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A test for excess noise in the Hytec constrained-layer coil springs.

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Abstract

An experiment to measure excess noise in the Hytec damped coil springs is described. Results from 13 hours of run time are presented, along with interpretation and some implications for LIGO test mass noise. The spring tested would almost certainly be acceptable for use in the second stage of the isolation stack, and it will probably also be acceptable for use in contact with the downtube.

Keywords

seismic isolation, mechanical noise, constrained-layer damped coil springs.

1 Introduction

In order to improve performance in LIGO's earlier design for the seismic isolation stack[1], Hytec has redesigned the solid mass shapes and devised an internally damped coil spring.[2] The new spring design is intended to provide enough damping to limit the Q's of the stack's modes to about 30, while maintaining ultra-high vacuum compatibility. To accomplish this, the damping materials are placed between an outer phosphor bronze tube and an inner series of aluminum cylinders to form a constrained layer to enhance the mechanical loss with spring flex.

Initial mechanical tests demonstrate appropriate loss qualities,[3] but it is still necessary to experimentally determine whether the springs meet LIGO's requirements for excess burst noise rates.[4] Fred Raab[5] discusses using a force gauge on a loaded spring to record excess noise over an extended data-taking run.

This experiment is intended to measure excess force noise between the spring and its load, due to the static deformation (creep) as well as due to the gentle motion of the system due to unfiltered ground noise exciting the mini-stack's normal modes (creak). This report describes the measurement and the implications of its results.

2 Experiment Description

The experimental apparatus is sketched in Figure 1. A vacuum tank sits on hard viton springs atop an optics table, which itself is floated on air legs. Inside the vacuum, there are two layers of passive isolation stack, using RTV springs and metal cylinders. On top of that are three springs under test, which together are loaded with a 140 kg mass, the nominal design load.

Between one of the springs and the load is a (vertical) force gauge consisting of a 3 cm tall by 1 cm diameter cylindrical PZT, electrically insulated top and bottom, with electrodes connected to an in-vacuum high-impedance preamplifier. (Although the gauge measures vertical force, it should also be sensitive to horizontal excitation of the load mass, since it contacts below the load's center of mass.) The preamp's signal is led out through a active-guard shielded twisted pair to a differential amplifier and a SR560 12 dB/octave 100 Hz highpass filter/amplifier to the data acquisition system. The highpass filter is used to reduce the isolation stack's ground-noise-driven normal modes to prevent ADC overflow.

For the runs described in this report, 13 hours of data were taken at 10,000 samples/second. A second channel was also recorded, of a commercial accelerometer mounted on the optics table in air, to provide an environmental-noise veto, if needed.

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[1] J. Giaime, P. Saha, D. Shoemaker, and L. Sievers, "A passive vibration isolation stack for LIGO: design, modeling, and testing," Review of Scientific Instruments, **67:1**, 208. (1996)

[2] E. Ponslet, "Design of Vacuum Compatible Damped Metal Springs for Passive Vibration Isolation of the LIGO detectors," HTEC-TN-LIGO-04a, 10/31/96

[3] E. Ponslet, "Low Frequency Damping Measurement Setup and First Results," HYTEC-TN-LIGO-17, 6/5/97.

[4] R. Vogt, *et. al.*, Laser Interferometer Gravitational-wave Observatory, p69 (the LIGO Proposal to the NSF)

[5] F. Raab, "Requirements for Creep Testing of SEI Spring Elements," LIGO-T970069-01-D. (Method suggested by D. Shoemaker)

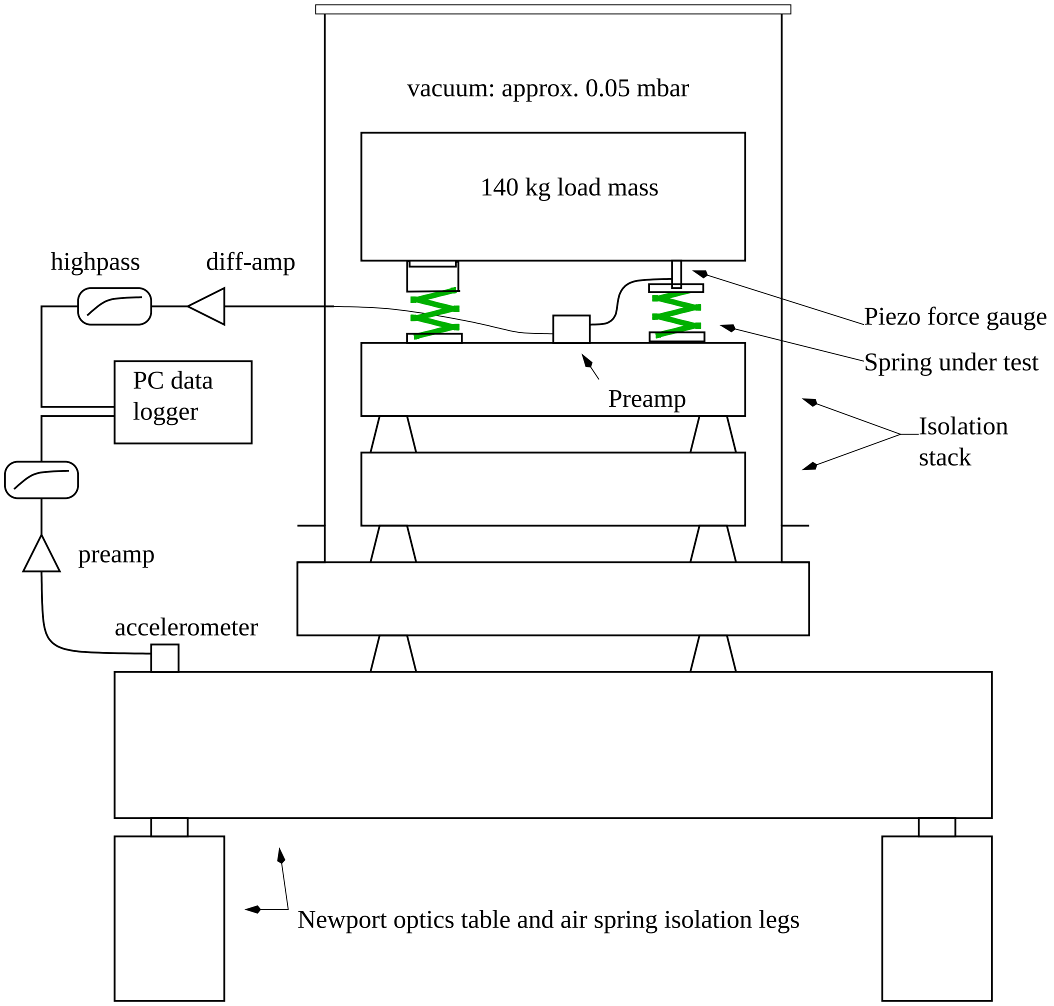

Figure 1: Sketch of excess noise test apparatus. One of the three Hytec internally-damped coil springs is instrumented with a force gauge.

The data were reduced in two ways. Method 1: First, the data stream was digitally filtered with an 8-pole butterworth bandpass to leave signals in the 90 - 3000 Hz band. Next, variances in 100-sample segments (i.e., 10 ms intervals) were calculated and plotted in a histogram. The highpass filtering was used because below this band the signal is dominated by motion at the isolation stack's normal modes. Figure 2 is a histogram of the square root of the 100-sample variance, which is the standard deviation, and should equal F_{rms} in the 90 - 3000 Hz band. The data were taken on three different days, and three different distribution centers are evident in the plot. This might be due to changes in force/voltage sensitivity of the PZT rod in its extremely high impedence circuit, as water and contaminants move on the PZT surface. The calibration used was derived from an in-air test immediately before the lowest noise segment of the distribution (the left bump of Fig. 2, representing the first day's data). Therefore, the interpretation below is probably conservative by a factor of 2 or so if the signal represents actual force noise, but not if it represents changing electronic noise in the preamp. In any case, it is

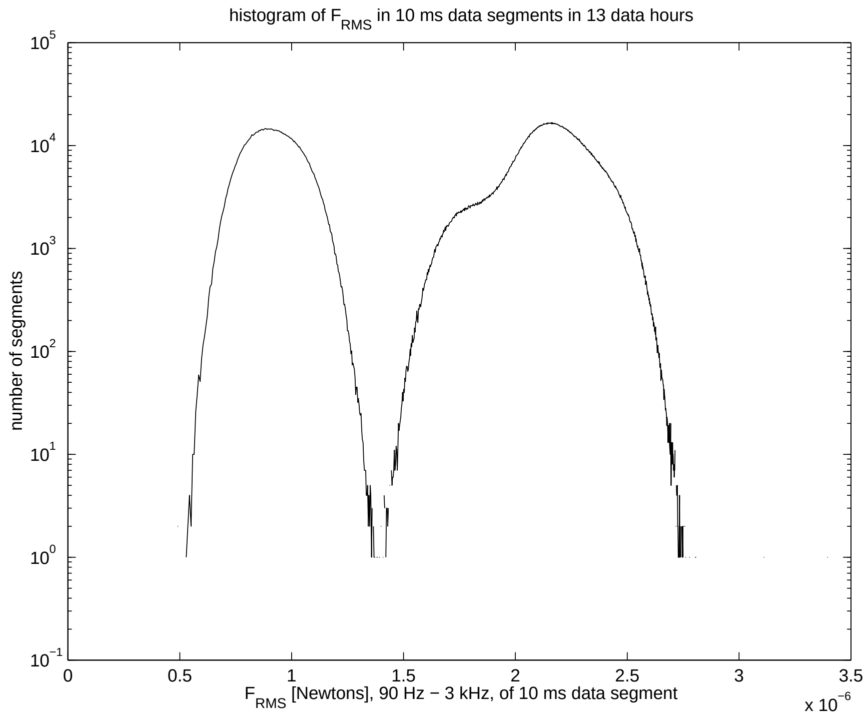

Figure 2: Analysis method 1, equivalent root mean squared force noise in 10 ms data segments over 13 hours.

unlikely that we are under-estimating the equivalent force noise.

Also (Method 2), the data were 8-pole butterworth highpassed at 110 Hz, and the differences between consecutive samples were plotted in a histogram for each of the three days of data-taking. This is shown in Fig. 3, which plots $\log N$ vs. $(\delta F)^2$ in order to allow evaluation of the gaussian nature of the data sets. A Gaussian data set gives a histogram of constant negative slope, with no tail at large values of $(\delta F)^2$. The slope is a measure of the variance, which in this case is approximately 2×10^{-6} N.

3 Analysis

The highest point from the F_{rms} distribution was approximately 2.7×10^{-6} N. This event was at the upper boundary of a compact distribution with no high variance outliers. (See note above about likely calibration changes.) It is quite possible that the measured signal was merely electronic noise in the force gauge and its amplifier.

Since we are set up to measure vertical force, and are really interested in the LIGO test mass motion, some analysis using reasonable assumptions is needed. First, consider the measured noise force as applied to the downtube from a spring on the top layer of the stack. The downtube's mass is approximately 650 kg, so this force range is equivalent to accelerations between 7.7×10^{-10} m/s^2 and 4.1×10^{-9} m/s^2. If we use 200 Hz as a typical exitation, the upper number corresponds to an rms displacement of 2.6×10^{-15} m on the downtube. (100 Hz:

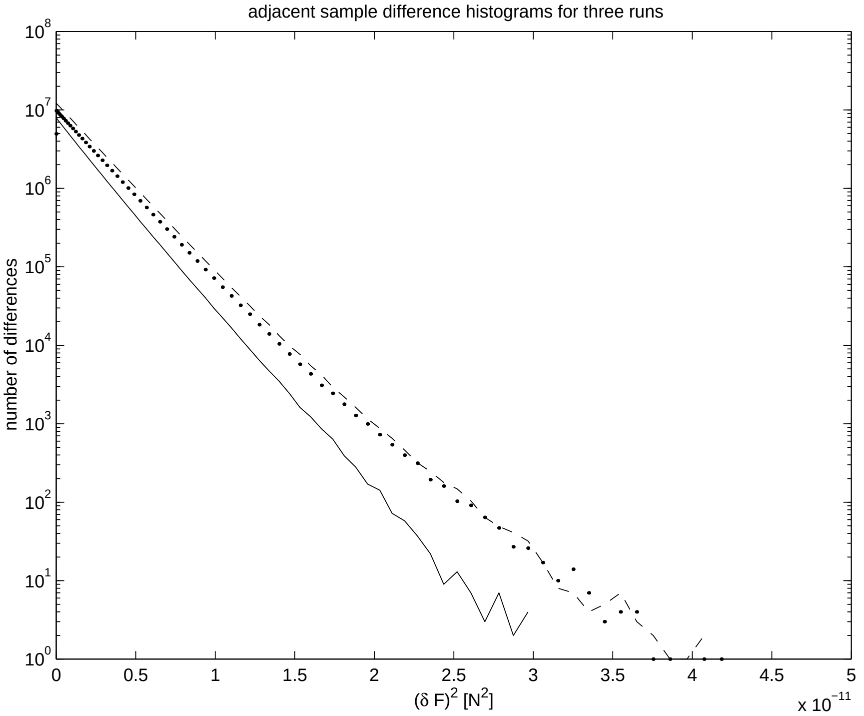

Figure 3: Method 2, histogram of differences between adjacent ($\Delta t = 0.1$ ms) data points of three data-taking days. (solid, 18 Sept. '97; dashed, 20 Sept. '97; dotted, 21 Sept. '97.)

Frequency	Force noise	Downtube motion from (m)		Horiz. signal from horiz. spring noise (m)		Horiz. signal from vert. spring noise (m)	
		top-layer spring	second-layer spring	top-layer spring	second-layer spring	top-layer spring	second-layer spring
200 Hz	2.7×10^{-6} N	2.6×10^{-15}	2.3×10^{-18}	3.5×10^{-20}	3.1×10^{-23}	1×10^{-20}	9.0×10^{-24}
100 Hz	2.7×10^{-6} N	1×10^{-14}	3.6×10^{-17}	1.4×10^{-19}	5.0×10^{-22}	4×10^{-20}	1.4×10^{-22}

Table 1: Estimates of noise propagation through the LIGO suspension/isolation system. The columns at right are the rms test mass displacements as seen by the detector due to vertical and horizontal spring noise, without taking into account vertical/horizontal mixing in the downtube and stack.

1×10^{-14} m.) This vertical downtube motion gets filtered by the 13 Hz vertical resonance of the test mass suspension, so the test mass would move 1.1×10^{-17} m, resulting in a horizontal measured signal of 1×10^{-20} m or so (100 Hz: 4×10^{-20} m).

We can guess that any horizontal force releases in the springs are the same size and frequency as the vertical ones. The horizontal motion gets filtered by a .74 Hz pendulum, resulting in 3.5×10^{-20} m (100 Hz: 1.4×10^{-19} m) detected displacement. This does not take into account the moment of inertia of the downtube, and its associated lever arm. Because of the highpass filtering done in this experiment and analysis, not much can be said about noise below 100 Hz.

The springs one layer down in the stack have the benefit that any noise they produce is filtered by the final layer approximately as f_0^2/f^2, where $f_0 \approx 6$ Hz so requirements on their

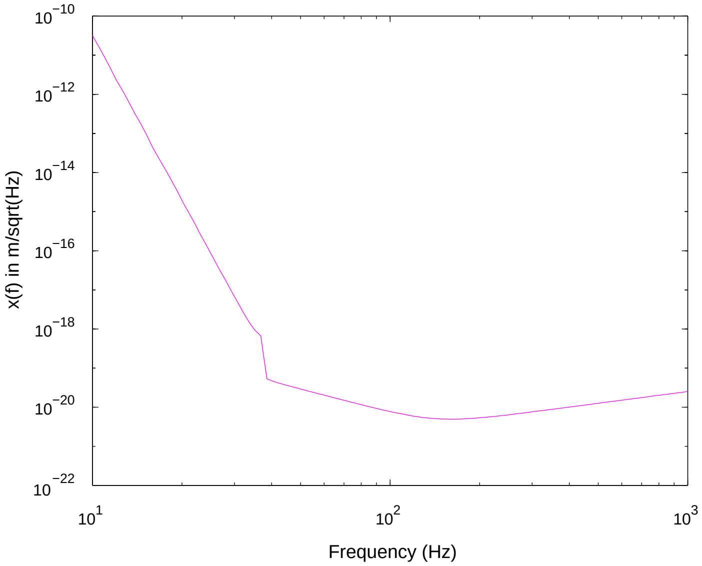

Figure 4: figure 21 from the SEI DRD, showing the requirement for seismic noise transmitted to the suspended test mass.

noise can be relaxed accordingly. The noise reaching the test mass from the springs one layer down, as well as the ones from the top layer, are summarized in Table 1.

4 Implications for LIGO spurious event rate

The LIGO requirements for continuous noise sources[6] due to sources within and propagating through the SEI system are reproduced in Figure 4. The requirement for frequencies above 100 Hz, which the results discussed here can address, is essentially $x(f) < 1 \times 10^{-20}$ m/$\sqrt{\mathrm{Hz}}$. To convert this to units equivalent to those measured in this work (meter, rms) we can guess that the spring burst noises have approximately a bandwidth equal to their frequency, so the requirement is about $1 \times 10^{-20}\sqrt{f}$ m; which is 1×10^{-19} m at 100 Hz and 1.4×10^{-19} m at 200 Hz. It is clear from Table 1 that the the spring tested here is acceptable if placed in the second stack layer, and that we cannot quite determine from this experiment whether it would be acceptable on the top layer, although this is probable.

The LIGO '89 proposal, pp. 68-70, discusses the effect of double and triple coincidence detection on spurious noise events. Of order 100 / hour can be tolerated in each interferometer. There are 16 springs touching each down tube, and (at least) 5 test masses that can contribute directly to the output signal, making the acceptable single spring rate about 1/hour. This rate corresponds to a horizontal line in Figure 2 at the value 12, which does not intersect the locus of points appreciably below the maximum force value used in the analysis above.

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[6] F. Raab, N. Solomonson, M. Fine, "Seismic Isolation Design Requirements Document," LIGO-T960065-03-D, 2/20/97, page 21.