - bolt (D972101: Item 22) 2 nylon seats on bottom frame (D972101: Item 4). Torque bolts to 20-25 in-lbs.
   - bolt (D972101: Item 17) ball seat on bottom frame (socket head screws from the inside). Torque bolts to 75 in-lbs.

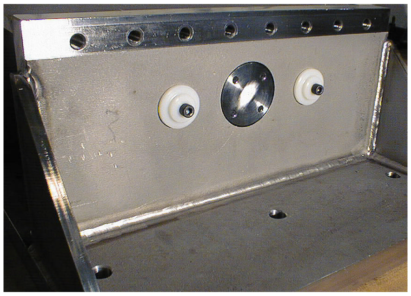

Figure 1: spring seats and ball seat attached to bottom frame

2. install flexures (D972101: Items 6 & 7)
   - make sure the alignment ledges are clean and free of particles.
   - seat flexures in place, engage all bolts (D972101: Item 19), 8 each side, and get them finger tight; center flexures laterally relative to bolts.
   - tighten bolts with wrench progressively. As you tighten, tap the flexures down with plastic hammer to insure tight contact with alignment ledges. Torque bolts to 20 ft-lbs.

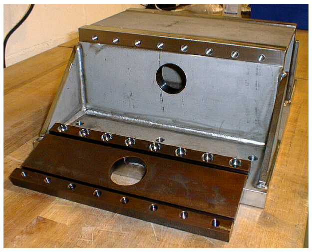

Figure 2: flexure ready for installation (PZT adjuster side)

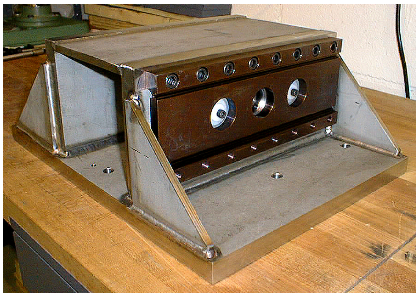

Figure 3: flexure and spring seats installed (pre-compression spring side)

3. lower and bolt top frame (D972101: Item 5) in place
   - using crane, align top frame relative to bottom frame (side with 3 large holes matching 3 holes in one flexure).
   - carefully lower the top frame in place until seated on flexure ledges.
   - engage all bolts (D972101: Item 20) and center top frame relative to bolts.
   - tighten bolts with wrench progressively. As you tighten, tap the top frame down with plastic hammer to insure tight contact with alignment ledges. Torque bolts to 20 ft-lbs.

Figure 4: lowering top frame in place.

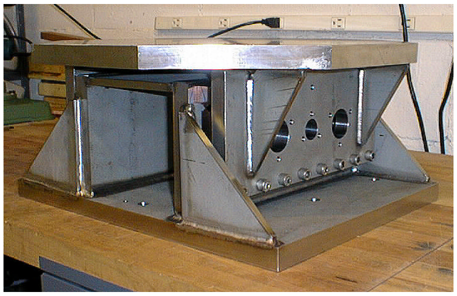

Figure 5: top frame bolted in place.

4. install two stop screws (D972101: Item 18) and dial indicator (D972101: Item 10)
   - install back nuts (D972101: Item 21) onto each stop screw.

- insert the stop screws into the threaded holes located at the top center of the top frame sides; do not bring them in contact with flexure yet (visual check is possible from the sides)
- insert dial indicator in one of two holes located at the top right or left of top frame (column location dependent) and lock in place with set screw (D972101: Item 27).
- the flexures are now hanging with minimal stresses; **the indicator will remain in place as a monitor of flexure deflections** until the fine stage is installed in the BSC system and adjusted; rotate the indicator grating so it points to zero and lock it in place; move limit markers of the indicator to .005" (125 microns) on either side of zero; throughout the remainder of the assembly and installation, the flexures should never be allowed to deflect beyond those markers.
- now bring the stop screws in contact with the flexures (visual feedback from the sides) and tighten them progressively, one at a time until tight, all the while monitoring the indicator to prevent over travel; lock into position with back nut. The final locked position should be exactly at zero deflection.

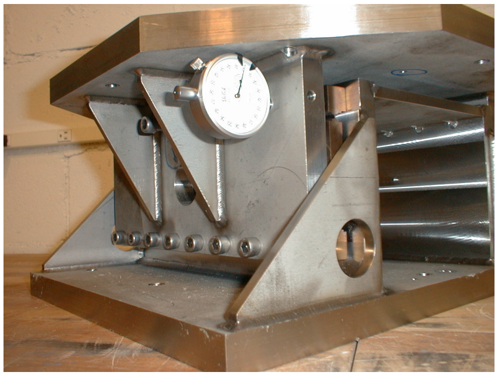

Figure 6: dial indicator and stop screw installed; note that the indicator is zeroed and limit markers set to +/- 0.005 .

5. Assemble bearing housing assembly
   - insert bearing (D972101: Item 23) onto bearing conical seat (D972101: Item 12). NOTE: *Assure race, with smaller diameter inner hole, is placed on seat first*
   - insert bearing/bearing conical seat assembly, shaft first, into bearing housing (D972101: Item 25).
   - secure bearing/bearing conical seat assembly in bearing housing using screw (D972101: Item 25) and nylon washer (D972101: Item 24). Assure screw is snug.
   - install bearing housing lock nut (D972101: Item 1) onto bearing housing from hex head end of bearing housing.
   - install bearing housing assembly into threaded hole in the side of top frame. Visually monitor until edge of bearing conical seat is flush with inner wall surface of top frame.

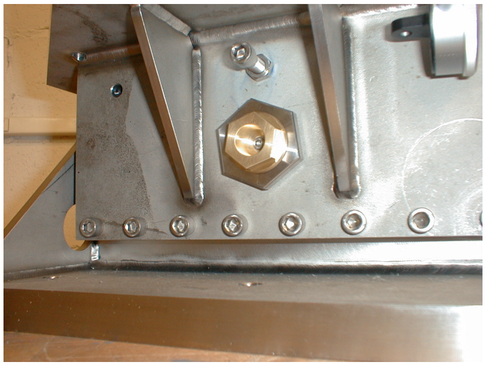

Figure 7: PZT adjuster screw in place with back nut.

6. install the pre-compression springs
   - prepare 2 springs (D972101: Item 15), 2 backing plates (D972101: Item 9 - *attach nylon seats on those*), and 6 standoffs (D972101: Item 14)
   - mount all standoffs on assembly. Torque to 65 in-lbs.
   - after checking again that the flexures are properly locked with the stop screws, install the springs and back-plates, using 1/4”-20 x 3/4” screws (D972101: Item 28) and compress them until the backing plates are tight on the standoffs. Some hand pressure on the back plates will be needed to engage the 1/4” screws.
   - due to the pressure from the springs, the indicator may show up to 0.001” deflection from the original state.

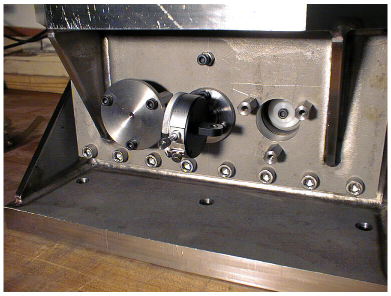

Figure 8: standoffs, spring and back-plate being installed; the stop screws must be holding the flexures locked during this step.

4. Installation of Flexure Stages in BSC System

Four flexure stages are installed on top of the Z-stage scissor tables during assembly of the BSC support systems. Note that all 4 flexure stages are identical and must be installed on the system with all 4 dial indicators facing the same direction.

Figure 9: flexure stage in place in BSC support and actuation system (prototype version shown).

5. Preparation and Initial Adjustments of PZT Drive Components

Before the PZT stacks can be installed in the BSC system, and besides checking the PZT stages for function, two important adjustments need to be made to the controllers: the notch filters in the feedback loops must be adjusted to the dominant U mode of the support structure, and the "zero" of the strain gage sensors must be set in a way that avoids saturation of the high voltage amplifiers and maximizes the available dynamic deflection range. Procedures to achieve these adjustments are explained below.

<u>Important note</u>: PZT stack actuators are sensitive to humidity, mechanical overloads, and accidental electrical discharge; they can be easily and permanently damaged by inappropriate mechanical and electrical handling.
In particular (refer to PI catalogs for more details):

- *Traction loads greater than 110 lb (500 N) should never be applied to a stack.*
- *Compressive loads should never exceed 1000 lb (4500N).*
- *Any torque applied to a stack should never exceed 8.8 lb.in (1 Nm). When tightening threaded parts into the ends of the PZT, the torque should only be*

applied between the part being tightened and the flats provided on the stack body, at the end the part is being attached to.

- *Stacks should not be dropped or exposed to significant shock loads*
- *Exposure to high humidity should be avoided. Ambient relative humidity during operation should be minimized.*
- *Before disconnecting a stack from its high voltage amplifier, always bring the voltage back to a value close to zero to avoid carrying charges in the stack once disconnected. Sudden shorting of accumulated charges can cause a shock wave in the stack and lead to cracking.*
- *PZT stacks have limited life; turn them off when not in use.*

5.1 Channel Identification and Functional Checks

Note that each controller and HV amplifier channel is individually matched to a specific PZT stack. The serial numbers of the stacks associated with specific channels are listed on the back of the controller racks. Channel-stack matching is required to achieve the specified deflection accuracies.

Before starting the installation of the stacks, identify a pair of control racks that will be used for the particular BSC (one 3 channel rack and one 1 channel rack). Note the serial numbers of the stacks to be used with each of the 4 channels and find the corresponding stacks. Wire the stacks to the controllers, using the 10 meter extension cords for both the high voltage and the strain gage signal. Following instructions in the PI manuals, turn the controllers ON and verify proper operation of all channels in open and in closed loop.

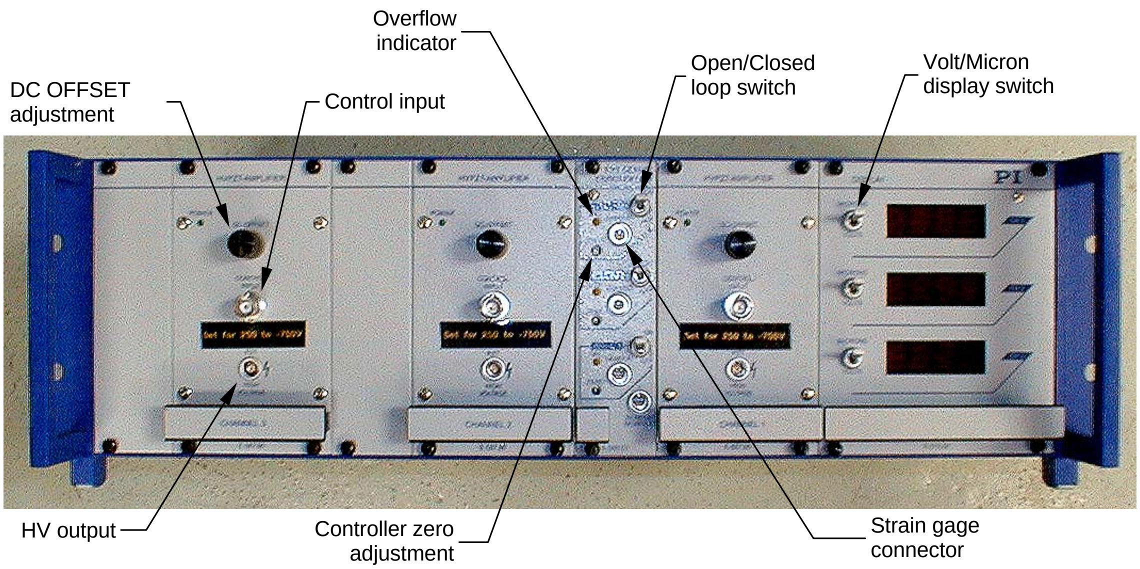

Figure 10: A 3-channel control rack from PI.

Appendix A contains a copy of the specifications that were provided to PI for this purchase. HYTEC has not verified that the hardware delivered by PI is according to those specifications. We recommend performing simple tests on each stack/controller/amplifier group to verify bipolar operation of the HV amplifiers, the presence and correct adjustement of the notch filter, and the control bandwidth.

5.2 Zeroing Controller Loops under Load

The PZT stacks and the associated electronics as delivered from the factory are adjusted for maximum deflection range under zero (or small) static load. Once installed in the flexure stages, the stacks will be under approximately 330 lb of compressive load from the external preload springs. This preload produces a small amount of elastic deformation in the ceramic stack, which is sensed by the strain gages, and automatically compensated for by the controllers. As a result, the controllers and HV amplifiers use a portion of their range to compensate for the effect of the external load. This initial input voltage then limits the upper limit of deflection available because of amplifier saturation. To "re-center" the controller/amplifier range, the strain gage feedback signal can be zeroed to redefine the "zero-deflection length" of the stack under a known compressive load.

Since a symmetric deflection range around a "zero" is required for LIGO, the PZT stacks are operated by varying their high voltage supply around a non-zero initial value. The amplifiers provided by PI were configured to operate between +260 and –780V. This voltage range was selected instead of the standard 0 to –1000V to reduce the average DC voltage experienced by the PZTs and avoid voltages in excess of –750V, thereby expanding their useful life. To maximize available expansion range about an initial (loaded) condition, the output voltage of the amplifiers, with the controllers operating in closed loop, must be adjusted near the middle of the voltage range, in this case about -250V. There are at least 3 approaches to do this: the first uses a load frame to apply a compressive load to the stack, the second uses an extra flexure stage to apply the external preload, and the third simply performs this adjustment in situ after installing the stacks in the BSC system. The load frame approach requires more equipment but has the advantage of also calibrating the stacks as load cells for future monitoring of the system as described in Section 5.3. The second approach, using a flexure stage, gives an approximate adjustment of the zeros before installation of the stacks and does not require special equipment. The third approach is not recommended because is has the potential of inducing initial stresses in the BSC support system; that approach should only be used to refine an initial adjustment. The first two approaches are described below.

5.2.1 Zeroing controllers using a load frame

This approach requires a load frame capable of applying about 330 lb compressive load to a PZT stack, a load cell to measure the applied mechanical load, and the appropriate adapters. The stack should be compressed between two compression-only ball joints to avoid inducing traction, bending, or twist loads. The best approach is to use the conical seats and balls of the fine stage assemblies and to build matching adapters for the load frame and the load cell.

- Connect the stack to the appropriate controller and amplifier, power up the system, and make sure the controller is switched to closed-loop.
- With no mechanical load applied, and the display unit switched to deflection reading, set the DC-offset potentiometer on the E-509 HV amplifier to read 90.0 micron (mid-range).

- Switch the display to Voltage readout; it should read about -250+/-30 V (mid-range).
- Install the stack in the load frame, with the load cell ready to measure loads in the 0-500 lb range.
- Adjust the load frame to a 330 lb compressive load. The display should now show about -490+/-30 V (the controller is compensating for the external load).
- With a small screwdriver, adjust the "zero" potentiometer on the E-509 controller module until the voltage reads about 250 V again. Note that the adjustment may feel "sloppy" due to hysteretic response of the PZT.
- This completes the initial adjustment of the controller zero. The stack can also be calibrated as a rough load cell as described in Section 5.3 below. The adjustment may have to be touched up during system checks as described in section 6.

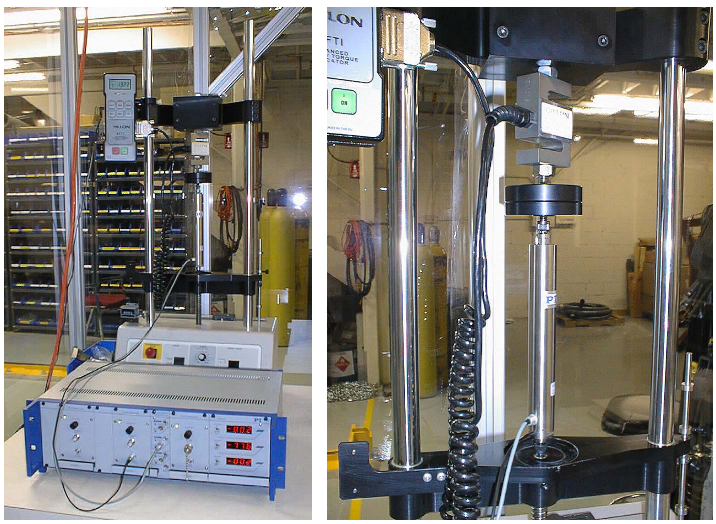

Figure 11: Adjusting controller zero and calibrating PZT stack as load cell in a load frame.

5.2.2 Zeroing controllers using a spare flexure stage

This alternate approach only requires a spare flexure stage (or one that is awaiting installation).

- Before installing the stack in the flexure stage, connect the stack to its controller and HV amplifier, power up the system, make sure the controller is switched to closed-loop.
- With the display unit switched to deflection reading, set the DC-offset potentiometer on the E-507 HV amplifier to read 90.0 micron (mid-range).
- Install the stack in the flexure stage as described in Section 6 below (steps 4 to 14). The external preload springs should be applying about 330 lb to the stack.
- Connect a function generator to the control input of the controller and apply a slow (1/2 Hz max), centered (0VDC mean) sine wave with 10 V p-p amplitude.
- Observe the overflow indicator ("ofl") on the controller module. It will come on during the high expansion peak of the sine wave since the HV amplifier will saturate due to the external preload.

- With a small screwdriver, adjust the "zero" potentiometer on the E-509 controller module until the overflow indicator no longer comes ON at any time. Note that the adjustment may feel "sloppy" due to hysteretic response of the PZT.
- This completes the initial adjustment of the controller zero. The adjustment may have to be touched up during system checks as described in section 6.

5.3 Optional: Calibration of PZT Stack as a Load Cell (requires load frame)

In the closed loop position, the PZT controller automatically compensates for the elastic deflections in the stack due to changes in the applied load. For that reason, measuring the high voltage applied to the PZT, for a given deflection command, is a measure of the applied load (not a very accurate one, because of the ~10% hysteresis, but still a useful approximation). The display module can be used to monitor the applied voltage (toggle switch to VOLTS position). This can be used at any time after installation in the system to check the compressive load applied to each individual stack and insure that it has remain in the acceptable range (about 200 to 400 lbf). The preload can be affected by load build-up in the coarse actuation system.

Because all PZT stacks are different, the Voltage VS load characteristics should be calibrated:

1. install the stack in the load frame as described in Section 5.2.1 above and connect it to its controler and amplifier; make sure that the controller is operating in closed loop, and that the DC offset is adjusted to 90 microns.
2. vary the external load between 150 and 500 lb and record the corresponding control voltages (without changing any of the adjustments). Going through a few loading and unloading cycles will provide a measure of hysteresis and an "average" calibration of the PZT as a load cell.

This calibration was performed on one of the 4 prototype stacks and showed an average load cell effect of 0.73 V/lb (0.16 V/N).

5.4 Adjusting the Notch Filters

Notch filters are installed in the feedback loops to avoid destabilizing the controllers at the dominant elastic mode of the BSC support system in the U direction. One such mode is expected from analysis at about 23 Hz. Note that the analysis assumes an infinitely stiff concrete slabs and makes extreme simplifications in the modeling of the coarse and fine actuator components.

The specifications (see appendix) for the PZT controllers required factory adjustment of the notch filters to 15 Hz +/- 0.2 Hz on all channels. The notch frequency is adjustable with a trim-pot in the controller module. The minimum adjustment range was specified as 10 to 30 Hz.

Ideally, the notch filters of the 4 controllers to be used for a particular BSC system should be adjusted to the measured frequency of the fundamental U-direction mode of the BSC support system. If such measurement is performed, it should be done in the following conditions:

1. the PZT stacks should be installed in the flexure stages and connected to the HV amplifiers. The controllers should receive 0 VDC control signals but the control loops should be open (switch on front panel of controllers).
2. all components of the support system, from the slab to the support platform should be installed as expected in operation. In particular all 4 piers should be grouted to the slab.
3. the mass of the stack and the downtube should not be dynamically coupled to the support platform. There are 2 ways to achieve this: one (preferable) is to completely assemble the stack with all the springs and suspend the DT on it, the other is to temporarily suspend the DT from the crane in such a way that it does not touch the support platform and remove any stack components from the support platform.
4. whether bellows are installed or not and whether the chamber is pumped down or not does not matter.

Note also that this measurement does not have to be extremely accurate (+/- 1 or 2 Hz should be good enough since the notch filters are not very sharp) so that a simple impulse test with a heavy instrumented hammer and a single response accelerometer attached to one end of a support tube, in the U direction should suffice. Also, assuming that the slabs and grouting are reasonably identical for all BSCs with fine actuation, the measurement may only have to be performed once.

In the absence of a measured value for the support mode, the factory adjusted notch frequency may give good results. If not, the adjustment of the notch filters can probably be achieved by trial and error until unstable self-excited oscillations of the fine actuator system are eliminated. However, because there are 4 controllers driving a single degree of freedom, any readjustment of the notch frequency should be done while measuring the notch characteristics with an FFT analyser to insure similar adjustments of the 4 channels. Refer to PI manuals for more detail. Since those adjustments are done by tuning an internally mounted trim-pot, it will be necessary to pull the control module out of the rack and reattach it temporarily using the 32 pin bus extension board P-895.00.

6. Installation of PZT stacks in BSC System

1. install the 2 19” rack units (one has a 3 channels, the other has only 1), in the control rack near the chamber (within 1 meter of the base of any pier).
2. prepare 4 high voltage extension cords (PI #P209.10, 10 meters) and 4 strain gage feedback extension cords (PI #892.10, 10 meters); route the cables as desired from the control rack to within 0.5 meter of the flexure stages. Secure the cables in place, identify both ends with channel numbers and connect to the rack.
3. Prepare the 4 PZT stacks (D972101: Item 13), set them temporarily near the corresponding flexure stage (do not install them yet), and connect all HV and SG wires.

4. Turn control racks ON, ensure that all control loops are closed, and check that all 4 channels are set to 90 micron DC OFFSET; lock[1] all DC OFFSET adjustment knobs in this position – ***they should never be moved again after this step is completed***. The rest of the installation procedure MUST be done while the controllers are turned ON, holding the PZT stacks at the 90 micron (mid-range) deflection.

One stack at a time, perform the remaining operations:

5. attach the conical seat adapters (D972101: Items 2 & 3) to the stack (one at each end).

NOTE: Do not hold the PZT body when tightening the conical seat adapters onto the PZT shaft. Instead, use a wrench of the flats that are available at the end of the stack where the seat is being attached. Applying torques in excess of 1 Nm (8.8 lb.in) to the PZT stack itself will cause permanent damage to the stack.

6. Insert an Aluminum Oxide ball (D972101: Item 16) in the fixed seat of the flexure stage (a bit of Vacuum approved grease will hold the ball in place).
7. put the other ball in the seat at the moving end of the stack (the end without wires); keep it in place with vacuum approved grease.
8. back the bearing housing of the flexure stage (adjustable seat) until conical seat is flush with the inner surface of the outer frame (visual from side).
9. insert the stack at an angle, the moving end first, until the moving end drops into the adjustable seat and onto the ball, then rotate the stack into alignment with the fixed seat and move the adjustable seat (CW) until the stack is lightly seated between the 2 ball contacts. The stack should freely rotate around its longitudinal axis (except for limits from interference of cables with attachment bolts of fixed seat).
10. with tube wrench, lightly tighten the bearing by hand; the stack will now feel pretty tight when trying to rotate it around its axis. Monitoring the applied voltage with the display module will give feedback on the amount of compressive load being applied to the stack.
11. unlock the counter-nuts on the two stop screws. Keeping a close eye on the dial indicator, slowly back up the stop screws, one at a time, making sure the deviation shown on the dial never exceeds +/-.005" (readjust the adjustable seat if necessary). Back up the stops in this fashion until they are completely off and the spring load is entirely taken by the stack.
12. now adjust the bearing housing until the dial indicator reads zero again. Lock it in place with the lock nut.
13. adjust the stop screws to a gap of 0.010" between the tip of the screw and the contact surface (check with long feeler gages from side). Lock them in this position with the counter nuts.

Repeat steps 5 to 13 with the other 3 stacks.

---

[1] A simple way of holding those knobs in position is to insert a soft rubber washer between the knob and the front panel (a thin slice of surgical tubing works well). A more definitive approach may be to saw the shafts of the adjustment potentiometers off and cut a screwdriver slot in what's left.

14. the fine actuation system should now be operational. As a check for proper installation, switch the display modules to Voltage readout and, using the pre-established calibration curves for each channel, measure the compressive load on each stack. It should be between 200 and 450 lbf (in case the load calibration was not performed, the voltage readout should be between approximately 150 and 350V).

7. Check DC and Low Frequency Operation

The PZT drive system can now be checked for DC range and amplifier saturation.

1. Tee all 4 control inputs together so they share the same control signal.
2. Connect a signal generator (capable of DC offsets) to the control input.
3. Apply a slow (0.5 Hz max) sinusoidal signal, centered at 0V, with a 0-P amplitude of 5.0V. Look at the overflow indicators on the E-509 controller modules; some may be flashing ON at the positive or negative peaks of the control input. This indicates HV amplifier saturation and is due to slight misadjustment of the SG zeros (because of hysteresis) or a slightly off-nominal DC compression on the stack (due to imperfect load sharing between the 4 stacks). If any channel is showing saturation, touch up the SG zero potentiometer on the E-509 controller (a little at a time, trying both directions) until the amplifier no longer saturates. Repeat for all channels as necessary.
4. Applying 0 VDC to the control input, check and record the readings from the 4 dial indicators. They should be very close to zero and define the initial position (DO NOT reset the dials to zero as they indicators are primarily intended to monitor the accumulated deflection of the flexures).
5. Apply +4.5 VDC to the control input and record the change in each dial indicator reading. The measured displacement should be close to 81 microns.
6. Repeat step 5 with –4.5 VDC; the displacement should be close to 81 microns in the opposite direction.

8. Appendix A: PZT Drive Specifications (In Addition to Standard PI Specs)

The following specifications were attached to purchase orders for all but one set (prototype) of stacks and controllers purchased for PI for the LIGO project:

The following specifications apply *in addition* to all standard PI specifications as published in the 1998 issue of the PI catalog.

Control Rack Configuration:

The amplifiers, controllers and display will be arranged into five (5) one-channel racks and five (5) three-channel racks. The 11th rack is extra.

Expected Commanded Motions (for information):

The PZT stacks covered by this RFQ will be used to position a large, massive, and rigid system in a horizontal plane, at very low frequencies. The mass per stack is approximately 1500 kg. That weight of that mass is NOT applied to the stack (it is supported externally). The "typical" controlled motion may be described as the superposition of three components:

- a very low frequency (<0.01 Hz), large amplitude (105 microns P-P max) sinusoidal motion
- a low frequency sinusoidal component (~0.15 Hz) with moderate amplitude (40 micron P-P max)
- wide band random motion at frequencies in the 0-5 Hz range, with low amplitude (<1 micron)

Loads:

The stacks are not subject to any gravity loads from the system.

The motions described above do not generate measurable inertial loads.

The stacks will experience a constant (soft spring) external compressive preload of 350+/-50 lbf (1560+/-220 N).

No other external loads will be applied to the stacks.

Operating Conditions:

The stack will operate continuously, in closed-loop, at room temperature, in a controlled office type environment: 72+/-3.5 ºF (22+/-2 ºC), 20 to 70% relative humidity, non-condensing.

Any controlled motion will be applied symmetrically around a mid point, i.e. the range of motion will be –90 to +90 micron.

To reduce aging problems due to the application of a DC voltage to the stack to achieve symmetric operation, the amplifiers shall be configured to drive the stacks in Bipolar mode, i.e. from +260 to –780V.

The stacks will be operated with 10 meter extension cables (both HV and SG feedback).

Controller Dynamics:

Strain gage controllers shall be factory adjusted and calibrated to the following specifications:

- Bandwidth: 0 to 5 (five) Hz @ -3dB, with a minimum rolloff of -20dB/decade above 5 Hz
- Settling Time: Not critical / consistent with 5Hz bandwidth
- Notch filter: user-adjustable via trim-pot in range from 10.0 Hz to 30.0 Hz or wider; factory set to 15.0 Hz +/- 0.2 Hz.

Other:

- it is essential that all 20 channels be matched as closely as possible
- channel-to-channel mismatch: the largest difference between actual deflections of any two of the 20 stack+controller systems at any control input in the nominal range shall be less than 1.5 micron.
- electronic noise in the controllers and amplifiers is a primary concern in our application; any required modifications to the controller and/or amplifier circuits shall use low noise practices and components.
- resolution of all display modules: 0.1 micron.