**Design and Testing of a Measurement Apparatus for the GS-13 Flexures**Graham Allen, Daniel Clark, Brian Lantz  
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This document describes a simple metrology for verification of the critical web thickness of the GS-13 replacement flexures. The flexure web thickness is required to be 4.0±0.5 mil. This tolerance is set by the need to maintain a 1 Hz frequency of the GS-13 seismometer, and a 20 g maximum static load. Using a precision digital indicator and a set of reference spheres to kinematically constraint the flexure, we have verified measurements of the web thickness with accuracy and repeatability exceeding 0.1 mil.

# Necessity of measuring web thickness

The replacement flexures for the GS-13 seismometers are designed to allow the seismometer to be installed in a vacuum pod without the need of a motor to actuator the proof-mass lock of the seismometer. This considerably simplifies installation procedures and ensures reliable seismometer operation.

The replacement flexures are designed to maintain the GS-13’s natural resonant frequency of 1 Hz while allowing the seismometer to withstand 20 g shock loads during handling and installation. Measurement of the web thickness is critical because the flexure stiffness scales as *t*5/2 where *t* is the flexure thickness. Additionally, the maximum g load is also a strong function of the web thickness. If the web is too thick, the flexure will be too stiff, resulting in an increase natural frequency of the GS-13. If the web is too thin, the flexure may break during installation. The flexures are currently designed to have a web thickness of 4.0 ± 0.5 mils.

The originally installed GS-13 flexures have a nominal stiffness of approximately *keff*= 0.136 N∙m. We have developed two techniques for measurement of the flexures. The first is an apparatus which measures the minimum web thickness using a digital indicator and a reference sphere. The second technique measures the flexure stiffness by measurement of the resonant frequency of the flexure mounting flange.

# Web thickness measurement

# Apparatus Design

The flexure test stand is designed to directly measure the web thickness of all GS-13 flexures. A digital dial indicator is used to measure the thickness between the surface of a precision reference sphere and the indicator tip.



Figure 1. SolidWorks rendering of the assembled flexure gauge.

The flexure is kinematically positioned for repeatable measurement. The measurement point is nominally located in the middle of web at a height of 0.121 in. The measurement height is set by height of the center point of the drilled reference sphere. The drilled hole used to mount the sphere via a press-fit dowel pin results in the center of the sphere sitting lower by 0.004 in.

The flexure is kinematically located by two spheres. One locating sphere sets the location of flexure axis and is used to hold the flexure in place. A spring loaded set screw is used to hold the flexure against this locating sphere. The spring pin depth is set so that the flexure fits snugly, but can still be easily inserted and removed. The main reference sphere is positioned directly in the center of the flexure web. The indicator is mounted in a co-aligned v-groove so that the flexure is measured at its minimum thickness point. The location of the minimum flexure is obtained by manually sliding the flexure until the digital indicator readout is minimized.

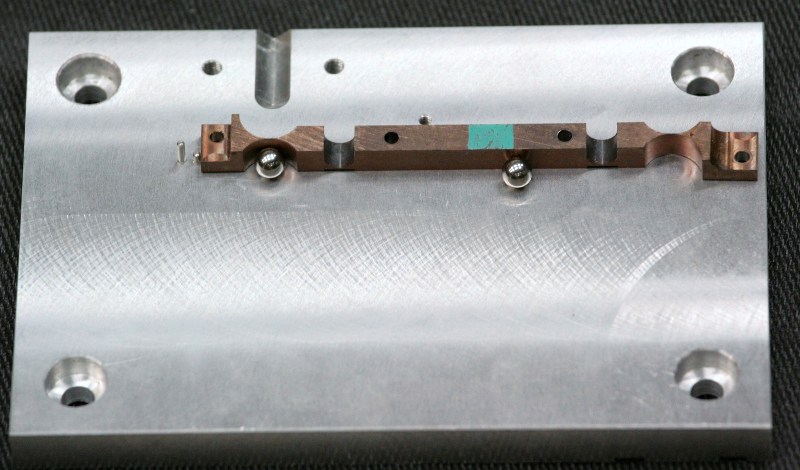


Figure 2. Picture of the machined flexure gauge before installation of digital indicator.

All of the kinematic features are mounted using 1/16 in dowel pins, drilled and reamed in a single pass. Machining these features with a common tool and mounting configuration minimizes possible relative errors between the reference features, ensuring a precise setup. The locating spheres are epoxied to the dowel pin and the dowel pin is epoxied into the hole. This prevents the spheres from rotating and eliminates any possible wobble in the locating spheres.

# Measurement procedure:

### Calibration of gauge accuracy.

1. Turn on digital indicator. With nothing in the flexure allow the indicator to touch the reference sphere. Record the absolute indicator reading.
2. Zero the indicator.
3. Insert 0.1000 in precision gauge block.
4. Verify that indicator reads 0.1000±.0001 in as the thickness of the gauge block.

Record the indicator reading.

### Measuring flexures:

1. Record flexure serial number, indicate if a top or bottom flexure.
2. Insert flexure into gauge, slide flexure laterally until minimum indicator reaches a minimum.
3. Reverse flexure to measure thickness of second web.

### After measuring a set of flexures:

1. Insert 0.1000 in precision gauge block.
2. Record measurement of gauge block thickness.
3. If measured gauge block thickness varies from previous result by more than ±0.0001 in flag all flexures to be re-measured.

# Accuracy analysis and error stack-up:

## Error in locating minimum web location

The minimum thickness of the flexure needs to be located within ±0.002 in. This is accomplished by manually sliding the flexure laterally until the indicated thickness is minimized. A future version of the flexure tester could incorporate adjustment via screw or lever.

## Geometric offsets

Geometric offsets between the reference ball and the axis of the digital indicator will cause two sources of error. The zero is artificially set negative, resulting in an indicated thickness which greater than the actual thickness. The second error source is due to the curvature of the flexure web. This will also cause a measured increase in the flexure thickness.

## Indicator accuracy

The Mitutoyo digital dial indicator has a stated accuracy of ±0.0001 in over its full range of motion. The indicator readout increment is 5×10-5 in, which is less than the stated indicator accuracy. The extra half-digit of precision should be recorded, despite it being at the limits of indicator accuracy.

## Zero point set error:

Offset between the measurement tip of the indicator and the reference result in a zero point that is slightly negative when compared with reference point if a zero thickness plane were measured. This results in a flexure thickness reading which is erroneously high. Errors in zero point are common to all measured surfaces, so a calibrated gauge block can be used to eliminate error in the zero point. It is desirable to minimize error in the zero point but not required.

## Repeatability

Repeatability was measured by systematically measuring several different reference objects. A set of shims of varying thickness was measured five times. Each shim in the set was measured in sequence, and the then standard deviation for each shim was compared. Then shims were then measured by micrometer to verify the thickness.

## Accuracy

Accuracy of the flexure tester was measured by comparing the measured thickness with a set of gage blocks. Five gage blocks were measured with an accuracy of +6e-5 ± 3e-5 in. The flexure tester tends to overestimate the thickness due to an improperly set zero point.

## Summary of fixture testing

|  |  |  |
| --- | --- | --- |
| **Parameter** | **Specification**  (10-3 in = 1 mil) | **Actual**  (10-3 in = 1 mil) |
| Accuracy | ±0.1 | +0.1,-0.0 |
| Zero Point | < 0.1 | 0.06±0.03 |
| Repeatability[[1]](#footnote-1) | ±0.1 | ±0.05 |
| Maximum Variation[[2]](#footnote-2) |  | 0.15 |

# Uneven flexure web thickness

Measurements of the prototype flexures machined by D. Clark showed that the some of the flexure web were extremely uneven. This was further verified by direct measurement with a coordinate measure machine (CMM). The radius of both sides of the flexure was recorded by the CMM and the cloud of touch points exported directly to MATLAB. Within MATLAB the web thickness was calculated as a function of the height along the flexure by fitting the cloud of points to an angled cylinder.

In the case of the long web of flexure #1, the calculated thickness varied between 2.9 mil and 5 mil, a range of 2.1 mil, which greatly exceeds the tolerance for the flexure. The geometric model used to calculate the thickness assumes a constant cylinder radius and a small angle to the vertical. In cases where the flexure web shows large variations a simple one point measurement may not be sufficient to accept or reject a flexure.

# Direct measurement of flexure stiffness

## Principle

The stiffness of a flexure web can be calculated by measurement of the resonant frequency of the unsupported flexure mounting tab. The natural frequency is measured using an optical shadow sensor to the deflection of the mounting tip. The deflection is recorded and used to fit a damped sinusoid, resulting in the natural frequency and Q of the flexure.

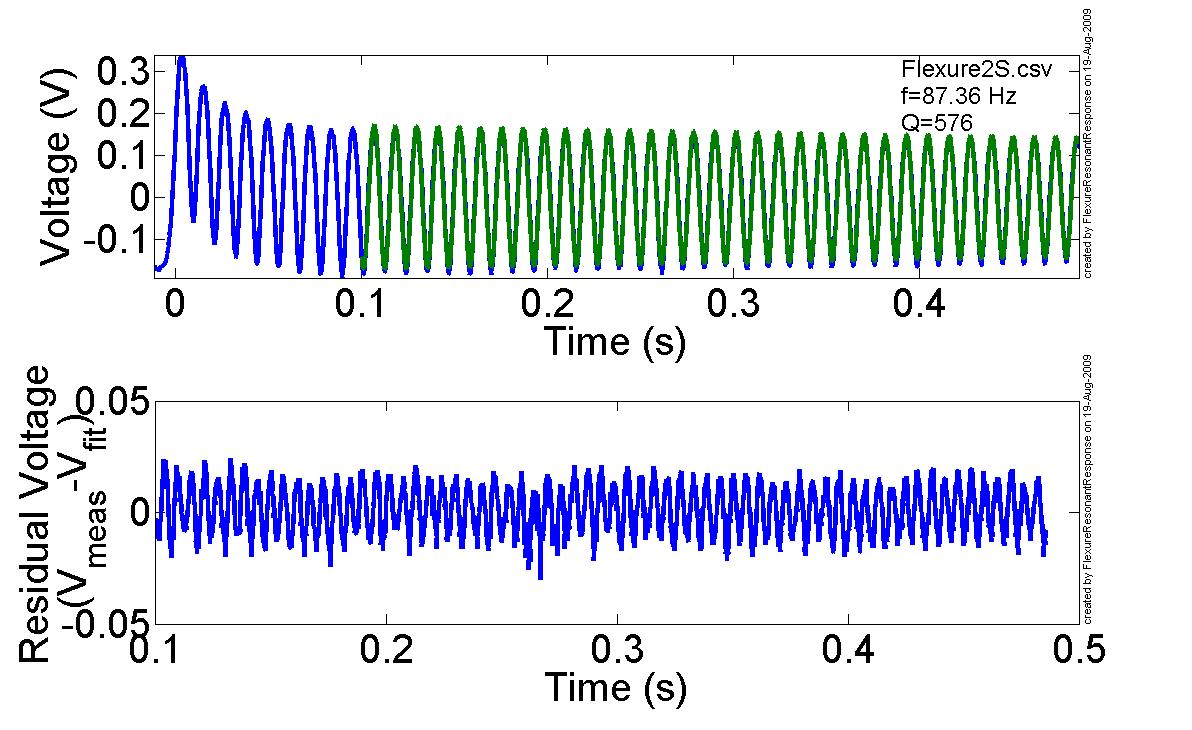
The natural frequency, of the flexure is related to its stiffness, *k*, via,

|  |  |
| --- | --- |
|  | (1) |

where, *Ieff* is the moment of inertia of the flexure end point about an axis along the center of the web. The effective moment can be calculated from the Solidworks models of the parts.

|  |  |  |
| --- | --- | --- |
| Table . Calculated moments of inertia for flexure end tabs (*Ieff*). | | |
|  |  |  |
|  | Long tab  (g∙cm2) | Short tab  (g∙cm2) |
| Top Flexure | 3.40503 | 2.6285 |
| Bottom Flexure | 4.91823 | 3.00628 |

# Measurements

Each flexure was rigidly clamped with two clamps in the middle of the flexure. The end tab was freely hanging. Oscillation of the end tip was excited by plucking the flexure tab. The displacement of the tab was recorded by an oscilloscope. The data was given 100 ms to stabilize before data is used for numeric fitting. The ringdown response of the flexure is fit to a damped sinusoid using a non-linear least squares fit over a section of 300 ms of data, corresponding to approximately 30 cycles of oscillation for the flexure. As shown in the Figure X, the fit tracks the phase of the ringdown response accurately, leading to extremely accurate estimates of the flexure resonant frequency.

# Conclusions

The flexure test gauge demonstrates sufficient accuracy and repeatability for acceptance of GS-13 replacement flexures. The demonstrated repeatability exceeds 0.1 mil with an accuracy of 0.06 mil.

# References

1. **Daniel Clark, Brian Lantz.** *Replacement Flexures for the GS-13 Seismometer.* Stanford University. 2009. LIGO DCC. T0900089-v1.

# Drawings and photographs

## Fixture assembly drawings:

## Fixture machine drawings:

1. Standard deviation of five samples, each measured five times. [↑](#footnote-ref-1)
2. Maximum difference of five samples, each measured five times. [↑](#footnote-ref-2)