LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Observations and Notes on Vibration Absorber Testing

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1 Purpose

The purpose of this technical note is to document and characterize the results of various experiments on the parameters of a vibration absorber, in particular how frequency response varies as the function of viton characteristics and shim displacement between the top and base clamps.

2 Visual Reference for Vibration Absorber Testing

Important locations called out in testing notes are shown below.

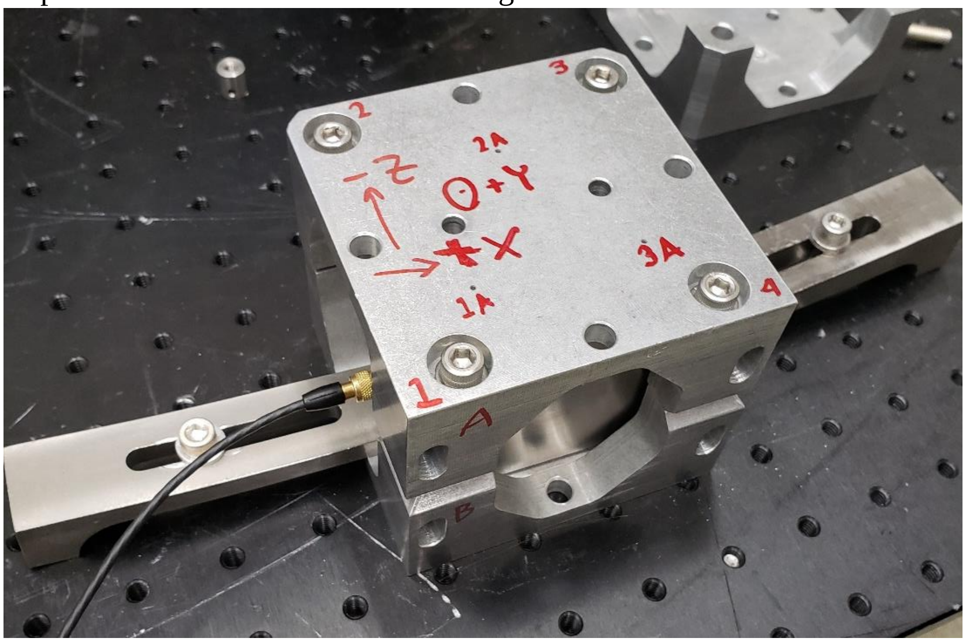


Figure 1. Vibration absorber in test configuration, described below.

In particular, singular numbers alone (1 to 4) refer to features along the height of the screw hole (shims, screws, clamp corner). A/B lettering is used to refer to the clamp part: A for the top clamp (D1002426) and B for the base clamp (D1002425). Number/letter pairing (i.e. 1A, 2B) refer to the vents located on each clamp part and to the viton located directly underneath the vent/in the recesses of the clamp. The axes shown on the top clamp (clamp A) are for reference in attaching the accelerometer (pictured here, connected to the vibration absorber mass). The same reference axis is used throughout vibration absorber measurements to provide a common axis.

2.1 Test Procedures

The vibration absorber was assembled as per the instructions in T1100057 (D1002424 Vibration Absorber Assembly Instructions). Various experimental alterations were done to test the vibration absorber under different parts or conditions, however, and those alterations are noted in Section 3 under each measurement result.

After the vibration absorber was assembled, it was attached to the test table using dogclamps in contact with solely the base frame, as shown in Figure 1; each screw was tightened to 100 in-lbs. After securely fastening the vibration absorber to the test table, the accelerometer was attached to the mass of the vibration absorber (pictured above, attached to the –X face) by applying beeswax to the accelerometer face and firmly pushing it onto the mass. The hammer impact was directed onto the +X face of the vibration absorber, as close as possible onto the center of the face on the mass.

2.2 Example Viton Compression Calculation

To determine the viton compression, we first noted the nominal viton thickness. The nominal height of the vibration absorber assembly is determined by the mass and viton, while height after assembly (when the vibration absorber is compressed) is determined by the shim stack thickness.

+0.300”

(clamp, flat top)

+0.100 to 0.200” (dependent on test)

(viton thickness)

-0.040”

(groove for viton, bored into clamp)

+2.500”

(mass thickness)

+0.100 to 0.200” (dependent on test)

(viton thickness)

-0.040”

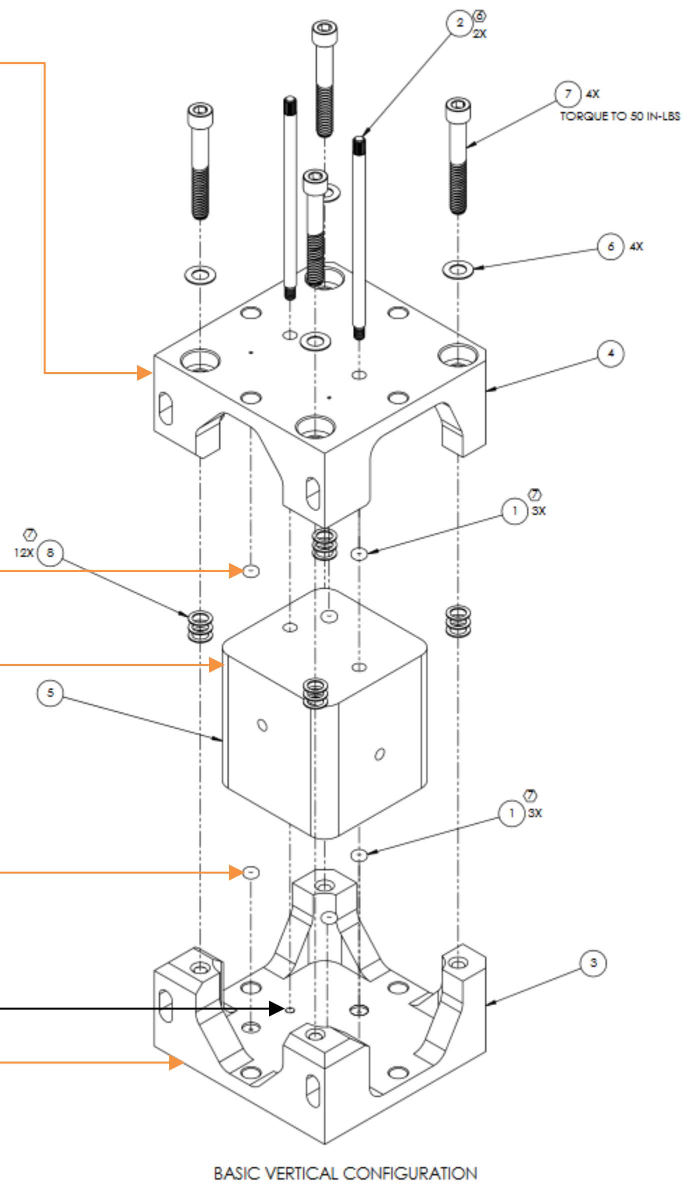
(groove for viton)

+0.300”

(top clamp, flat top)

= 3.22”

vibration absorber height, nominal



Actual measurement post-assembly (prior to tightening) is 3.226” for the nominal viton thickness of 0.100” specified in D1002424-v5, within manufacturing margin of error.

Figure 2. Exploded view of vibration absorber, from D1002424-v5.

Viton compression was determined experimentally, by compressing screws to 50 in-lbs (as in assembly procedure) and taking the height measurement using calipers. By using a shim stack thickness of 0.065", viton compression was measured at

3.226" (uncompressed) – 3.206" (compressed) = 0.020" compression

Compression/total thickness determined that the viton stack was compressed by $0.020/0.200 = 0.10 = 10\%$, in line with testing procedures.

3 Measurements: Replication of Testing Procedure E1200009

3.1 Notes on Results

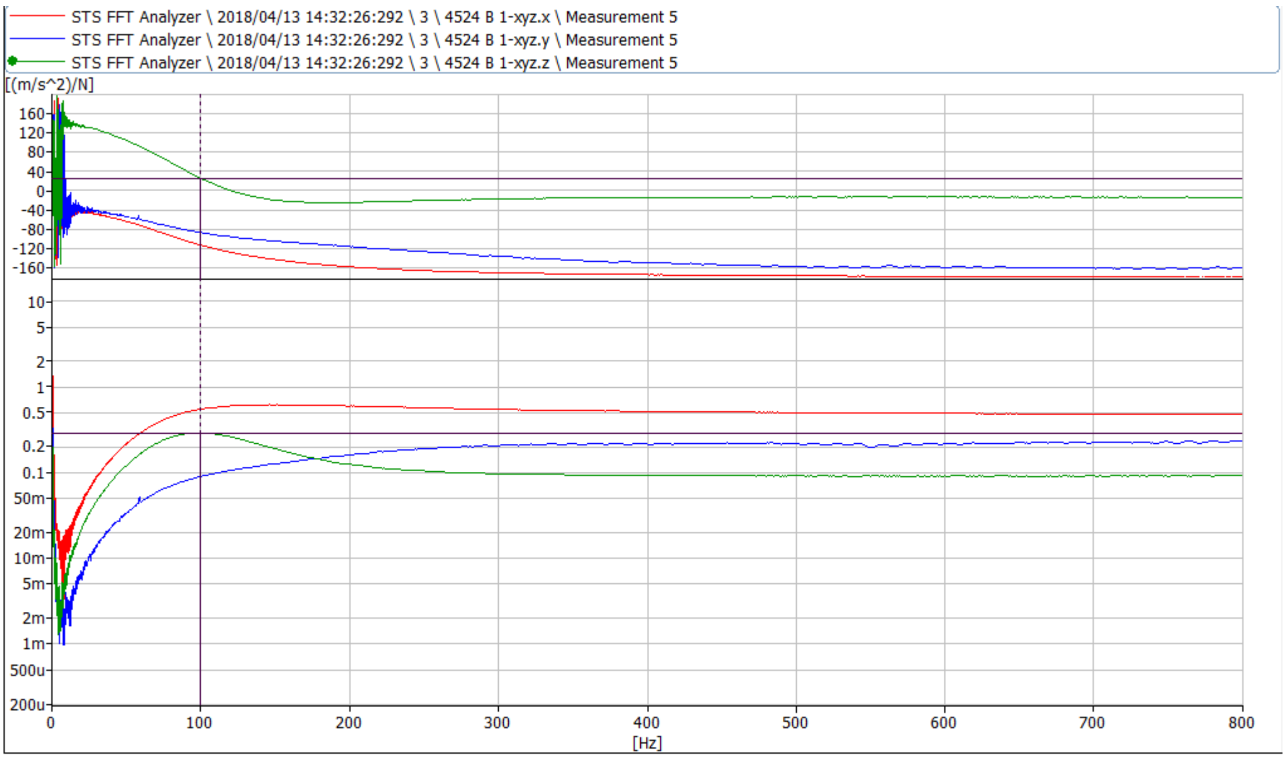


Figure 3. Example frequency response for all three axes. Axes are with respect to those shown in Figure 1; the legend is shown at the top of the figure.

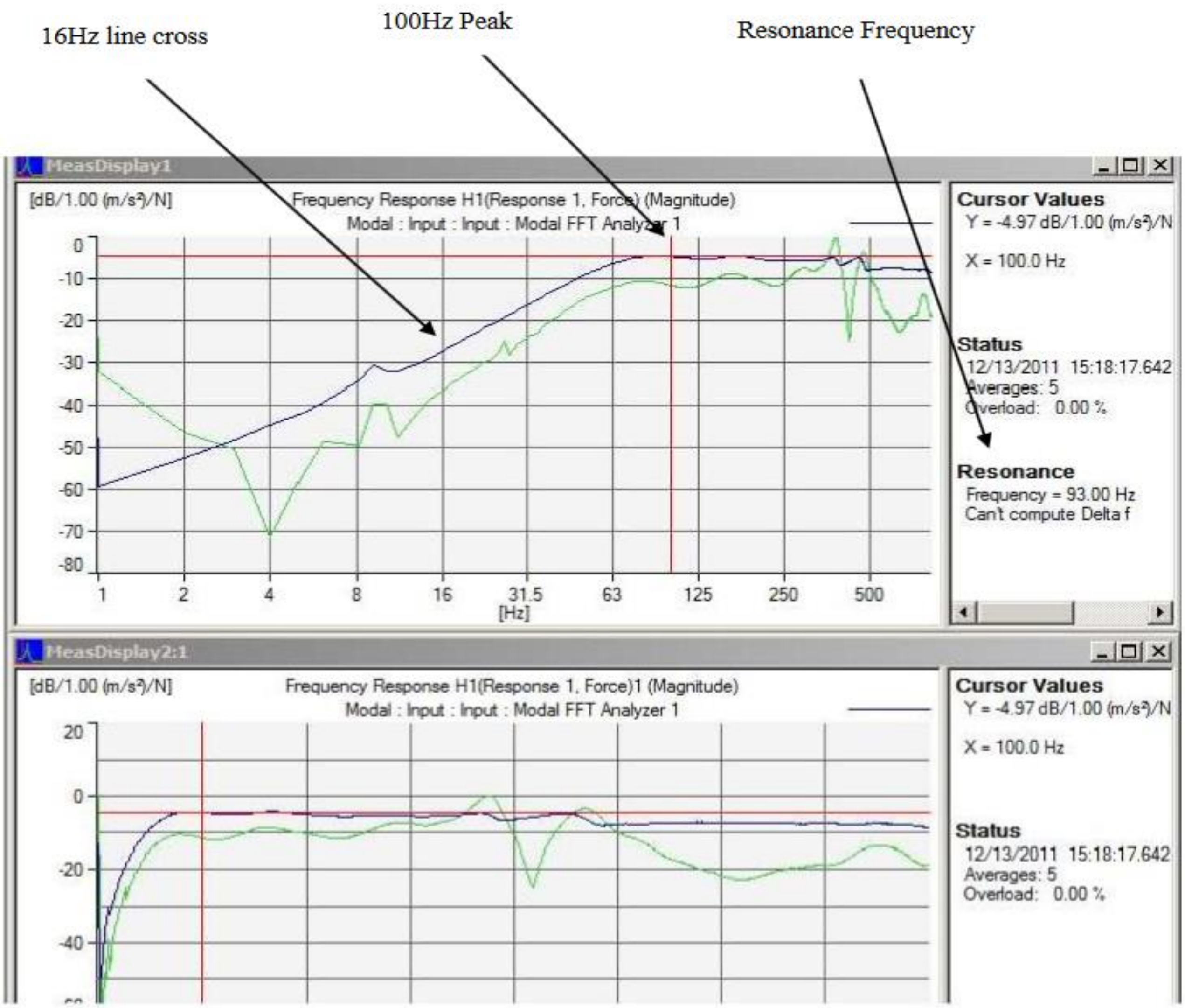


Figure 4. "Figure 4: Sample Results Data File" from E1200009, for reference to results.

All frequency response results shown below this section are cited for the Z-axis frequency response. As shown above in figure 2, only the Z-axis results demonstrated a notable frequency response. Accounting for separate y-axis scaling between our results and those demonstrated in the Testing Procedures, our Z-axis results most closely resembled those shown in E1200009. For detailed results for all measurements below, refer to the “B&K Results - Vibration Absorber with varying shim disp v4.xlsx” and “HSTS damping results v4.xlsx” attached to this LIGO Document.

3.2 Measurements, 04/04/2018

3.2.1 Measurement 1

- non-standard parts used in assembly

  - in particular, shims were non-standard but close to nominal mentioned height in "Vibration Absorber Testing Procedures" (identifier E1200009), 0.065" shim height vs. 0.059" noted in example
  - otherwise, assembly procedure matched T1100057
- initial testing procedure followed E1200009 closely, in attempt to replicate results
  - Hammer impacts measured on average 120-160 N (done via hammer calibration), repeated throughout measurements (unless otherwise stated)
- poor quality average
  - third hit of three-hit sequence likely hit frame – most notable in high-frequency portion of graph ("wobble" in the frequency response)
- despite issues, results roughly agree with test results in E1200009 in identifying ~100-Hz peak in frequency response

3.2.2 Measurement 2

- repeat of measurement 1 without reassembly to test replication
- results agree with measurement 1, E1200009

3.3 Measurements, 04/11/2018

3.3.1 Measurement 3

- Reassembled vibration absorber from 04/04/18, using same procedure as in 04/04/18 (T1100057)
- Frequency response curve drastically different from 04/04 measurements!
  - No "drop-off" in response at high frequencies
- NOTE: shim misaligned at corner 4, jammed between two frame parts but not aligned with screw and hole; fixed "in situ" for measurement 4

3.3.2 Measurement 4

- Taken almost immediately after measurement 3
- Same issue regarding differences in results in measurement 3 vs. prior measurements demonstrated
  - Measurement 4 frequency response looked more like measurement 3 than 1 & 2
  - Suggests mistake in assembly for measurements 3 and 4 (04/11/18)

3.4 Measurements, 04/13/2018

3.4.1 Measurement 5

- Reassembled vibration absorber from 04/11/18, using same procedure as prior assemblies
- Frequency response resembled those of measurements 1 & 2 (taken 04/04/18)
  - Supports hypothesis that there was a heretofore-unseen mistake in assembly, as frequency response matches with prior testing procedure (E1200009) and measurements for which the assembly was well-put-together

   - With that in mind, peak frequency response occurred at slightly lower frequency than before – perhaps some variability with respect to either test hit location or uncontrolled variable?

3.4.2 Measurement 6

- Reassembled vibration absorber from last measurement, as final test of replicability
- Same peak frequency response as Measurement 5, minor change in 3db width response

3.5 Conclusions: Replication of Testing Procedure E1200009

- 4/6 measurements across three different measurement periods demonstrated similar results to those in E1200009
   - Two outlier trials can likely be chalked up to errors in assembly, but worth noting for future procedure
   - Some variability between the four "consistent" trials appeared within peak frequency and 3db width measured – variability appears to be too large to be accounted for by simple chance, something else to keep account of
- Replication of E1200009 occurred despite using non-standardized parts
   - Nominal dimensions were close to what was called out in test procedure, but there is an as-of-now-unproven implication that changes of ~5 thousandths of an inch (0.005") between these measurements and those demonstrated in E1200009 in shim displacement does not drastically change the frequency response
      - Notable because a compression change of 0.005" out of a total 0.010" compression accounts for a ~50% change in viton compression, which would seem to be a major change
   - Peak frequency results from vibration absorber testing were within ballpark range of peak frequency demonstrated in E1200009
      - Peak frequency ranges of 95-110 Hz found via measurements 1-6, compared to peak frequency of 100 Hz demonstrated in Figure 4 of E1200009
      - 3db resonance widths not supplied in E1200009; range of 3db widths varied drastically in above measurements

4 Measurements: Standardized Shims

4.1 Purpose

The purpose of this batch of measurements was to first reassemble the vibration absorbers using standardized shims, to more closely approximate assembly instructions and provide a more standardized control for future vibration tests (Measurement 7-Measurement 10). The next step, after isolating potential disturbances (Measurement 11 – Replication of Measurement 10Measurement 18 – Impact Variation), was to vary the compression from the specified compression in assembly and testing documents to determine the extent to which the primary frequency response of the vibration absorber could be controlled by changing the size of the shim stack between the vibration absorber frames (Measurement 19 – Increased Shim DisplacementMeasurement 22 – Replication of Measurement 21.

4.2 Measurements, 04/18/2018

4.2.1 Measurement 7

- Reassembled vibration absorber from 04/13/18, but used standardized shims, 0.02" thick, instead in each corner
  - Shims from McMaster-Carr, part 93574A513
  - Three shims were used for total displacement of 0.06"/60 thousandths
  - All other parameters (screws, viton) kept constant
- Despite 5 thou difference in shim displacement, frequency response curves looked similar to those in Section 3, with peak frequency response f = 113 Hz and large 3db width (87 Hz)

4.2.2 Measurement 8

- Reassembled vibration absorber, using same shims as in Measurement 7 and same procedure as before
- Similar results as Measurement 7

4.2.3 Measurement 9

- Reassembled vibration absorber, but added additional 5 thou thick shim to all four corners
  - Total shim displacement at each corner ~0.065"/65 thou
  - Additional shim used from McMaster-Carr, part 93574A507
  - As before, all other parameters (screws, viton) kept constant
  - Nominal shim thickness close to that of the first six measurements (1-6), so would expect results close to those trials
- Frequency response similar to above trials in demonstrating ~100-Hz peak

4.2.4 Measurement 10

- Vibration absorber reassembled, no changes implemented
- Peak frequency ~10% lower than in prior trials (~87 Hz versus >100 Hz peaks)
  - No changes implemented, leaving source of frequency drop unknown
- Vibration absorber left in test configuration after measurement concluded, with accelerometer unattached

4.3 Measurements, 04/20/2018

The below set of measurements, done on 04/20, attempted to isolate the cause of the drop in peak frequency response demonstrated in Measurement 10.

4.3.1 Measurement 11 – Replication of Measurement 10

- Vibration absorber in same configuration as in Measurement 10, left to sit on test bed for two days
  - Accelerometer reapplied prior to testing
- Frequency response peak at ~105 Hz, similar to prior tests and established test procedure
  - Possible that there is a temporal aspect to vibration absorber testing? May take time for vibration absorber to "settle" at its natural frequency, given parameters
    - Possible mechanisms may include timespan for viton compression, ???

4.3.2 Measurement 12 – Replication #2 of Measurement 10

- Repeated Measurement #11 parameters
- Similar frequency response peak of ~105 Hz

4.3.3 Measurement 13 – Accelerometer

- Measurement taken after #12, no reassembly
  - Accelerometer was attached as loosely to vibration absorber mass as reasonably possible
  - A piece of foam was left under accelerometer, resting on dog clamp, in order to cushion the accelerometer in case of fall resulting from hammer impact to vibration absorber
- Results similar to test procedure, peak ~100 Hz
  - Third hit in averaged frequency response may be faulty or inaccurate – foam expanded out to contact accelerometer cable during 2nd and 3rd hits, which may have impacted accelerometer response

4.3.4 Measurement 14 – Accelerometer

- Same procedure as Measurement 13, but without foam under accelerometer to cushion potential drop
- Peak frequency response measured at ~110 Hz, about the same as prior measurements

4.3.5 Measurement 16 – Impact Variation

- Vibration absorber left in same configuration, but used hammer calibration menu to attempt impacts at ~40-80 N
- Frequency response demonstrated low coherence, high “wobble” resulting from poor vibration content
  - Estimated peak ~130 Hz, but B&K software could not extract an exact peak

4.3.6 Measurement 17 – Impact Variation

- Vibration absorber left in same configuration, but used hammer calibration menu to attempt impacts >200 N
  - Side effect of high-force impacts was a translation of the vibration absorber mass, especially for impacts >300 N
    - Impacts that noticeably translated central mass were deleted and the mass “forced” back into its normal configuration manually (via pushing mass with fingers), which may have introduced errors
- Peak frequency response measured at ~90 Hz, similar to that encountered in Measurement 10
  - “Impact variation” as cause of peak frequency response drop unlikely however, as average force measured through accelerometer in Measurement 10 agreed with prior measurements (#1-9) at ~160 N, compared to average of 360 N in this measurement

4.3.7 Measurement 18 – Impact Variation

- Vibration absorber left in similar configuration, save for potentially shifted mass as a result of Measurement 17

- Peak frequency response ~90 Hz
  - Response measured with average applied force of ~240 N, in between both measurements with similar frequency response (measurement 10: F~160 N, measurement 17: F~360 N)

4.4 Measurements, 04/30/2018

4.4.1 Measurement 19 – Increased Shim Displacement

- Reassembled vibration absorber, added 0.005" shim to previous baseline for total of 0.070" nominal shim displacement
  - Goal to determine if decreasing viton compression (done by increasing shim stack size) would provide additional frequency shift downward
  - Viton compression measured at 0.005" (5% compression)
- Peak frequency response ~90 Hz

4.4.2 Measurement 20 – Replication of Measurement 19

- Reassembled vibration absorber, preserved shim stack heights
- Peak frequency response ~90 Hz
  - Good evidence that vibration absorber finding is consistent
  - More data required (more replications) to determine if ~90 Hz is the "floor" for given viton
  - The decreased compression of the viton appeared to have shifted the peak frequency response of the vibration absorber to a consistent 90 Hz
    - In comparison, all non-outlier measurements beforehand with a shim stack height of 0.065" varied from a low peak frequency response of 90 Hz to a high of ~130 Hz

4.5 Measurements, 05/02/2018

4.5.1 Measurement 21 – Decreased Shim Displacement

- Reassembled vibration absorber, took out shims (to increase compression) for total nominal stack height of 0.055"
  - Stack height corresponded to measured viton compression ~0.030" (15% compression)
  - Measurement done to test theoretical understanding – expected that increased compression should increase peak frequency response
- Peak frequency response ~140 Hz
  - Confirms general trend that increasing compression => higher peak response

4.5.2 Measurement 22 – Replication of Measurement 21

- Reassembled vibration absorber, preserved shim stack heights
- Peak frequency response of ~135 Hz
  - Not significantly different from prior trial

4.6 Conclusions

- Peak frequency response for compression between 5%-10% varied between 90-110 Hz, with outlier at 130 Hz
    - Typical 3db width ranged from 70-100 Hz, resulting in typical Q values between 1.0 and 1.6
    - Outlier results attributed to low vibration content due to low-intensity hammer impacts
    - Best possible explanation for variation in peak response currently may be due to variations introduced via assembly and experimental procedure between measurements
        - Imprecisions in assembly can be introduced via imprecision in viton O-ring settlement into clamp grooves (likely primary issue in assembly)
        - Experimental procedure imprecision may arise from dogclamp positioning, accelerometer wiring & attachment, vibration absorber mass translation
- Increased compression of ~15% led to increased frequency response around 140 Hz
    - To be expected, but results were a good check
- Measurement 19 – Increased Shim DisplacementMeasurement 20 – Replication of Measurement 19 demonstrated a consistent peak frequency response at 90 Hz using a lower compression (~5%) on the vibration absorber
    - In comparison, measurements done at a higher viton compression value (~10%, Measurements 1-18) demonstrated variability in peak frequency responses, from a low of 90 Hz to a high of ~130 Hz
    - Seeming confirmation that decreasing compression can lead to a decrease in the primary frequency response of the vibration absorber (and vice versa for increasing compression)

5 Measurements: Viton Variation

5.1 Purpose

The purpose of this batch of measurements was to determine the extent to which the peak frequency response of a vibration absorber could be varied by changing the dimensions and parameters of the viton in use. By pairing the effect of any viton variation with decreasing compression via shim stack size variation, we sought to determine a minimum peak frequency response for a vibration absorber unit.

5.2 Measurements, 05/02/2018

5.2.1 Measurement 23 – Change in Viton

- To test variability in vibration absorber performance, the viton used was swapped out
    - New viton had dimensions: 1/8” ID x ¼” OD x ~0.060” thickness (part #93412A401, McMaster-Carr)
    - Began with shim stack height of 0.003”, to account for difference in thickness versus old viton (thickness 0.100”), and to start at low baseline
- Compression was negligible (within measurement error of calipers) – impossible to measure whether or not viton was compressed

  - For completeness' sake, compression was measured at 0.0010" – within variation of caliper measurement
- Peak frequency ~200 Hz
  - Due to viton's small thickness and difficulty measuring compression, decided not to further pursue using this viton

5.2.2 Measurement 24 – Double-Stacking Viton

- In attempt to simulate increased viton thickness and consequently decrease the vibration absorber peak frequency, two pieces of viton were "taped together" and stacked one on top of the other using double-sided tape (see Figure 5)
  - Viton used was part #9464K107, McMaster-Carr
  - Tape had side effect of "fixing" viton to the grooves carved into each frame part via attaching to frame – potential effect on results if tape interacts with vibration absorber properties
  - Shim stack height 0.120" nominal – no criterion for using stack height
- Compression of viton stack difficult to assess
  - Nominal compression of 0.1400" measured for ~30% compression ratio
  - However, viton did not end up in straight stack, so the expected viton thickness = 2*L was likely smaller in reality; however, viton "slanting" (see Figure 6) may have reduced effective cross-sectional area that the vibration absorber frame compressed, potentially reducing overall peak frequency
  - spring constant k = A/L, so lower area and lower L "effects" may cancel out
- Peak frequency ~160 Hz

5.3 Measurements, 05/04/2018

5.3.1 Measurement 25 – Double-Stacking Viton, Increase Shim Stack Displacement

Figure 5. Viton stack, attached using double-sided tape.

- As shown before, decreased compression also decreased peak frequency response – wanted to determine size of effect on new viton stack by increasing shim stack displacement
  - Shim stack height increased to 0.200" nominal height
- Peak frequency ~57 Hz
  - Noticeable decrease, very promising result for decreasing frequency response
  - 3db width of ~40 Hz, for a Q ~ 1.5
  - Cause for potential concern: as noted in Measurement 24 observations (section 5.2.2), viton shifted during assembly and testing, meaning that effective thickness was likely lower than expected

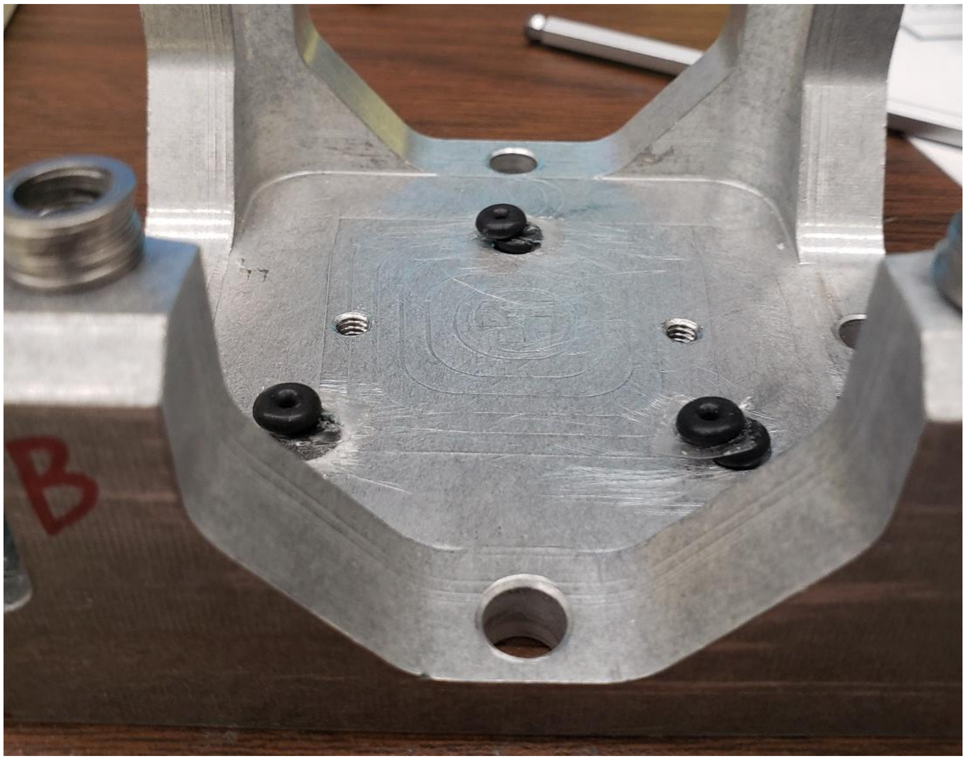


Figure 6. Viton not perfectly aligned after testing. Picture taken after measurement 24.

5.3.2 Measurement 26 – Replication of Measurement 25

- Reassembled vibration absorber, shifted viton pieces to attempt to line them up with each other and the groove (to increase effective thickness)
- Peak frequency ~57 Hz
    - In close agreement with measurement 25

5.4 Measurements, 05/11/2018

5.4.1 Measurement 27 – Increased Viton Thickness, One Piece

- Reassembled vibration absorber, used newly-fabricated viton pieces from viton fluoroelastomer rubber rod, 36" long (part # 9029K12), with nominal thickness ~0.206" (actual lengths in Appendi)
- Compression of vibration absorber ~23.5%
- Peak frequency response ~90 Hz

5.4.2 Measurement 28 – Replication of Measurement 27, with Decreased Compression

- Reassembled vibration absorber, decreased compression from ~23.5% to ~12.7%
- Peak frequency response ~ 60 Hz
    - Results as seen before with Measurements 25 & 26, similar 3db width, Q ~ 1.5

5.4.3 Measurement 30 – Replication of Measurement 28

- Reassembled vibration absorber, with similar parameters as Measurement 28
- Peak frequency response ~60 Hz, Q ~ 1.5
  - Very good replication, will proceed using currently set-up cube on HSTS

5.5 Measurements, 05/18/2018

Note: vibration absorber measurements taken today were done in tandem with B&K measurements of the HSTS structure.

5.5.1 Measurement 24 (HSTS) – Replication of T1100494

- Observed that T1100494 posits potential peak frequency minimum for standard-size viton O-rings (0.100" thick) of f ~ 35 Hz
  - Reassembled vibration absorber, used viton O-rings ~0.106" thick with shim stack thickness ~0.090"
  - Compression measurements unreliable, but linear estimate of compression dictate that vibration absorber is lightly compressed (~0-1%)
- During testing, assembly pins were screwed into the vibration absorber to avoid mass shifting
  - Observed that even light taps (~30-50 N) would cause mass to shift, likely consequence of light compression
- Peak frequency f ~ 52 Hz

5.5.2 Measurement 25 (HSTS) – Second Replication of T1100494

- Same assembly and testing procedure as Measurement 24, with assembly pins taken out
- During testing, noted that mass shifted as a result of hammer impacts (~50 N)
- Peak frequency ~ 36 Hz
  - Despite promising result, this minimum bound frequency is likely unworkable, as the vibration absorber mass would constantly shift at the slightest impacts

5.5.3 Measurement 26 (HSTS) – Reassembly with 2x Thick Viton

- Reassembled vibration absorber, using 2x thick viton pieces cut from viton tubing again (nominal thickness ~ 0.206")
  - Shim stack height nominal 0.270", using standardized shims this time (as opposed to array of shims found in lab prior)
- Peak frequency response ~ 51 Hz
  - Noticeable drop over peak response observed around 60 Hz prior (Measurements 27, 28, 30) but cannot read too much into single test

5.6 Measurements, 05/23/2018

5.6.1 Measurement 36 (HSTS) – 2x Thick Viton, Increase Shim Stack Size

- Inspired by the results in T1100494 and Measurements 24-26 (HSTS), we sought to increase the shim stack size with the 2x thick viton (nominal thickness ~ 0.206") to determine a lower bound for the peak frequency response of the vibration absorber

    - Interested in this case as a pattern – is it possible to push the "lower bound" peak frequency response using thicker viton pieces to cushion the vibration absorber mass?
- Shim stack maximum for 2x thick viton for reliable testing determined to be 0.290"
    - Further increases in the shim stack height uncoupled the mass from the top frame of the vibration absorber; the theoretical maximum for bare contact between the viton and the top frame should be ~0.320" (viton thickness – groove height = ~0.400" – 2*0.080" = ~0.320") but this condition is untenable for testing (see Measurement 25 (HSTS) notes)
    - Note that at this compression (which was negligible via direct measurement), vibration absorber mass would shift at slightest hammer impact, indicating that it was not well-coupled to the frame
- Peak frequency response ~ 33 Hz
    - A slight decrease over the best results from Measurements 24-26 (HSTS), where a similar "lower bound" test achieved a peak response at ~ 36 Hz
    - Apropos of further testing, a peak frequency response of ~ 30 Hz at minimum compression appears to be the absolute lowest response that the tested vibration absorber can achieve
        - However, due to experimental issues, this limit is impractical for any outside use

5.7 Conclusions

Vibration absorber testing has effectively replicated multiple LIGO Document results. In addition, testing has shown that the standard vibration absorber peak frequency response can be tuned from 50 Hz to over 150 Hz by changing various parameters such as the viton and shim stack height. This "effective tuning range" can greatly expand the utility of the vibration absorbers, but further testing should be conducted to probe damping quality at peak frequencies outside of the standard build.

The replication of LIGO Document T1100494 with two different sets of viton (of different dimensions) has pointed to a potential minimum peak frequency of ~35 Hz. However, the vibration absorber was difficult to handle and would shift under any impact, making this limit unsustainable for any practical use.

6 HSTS Testing

6.1 Purpose

The purpose of implementing tests using the HSTS was to investigate the damping of a structure with a resonance of 30 Hz. The ultimate goal was to determine how effectively vibration absorbers could damp "far-field" resonances (i.e. those further away from its designed primary frequency) for other experimental applications. In these tests, a peak frequency of 30 Hz was targeted as an appropriate "far-field" frequency resonance.

The nominal first resonance of the HSTS is about 60 Hz. In order to decrease its resonance to 30 Hz, masses summing up to 40 kg were added to the structure (as shown in the following figures) to achieve a first resonance peak of ~30 Hz.

NOTE: There are two accelerometer configurations used in the below tests. Each measurement will also state the accelerometer configuration during testing – the referred axes' meaning will differ depending on the given configuration!

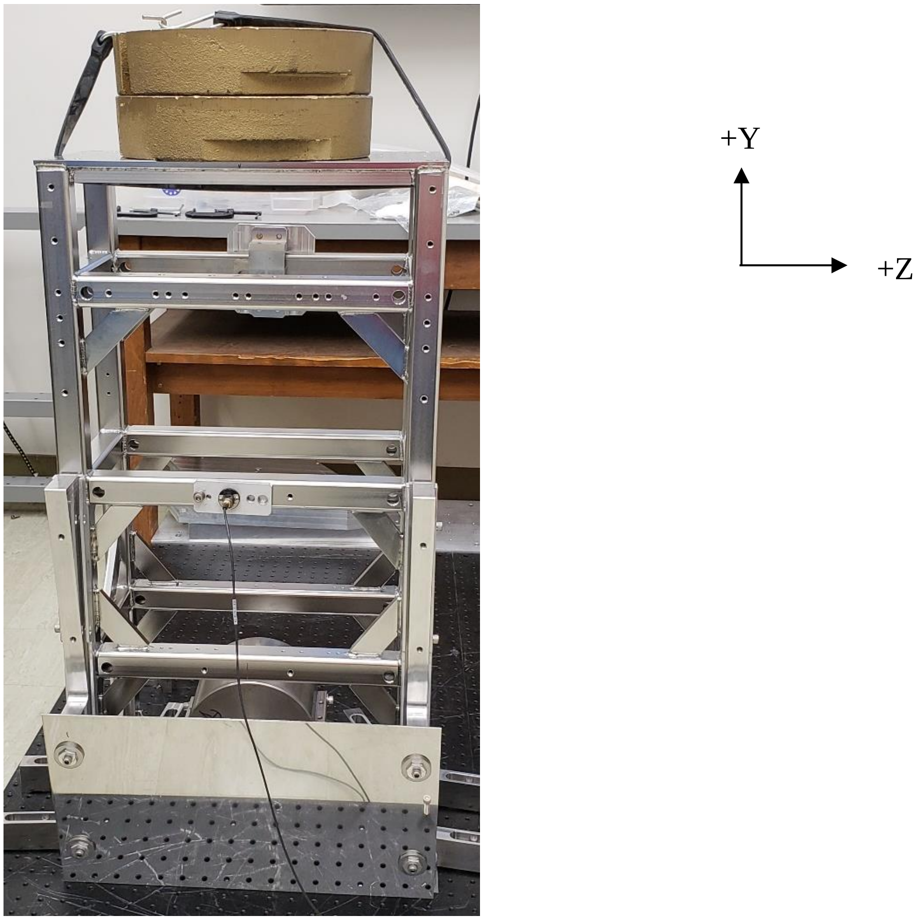


Figure 7. Experimental setup for HSTS testing. 2 20-kg masses (brass) are mounted on top of the HSTS during testing by a bungee cord. The accelerometer (middle) is attached via a mounting plate above; in some trials, the accelerometer is instead attached via beeswax to the beam directly above it. The accelerometer axes are shown beside the figure for the given configuration - +X is into the plane of the page. This configuration will be referred to as "Accelerometer Config 1."

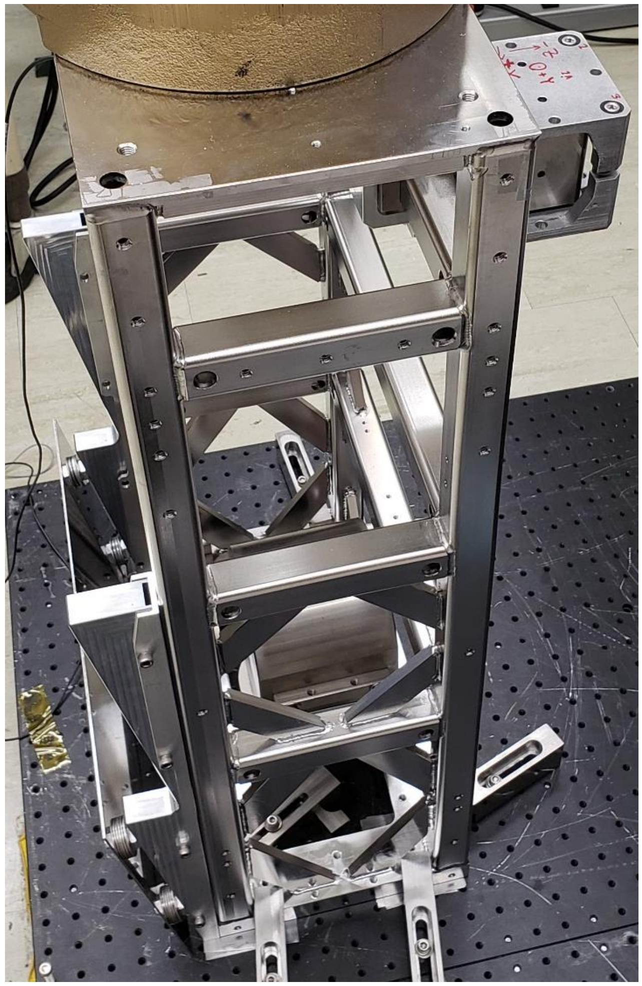


Figure 8. Side view of configuration in Figure 7. The vibration absorber is attached to the back of the HSTS – the plate can be seen in Figure 7.

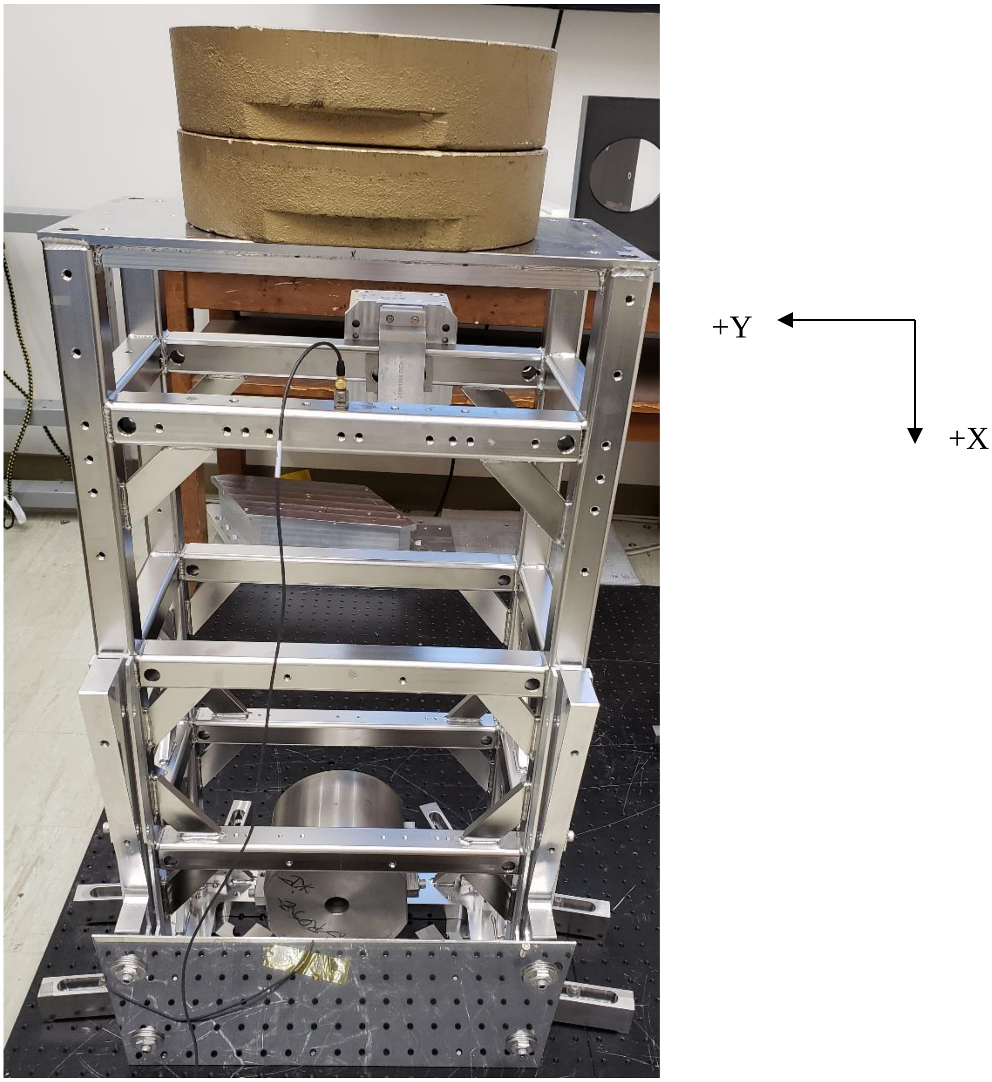


Figure 9. Experimental setup for HSTS testing, with accelerometer attached to the structure directly via beeswax. Axes in this configuration are displayed to the side; the +Z axis points into the plane of the page. This configuration will be referred to in shorthand as "Accelerometer Config 2."

6.2 Measurements, 05/14/2018

6.2.1 Measurement 1 – HSTS, No Vibration Absorber, 40 kg Mass

- Initial test on HSTS to observe qualitative response without damper, but with vibration absorber plate and accelerometer plate attached – see Figure 7 & Figure 8
- Frequency resolution for B&K analysis set to 1/8 Hz (0.125 Hz) and used throughout testing
- HSTS hit in –Z direction, near top of structure (accelerometer configuration 1)
- Peak frequency response (X-axis) = 29.25 Hz, 3db = 0.445 Hz

6.2.2 Measurement 3 – No Vibration Absorber, 40 kg Mass

- HSTS set up in same configuration as Measurement 1

  - Accelerometer configuration 1
  - HSTS hit in +X direction, on beam directly above accelerometer mounting plate
- Peak frequency response (Z-axis) = 35.75 Hz, 3db = 1.070 Hz
  - Difference in response between axial direction being examined (and potentially impact direction as well)

6.3 Measurements, 05/16/2018

6.3.1 Measurement 19 – No Vibration Absorber, 40 kg Mass

- 2 20-kg masses placed on top of HSTS without supporting bungee cord (see Figure 9)
- Accelerometer mounted with beeswax in lieu of mounting plate
  - Accelerometer config 2, hammer impact on +Z face
- Peak frequency response (Z-axis) = 28.813 Hz, 3db = 0.538 Hz
  - Virtually no change in frequency response

6.3.2 Measurement 20 – Vibration Absorber, 40 kg Mass

- Same configuration as Measurement 19, but with vibration absorber attached to back of HSTS
  - Accelerometer config 2, hammer impact on +Z face
  - Vibration absorber operating at primary frequency f ~ 60 Hz (see **5.4.3**: Measurement 30 – Replication of Measurement 28, Vibration Absorber Testing)
- Peak frequency response (Z-axis) = 28.438 Hz, 3db = 0.618 Hz
  - Poor damping even with vibration absorber attached to HSTS
  - Comparison of loss factors between **6.3.1**: Measurement 19 – No Vibration Absorber, 40 kg Mass and **6.3.2**: Measurement 20 – Vibration Absorber, 40 kg Mass finds that $Q_{vib,loss}$~325, corresponding to poor performance (see Appendix B: Calculations of Loss for details)

6.3.3 Measurement 21 – Vibration Absorber, No Mass

- 2 20-kg masses removed from top of HSTS, with vibration absorber still mounted
  - Accelerometer config 2, hammer impact on +Z face
  - Vibration absorber configured for 60 Hz peak resonance (from **5.4.3**: Measurement 30 – Replication of Measurement 28)
- Peak frequency response (Z-axis) = 59.375 Hz, 3db = 7.034 Hz, Q = 8.44

6.3.4 Measurement 22 – No Vib. Abs., No Mass, No Clamp

- 2 20-kg masses absent from HSTS top; no vibration absorber mounted; all extraneous parts removed from HSTS
  - Interested in only HSTS flagpole resonance, to compare to **6.3.3**: Measurement 21 – Vibration Absorber, No Mass
  - Accelerometer config 2, hammer impact on +Z face
- Peak frequency response (Z-axis) = 63.313 Hz, 3db = 1.724 Hz, Q = 36.7
  - Notable decrease in 3db resonance width resulting from taking off vibration absorber
  - Loss factor associated with vibration absorber as a results of Measurements 21 and 22 (**6.3.3** and **6.3.4**) show $\phi_{vib} = \frac{1}{10.96}, Q_{vib,loss} = 10.96$

    - Substantial increase in performance associated with closer resonance frequencies between vibration absorber and HSTS (no masses)

6.4 Measurements, 05/18/2018

6.4.1 Measurement 27 – No Vibration Absorber, No Mass

- HSTS-only test, with no masses or extraneous parts attached
  - Accelerometer config 2, hammer impact on +Z face
  - Repetition of **6.3.4**: Measurement 22 – No Vib. Abs., No Mass, No Clamp (HSTS), done as a starting test to compare with future attached vibration absorber HSTS resonance
- Peak frequency response (Z-axis) = 63.125 Hz, 3db = 1.876 Hz, Q = 33.64
  - Parameters virtually unchanged from prior HSTS test

6.4.2 Measurement 28 – Vibration Absorber, No Mass

- HSTS test with vibration absorber from Measurement 26 – Replication of Measurement 25 attached
  - Accelerometer config 2, hammer impact on +Z face
- Peak frequency response (Z-axis) = 60.438 Hz
  - Noisy peak frequency response data precluded automatic collection of 3db resonance width – repeated trial to attempt to collect less noisy data

6.4.3 Measurement 29 – Replication of Measurement 28

- Direct repetition of Measurement 28 immediately following its completion
  - Accelerometer config 2, hammer impact on +Z face
- Peak frequency response (Z-axis) = 60.188 Hz, 3db = 8.866 Hz, Q = 6.79
  - Loss factor for vibration absorber $\phi_{vib} = \frac{1}{8.5}, Q_{vib,loss} = 8.5$
  - Similar analysis to Measurement 22 – No Vib. Abs., No Mass, No Clamp; vibration absorber effectively damped out nearby resonance frequency

6.4.4 Measurement 30 – Vibration Absorber & 40 kg Mass

- 2 20-kg masses added to top of HSTS, in addition to already-attached vibration absorber (from Measurement 26 – Replication of Measurement 25)
  - Direct comparison to Measurement 20 – Vibration Absorber,
  - Accelerometer config 2, hammer impact on +Z face
- Peak frequency response (Z-axis) = 28.06 Hz
  - Peak data too noisy to recover 3db width data, even via manual calculation

6.4.5 Measurement 31 – Replication of Measurement 30

- Direct repetition of Measurement 30 immediately following its completion
  - Accelerometer config 2, hammer impact on +Z face
  - Attempt to collect cleaner data
- Peak frequency response (Z-axis) = 28.563 Hz
  - As in previous measurement, peak data too noisy to effectively collect 3db width data

6.4.6 Measurement 32 – Second Replication of Measurement 30

- Direct repetition of Measurement 30 immediately following Measurement 31
  - Accelerometer config 2, hammer impact on +Z face
  - Third attempt to collect cleaner data
- Peak frequency response (Z-axis) = 28.813 Hz, 3db = 0.862 Hz
  - Broader peak than expected from previous trials, almost doubled width compared to last comparable trial (see Measurement 20 – Vibration Absorber, 40 kg Mass for direct comparison)
- Recurring issue between Measurements 30-32 of noisy measurement data from B&K system
  - Potential culprits: poor coupling between vibration absorber and HSTS; unsettled masses resting on top of HSTS

6.4.7 Measurement 33 – No Vibration Absorber, 20 kg Mass

- Only 1 20-kg mass resting on top of HSTS; no vibration absorber resting on structure
  - Measurement done as an attempt to isolate source of noise
  - Accelerometer config 2, hammer impact on +Z face
- Peak frequency response (Z-axis) = 38.750 Hz, 3db = 0.921 Hz
  - Peak frequency about expected for given mass
- After measurement, 2 20-kg masses left resting on top of HSTS

6.5 Measurements, 05/23/2018

6.5.1 Measurement 34 – Replication of Measurement 30 w/o Vibration Absorber

- Moved 2 20-kg masses off of HSTS and placed them back on, in attempt to mitigate noise in measurement again
  - Accelerometer config 2, hammer impact on +Z face
- Peak frequency response (Z-axis) = 27.625 Hz, 3db width = 80.09*10^-3 Hz, Q = 345
  - Very sharp peak despite functionally little change in experimental layout

6.5.2 Measurement 35 – 40 kg Mass Bound to HSTS

Figure 10. 2 20-kg masses bound to HSTS via large clamp. A small plate (not shown) was placed between the bottom part of the clamp and the HSTS to more securely fasten the clamp to the structure.

- Replicated setup of Measurement 34, but bound masses to HSTS using large clamp (seen in Figure 10)
  - Accelerometer config 2, hammer impact on +Z face
- Cleaner peak, but clamp seemingly introduced its own resonance into frequency response (seen around 20-30 Hz in broad peak)
  - The large clamp eliminated noise from the frequency response but introduced its own effects into the data (see next point)
- Peak frequency response (HSTS, Z-axis) = 30.250 Hz, 3db width = 1.722 Hz, Q = 17.57

- Clamp may be influencing behavior of HSTS near peak resonance:
  - Clamp frequency response noticeable in readout, with noticeable resonance at f_{clamp} = 20.438 Hz, 3dB width = 0.770 Hz
  - 3db width of structure with 40 kg mass and without vibration absorber (from Measurement 19 – No Vibration Absorber, 40 kg Mass) was 0.538 Hz vs. 1.722 Hz with added clamp, demonstrating large damping effect
- General warning regarding interpreting resonances from these tests!
  - Must find better way to clamp down masses without introducing fringe effects into frequency response

6.5.3 Measurement 38 – Vibration Absorber [Measurement 36 (HSTS) – 2x Thick Viton, Increase Shim Stack Size] with Masses

- Final HSTS test, with vibration absorber from Measurement 36 (HSTS) – 2x Thick Viton, Increase Shim Stack Size and with 2 20-kg masses clamped down using setup in Figure 10
  - Accelerometer config 2, hammer impact on +Z face
- Peak frequency response (HSTS, Z-axis) = 29.563 Hz, 3db width = 2.174 Hz, Q = 13.60
  - "Clamp frequency response" (Z-axis) = 20.688 Hz, 3db width = 0.761 Hz
  - Slight increase in 3db width with the introduction of the vibration absorber (26% increase) but clamp resonance introduced in prior measurement is still present in this data

6.6 Conclusions (HSTS Testing)

HSTS testing demonstrated the effectiveness of the vibration absorber under its normal flagpole resonance (without added mass), greatly damping peak resonances near 60 Hz. However, testing done to target a 30 Hz frequency demonstrated that using a damper calibrated to 60 Hz did little to damp primary frequencies at 30 Hz.

Various issues discovered by testing the HSTS still need to be adequately resolved, such that future testing can be effectively done with the HSTS and vibration absorber. Namely, issues remain with effectively coupling additional mass to the HSTS without introducing additional resonances and thus changing frequency response results. Improper coupling – for example, masses simply resting on top of the HSTS without additional support – can also introduce noise into the data, making it more difficult or impossible to analyze (as seen in Measurements 27-32, HSTS Testing).

7 Summary of Work

Vibration absorber testing successfully verified multiple LIGO document results, notably demonstrating a nominal primary frequency of 100 Hz and a minimum reliable primary response of roughly 60 Hz. Alterations to the shim stack size and viton parameters employed in the vibration absorber allowed us to reliably achieve primary frequency responses ranging from 60 Hz to over 150 Hz. The 60 Hz vibration absorber was the lowest frequency vibration absorber to reliably perform at its designated frequency, and has been successfully shown to damp the HSTS 60 Hz mode.

However, tests done to determine the "far-field" damping response of the vibration absorber were largely unsuccessful. Using the 60 Hz vibration absorber design, we were unable to damp

30 Hz modes of the HSTS appreciably. Various attempts to decrease the effective frequency of the vibration absorber below 60 Hz were unreliable and impractical for the current design.

8 References

D1002424 – aLIGO, SUS, VIBRATION ABSORBER, 5LB VERTICAL WITH O-RINGS

D1002425 – aLIGO, SUS, VIBRATION ABSORBER, 5LB CLAMP BASE

D1002426 – aLIGO, SUS, VIBRATION ABSORBER, 5LB CLAMP TOP

T1100057 – D1002424 Vibration Absorber Assembly Instructions

E1200009 – Vibration Absorber Testing Procedures

9 Appendices

9.1 Appendix A: Viton Piece Thicknesses, for Measurements 27-30 (Vibration Absorber Testing)

1A	2A	3A	1B	2B	3B
0.2065”	0.2040”	0.2030”	0.2110”	0.2125”	0.2130”

Table A. Viton thicknesses, machined from viton fluoroelastomer rubber rod. Top row refers to location on vibration absorber, as specified in Figure 1.

9.2 Appendix B: Calculations of Loss

To determine the effectiveness of the vibration absorber in damping a system (such as the HSTS), we calculated its Q-factor through loss calculations.

The loss factor, denoted as ϕ, is a measure of the damping introduced by a particular component in a multi-component system. Losses are calculated as follows:

$$\phi_{total} = \phi_1 + \phi_2 + \cdots = \frac{1}{Q_1} + \frac{1}{Q_2} + \cdots$$

Equation 1. Loss addition and its relation to quality factor Q.

In essence, loss factors are the reciprocal of the quality factor of a component, and are nice to work with because they add in series. Using this system, one can determine the loss factor of a single component, provided one has the loss factors of every other component via measurement or some other discovery method.

In our measurements involving the HSTS, the general loss factor system was as follows:

$$\phi_{total} = \phi_{HSTS} + \phi_{vib}$$

Equation 2. Loss factor equation applicable to HSTS testing.

We recognized that the total loss factor of the system (“total” here meaning the HSTS structure with a mounted vibration absorber) can be treated as the sum of loss factors between the HSTS and the vibration absorber on its own. To determine ϕ_{vib}, the contribution from the vibration absorber mounted on the HSTS, we took two measurements: one of the HSTS without any extraneous parts attached (ϕ_{HSTS}) and a second measurement where the vibration absorber was mounted on the HSTS (ϕ_{total}). From Equation 2, we determined ϕ_{HSTS} and ϕ_{total} by finding the standard quality factor associated with each experiment, defined as:

$$Q = \frac{\text{peak frequency}}{\text{3db resonance width}}$$

Equation 3. Traditional quality factor definition for a standalone system.

With ϕ_{HSTS} and ϕ_{total} defined via vibration testing, we back-solved Equation 2 to find ϕ_{vib}, the contribution of the vibration absorber to the damping of the entire system. With ϕ_{vib}, the quality factor as determined by the loss factor system $Q_{vib,loss}$ can be found. Outside of the appendices, we refer to quality factors found this way as $Q_{X,loss}$ where "X" is the object of interest in the system. Quality factors without any subscript (stated as simply Q = number) can be assumed to refer to the object being tested, and are calculated via Equation 3.