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Investigations with the Prototype Output Mode Cleaner Suspension: A Study of its Design and Performance

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The Output Mode Cleaner (OMC) has been designed for use in the Advanced LIGO gravitational wave detectors, and will work as a resonant cavity to filter unwanted noise from the output signal of a detector. The OMC will consist of a silica bench supporting the cavity optics. It is required to be isolated from ground vibrations to avoid addition of noise to the output signal. The isolation is provided by suspending the bench as the bottom mass of a double pendulum. Aspects of the OMC suspension were tested using a dummy metal bench. Transfer functions were measured to obtain the resonant modes, which were in good agreement with results obtained from a MATLAB model of the suspension. Damping tests were carried out to ensure all the modes can be effectively damped using six optical sensors and electromagnetic actuators (OSEMs). Cross-coupling in OSEM sensitivity was also measured, and the maximum range of angular motion of the dummy metal bench was calculated. The tests completed have shown that the suspension is functioning in an expected and adequate manner.

The Laser Interferometer Gravitational-Wave Observatory (LIGO), a joint project by Caltech and MIT with the purpose of directly observing gravitational waves with the use of Michelson Interferometers, will replace its current detectors with new instrumentation that will improve the sensitivity by a factor of 10. The upgrade is referred to as Advanced LIGO. Before Advanced LIGO takes place, an Enhanced LIGO upgrade will occur to test some of the technologies developed for Advanced LIGO. The installation of the Output Mode Cleaner (OMC) is one of the upgrades designed for Enhanced and Advanced LIGO. The OMC consists of optics mounted on a silica bench, and will serve as a resonant cavity to filter unwanted noise from the output signal of the interferometers. To avoid addition of noise to the detector, the OMC needs to be isolated from ground vibrations. This isolation is provided by suspending the OMC as the bottom mass of a double pendulum (Figure 1). Tests on the suspension have shown it will effectively isolate the OMC.

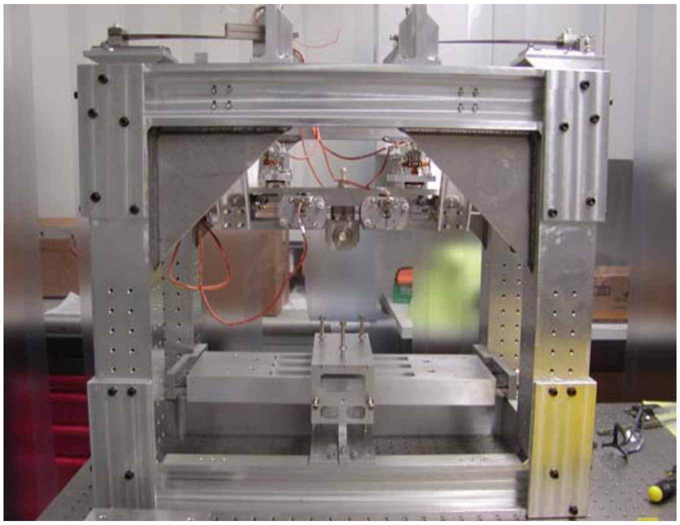

Figure 1. Output Mode Cleaner Suspension. A dummy metal bench, which replaces the OMC optics bench, hangs as the bottom mass of a double pendulum suspension supported by a metal structure.

Design

The Suspensions group decided to build a double pendulum suspension, as opposed to a single pendulum, to provide extra isolation. The double pendulum suspension consists on an optics bench on which OMC optics will be mounted, as shown in figure 2. The bench will be made out of silica,

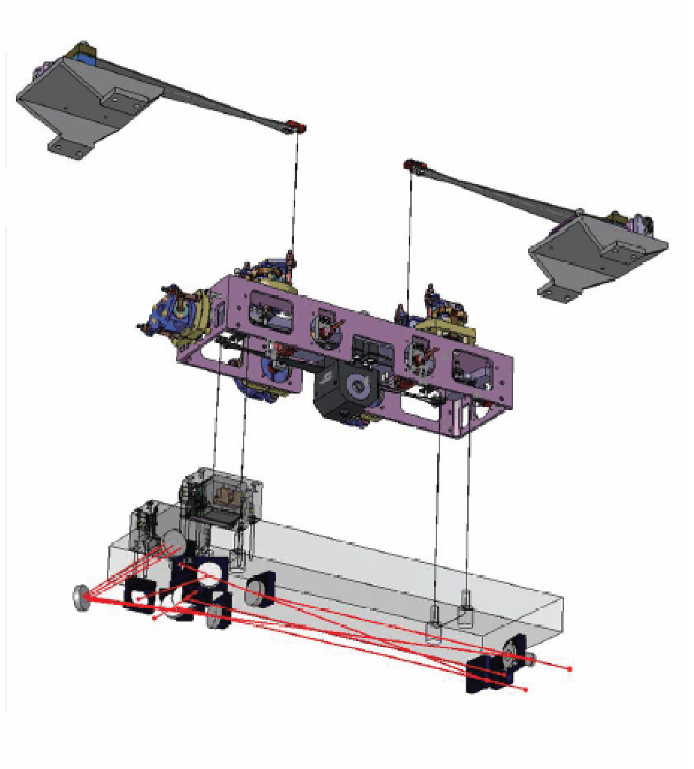

Figure 2. Double Pendulum Suspension. The OMC hangs from the upper mass, which in turn hangs from two wires connected to two blades that are attached to the support structure.

even though all testing on the suspension has been performed with a dummy metal bench. Both benches have dimensions of 450mm x 150mm x 40mm and have a mass slightly over 6 kg. The suspension provides isolation for the bench in all six degrees of freedom: longitudinal, transverse, vertical, roll, pitch, and yaw. The bench hangs from four wires connected to four blades mounted on the bottom of an upper mass. The upper mass hangs from two wires connected to two bigger blades that are attached to the support structure of the suspension. The upper mass has a mass of about 3 kg, which contributes to a total mass of about 9 kg for the entire suspension.

Damping of the double pendulum is applied by 6 Optical Sensor and Electro-Magnetic actuators (OSEMs), developed at the University of Birmingham, to reduce motion of the suspension at the resonant frequencies. The OSEMs add electronic noise to the suspension, and hence damping is applied to the upper mass. The optics bench hangs from the upper mass, and this second pendulum stage provides further isolation, reducing the effect of electronic noise on the bench. Three OSEMs are mounted above the upper mass to damp excitations in the vertical, pitch, and roll degrees of freedom, two behind the upper mass to damp longitudinal and yaw excitations, and one on the side for transverse movement. The OSEMs consist of an LED-Photodiode combination that detects the position of the upper mass, and coils that produce a magnetic field that damps the oscillations of the upper mass.

The support structure, made of welded aluminum, holds the suspension. Its first resonance is around 140 Hz. Even though this value does not satisfy the 150 Hz lower limit, the design is likely to be acceptable.

Testing – Methods and Results

Different tests were carried out to ensure an effective performance of the suspension, and to obtain further information regarding its properties.

Decay Curves were measured to ensure the OSEMs and the feedback loops were damping the suspension effectively, that is, with a settling time of 10 seconds for the amplitude to decay to 1/e of its initial value. The test consisted on applying an excitation, either electronic or human made, and measuring the impulse response in all six degrees of freedom by having the feedback loops closed and the damping filters on. We recorded the decay curves by using a program called Diagnostic Test Tools (DTT). Specifically, we used the triggered time response testing method of DTT to observe the decay of the oscillations of the suspension. The test was run for fifty seconds. The results obtained showed the feedback loops damp the suspension with settling times as small as five seconds, as can be deduced from figure 3. Un-damped decay curves showed the suspension's vibrations also decay, which is due to the effect of air acting as a natural damping agent. However, un-damped oscillations have much higher settling times, around 35 seconds for longitudinal oscillations, for example.

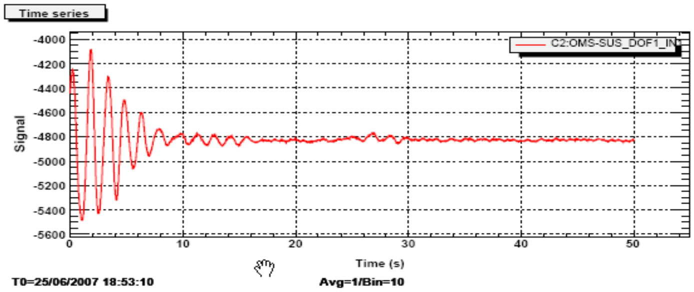

Figure 3. Decay Curve. Decay Curve for the longitudinal degree of freedom with the feedback loop closed. The settling time requirement is 10 seconds.

Transfer functions of the suspension were also measured to compare the resonant frequencies and the behavior of the suspension with a MATLAB model. The transfer function of a system is defined as the ratio of the Laplace transform of a time domain output function and the Laplace transform of a time domain input function, as shown by the following equation, where H(s) denotes the transfer function.

$$H(s) = \frac{Y(s)}{X(s)} = \frac{\mathcal{L}\{y(t)\}}{\mathcal{L}\{x(t)\}}$$

My system's output of the transfer function consisted of the displacement signal of the upper mass, as recorded by the OSEM sensors, while the input was the electronic excitation applied to the upper mass.

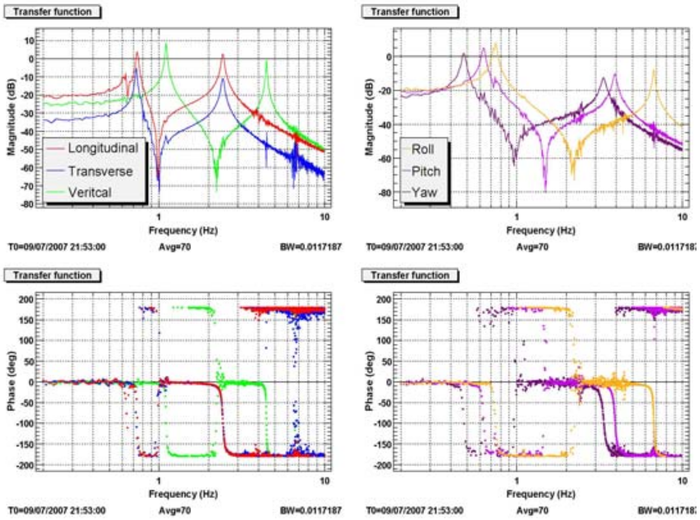

Figure 4. Transfer Function. The transfer functions were obtained for all six degrees of freedom. Their magnitude is shown in the two upper plots and their phase is shown in the two lower plots. The frequency domain ranges from 0.2 Hz to 10 Hz, with a bandwidth of 0.01 Hz.

The transfer functions for all six degrees of freedom were recorded by using DTT's Fourier Tools measurement method. Also, using DTT we injected a uniform noise excitation with appropriate filters to get a clean signal at resonances and zeros. The results obtained, shown in figure 4, show resonant frequencies that are in good agreement with the ones expected from the model. These resonant frequencies are 0.735 Hz and 2.440 Hz for longitudinal, 0.732 Hz and 2.430 Hz for transverse, 1.120 Hz and 4.460 Hz for vertical, 0.632 Hz and 3.940 Hz for pitch, 0.480 Hz and 3.350 Hz for Yaw, and 0.743 Hz and 6.730 Hz for Roll. The highest percentage difference is 7.04 for the first pitch mode, but most resonant frequencies differ by less than 2% from the model. A plot of the transfer function for the longitudinal direction as predicted by the MATLAB model follows (figure 5), which shows its similarity with the actual longitudinal transfer function. The slight difference in mode frequencies may be due to slightly different parameters of the suspension as compared with those of the MATLAB model, such as different masses, moments of inertia, or d values, which are the distances from the center of gravity of a mass to the break off points of the suspending wires.

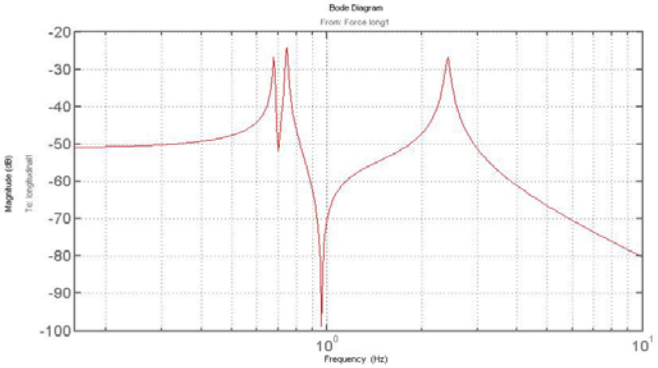

Figure 5. Longitudinal Transfer Function. Using the MATLAB model of the suspension the transfer function for the longitudinal degree of freedom was plotted and compared with the suspension's longitudinal transfer function.

Cross-Coupling in OSEM sensitivity was also measured. The experiment consisted on applying an excitation in either the longitudinal or vertical direction, and observing this excitation as recorded by the side OSEM, that is, in the transverse direction. The excitations for the longitudinal and vertical degrees of freedom were created using a program called Arbitrary Waveform Generator. The frequency of the excitations was 9 Hz with amplitude of 1. The gains of the feedback loops were systematically increased to observe stronger and stronger excitations. To observe and analyze the cross-coupling between OSEMs we used DTT's Fourier Tools measurement method to obtain transfer functions between transverse and longitudinal degrees of freedom, or between transverse and vertical degrees of freedom, their coherence, and power spectrums. Figure 6 shows the power spectrum for the longitudinal and transverse degrees of freedom.

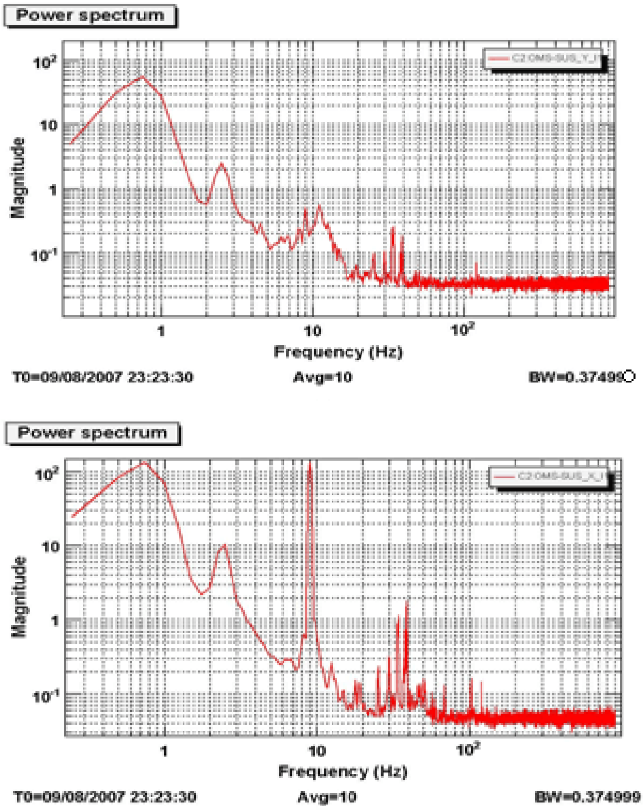

Figure 6. Power Spectrum. The top graph shows the power spectrum for the transverse degree of freedom. The excitation at 9 Hz can be observed, yet it has a small value. The bottom graph shows the power spectrum for the longitudinal degree of freedom. The 9 Hz excitation can be easily recognized due to its high magnitude, as expected.

The 9 Hz excitation can be clearly observed in the power spectrum for the longitudinal direction, but is much smaller in the power spectrum for the transverse direction. This indicates a small cross coupling between transverse and longitudinal directions. The best values for cross-coupling obtained when centering the OSEMs with the greatest precision from my eye's perspective were -53 dB between transverse and longitudinal, and -37 dB between transverse and vertical. However, since the longitudinal excitation was created by two OSEMs, and the vertical direction was created by OSEM Top 3 and half of Top 1 and 2, totaling a value of two OSEMs, the results obtained had to be multiplied by a factor of two. This corresponds to adding 6 dB to the results mentioned before. Hence, the actual cross-coupling between transverse and longitudinal directions has a value of -47 dB, and the cross-coupling between transverse and vertical has an actual value of -31 dB. Cross-coupling between other degrees of freedom hasn't been measured, and this is an activity that may be performed in the following weeks.

The final test I performed was a measurement of DC angular alignment. The purpose of this experiment was to see how much the optics bench could rotate when the maximum offset was applied to the OSEMs. The set up for the experiment consisted on mounting a small mirror on the top of the dummy metal bench and reflecting HeNe laser light from the mirror to a wall. The position of the beam spot on the wall was marked, and the maximum allowed positive and negative value of DC current (corresponding to an offset value of +/- 30000 counts in the digital system) was applied to the coils in the appropriate OSEMs to rotate the bench in either the yaw, pitch or roll directions. The new position of the beam spot on the wall was marked, and the displacement between beam spots was measured. Using the following equation, which can be deduced from figure 7, I was able to obtain

$$\alpha = \frac{X}{2L}$$

the angular range of motion of the bench. The distance between beam spots is denoted by X, while L is the distance between the mirror and the beam spot on the wall, and α is the angular rotation of the bench. The results obtained are 0.10° (1.8 millirads) for Roll, 0.15° (2.7 millirads) for Pitch, and 0.13°

(2.3 millirads) for Yaw. These values, even though quite small, were the ones expected.

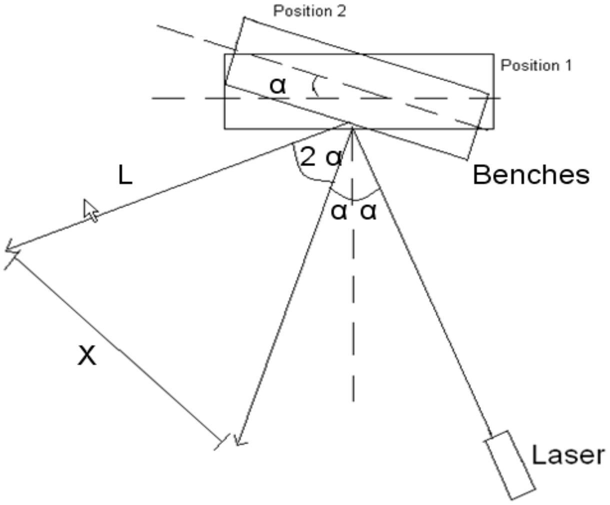

Figure 7. Angular Motion. The diagram above exemplifies the experiment performed to measure α, the maximum angular range of the optics bench. The distance between beam spots is denoted by X, and the distance from the wall to the mirror mounted on the bench is denoted by L.

Conclusions

The Output Mode Cleaner needs to be isolated from ground vibrations, and the isolation is provided by a double pendulum suspension. I have presented the design of this suspension, and have later explained tests performed to test its functionality. Our research group has concluded from the tests completed that the suspension is performing in an efficient and expected manner. The feedback loops effectively damp the oscillations of the upper mass and the optics bench by the settling times required, as shown by decay curves. Also, the resonant modes are in good agreement with those predicted by a MATLAB model. Moreover, cross-coupling between OSEM sensitivity is minimal. Finally, the ranges of angular rotations of the optics bench in different degrees of freedom when excited by the OSEMs have expected values (of the order of one milliradian).

The OMC suspension will now be disassembled to perform modifications to the table cloth and structure. The suspension will then be reassembled and further tests will be done with the silica bench by mid September. The OMC and the suspension are scheduled to be delivered to the LIGO Livingston Laboratory by December, and a second OMC suspension, built and tested at Caltech, will be delivered to LIGO Hanford Observatory by April, 2008.

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