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LIGO Coil Springs
Test Plan

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Abstract

This document describes various tests that are currently envisioned to qualify the damped coil springs for use in the seismic isolation stacks of the LIGO detectors. Tests are described to assess static load capacity and spring constants, set, drift, fatigue, dynamic stiffnesses and damping, acoustic transmission, creak, and vacuum compatibility. It should be noted that, as the first prototypes are being produced and tested it is likely that some of those tests will be modified, extended or even eliminated.

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LIGO PROJECT

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1. Spring Geometry

The coil (Fig. 1) has 4 complete turns, with a 56 mm nominal mean coil diameter, and a 14 mm nominal pitch, and open ends. The “wire” cross section is a multi-layer assembly of (from the inside out) 5.27mm (.207”) diameter Viton, aluminum tube sections 35 mm (1.375”) long with a 0.92 mm (.036”) wall, Soundcoat DYAD damping material 0.5 mm (0.020”) thick, and an outer tube of ¾ hard phosphor bronze C510 with a 0.83 mm (0.032”) wall. A vacuum cap is welded at each end of the coil to seal the viscoelastic material inside a continuous metal envelope. Details can be found in [1].

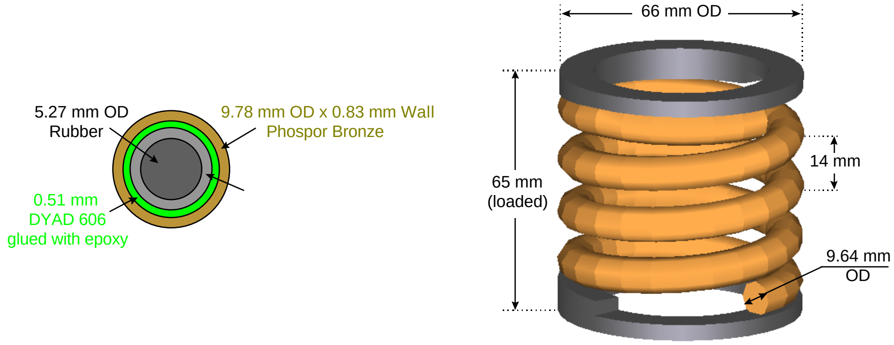

Figure 1: coil spring geometry.

At each end of the coil, ¾ turn is supported in a helicoidal seat made of durometer 75 Viton. The overall length of the spring is about 73 mm (2.89”) unloaded and 65 mm (2.56”) under a 100 lb static load.

2. Expected Properties

Analytical calculations lead to the following expected properties for the spring[1]:

- Static Spring constant: $K_{ax}\ (DC)$ = 54.4 N/mm (311 lb/in)
- Design Load (@ 80% of deflection to solid): P_{nom} = 445 N (100 lbs)
- Design length (under design load): L_{nom} = 65 mm (2.56”)
- Dynamic properties (spring constant and loss factor): frequency dependent, see Fig. 2.

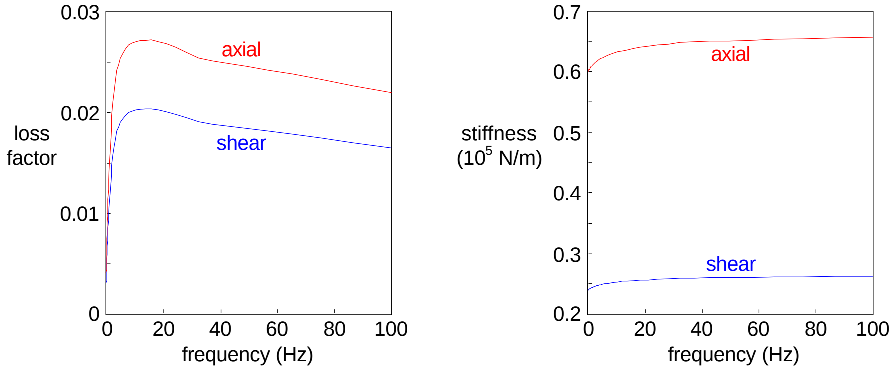

Figure 2: Coil spring; expected dynamic properties.

3. Characteristics to be Evaluated

This test plan is intended to evaluate the spring for the following characteristics:

- Admissible load
- static spring constant
- permanent set
- creep/drift/relaxation under static load
- dynamic properties at low frequencies (<100 Hz typ.) (frequency dependent stiffness and damping)
- creak (burst releases of energy under constant or slowly varying deformation)
- acoustic transmission through outer metal shell
- fatigue life
- vacuum compatibility, outgassing

Tests are staged in increasing order of complexity. Failure at any stage in the plan would call for adjustments in the design and/or manufacturing process or interruption of the spring development.

4. Undamped Prototypes

Three undamped prototypes will be tested. In those prototypes, a solid viton core (8mm OD, durometer 75) replaces the various damping layers inside the phosphor bronze tube. Before coiling, the phosphor bronze tube is swaged around the Viton core (the percentage diameter reduction is similar to that of the damped spring). Those 3 springs will receive the following partial stress relief treatments after coiling (note that with only 1 spring for each treatment, differences observed in mechanical properties are in no way statistically meaningfull; only gross changes in properties will be attributable to differences in heat treatment as opposed to random manufacturing variability):

- UC01: no heat treatment.
- UC02: air oven, 1 hour (60 minutes) @ 310±10°F (154±6°C) (TBD)
- UC02: air oven, 3 hours (180 minutes) @ 310±10°F (154±6°C) (TBD)

Mechanical tests must be performed in the order they are described below. The springs are supported in temporary helicoidal seats molded out of Epoxy resin. Unless otherwise specified, tolerances on loads are ±0.1 lb (±0.5 N). Test reports must contain complete description of instrumentation used and calibration records.

4.1 Static Testing for Spring Constant and Permanent Set

For each spring (UC01, UC02, UC03):

1. Preload to 5.0 lb (22 N) and reset displacement sensor
2. Pseudostatic ramp load/unload from 5.0 lb (22 N) to 80.0 lb (356 N) to 5.0 lb (22 N), 4 cycles, 1.0 lb/sec (4.5 N/sec) typ. loading/unloading rate, record axial load ±0.1 lb (±0.5 N) or better, and axial deformation ±0.001" (0.025 mm) or better.
3. Repeat step 2 from 5.0 lb (22 N) to 100.0 lb (445 N) to 5.0 lb (22 N), 4 cycles.
4. Determine load to solid length P_{solid}, by slowly and carefully ramp-loading the spring until the coil to coil gap is reduced to less than approximately 0.004" (0.1 mm) at any point along the spring (gap can be checked with piece of paper).

5. Repeat step 2 from 5.0 lb (22 N) to 95% P_{solid} to 5.0 lb (22 N), 4 cycles.
6. Examine spring for visible damage (cracking, asymmetric deformation, etc.).

All measurement results to be provided in writing and electronic ASCII format (floppy disk).

4.2 Static Testing for Relaxation

This test will be performed in a mechanical testing machine (screw driven). To eliminate possible drift in the plastic seats, the springs may be equipped with an external strain sensor, measuring variations in pitch directly on the coil.

For all 3 springs (UC01, UC02, UC03):

1. Preload to approx 5.0 lb (22 N) and reset displacement sensor to zero.
2. Quickly (5 sec. max) load to 100.0 lbs (445 N), maintain and monitor constant deflection (max fluctuation ±.002"/ ±0.05 mm) for 48 hrs while recording load. Time steps or resolution should be about 5 seconds during the initial 5 minutes under load, and 5 minute during the rest of the test.
3. Unload back to 0 deflection and record load (±0.1 lb) for 5 minutes (±1 second).

Measurement results (load and deflection VS time) to be provided on paper (and electronic ASCII format if possible). Data about electronic drift in load cell and associated electronics is required.

4.3 Fatigue Test

Potentially destructive test intended to investigate potential failure of the Ph Br tube due to repeated loading/unloading of the stacks

For all 3 springs (UC01, UC02, UC03)

1. Preload to 5.0 lb (22 N), and reset displacement sensor to 0.
2. Sinusoidal or sawtooth load/unload cycles 5 lb to 100 lb (TBD), minimum period of load/unload cycle = 2 seconds, record load and displacement extremes for 1000 cycles or to failure.

All measurement results to be provided in writing (and electronic ASCII format if possible).

5. Damped Prototypes - Initial Testing

Four initial prototypes of the damped coil spring will be produced, numbered DC01 to DC04. All springs may be given an identical partial stress relief heat treatment as determined from results of section 4. The springs will be supported in molded Viton seats.

Because of the extreme temprature sensitivity of the damping layers used in the spring, all tests should be performed under controlled temperature conditions. The temperature in the immediate vicinity of the springs should be as close as possible to 21ºC (70ºF). Any deviation from that temperature should be measured and recorded. Also, sufficient time should be allowed between any manipulation of the springs and the actual measurements to allow the springs to reach thermal equilibrium with the ambiance (1/2 hour typ.).

5.1 Static Testing for Spring Constant and Permanent Set

For all 4 springs (DC01, DC02, DC03, DC04):

1. Preload to 5.0 lb (22 N), maintain for at least 5 minutes, and reset displacement sensor to 0.
2. Pseudostatic ramp load/unload from 5.0 lb (22 N) to 80.0 lb (356 N) to 5.0 lb (22 N), 4 cycles, 1.0 lb/sec (4.5 N/sec) loading/unloading rate, record axial load ±0.1 lb (±0.5 N) or better, and axial deformation ±0.001” (0.025 mm) or better.
3. Repeat step 2 from 5.0 lb (22 N) to 100.0 lb (445 N) to 5.0 lb (22 N), 4 cycles.
4. Determine load to solid length P_{solid}, by slowly and carefully compressing the spring (displacement control recommended) until the coil to coil gap is reduced to less than approximately 0.004” (0.1 mm) at any point along the spring (gap can be checked with piece of paper).
5. Repeat step 2 from 5.0 lb (22 N) to 95% P_{solid} to 5.0 lb (22 N), 4 cycles.

All measurement results to be provided in writing and electronic ASCII format (floppy disk).

5.2 Static Testing for Relaxation

This test will be performed in a mechanical testing machine (screw driven). To eliminate possible drift in the plastic seats, the springs may be equipped with an external strain sensor, measuring variations in pitch directly on the coil.

For all 4 springs (DC01, DC02, D03, DC04):

1. Preload to approximately 5.0 lb (22 N), maintain constant deflection for at least 5 minutes, then reset displacement sensor.
2. Quickly (5 sec. max) load to 100.0 lbs (445 N) in mechanical testing machine, maintain and monitor constant deflection (±0.002”/ ±0.05 mm) for 48 hrs while recording load (±0.1 lb). Time steps or resolution should be about 5 seconds during the initial 5 minutes under load, and 5 minute during the rest of the test.
3. Unload to back to 0 deflection and record load (±0.1 lb) for 5 minutes (±1 second).

Measurement results (load and deflection VS time) to be provided on paper (and electronic ASCII format if possible). Data about electronic drift in load cell and associated electronics is required.

5.3 Inspection for Defects in Internal Structure

Spring DC01 will be cut at various locations along the coil, both in cross-wise and length-wise directions, and the cross sections will be examined for defects (wrinkling/cracking of the aluminum sections, delaminations between various layers, discontinuities in epoxy layer, aluminum/PhBr contact points, etc.).

5.4 Dynamic Properties at Discrete Low Frequencies

The 3 remaining prototypes (DC02, DC03, DC04) are arranged under a table weighing 3*P_{nom}= 300 lb (1334.4 N) (TBD) to form a single stage isolation platform (Fig. 3). Experimental modal analysis is performed on that system to extract natural frequencies and damping ratios which in turn provide values of spring constants and loss factors at discrete frequencies and in both axial and shear directions.

The table is a rectangular aluminum plate 48” x 36” x 1.25” with 4 embedded triaxial accelerometers and weighing 200.5 lb. Four discrete masses (steel cylinders, 25 lb (TBD) each) are added symmetrically around the center to increase the weight to 300 lb (TBD). The 3 springs are arranged symmetrically around the center of mass of the table (at 0, 120, and 240 degrees on a circle of radius *R*=15”) to equalize the static load on the springs and minimize coupling between shear and axial vibration modes. This system is resting on a solid aluminum base weighing more than 4000 lbs. The table is excited at its front right (FR) corner with an electromagnetic shaker. The shaker can be rotated to provide excitation in 3 mutually orthogonal directions. Note that a similar setup was previously used with undamped steel coil springs; measured damping ratios were between 0.12 and 0.20 %.

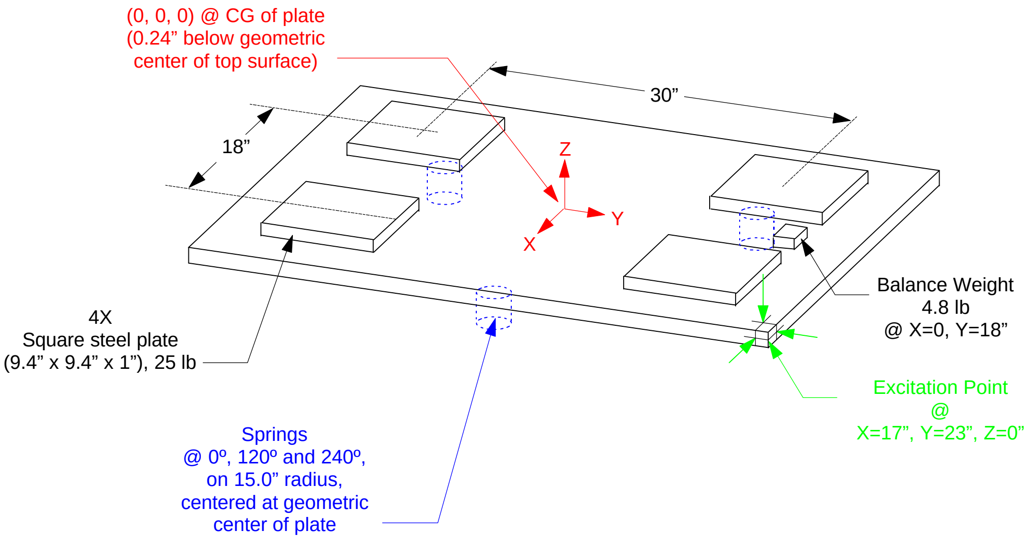

Figure 3: setup for rough dynamic stiffness and damping test.

Analytical simulations of the setup of Fig. 3 predict the following natural frequencies and damping ratios:

Mode #	Nat. Frequency [Hz]	Damping ratio V= h/2 [%]	Quality Factor Q = 1/h	Mode Shape
1	3.21	1.01	50	twist around Z (yaw)
2	3.62	1.06	47	shear along Y
3	3.67	1.03	48	shear along X
4	4.51	1.30	38	rocking around X
5	5.89	1.35	37	up/down along Z
6	6.30	1.33	38	rocking around Y

Table 1 Analytical predictions of natural modes of setup of Fig.1.

Extraction of modal characteristics from measured transfer functions will provide stiffness and damping information at these discrete frequencies. Analytical models can be readjusted based on those results then used to predict the transfer functions for direct comparison with measurements.

Equipment required

- Vibration isolation setup in experimental dynamics lab., Sandia National Laboratories, Building 878. Includes 4100 lb base block, upper table with optics platform removed (i.e. drawer plate alone) and embedded triaxial accelerometers (Endevco 63-500).
- Electromagnetic shaker (MB Dynamics 50A or similar model), and power amplifier (MB Dynamics SS250 or similar).
- 12 channel signal conditioning unit (PCB 483A10)
- Computer account on workstation with access to IDEAS data acquisition and modal analysis software.
- Hewlett-Packard front end with 2, 8-channel input modules (HP35655A), and 1 output module (HP35653A)

Test procedure

1. If possible (i.e. if undamped test coils have not been damaged or destructed by static testing), prepare test setup using 3 undamped springs UC01, UC02, and UC03.
2. Measure transfer functions from excitation F_x to all 12 accelerometer channels. Random (white noise) excitation, approx. frequency range 1 to 10 Hz, using 1024 freq. pts minimum, Hanning window, and frequency domain averaging.
3. Process data from 2 to extract 6 natural frequencies and damping ratios (IDEAS).
4. Prepare test setup using 3 damped coil springs DC02, DC03, and DC04.
5. Repeat Steps 2 and 3 on this new setup.

Interpretation:

1. Identify yaw mode (table rotating around vertical axis at CG). Extract shear stiffness and shear loss factor from natural frequency f_{yaw} and damping ratio ζ_{yaw} as

$$k_{shear}\left(f_{yaw}\right)=\frac{4\pi^2}{3}\frac{f_{yaw}^2 I_{zz}}{R} \tag{1}$$

$$\eta_{shear}\left(f_{yaw}\right)=2\zeta_{yaw} \tag{2}$$

   where I_{zz} is the mass moment of inertia of the table with masses around a vertical axis through the center of mass.

2. Identify vertical mode (table moving up and down in pure translation). Extract axial stiffness and axial loss factor from natural frequency f_{vert} and damping ratio ζ_{vert} as

$$k_{axial}\left(f_{vert}\right)=\frac{4\pi^2}{3}f_{vert}^2 M\,, \tag{3}$$

$$\eta_{axia}(f_{vert})=2\zeta_{vert}\,, \tag{4}$$

   where M is the total mass of the table (300 lbs typ. TBD).

These values can be compared to analytical estimates at the two discrete frequencies.

5.5 Acoustic Coupling (rough, in air)

Three spring assemblies DC02, DC03, and DC04 will be tested for acoustic coupling in air. The test setup is shown schematically in Fig. 4. A base plate is hanging from fixed points using long flexible bungee cords. On this base, a 3-spring single stage stack is build, using a 300 lb (TBD) top plate. The bottom plate is excited with a white noise signal in the 100 to 10000 Hz range. The bottom and top plates are equipped with accelerometers to measure excitation and transmitted noise. The noise transmission in the metal springs will be compared to that of the VITON springs. To reduce acoustic coupling through air between the bottom and top plates, acoustic blankets (1/2" foam typ., Soundcoat's Soundmat FVP for example) will be laid on top and bottom of the support platform (fig. 4)

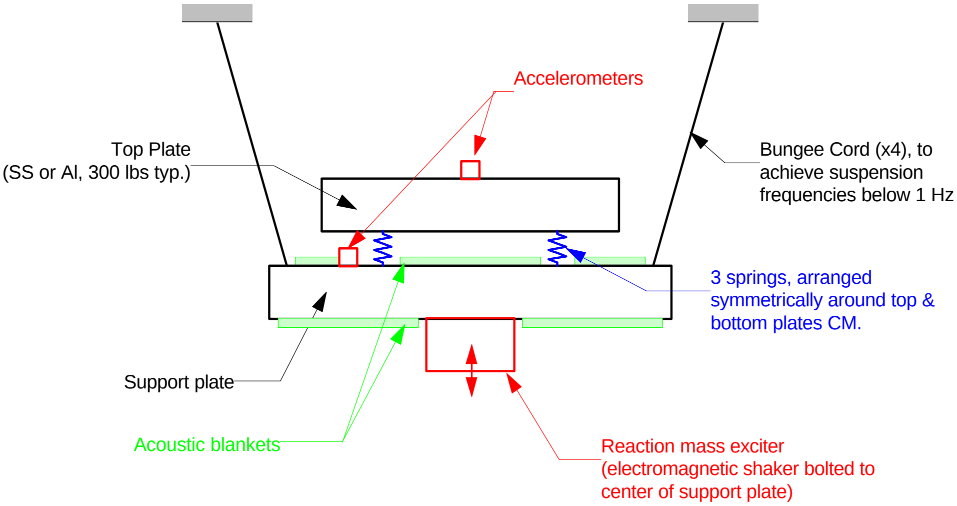

Figure 4: test setup for acoustic transmission.

Test Procedure

1. Prepare test setup using 3 Viton cone springs.
2. Turn excitation ON, white noise, 100 Hz to 10 kHz.
3. Measure top plate residual noise spectrum and bottom to top plate transfer function(s), averaging a minimum of 10 samples in the frequency domain and store data. Sine sweeps may also be performed to increase S/N ratio in frequency ranges of particular interest.
4. Replace the Viton springs with coil springs DC02, DC03, and DC04 at identical locations.
5. repeat step 3

(Note: care should be taken to insure that the background acoustic noise level in the lab is as low as possible and as similar as possible during steps 3 and 5. An acoustic envelope may be used around the setup if necessary)

Interpretation

The noise spectrum measured in step 3 serves as a baseline and includes any parasite coupling through the air and external noise sources. The spectrum from step 4 is compared to it.

5.6 Creak (rough, in air)

The purpose of this test is to detect the presence of creak (small energy releases due to stick/slip interfaces, cracking, etc) in the coil springs subjected to a large static preload (100 lb/spring TBD) and small amplitude, low frequency load variations. A setup similar to that of Fig. 4 is used for this test (see Fig. 5). It is equipped with a couple of non-contacting electromagnetic exciters (in vertical and horizontal directions) that apply a small amplitude load to the upper table (1 lb p-p typical) at a low frequency (0.2 Hz typ.). The load variation induced in the springs is expected to activate any creaking mechanism in the springs. It is critical to insure that no high frequency noise appears in the power supply to the coils. Low-pass filtered high quality source and amplifiers may be required. The electric input to the coil will be monitored during the tests to allow detection of any correlation between it and accelerometer signal.

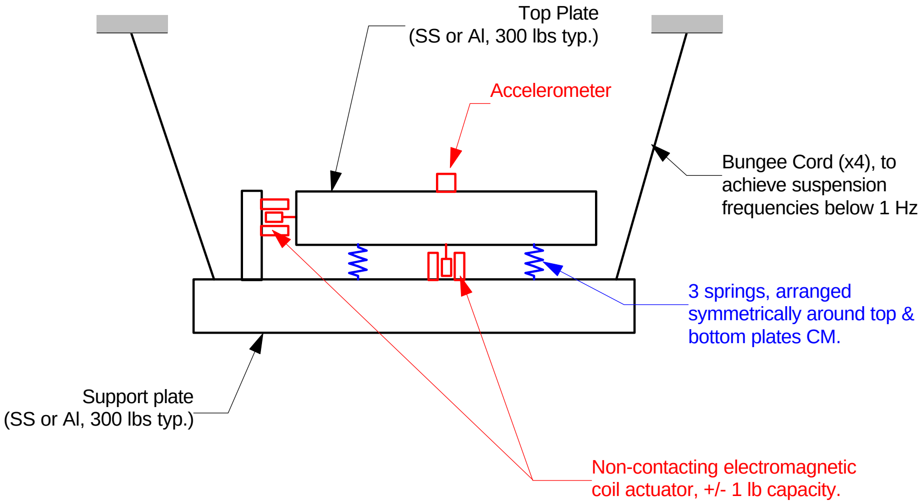

Figure 5: test setup for rough creak testing.

<u>Test Procedure</u>

1. Prepare test setup using 3 Viton cone springs.
2. Turn excitation ON, 0.2 Hz monochromatic (typ.), 1.0 lb P-P (typ.)
3. Monitor top plate accelerometer and excitation signals on oscilloscope for presence of pulses in accelerometer signal. Also, measure and store PSD of accelerometer and excitation signals: frequency range 10 Hz to 20 kHz, no windowing, average 20 samples in freq. domain.
4. Replace the Viton springs with coil springs DC02, DC03, and DC04 at identical locations.
5. repeat step 3

(Note: care should be taken to insure that the background acoustic noise level in the lab is as low as possible and as similar as possible during steps 3 and 5. An acoustic envelope may be used around the setup if necessary)

5.7 Vacuum Compatibility, Outgassing

After welding end caps at the coil ends, three spring assemblies (with seats, DC02, DC03, DC04) will be tested for vacuum compatibility following the procedures described in Section 6 of the *LIGO Vacuum Compatibility, Cleaning Methods and Qualification Procedures*[1]. Outside of part is Phosphor Bronze C510. Clean according to Section 4.A of [1] and bake at 120°C (250°F) for 24 hours prior to test. Vacuum bake temperature during test should not exceed 120°C (250°F).

5.8 Static Testing for Effect of Vacuum Bake Treatments

To investigate any effect the vacuum bake treatments may have on the mechanical properties of the springs, repeat the tests in Sections 5.1, 5.2, and 5.3 on all 3 remaining springs (DC02, DC03, DC04).

5.9 Fatigue Test

Potentially destructive test intended to investigate potential failure mechanisms due to repeated loading and unloading of the stacks (in particular in the internal structure: delaminations, damage to damping layer, etc.).

1. Preload to 5.0 lb (22 N), and reset displacement sensor to 0.
2. Sinusoidal or sawtooth load/unload cycles 5 lb to 100 lb (TBD), minimum period of load/unload cycle = 2 seconds, record load and displacement extremes for 1000 cycles or to failure.

All measurement results to be provided in writing and electronic ASCII format (floppy disk).

6. Damped Springs - Advanced Testing

In a third phase of development, we will produce about 50 identical damped coil springs (and 100 Viton seats). If time permits a number of advanced tests described below may be performed.

6.1 Static testing for scatter in mechanical properties

The goal is to evaluate the amount of scatter in mechanical properties. For simplicity, only static stiffness and spring length under load are examined.

For all 50 springs:

1. Preload to 5.0 lb (22 N) and reset displacement sensor
2. Pseudostatic ramp load/unload from 5.0 lb (22 N) to 100.0 lb (TBD) (356 N) to 5.0 lb (22 N), 4 cycles, 5.0 lb/sec (22.2 N/sec) loading/unloading rate, record axial load ±0.1 lb (±0.5 N) or better, and axial deformation ±0.001" (0.025 mm) or better.
3. Examine spring for visible damage (cracking, asymmetric deformation, etc.).

All measurement results to be provided in electronic ASCII format (floppy disk).

6.2 Long Term Drift

1. construct a symmetric single-stage stack with 3 springs supporting 300 lbs (TBD) and equip with 3 mechanical micrometers to measure vertical drift at each spring.
2. maintain loaded and unperturbed for 30 to 60 days, recording micrometer measurements every hour during the first 8 hours then roughly every day for the rest of the test.

6.3 Dynamic testing for properties at vanishingly small amplitudes

This is a particularly difficult test to perform since the amplitudes seen by the springs in the actual detector (last stages of the stack) are so small they can only be measured by interferometry and any small external disturbance (seismic noise for example) is likely to overshadow any meaningful signal. Short of an actual prototype test in a LIGO-like interferometer, we consider unlikely that reliable data will be obtained for deflection amplitudes of the order of magnitude that the springs will experience in the LIGO detectors.

6.4 Acoustic Transmission

A more sensitive measurement of acoustic noise transmission could be performed by repeating test 5.5 in a vacuum. The lower noise floor should allow the use of much reduced excitation amplitudes.

6.5 Creak

Test 5.6 could be repeated in a vacuum chamber.

7. References

1. E. Ponslet, *Design of Vacuum Compatible Damped Metal Springs for Passive Vibration Isolation of the LIGO Detectors,* HYTEC Inc., Los Alamos, NM, document HYTE-TN-LIGO-09, November 1st, 1996.

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