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LLO MC2 Violin Mode Q

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# Introduction

## Purpose and Scope

This is a writeup of a quick calculation to understand the measured violin mode Q of the MC2 suspension at LLO but is applicable to all HSTS. The interesting conclusion is that the violin mode Q is dominated by thermoelastic damping which has its peak nearby.

## References

LLO alog entries [4470](https://alog.ligo-la.caltech.edu/aLOG/index.php?callRep=4470), [4472](https://alog.ligo-la.caltech.edu/aLOG/index.php?callRep=4472)

T070101: [Dissipation Dilution](https://dcc.ligo.org/cgi-bin/private/DocDB/ShowDocument?docid=27812)

T080096: [Wire Attachment Points and Flexure Corrections](https://dcc.ligo.org/cgi-bin/private/DocDB/ShowDocument?docid=10955)

LIGO-T0900435: [HAM Small Triple Suspension (HSTS) Final Design Document](https://dcc.ligo.org/cgi-bin/private/DocDB/ShowDocument?docid=5424)

LIGO-D020700: [HSTS Overall Assembly](https://dcc.ligo.org/cgi-bin/private/DocDB/ShowDocument?docid=6873)

Cumming et al., Design and development of the advanced LIGO monolithic fused silica suspension, Class. Quantum Grav. 29 (2012) 035003.

## Version history

8/28/12: -v1.

# Measurement

The violin mode of one of the wires supporting the optic in the MC2 was measured by Keiko Kokeyama, with advice from Gaby Gonzalez and Peter Fritschel. See LLO alog entries [4470](https://alog.ligo-la.caltech.edu/aLOG/index.php?callRep=4470) and [4472](https://alog.ligo-la.caltech.edu/aLOG/index.php?callRep=4472). The frequency and Q were 631.55 Hz and 2.3x105.

# Theory

To see whether this was reasonable, the frequency and Q were calculated using the Mathematica model of the suspension, specifically case {"mark.barton", "20120120hsts"} of the TripleLite2 model. This is equivalent to the Matlab parameter set ^/trunk/Common/MatlabTools/TripleModel\_Production/hstsopt\_metal.m revision 2007 which has given a good fit with measured TFs. However since neither the Mathematica nor Matlab models includes violin modes explicitly calculating these was a matter of using numerical values from the parameter sets in general formulae as described below.

The frequency of a violin mode is approximately

**c

where  is the mode number,  is the wire length,  is the linear mass density (is the volume mass density and  is the wire area),  is tension ( is optic mass and  is gravity; 4 is the number of wires) and  is a flexure correction defined (T080096) as

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where  is the Young’s Modulus and  (known as M in the model code) is the second moment of area of the wire, equal to  for a wire of circular cross-section. The flexure correction reflects the fact that a wire of non-zero intrinsic stiffness does not bend sharply at the clamp point but, effectively at least, at an effective point  away.

The Q of the violin mode depends on the material damping factor  and the dissipation dilution factor . The damping factor is modeled as a frequency-independent structural term plus a thermoelastic term:



where (e.g., Cumming et al.)



is a time constant for heat diffusion across the wire ( is heat capacity and  is heat conductivity)  is temperature,  is linear expansion, , and  is stress.

Because the energy in a violin mode is stored in second-order stress changes of the elastic material, dissipation dilution is applicable (T070101) and the quality factor  is not just  for the material, but  where



# Results

Using values from the model in the above frequency formula (see Appendix) gives f = 650.55 Hz, some 29 Hz or 4.5% high, which is fair but not as good as one might have hoped. Parameters that could plausibly be off include wire length l3, radius r3, and density rhosteel.

l3 was 0.22 m in the final design document (T0900435-v2) and the EASM file of the top level assembly (D020700-v1), but could conceivably have changed if the design of the wire jig didn’t quite match the design of the bottom stage, or if there’s some subtle difference between the metal and glass builds. The wire was nominally 0.047” in diameter, 597 µm in radius, but could conceivably have been slightly off depending on the tolerance and whether it was in fact in spec. A generic value of 7800 kg/m3 was used for carbon steel, but some sources suggest 7850 for piano wire specifically, e.g., <https://sites.google.com/site/lorenkoehlerwebsite/piano-craft/piano-wire> .

The thermoelastic term turns out to contribute the bulk of the damping in the frequency range of the violin modes. See Figure 1. c

Figure 1: Loss angle as a function of frequency for the wire. The thermoelastic peak is visible on the right.



At the violin mode frequency, the total  is 9.9x10-4, almost 5 times the structural term, 2x10-4. Together with a  of 0.00503, this gives an effective  of 4.97x10-6 or a of 2.01x105, which is quite close to the measured value of 2.3x105.

# Conclusion

The measured values of frequency and Q are both quite close to predicted values, although because the parameters that go into the frequency are more accurately measurable, the discrepancy is more significant, and some more work could usefully be done to understand it.

# Appendix

In the PDF version of this report, a printout of the Mathematica notebook contain the calculation will be appended.