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# Metal Quad Noise Prototype Balancing and Alignment Procedure

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*Distribution of this document:*

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# 1 Related Documents

Numbers cited throughout this document refer to these documents.

1. Noise prototype Assembly procedure - T060040-05

URL:
http://www.eng-external.rl.ac.uk/advligo/Reviews/FRR/Documents/t060040-06.doc

Description:
This is the assembly procedure from RAL which should at this point be completed before balancing and alignment is to begin.

2. Quad Suspension Balancing and Alignment Procedure (UK Document)

URL:
http://www.eng-external.rl.ac.uk/advligo/Reviews/FRR/Documents/Quad suspension Balancing and Alignment procedure.doc

Description:
This document is the precursor to this updated procedure. It is a valuable reference since it contains additional details on how all the adjustments work and ideas on how to trouble shoot. This update should be considered a continuation, not a replacement.

3. Useful Data for Noise Prototype Quad Assembly (UK Document)

URL:
http://www.eng-external.rl.ac.uk/advligo/documents/Useful data for Noise Prototype Quad assembly.pdf

Description:
This document contains useful information about basic aspects of the quad such as weights, wire lengths and diameters, a description of how the blade tip positions are determined, and suspension stability.

4. Alignment Requirements for Quad - T080128-00-K

Description:
All the final alignment requirements for the quad are listed here.

5. AdvLIGO Quad Suspension Controls Prototype Suspension and Adjustment Method - T060039-00

Description:
This is the assembly and alignment procedure written for the quad controls prototype. Although the controls prototype clearly has some differences, many of the principles of aligning a quad are the same. As a result, this document is still a valuable reference of experience gained during the prototyping phases of the quad.

6. Holo-Krome Bolt Torque Data Sheet

URL:
http://www.holo-krome.com/pdf/techbk34-40.pdf

Description: This data sheet provides recommended bolt torque values from Holo-Krome.

7. Quad Pendulum Structure Pushers - T080230-00-0

Description:
This document provides additional detail on the use of the quad pendulum structure pushers used to align the quad structure on the seismic table.

## 2 Introduction

This document provides an updated set of instructions on how to balance and align the metal quadruple pendulum noise prototype, based on the experience gained at LASTI. It should be thought of as a continuation of “Quad Suspension Balancing and Alignment Procedure” referenced above. It assumes a basic understanding of the quad, but provides sufficient detail such that the document can stand alone from the assembly procedure. Thus, even someone who was not directly involved in the assembly process should be able to follow this document and produce a balanced and aligned quad.

There is no one ’best’ way to align a quad. This procedure should only be thought of as a set of suggestions based on the experience gained thus far. The approach here is a bottom to top, coarse to fine approach. The bottom to top idea is that if you start with all the masses locked in a level configuration and rebalance them back to that level configuration as you suspend from the bottom up you will get a perfectly level, suspended pendulum at the end. The coarse to fine approach makes sense in the context of all the coupling between adjustments and is designed to minimize the number of iterations required to get a fully functional quad. It is because of these cross couplings and the constraints on the positions of the masses that simply suspending from the bottom up is not enough on its own. Likely there will be iterations between balancing the masses and aligning their positions. As a result, all the initial adjustments in this document are relatively quick and coarse to get everything in range. Then, when all the fine adjustments are made at the end, most of the alignment and balancing constraints will remain in tolerance and not need to be repeated.

## 3 Class B Tooling

$\frac{9}{32}$ inch nut driver or wrench for axial OSEM positioning.

$\frac{7}{16}$ inch nut driver or wrench for lateral OSEM positioning.

$\frac{9}{64}$, $\frac{3}{16}$, $\frac{1}{4}$, and $\frac{5}{16}$ inch allen wrenches.

A flat head screw driver for turning the top mass pitch adjusters.

Torque wrench for the blade clamp bolts capable of 400 in-lb (33 ft-lbs, 45 Nm).

Slip or block gauges for measuring 5 mm, 6.6 mm, and 12 mm gaps.

Dentist Mirror.

Flashlight or small lamp.

Structure pushers for rotating the structure on the optical table (see Figure 14).

5 axis table for safety while rotating the structure.

Lower structure tooling for use with the 5 axis table.

Safety goggles for working around the wires.

An optical alignment tool with 10 $\mu$Rad accuracy, such as an autocollimator.

A small, light, reliable level to place on suspended masses (optional).

# 4 Hints Before You Begin

In general, the more carefully each assembly and alignment step is done, the easier later steps will become. For example, the more accurately the blade springs were installed during assembly, the easier it will be to balance pitch. The more precisely pitch is balanced on the first time through the alignment procedure, the fewer iterations will be needed to align all OSEMs, ECDs, and ESD.

While making adjustments on the quad make sure to watch out for touching stops and for interferences between the chains at every step. In particular the top masses have tight clearance around the blade spring clamp bolts. These bolts tend to get caught under the top plate of the opposing top mass if pitch and roll are not carefully aligned. There is nothing worse than spending an hour making adjustments only to discover that it was all for naught because a screw you did not see was touching one of the masses.

Remember that the blade springs magnify the tilts of the masses below them because their compliance allows for differential tilt between the masses.

Pitch is likely to cause a lot of trouble if the blade spring alignment within the rectangular masses is off. Pitch specifically is sensitive to errors in the blade assembly because any lateral misalignment of the blade tips away from the center of mass at each stage will generate a torque that will introduce a differential pitch between that stage and the one above it. If this problem is too extreme, it will be impossible to meet all the constraints of the OSEMs and test masses simultaneously, and the springs will need to be repositioned. Each blade tip should have exactly 5 mm of clearance on either side. Intolerable errors are on the order of a few tenths of a mm. More details on the spring positioning are in the procedure below.

# 5 Preparation

1. Put on safety glasses. Lock all the masses in level (by eye) position. Take care not to over stress the wires, especially the lowest ones since they are the most delicate and have no added compliance from springs.

Much of the leveling and balancing of the masses throughout this procedure can quickly and easily be gauged by eye. A small, light, and reliable bubble level is also useful. Figures 1, 2, and 3 show useful places to inspect by eye how level each mass is. Figure 15 in Appendix B illustrates the coordinate systems referenced throughout this document.

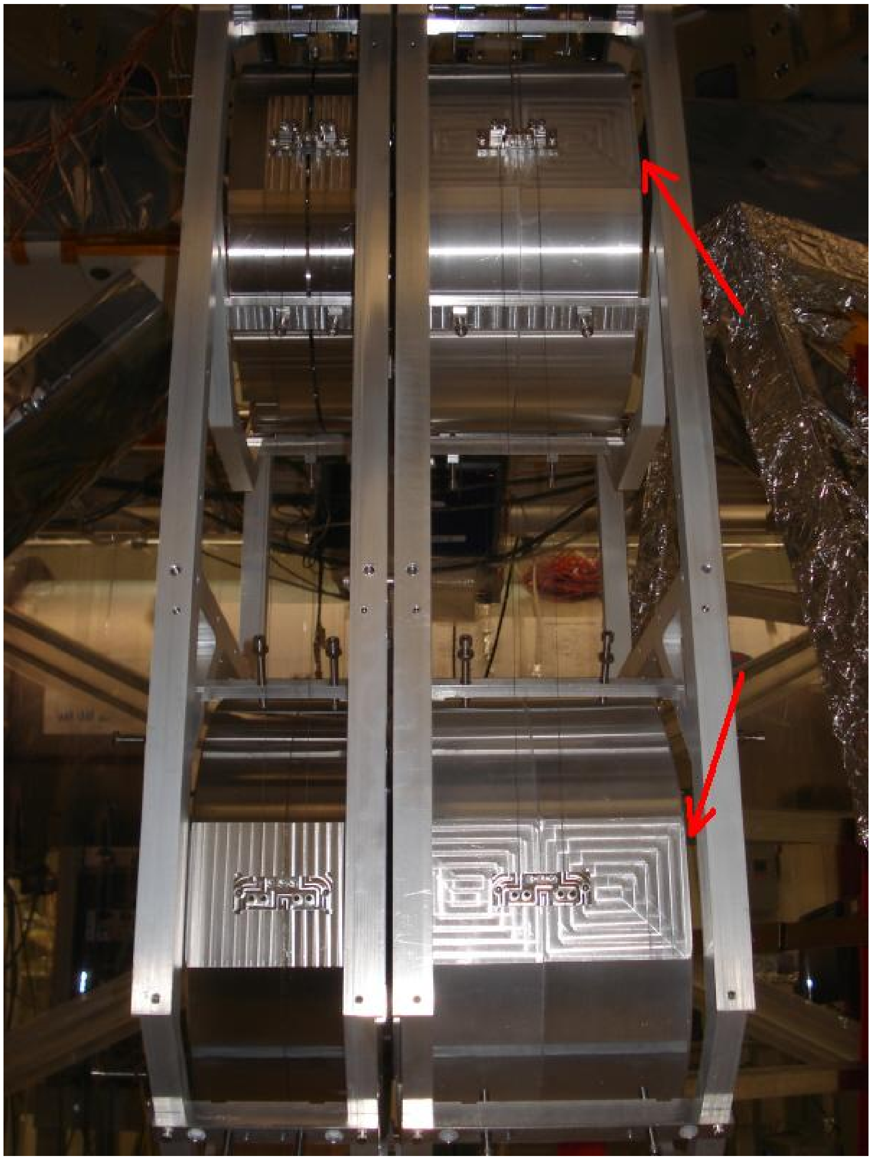

Figure 1: A quick and rough idea of the pitch of the 2 bottom masses is obtainable by inspecting the relative angle between each mass and the front/back edge of the structure. The red arrows indicate the gap between the main chain and front edge of the structure.

2. Make sure all the final suspended bits are installed so that the masses have the correct balance and weight. For example, if the UI mass flag-magnet assemblies are not yet installed, it will be necessary to align the pitch of the entire suspension again when they are installed. Other things to check for are all flags, magnets and bolts. Also check that all pitch adjusters are centered. The UI and penultimate mass OSEMs must be installed to have the correct weight in each mass. The top mass OSEMs are supported by the structure and should not yet be installed, they will just get in the way later. If suspended bits are added to the masses, they should be weighed first, so that the final weights can be kept track of.

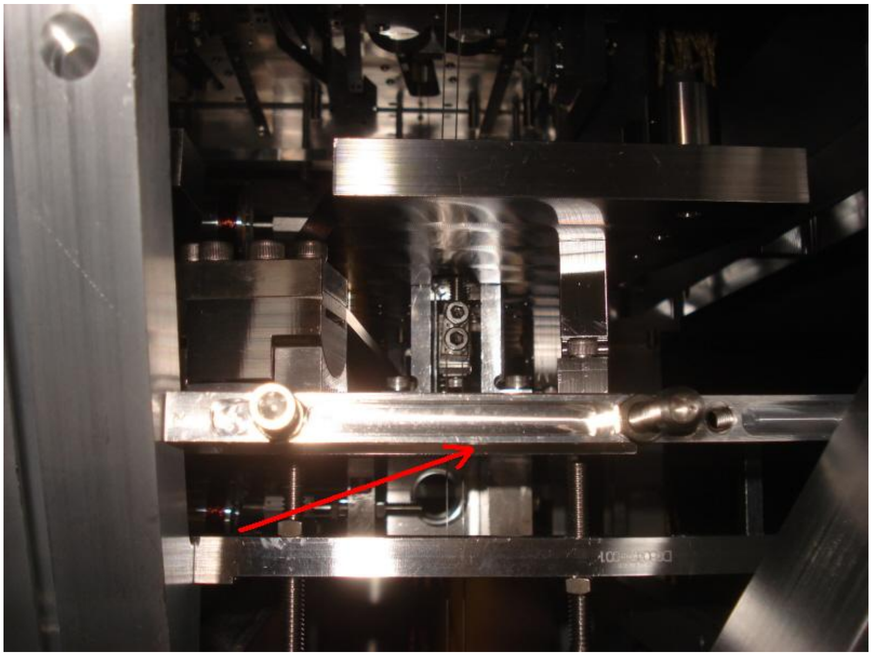

Figure 2: The pitch of the UI masses is visible by inspecting the relative angle between the mass's bottom plate and the stop mount bar indicated by the red arrow. This bar, along with the corresponding one on the other side, will also highlight roll by comparing the relative heights of the left and right sides of the mass.

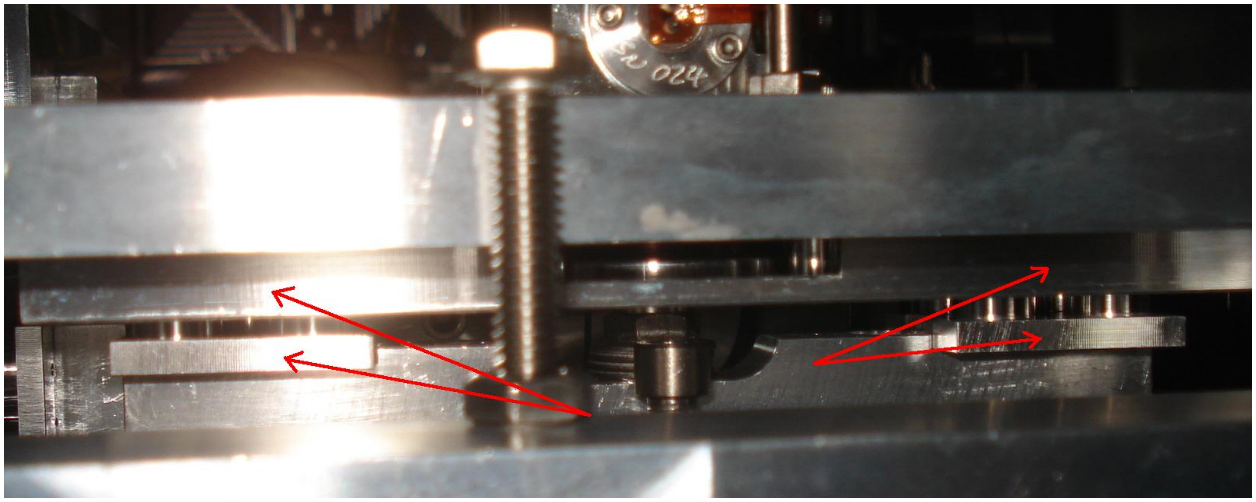

Figure 3: The pitch of the top masses is visible by inspecting the relative angle between the top ECD arrays and the bottom of the adjustable top OSEM plate indicated by the red arrows. Roll is also visible by inspecting the relative height of the top mass with these references on either side of the structure.

3. The orientation of the ECD magnets and shielded magnet pairs is important and should be double checked. The intention is to create magnetic dipoles in order to reduce the coupling of the magnets to stray fields. This means that the poles of the ECD magnets are placed in a checker board pattern around the top mass; see Figure 4. Two OSEMs around each top mass have shield magnets placed directly behind the coil magnet, the side OSEM and the OSEM at the front and center ('Side' and 'Face 1' respectively by LASTI notation). Additionally, the main chain UI mass has similar shield magnets behind the OSEM coil magnets. Figures 5 and 6 show the locations and orientations of the shielded magnet pairs.

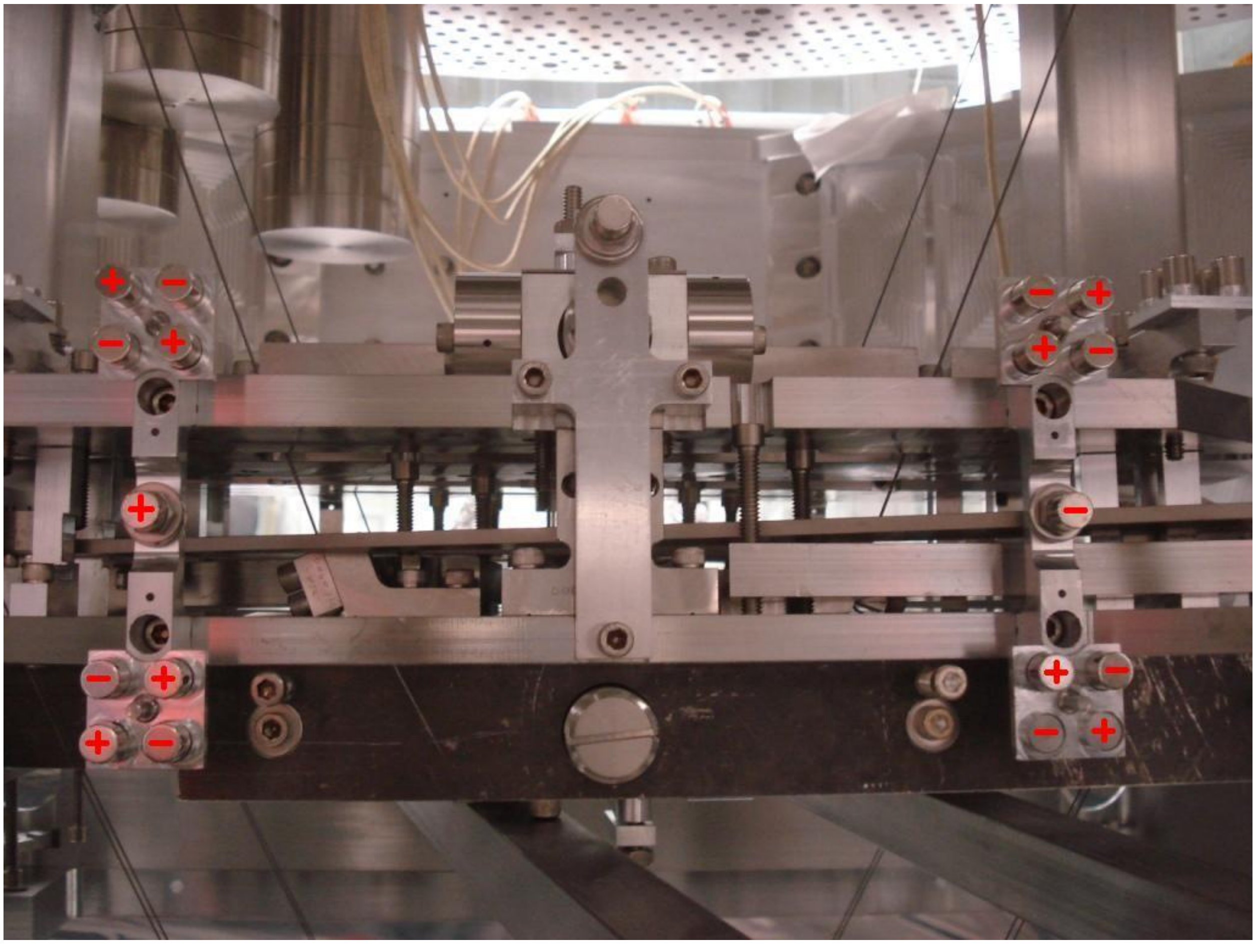

Figure 4: This photograph shows the checker board pattern of the ECD magnet polarity. There is an identical pattern for the ECD magnets on top of the top mass. This photograph does not show the tablecloth simply because it was taken during the assembly stages.

Figure 5: This photograph shows the locations of the shielded magnet pairs around the top mass. In LASTI notation these are the magnets belonging to the 'Side' and 'Face 1' OSEMs. The UI mass OSEMs also have shielded magnet pairs.

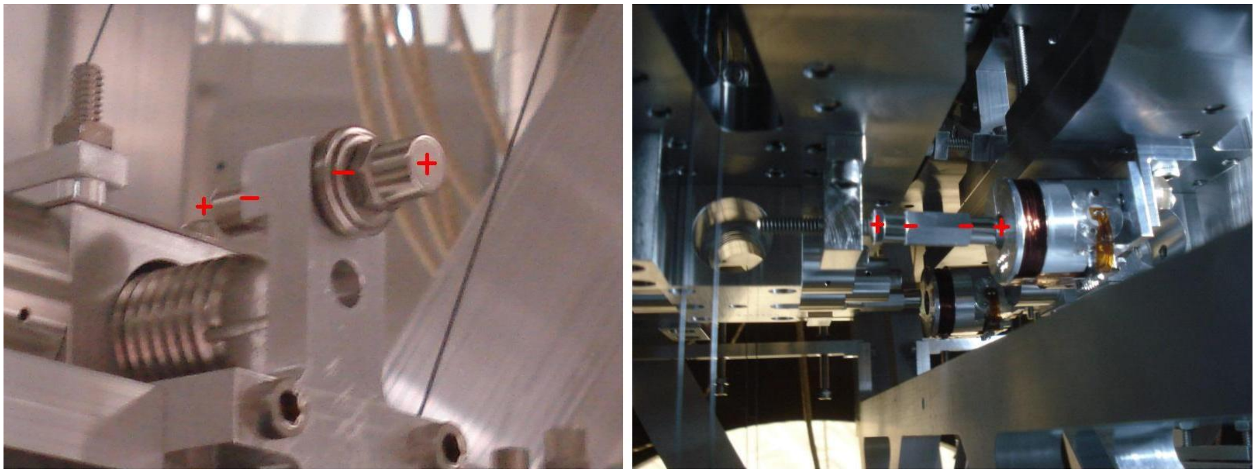

Figure 6: The left photograph shows the orientation of the 'Face 1' OSEM magnet pair. Which side is north and which is south is arbitrary as long as two like poles are facing each other so that magnets tend to cancel. The side magnet pair, and the UI magnets in the right hand side picture function in a similar way.

# 6 Suspend and Balance the Masses

Start the alignment process on one chain at a time. Both can be done simultaneously, but experience proved that balancing one chain at a time is the most reliable. Later on it will be necessary to consider both chains simultaneously. The main goals here are to set the blade spring tip positions and set the differential pitch of all the masses. It is important to make sure early on that the differential pitch is no greater than a few mRad.

1. Choose a chain and release the bottom mass. It should stay level and have the same pitch and roll as the penultimate mass. If this is not true, the wires have not been made or clamped properly and should be changed.

2. Release the penultimate mass. If you are on the main chain, both lower masses should now hang free and level in pitch on their own. If you are on the reaction chain, you may have to adjust the penultimate mass pitch adjuster to bring both masses to a level state. Figure 7 describes this adjuster. Errors in pitch are likely due to the errors in the wires. Errors in roll may be due to blade spring tip heights, which will be sorted next.

3. While the UI mass is still locked, release the blade spring tip stops and adjust the spring tip height to set the vertical height (d parameter in model). The blade tip height should be 12 mm from its reference point. Instructions for adjusting the height are in Figure 8. There should also be 5 mm of clearance on either side of the blade tip, as shown in this figure [3]. If the clearance is off by more than a few tenths of a millimeter the spring may have to be adjusted, which may not be allowed in situ for risk of undoing a heat treatment of the blade spring. Note that if the UI mass is not locked in a level position the wires will pull on the tip making it appear malpositioned even if it is not. The two lower masses should now be level in both pitch and roll.

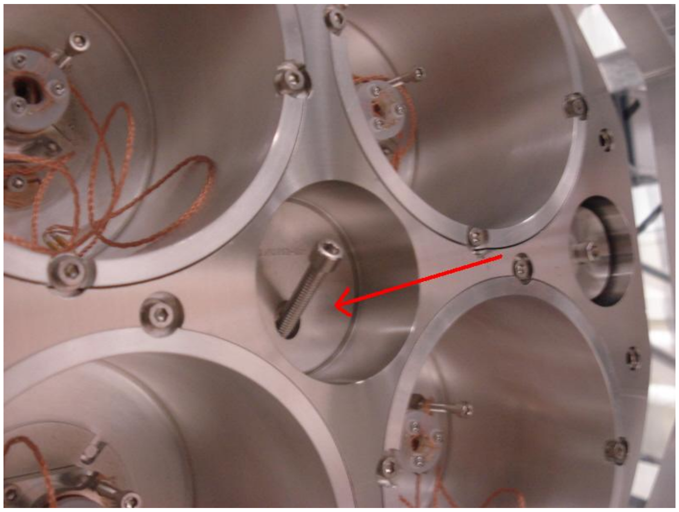

Figure 7: The reaction chain penultimate mass has a large pitch adjuster indicated by the red arrow. The long diagonal screw is a lock. If the lock is loosened the adjuster will slide back and forth altering pitch.

4. Problems are most likely to become visible when releasing the next two stages. Release the UI mass. At this point any significant pitch is likely due to lateral offsets on the blade spring tips. If the pitch is small enough you can compensate by repositioning some of the removable mass. If it is off by a large amount the spring will have to be repositioned. At the time of writing it is still uncertain whether repositioning the spring in situ will be an option because of a risk of undoing a heat treatment of the spring. If it is an option, the spring clamp bolts can be loosened and the spring tip can be forced to slide back and forth. The mass should be locked while making this adjustment. Make sure to retighten the bolts when the adjustment is complete. Clamp torque values are listed in Figure 8 and Appendix A.

5. Before releasing the top mass check the blade tip positions in the same way that they were checked on the UI mass. The vertical height should be 6.6 mm from the reference lip, and the lateral position should again allow 5 mm of clearance on either side [3].

6. Release the top mass. Check to make sure the other top mass is not interfering, see Figure 9. This stage has additional options to compensate for pitch errors. There are two coarse pitch adjusters underneath the top mass that slide the attachment of the top wires along the bottom plate. There are also two fine pitch adjusting 'screws' on the top mass as well. One is below the bottom plate, the other above the top plate behind the center OSEM. These can be turned in and out to adjust the pitch balance. See Figure 10. You should only use the coarse adjusters if the fine adjusters run out of range. Please note that using them will introduce a yaw and longitudinal displacement. These yaw and longitudinal offsets can be compensated for by adjusting the top stage springs, but doing so may impose additional pitch-roll coupling, making damping and control more difficult.

Ideally you should now have a level suspension chain with no differential pitch between the masses. A small amount of differential pitch below a few mRad is OK. If this is the case,

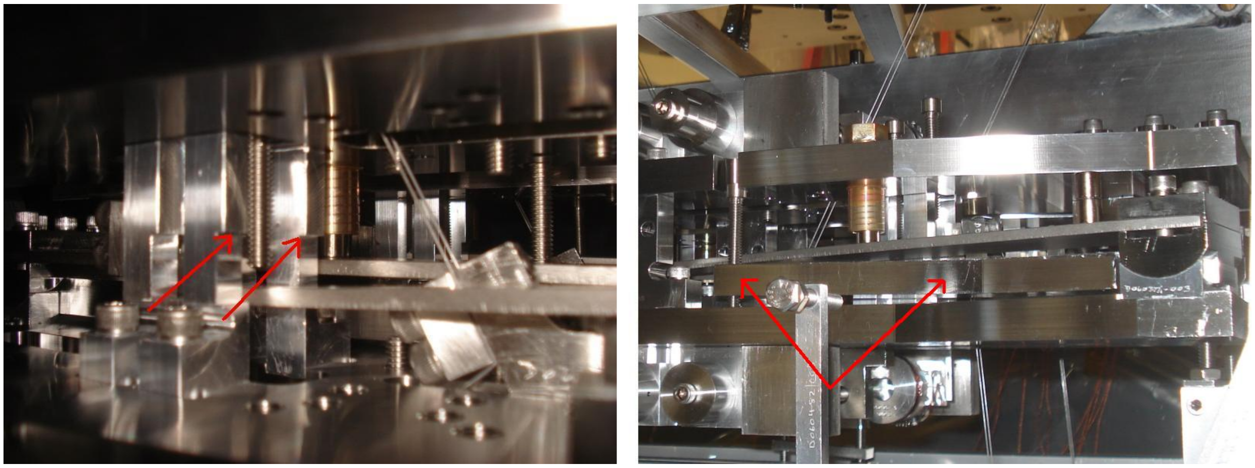

Figure 8: The left photograph shows the vertical blade tip reference points indicated by the red arrows. The arrows are pointing to a lip on one of the two upright U shaped aluminum parts that arch over the blade tip. For the UI mass, there should be 12 mm between the top of the blade and that lip when the round masses are suspended below. There should also be 5 mm of clearance on either side between the tip and these U shaped parts [3]. The right photograph shows the adjusting arm for the blade tip height. Just above the left red arrow is a long upright $\frac{1}{4}$-20 bolt. Turning this bolt will adjust the angle at which the blade leaves its clamp, allowing the tip to move up and down. It may be necessary to slightly loosen the two outer bolts in the clamp (the ones closest to and furthest from the opposing chain). The UI spring clamp bolts should be torqued back to 100 in-lbs (8.3 ft-lbs, 11.3 Nm) [6]. The top mass springs are referenced and adjusted in a similar way. The top mass clamp bolts get torqued to 330 in-lbs (27.5 ft-lbs, 37.3 Nm) [6].

keep the top masses as level as possible for the time being since the next few steps will require it.

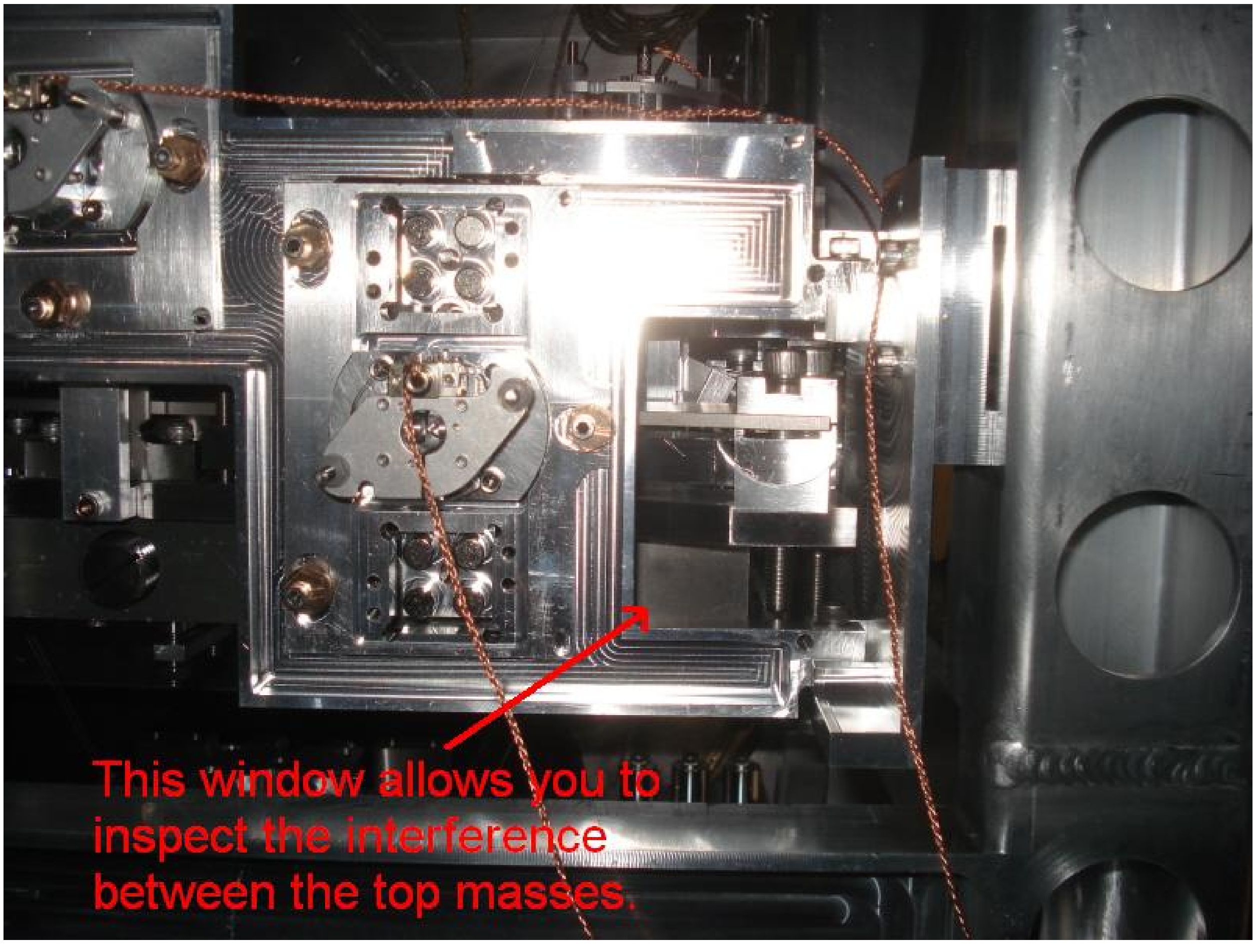

Figure 9: The clearance between the blade clamp bolt heads of one top mass and the top plate of the opposing top mass is small. When adjusting the top mass positions, always keep this possible interference in mind. This picture shows one of 4 possible windows to inspect the clearance. Getting the roll of each chain correct will help prevent pitch headaches later on since both of these adjustments alter the amount of space here.

7. The second chain should now be suspended. If it interferes with the first because of global roll, yaw, or longitudinal errors, the first chain should simply be held out of the way with stops. These offsets will be dealt with in the next section.

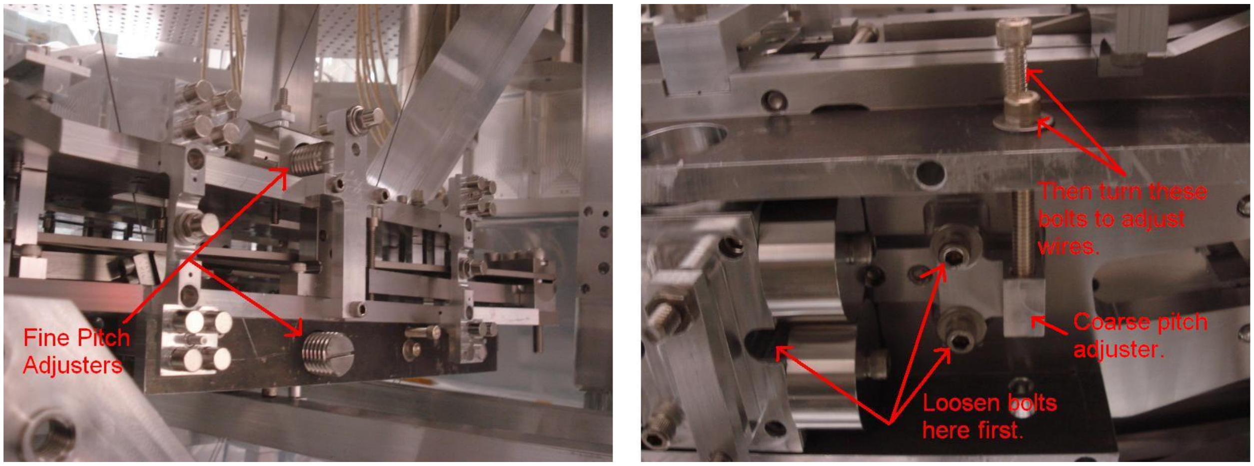

Figure 10: The left photograph shows the fine pitch adjusting screws. The tablecloth is not in place to show the pitch adjusters. The right photograph shows one of the two coarse pitch adjusters. The coarse adjusters should only be used if the fine adjusters have insufficient range. They work by moving the attachment points of the top wires. To use them, loosen the 3 $\frac{1}{4}$-20 bolts (one is hidden inside the center block) and turn the 2 $\frac{1}{4}$-20 pusher-puller screws to slide the adjuster forwards and backwards. Retighten the bolts after completing the adjustment.

## 7 Align the Chains

The following steps will now guide the alignment of the chains relative to each other, the structure, and the global coordinate system (i.e. pitch and yaw of the test masses). Virtually all adjustments at this point will couple to each other, so there will likely be some iterating back and forth until everything is met within its constraints.

1. Install the OSEM mount plates and set them to the center of their range. In the next few steps this will allow you to quickly inspect the alignment of each chain relative to the structure, help ensure that all the plates have enough range to adjust the OSEMs, and roughly set the spacing between the chains. See Figure 11.

2. Assuming the pitch of the top masses are roughly leveled, the offsets of the flags and magnets from their midpoints in the OSEM plates will tell you about longitudinal, yaw, vertical and roll relative to the structure. Use the top stage blade springs to adjust these degrees of freedom. Any transverse offset will also be visible, however there is no adjustment for this degree of freedom because there needs to be a gross error, likely in one of the top wires, for this to be the case. If so, wires may need to be remade.

3. Make sure all the spring stops are free. Roll and vertical can then be adjusted by packing the 0.5 mm and/or 1.0 mm shims underneath the blade tip clamps. These shims only allow one to raise, not lower one side of a chain at a time. If the chain appears too high, the masses may not be heavy enough, some wires were set too short, the tablecloth was not assembled correctly, or possibly the springs are stiffer than the design. See Figure 12.

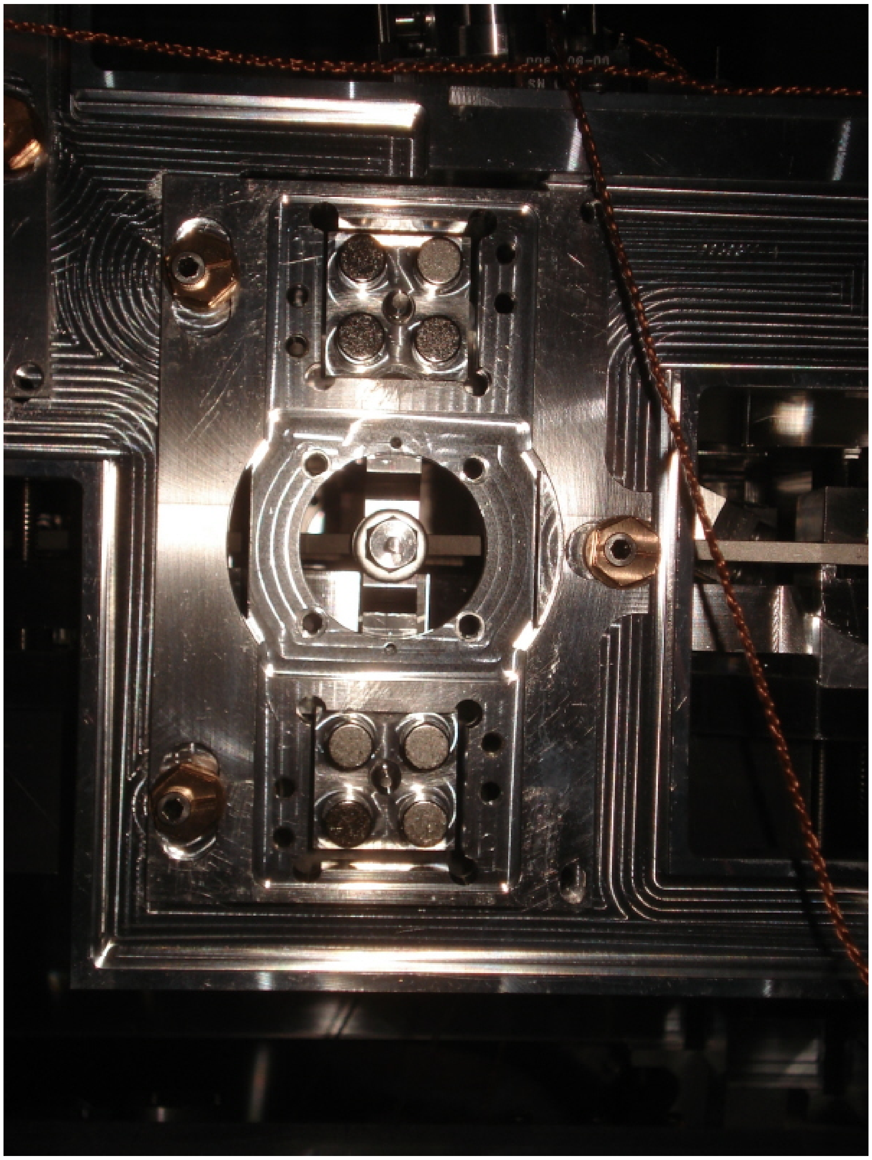

Figure 11: This figure shows one of the OSEM plates without the OSEM. Centering the plate on the structure using the 3 copper cams will allow you to quickly eyeball longitudinal, yaw, vertical and roll of the top masses relative to the structure

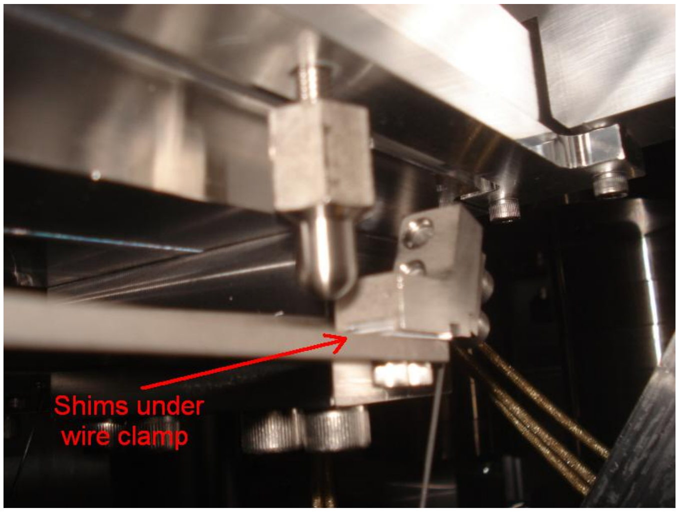

Figure 12: The red arrow points to a top stage wire clamp with shims packed underneath to alter the height of one end of the suspension. To insert these shims the clamp needs to be removed which requires giving the wire some slack by either raising the top mass or lowering the spring.

4. Adjust the yaw and longitudinal degrees of freedom using the top stage rotational adjusters. See Figure 13. To make this adjustment the top mass should be locked and the outer top stage blade clamp bolts loosened (the ones closest to and furthest from the opposing chain). The rotational adjuster has a push-pull bolt pair setup at the back of the spring to rotate the tip. The blade pivots near its midpoint, so tightening the pulling screw moves the tip away from you while tightening the pushing screw brings it toward you. After each adjustment resuspend to check the alignment. Set the space between the test masses close to 5 mm. The spacing will be fine tuned further down the procedure. When finished, tighten the pusher and puller bolts to lock the blade spring in place and torque the clamp bolts back to 330 in-lbs (27.5 ft-lbs, 37.3 Nm) [6]. The blade spring rotation may need to be tweaked again later on to optically align the test mass, but that will be a quick adjustment if this is done properly first.

5. Before moving onto the optical alignment, double check there are no interferences preventing the suspensions from resting in their natural positions. This includes checking all the stops, all around the tablecloth, and the spaces between the masses. The most rigorous check is to install OSEMs and measure transfer functions; however the OSEMs will likely need to come out again to continue the alignment procedure, since they themselves can introduce interference and at best will need realigning later. Nonetheless, installing one or two OSEMs is not much work and damping loops can make the final yaw alignment go much faster, so the preferred option can be chosen on a case by case basis. Section 8 describes how to install OSEMs.

6. The next two steps concern the optical alignment of the test mass. The main chain test mass should be aligned to within 100 $\mu$Rad in pitch and 10 $\mu$Rad in yaw. Yaw is conceptually the simplest and also the most stable, so it should be done first. Yaw can

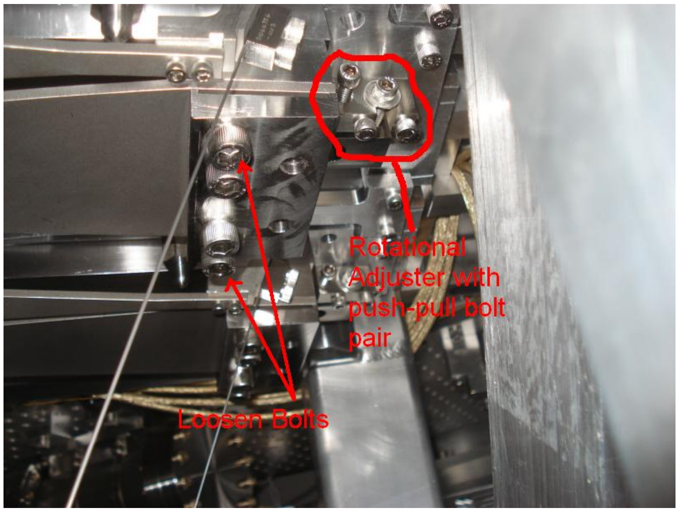

Figure 13: To rotate the top stage blade springs first lock the top mass and then loosen the two outer bolts indicated. The spring rotates by means of the push-pull bolt pair system shown at the back of the spring. The blade pivots near its midpoint, so tightening the pulling screw moves the tip away from you while tightening the pushing screw brings it toward you.

be roughed to 1 mRad by turning the entire structure with a couple of structure pushers anchored to the optics table, see Figure 14. The 5 axis table should be placed under the quad for safety. Using the 5 axis table requires installing the lower structure tooling around the lower structure of the quad. The table should not take the full weight of the quad because the lower structure was not designed to take the full weight of the upper structure (testing shows that it can, but there is a small risk of deforming the structure). The adjustment is done by loosening the dog clamps and adjusting the pushers until yaw is set within 1 mRad. If you do better than 1 mRad at this point you will likely lose it when you tighten the dog clamps. The remainder of the alignment can be achieved by using the top stage spring rotational adjusters. Alternatively, light tapping on the blade tips with a hammer may be sufficient to take up the last mRad. The reaction chain should be aligned such that its test mass is within 5±0.25 mm of the main test mass in yaw and longitudinal. At the time of writing this document the method for measuring this gap is still being reworked. Previously it was simply done with a 5 mm slip gauge or shim, preferentially with some damping loops running. Torque the blade spring bolts with the torque wrench up to 330 in-lb (27.5 ft-lbs, 37.3 Nm) [6].

7. A note about pitch hysteresis: pitch has the added complication of a hysteresis problem related to the wires which will cause the pitch alignment to drift. The sizes of the drifts are proportional to the amplitude of mass oscillations and inversely proportional to damping time. Thus, if the quad is given a large bump where the masses repeatedly bang into the stops and each other, the pitch alignment may find a new equilibrium which will need to be adjusted. For similar reasons, damping loops should not be used while making pitch adjustments. Small drifts can be removed by allowing the suspension to oscillate freely for a few minutes.

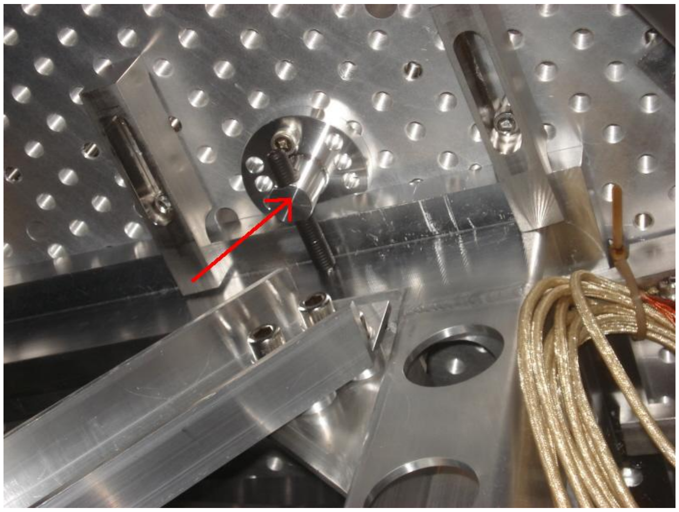

Figure 14: The entire structure should be rotated to further tune the main test mass yaw to within 1 mRad (after the top mass yaw has been aligned to the structure). This photograph shows one of the structure pushers that are useful for rotating the structure. To make this adjustment the dog clamps need to be slightly loosened. The 5 axis table should be placed under the lower structure (with the lower structure tooling) for added safety, however it should not take the full weight of the suspension because the lower structure is not designed to support the weight of the upper structure. To use this adjuster simply bolt it to the optics table with the large bearing tipped screw (black screw in this picture) facing the structure. When the screw is in contact with the structure tighten it to push on the structure [7].

8. To remove any hysteresis effects tap on one of the masses from each chain to set a pitch oscillation of a couple mRad. Allow the oscillation a few minutes to ring down. Pitch should now be close enough to be within range of the fine pitch adjusters. With a flat head screw driver, turn one of the main chain adjusters until pitch is within 100 $\mu$Rad. Because of hysteresis there is no sense in doing better than 100 $\mu$Rad. Adjust the reaction chain test mass to follow. The comments from step 6 on measuring the gap between the test masses apply here as well, with the caveat that damping loops may be undesirable because of the hysteresis problem.

9. Check again that everything is fully suspended.

# 8 OSEMs and Eddy Current Dampers (ECDs)

The experience at LASTI at the time of writing this document is that the clearance between the magnet-flag assembly and the inner bore of the OSEM is extremely tight and the assembly will often make contact with that inner bore. The vertical OSEMs on top of the tablecloth are most likely to present trouble since it is difficult to see inside the bore. Thus, they should be the last OSEMs installed and the first suspected for interference. New OSEMs with larger bores will be in use by the time assembly at the sites begins, which will alleviate this concern somewhat.

This section is also where it will be most obvious how well the previous steps have been done. If everything went carefully and smoothly, this section should not pose a problem. If not, the OSEMs will not have enough range and it may be necessary to repeat some earlier steps.

1. Plug in the 12 top mass OSEMs. Organize them, so that all the serial numbers appear in the same order as the OSEMs do in the software, and ideally make sense spatially on the quad. This will make life much easier if OSEMs need to be repeatedly removed and replaced. Make a note of all the DC open light voltages. They will need to be aligned to their respective midpoints later.

2. Starting with one at a time, install the OSEMs and zero them out ($< 2\%$ of the open light voltage). This step will involve both the axial adjustment of the OSEM and lateral adjustment of the mounting plate using the copper cams. Zeroing them makes sure they are aligned correctly with respect to the flag. Try to keep the ECD magnets centered when adjusting the OSEM plates. Also, keeping them at zero until all the OSEMs are in makes it more obvious when one of them begins to touch a magnet or flag since the voltages will tend to shift away from zero when this happens.

3. Once all the OSEMs are in and zeroed, bring them out to half their respective maximum voltages.

4. Measure transfer functions to ensure that there is no interference anywhere on the suspension. Make reference transfer functions for comparison later. Appendix B provides sample transfer functions.

5. Install the copper ECDs. The pin in the center of each 4 magnet group is designed such

that it will hit the ECD before the magnets do. Consequently, it functions as both a stop and a check on the ECD alignment. This step is at the end of the procedure because damping is one of the signs for interference (such as a rubbing stop). The ECDs also introduce an additional source of interference. Thus, it will be easier to install these once everything else is taken care of first.

6. Measure transfer functions again to check that the ECDs are functioning properly.

# A Useful Balancing and Alignment Data

Table 1 contains a summary of useful data needed to meet the alignment requirements for the metal suspension. Most of these parameters also apply to the glass suspension, those that do not are labeled with a * or **.

| **Parameter** | **Measurement** |
|---|---|
| UI blade spring tip height [3] | 12 mm |
| UI blade spring lateral position [3] | 5 mm |
| UI blade spring clamp bolt torque [6] | 100 in-lbs (8.3 ft-lbs, 11.3 Nm) |
| Top mass blade spring tip height [3] | 6.6 mm |
| Top mass blade spring lateral positions [3] | 5 mm |
| Top mass blade spring clamp bolt torque [6] | 330 in-lbs (27.5 ft-lbs, 37.3 Nm) |
| Top stage blade spring clamp bolt torque [6] | 330 in-lb (27.5 ft-lbs, 37.3 Nm) |
| Main chain test mass pitch * | ±100 $\mu$Rad |
| Main chain test mass yaw [4] | ±10 $\mu$Rad |
| Reaction test mass to main test mass ** | 5±0.25 mm around the circumference |

Table 1: Table of useful balancing and alignment parameters. All the blade spring measurements are relative to the references discussed in Section 6. * The glass test mass pitch tolerance is ±10 $\mu$Rad [4]. ** The glass reaction test mass still needs to be spaced 5±0.25 mm from the main test mass, however the parallelism requirement tightens to ±100 $\mu$Rad [4].

# B Sample Transfer Functions

Figure 15 illustrates the coordinate system referenced in this document and used in the following transfer functions in Figures 16 through 21. These transfer functions make good initial references while checking for interferences and debugging. Each suspension should eventually have a set of its own reference transfer functions. All the transfer functions here are measured only from the main chain since the reaction chain is nearly identical.

The preference for measuring transfer functions on the quad at LASTI has been to use either a white noise excitation or a Schroeder multi-sine excitation. Both of these methods are broadband and allow the entire interesting spectrum (0.1 Hz to 10 Hz) of the quad to be measured simultaneously. Using these methods, quick transfer functions are measurable in a few minutes or less which provide sufficient detail to search for interferences or debug. The Schroeder multi-sine excitation is the quickest because it injects many known sine waves simultaneously throughout the spectrum, thus providing enhanced coherence over white noise. The sample figures below, with the exception of pitch, were measured with the Schroeder approach (each measured over a few hours). Pitch, Figure 20, was measured with white noise.

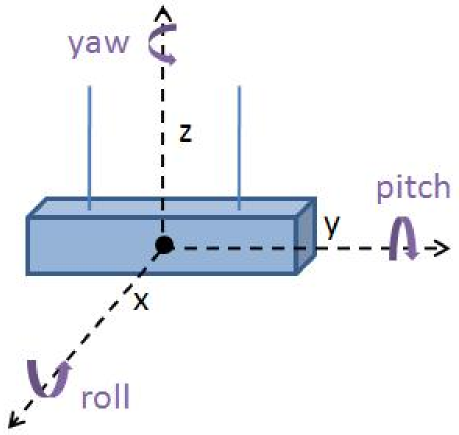

Figure 15: The coordinate system of one of the rectangular masses. All the masses have similar coordinate systems.

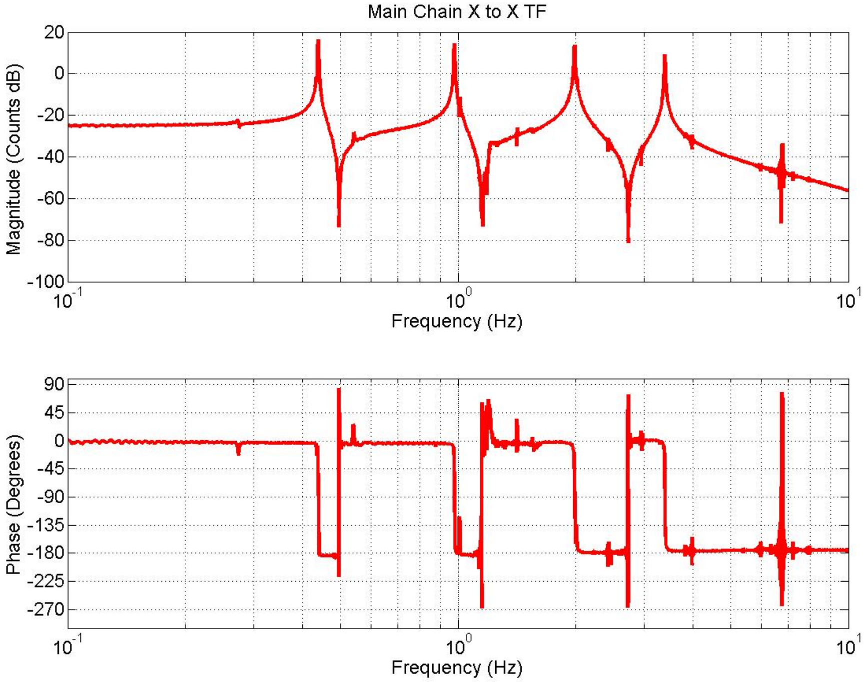

Figure 16: An x to x transfer function from the main chain top mass.

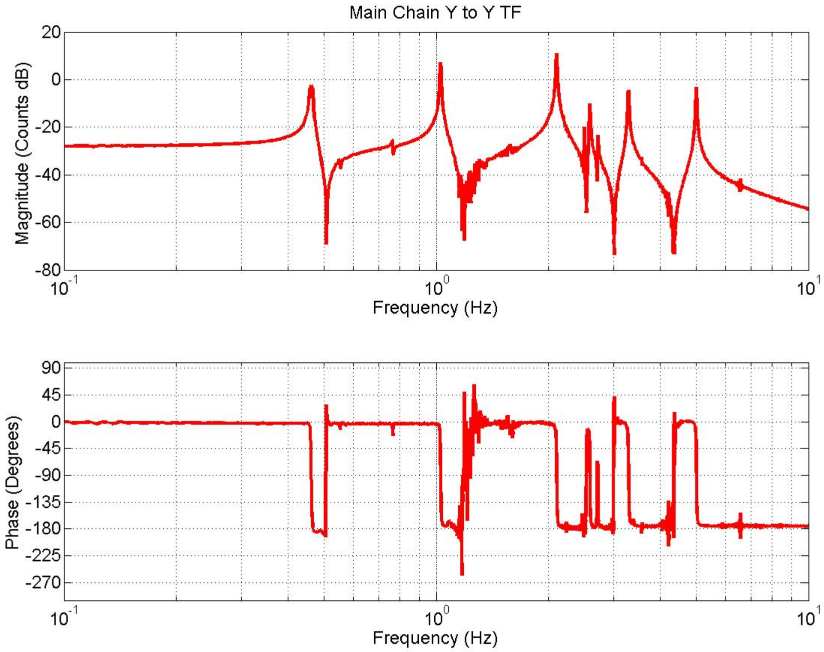

Figure 17: A y to y transfer function from the main chain top mass.

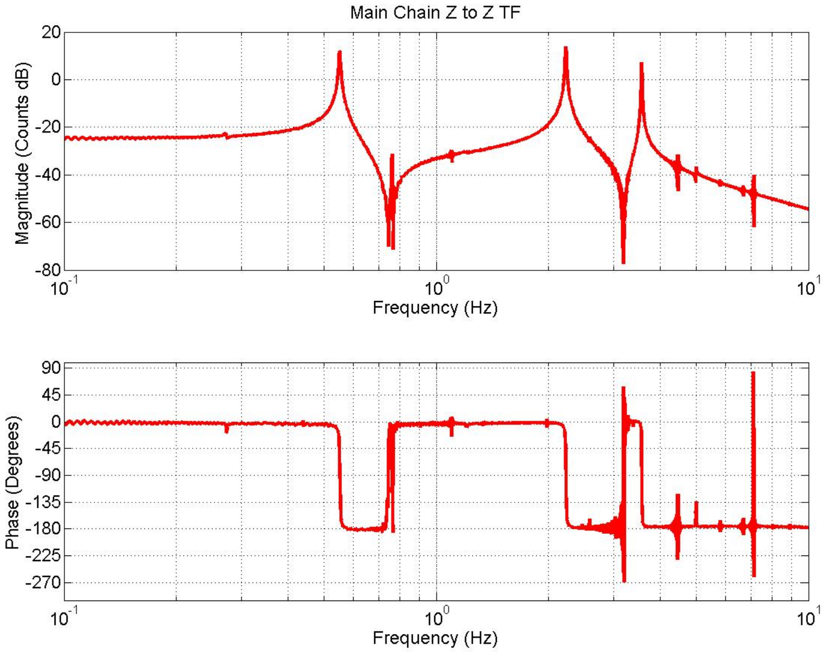

Figure 18: A z to z transfer function from the main chain top mass. The 4th vertical mode is near 17 Hz and is not observable from the top mass. The 4th mode exists mostly as the vibration of the wires between the two round masses.

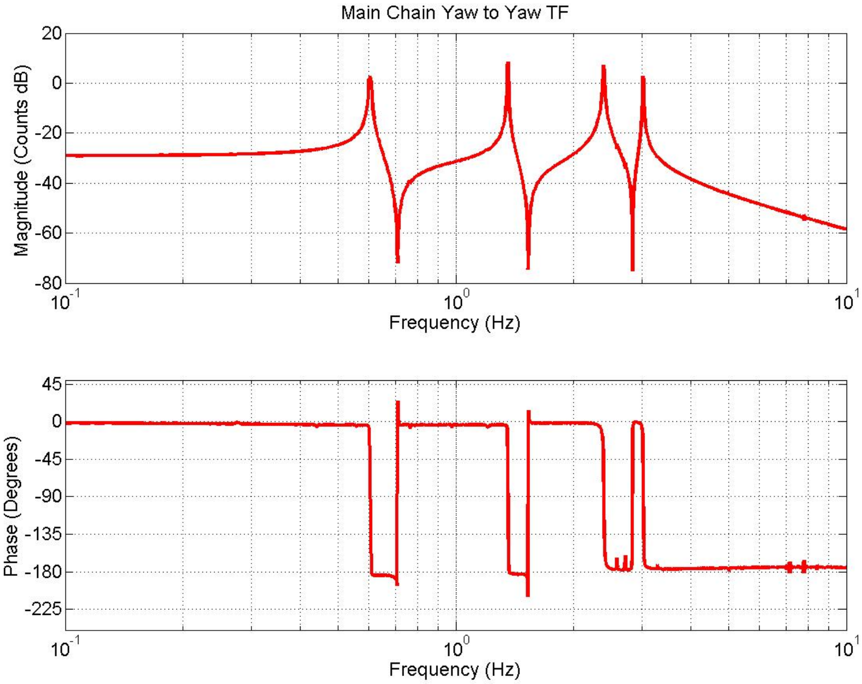

Figure 19: A yaw to yaw transfer function from the main chain top mass.

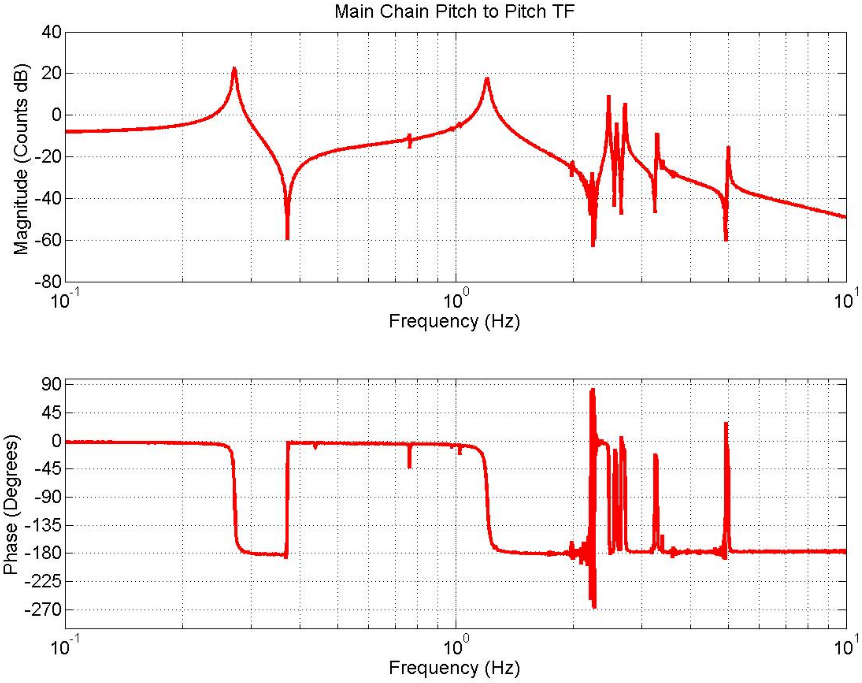

Figure 20: A pitch to pitch transfer function from the main chain top mass.

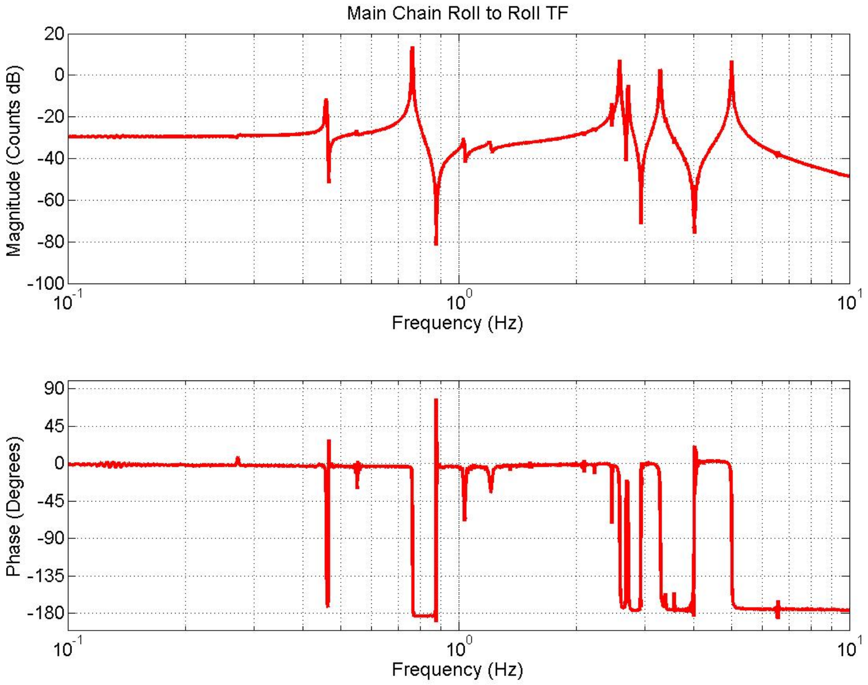

Figure 21: A roll to roll transfer function from the main chain top mass.