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ULTRA-PRECISE SENSING AND CONTROL OF SUSPEN IN THE CRACKLE EXPERIMI

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Background: What is Crackling noise?

James P. Sethna et. al. define Crackling noise as follows: "Crackling noise arises when a system responds to changing external conditions through discrete, impulsive events spanning a broad range of sizes". [1]This is a very broad definition; what this paper is interested in is a specific kind of Crackling noise: the kind that arises in maraging steel blade springs under stress. For an intuitive explanation, perform the following exercise: pick up a piece of paper and start crumpling it slowly. Notice that as your hand crumples it, you can hear the sound of paper being crumpled. Why does this happen? If you haven't already guessed, the answer is: Crackling Noise! In this case, the motion of the hand (changing external conditions) causes the system (paper) to respond in the form of sound (pulses of energy). The frequency of motion of the hand is of the order of a few hundred mHz, but the response (sound) is in the audio regime! This frequency up-conversion is of Crackling noise, and it shows the nonlinear behavior of dislocation interactions. A more formal way of understanding this is as follows: In metals, dislocations are "pinned" by obstacles like grain boundaries or other surfaces. Under small oscillatory stress, these dislocation lines bow in and out, but the response of the complex network of a large number of such dislocations on the whole is known to act nonlinearly through long-range interactions. This nonlinear behavior, among a broad class of other nonlinear phenomena, is known to be the cause of "Crackling." "Crackling" here refers to impulsive releases of energy, acoustic emissions, or changes in the geometry of attachments between suspension elements. The Laser Interferometer Gravitational Wave Observatory (LIGO) is a configuration similar to a Michelson interferometer. The lengths of the interferometer arms are 4km long each, and light bounces back and forth in these to interfere destructively at the output port. When a gravitational wave passes by, General Relativity predicts that these arms are stretched and squeezed by a tiny amount periodically. This can be detected in the output port, since when a GW passes by, there is non-zero difference in the lengths of the interferometer arms, causing an interference pattern at the output port. Figure 1 shows the test mass suspension scheme in Advanced LIGO, a large-scale experiment that endeavors to directly detect a gravitational wave.

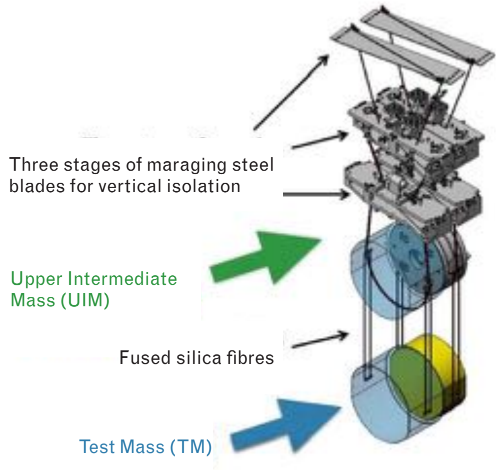

Figure 1: Suspension scheme in Advanced LIGO
Maraging steel blades are used for suspending the end mirror of the interferometer in four stages. Silica fibers are used to suspend the mirror and the other stages from the top stage.

The Maraging Steel blades used in suspensions have been under investigation in the first Crackle experiments, as they present a mechanical system which can be driven and stressed easily. As Crackling noise is inherently nonlinear, there is the potential for noise to be up-converted. Specifically, motion of the suspension at micro-seismic frequencies may induce blade motion, causing the blades' internal stresses to fluctuate, resulting in an avalanche of Crackle events with high-frequency content. This results in displacement noise in the stressed (vertical) direction. But why would vertical displacement noise matter at all when the gravitational wave would stretch or contract the arm in the horizontal direction? This is because the earth is curved over the length of each arm (4 km), the input and end mirrors are no longer parallel to each other; instead, they are perpendicular to the ground, aligned with gravity. In this situation where the mirrors are not parallel to each other, the laser beam will not "stay" in the cavity, and it would bounce off the mirrors a few times and exit the cavity. But because the cavity needs to be locked, where the light is "stored"

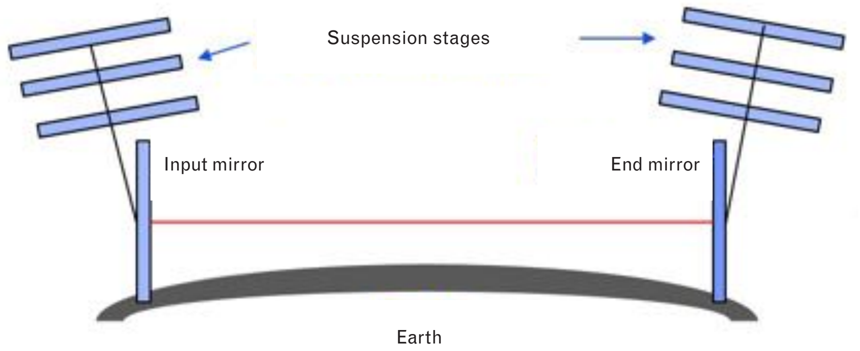

Figure 2 : Alignment of input and end mirrors in each arm of the LIGO interferometer
The path between the input and end mirrors is not flat. This is due to the curvature of the earth over the length of the arm; the input and end mirrors are ''held'' parallel to the each other.

in the cavity due to repeated reflections off the mirror surfaces, the mirrors are held parallel to each other (and perpendicular to the laser beam) by external force. The configuration is shown in Figure 2. Now, there's a problem: "vertical" displacement noise (the vertical direction is aligned with gravity, not along the length of the mirror, because the mirror is now held such that it is perpendicular to the laser beam) in the end mass suspension system has a horizontal coupling component. Therefore, Crackling noise in the maraging steel blade springs can potentially generate spurious signals in the GW detection signal. The motivation of the Crackle experiment is to measure this noise experimentally. This paper discusses our work on making progress towards building an ultra-sensitive Crackling noise detection setup.

Motivation: Why and where do we need a feedback damping system in the Crackling noise detection setup?

The setup to measure Crackling noise consists of a Michelson interferometer using blade-suspended masses as end mirrors. A Crackle event

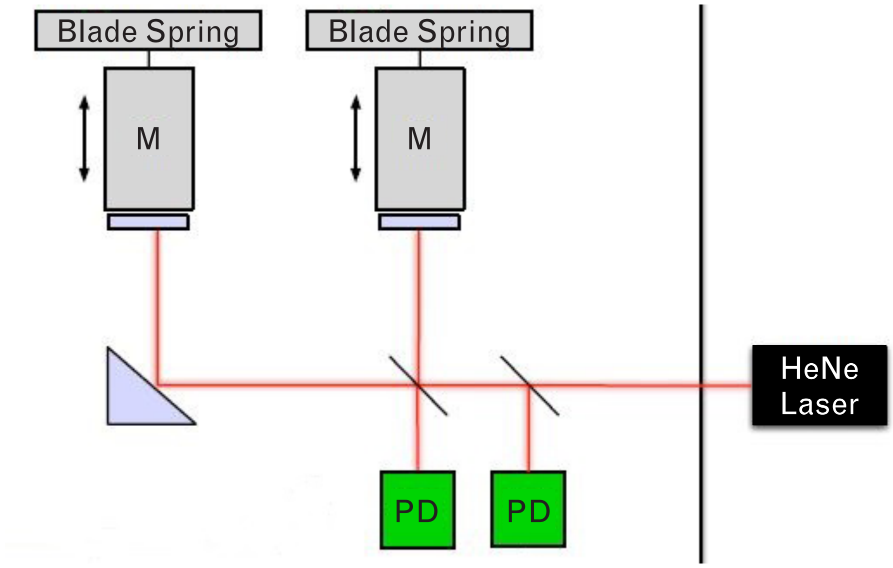

Figure 3:Crackling noise measurement strategy
This depicts a vertically aligned Michelson interferometer, where two mirrors are placed at the bottom face. As Crackling noise arises incoherently in each blade, it will be detected in the difference signal of the two photodiodes (labelled PD).

event will change the differential displacement of the mirrors, and hence be reflected in the interferometer output. The events are excited by a low frequency, common-mode, drive on the two blades [2]. The apparatus is going to be housed in a vacuum chamber to mitigate acoustic noise. A direct measurement of Crackling noise is very difficult. However, measurements can be made of the blade displacements directly using a Michelson interferometer with end mirrors mounted to loaded blade springs which are driven with a low frequency, common-mode force. Since Crackling noise occurs incoherently in each blade, it will show up in the Michelson's displacement signal. This is illustrated by Figure 3. The optical layout schematic is shown in Figure 4. The setup features a vertically suspended optics breadboard. The suspension is two-staged, and can be seen in the cartoon in Figure 5. The bottom-most rectangle represents the optics breadboard. The purpose of the suspension is to provide seismic isolation: a suspension acts as a mechanical filter that negates the effect of seismic motion. Ideally, seismic motion of the optical setup wouldn't couple to the Michelson signal because the motion would be common to both mirrors. However, any differential motion of the blades would result in a spurious signal. Figure 5 shows a simplified scheme of the suspension system. The breadboard shown in Figure 5 above is suspended from a two stages and is "free" to move. Even though the suspension stages provide isolation from seismic noise, the same suspension stages also cause two resonances elsewhere. This is simply because the system acts like a double spring- mass or pendulum system which has two resonant frequencies. What the values of these resonant frequencies are, in each degree of freedom, depends on the mechanical design of the whole setup. In this case, the setup has been designed such that the

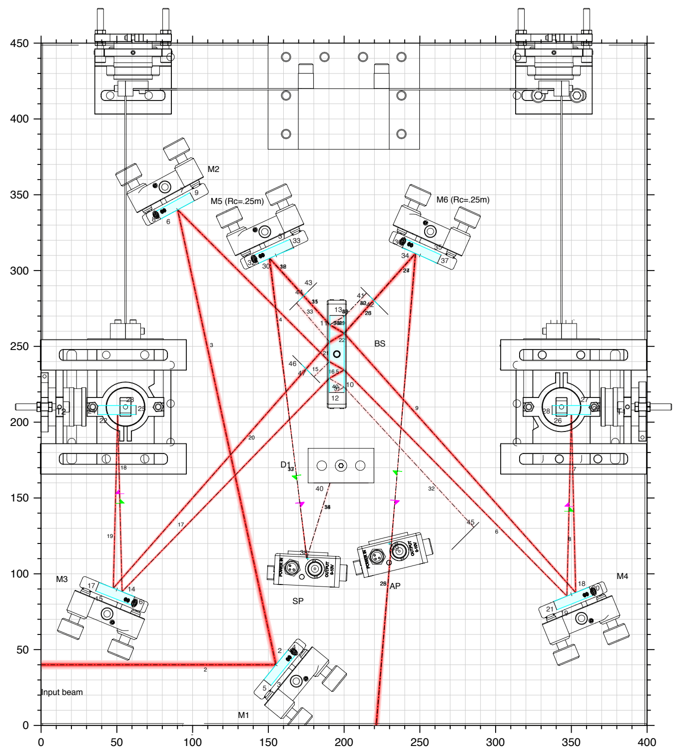

Figure 4: Optical layout
Light enters from the bottom left of the breadboard. This is a more detailed version of Figure 3. Light from the laser comes in from the bottom left corner through a viewport. Two folding mirrors then redirect the beam to the beam splitter. The two arms of the Michelson interferometer are folded in such a way that the beams impinging on the end mirrors are almost vertical, but tilted enough so that the beams propagating in opposite directions (before and after reflection from the mirror) are separate. The end mirrors of the Michelson arms are horizontal.

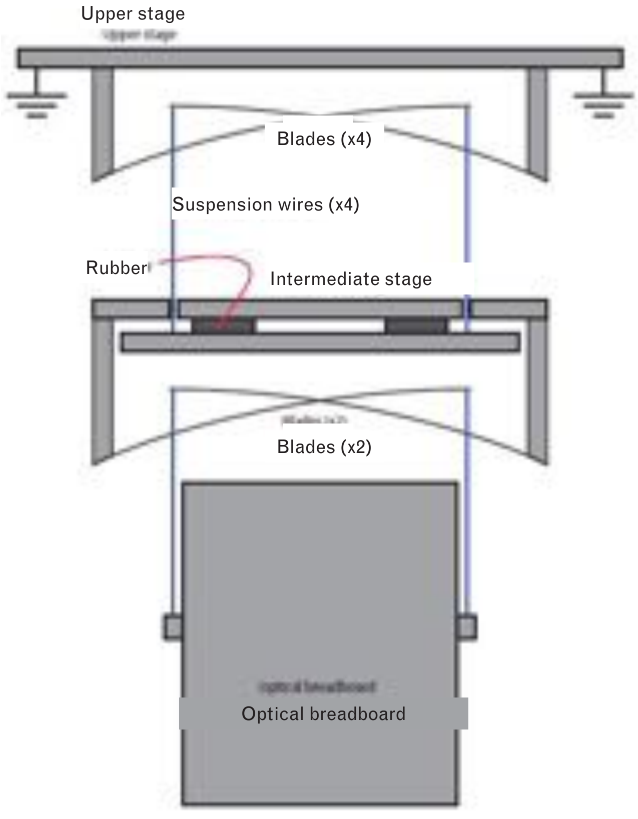

Figure 5: Scheme of the suspension system
The Crackling noise detection setup consists of a two stage suspension system. The bottom most part is where the Michelson interferometer is housed.

In metals, dislocations are “pinned” by obstacles like grain boundaries or other surfaces. Under small oscillatory stress, these dislocation lines bow in and out, but the response of the complex network of a large number of such dislocations on the whole is known to act nonlinearly through long-range interactions. This nonlinear behavior, among a broad class of other non-linear phenomena, is known to be the cause of “Crackling.”

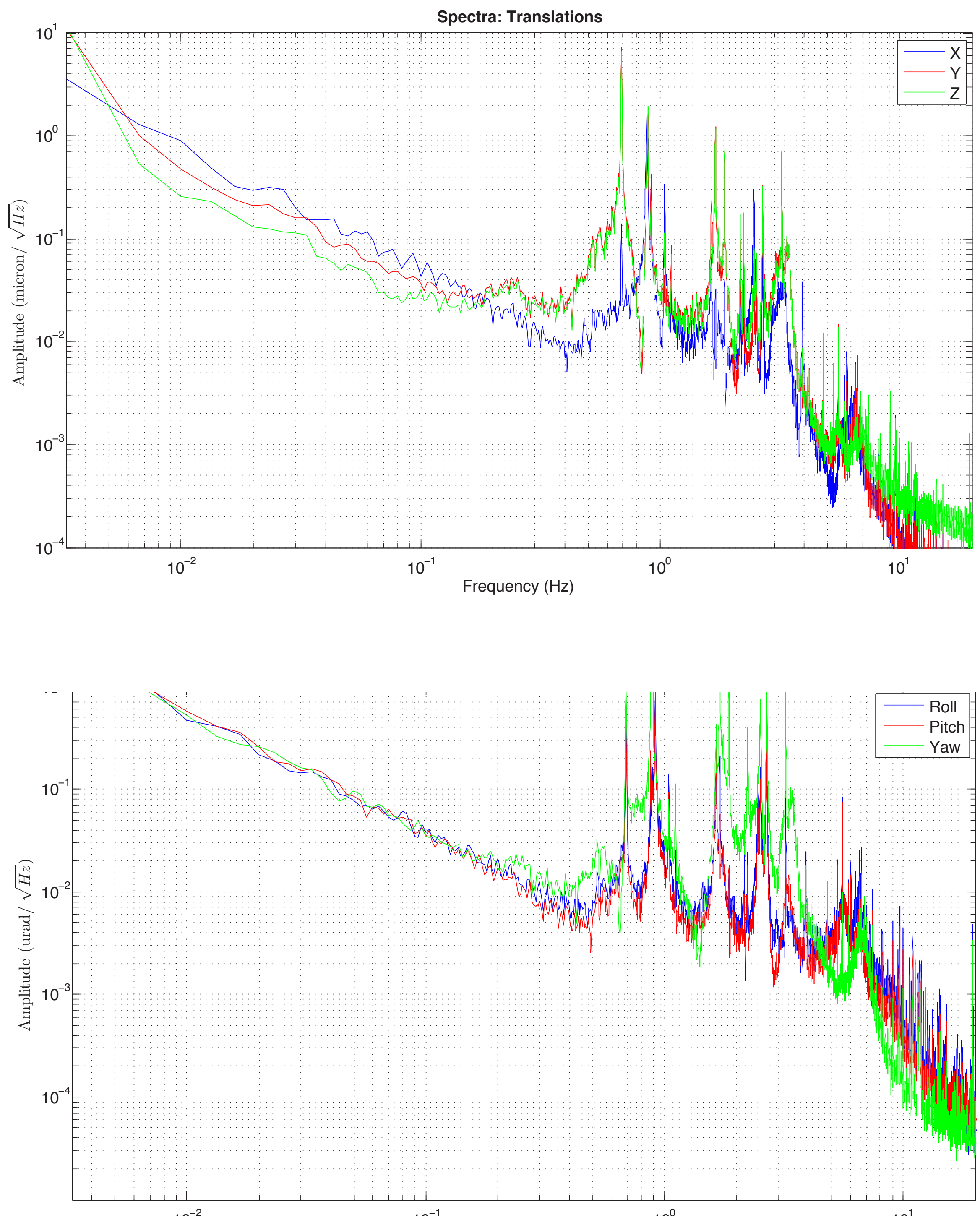

Figure 7: Spectra of motion in 6 d.o.f.
These spectra of the rotations and translations of the system were obtained by recording signals from analyzing various OSEM's mounted in the setup. The peaks around 1 Hz correspond to the resonance frequencies of the mechanical system of the setup.

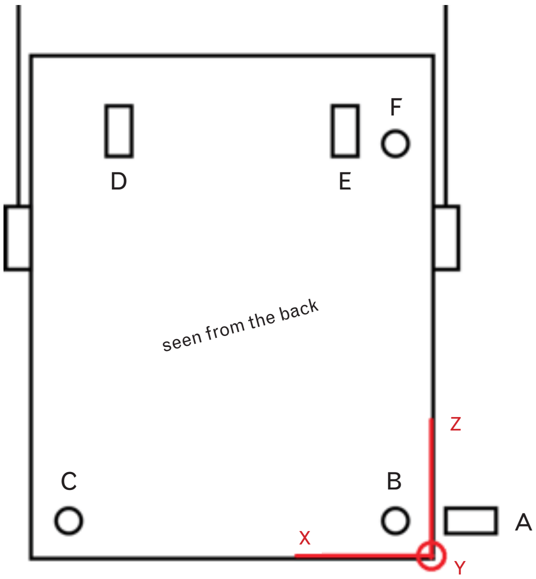

Figure 6: Scheme of OSEM's
The circles indicate an axis of the OSEM that points into the page, and the rectangles indicate an axis that points vertically upwards.

resonant frequencies are around 1 Hz, for all degrees of freedom. As a result of these resonances, any excitation of the breadboard around those frequencies can cause severe motion in the breadboard, leading the Michelson Interferometer (which measures Crackling noise) to be disturbed. Therefore, it is essential to keep the breadboard "calm" around resonances. Put in more technical terms, the Quality Factory (Q) of the resonant poles must be reduced. This is what forms the problem statement for our current work: to design a feedback controlled damping system for the suspended optics breadboard in the Crackle experiment. Data: How do we design a damping filter? Signals from Optical Shadow Sensor Electro Magnetic Actuators (OSEMs) were used to track the motion of the breadboard in physical degrees of freedom. Figure 6 shows the mounting scheme of the six OSEMs. It is possible to use the outputs of these shadow sensors to sense motion of the suspended breadboard in six degrees of freedom, creating a sensing matrix. From the plots in Figure 7, one can infer the following:

The breadboard is suspended, and the OSEMs are fixed relative to the ground. Most of what is seen in the spectrum is due to motion of the ground (seismic activity); this seems to be concentrated in the <10Hz region. This is the region of interest: the aim is to damp motion at resonant frequencies of the suspension. Seismic isolation has been achieved by using a suspension, but the modes of the suspension are in the 0.1-10Hz region. At these frequencies, the breadboard moves more than the ground, and so motion must be damped. Damping motion of the breadboard at resonant frequencies requires us to have an idea of the mechanical response of the system. Characterization of the mechanical response of the system consists of exciting the system (breadboard) in one of the degrees of freedom, and recording the response in all others. This amounts to measuring the "transfer functions" of the system: the ratio of motion sensed to excitation given in the frequency domain. Using the sensing matrix, it is possible to sense motion

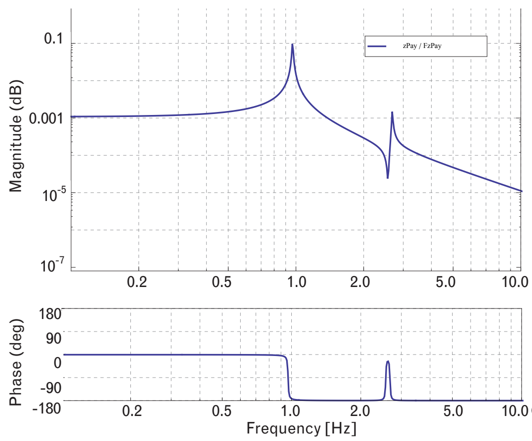

Figure 8: Analytical result for the Z-Z transfer function
This transfer function is a pure analytical prediction, based on Newton's laws. It was obtained by modeling the mechanical system on the SUMCON simulation platform.

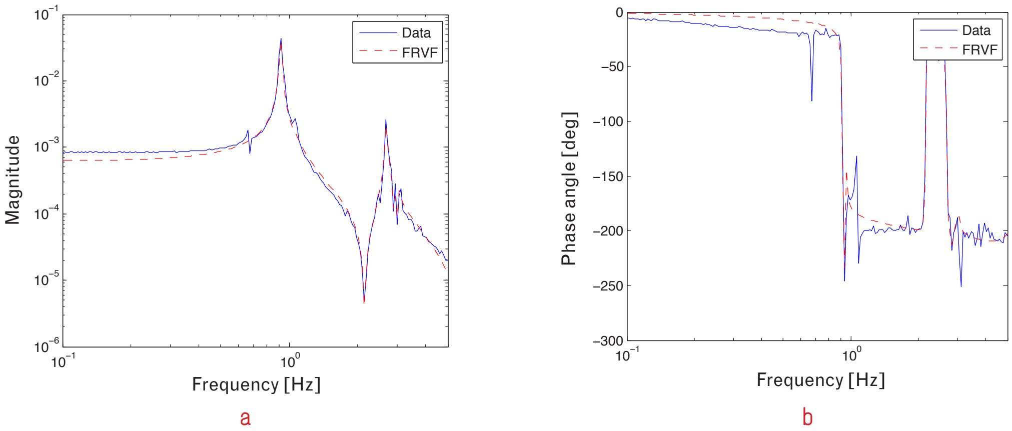

Figure 9: Vector fitting of the Z-Z transfer function
After experimentally measuring the transfer functions, they were vector-fit using the vectfit function on MATLAB. Plot a) is the magnitude plot, and Plot b) is the phase plot.

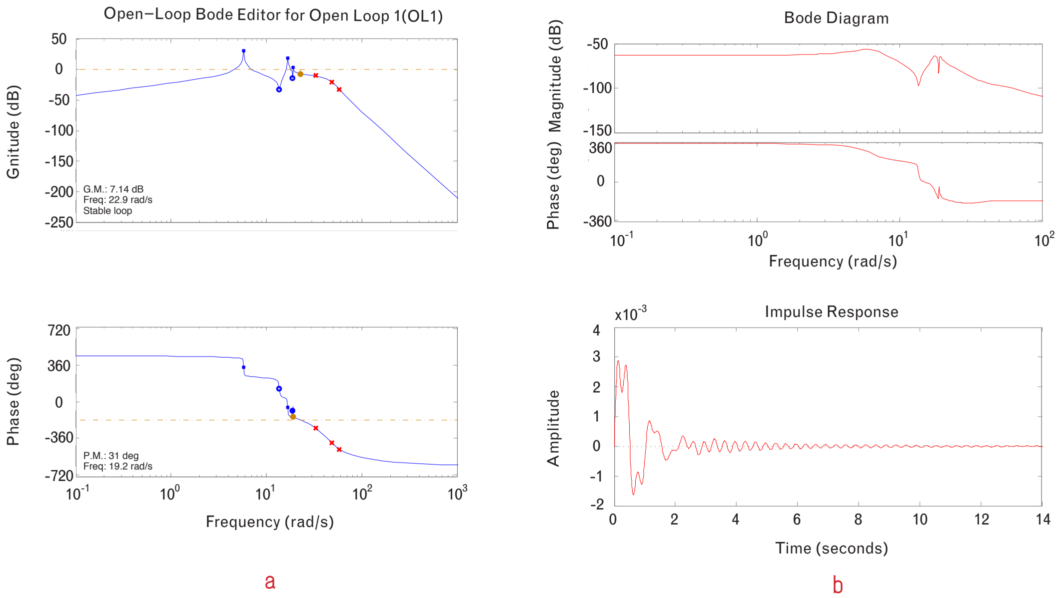

Figure 10: Open and closed loop transfer function analysis
a) The Open Loop Editor for Z-Z Open Loop Transfer Function (OLTF). The plot in blue is the OLTF. In the magnitude and phase plots, the red crosses depict complex poles added for roll off. The Gain Margin and Phase Margin are also plotted, and both the values are good enough for sustaining a stable loop.
b) Analysis Plot showing Bode diagram of Closed Loop Transfer Function (CLTF) and Impulse Response of the closed loop. The Bode Diagram of the CLTF has reduced Q of the poles. Also, the impulse
response of the closed loop system shows that the system quickly settles back to stable position after an impulse.

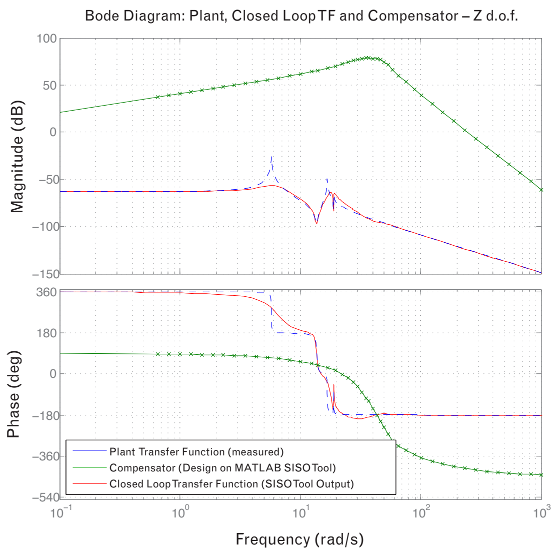

Figure 11: Filter design for Z-Z transfer function
This figure shows the measured transfer function of the system, the compensator (i.e. damping filter) designed, and the resultant closed loop transfer function as predicted by the MATLAB Single Input Single Output (SISO) tool.

along physical degrees of freedom. The equation that governs the drive of the suspended breadboard along the physical degrees of freedom, creating a driving matrix. Thus, both the drive and sense of the system can be characterized. The next step is to characterize the mechanical response of the system, by measuring transfer functions of the system. It is possible to run all of the six degree of freedom measurements in series, because the system is governed by Newton's laws, and is therefore linear. Thus, as long as the system is not excited by the same frequency through different coils at the same instant in time, the measurements should be sound as they were frequencies, there is no excess noise introduced by the damping, though it is important to note that the resolution of the OSEM signals is only of the order of microns for a few Hz. Since Crackling noise occurs incoherently in each of the test blades, it is expected to show up in the differential signal of the Michelson interferometer. Figure 13 shows the spectrum of the Michelson differential signal, with and without damping, along with a "local" sensor-to-coil feedback, the preliminary damping system used prior to the damping filters. Since the Michelson is locked, the breadboard motion peaks do not show up in this plot. The "local" damping system clearly reduced sensitivity of the Michelson by about two orders of

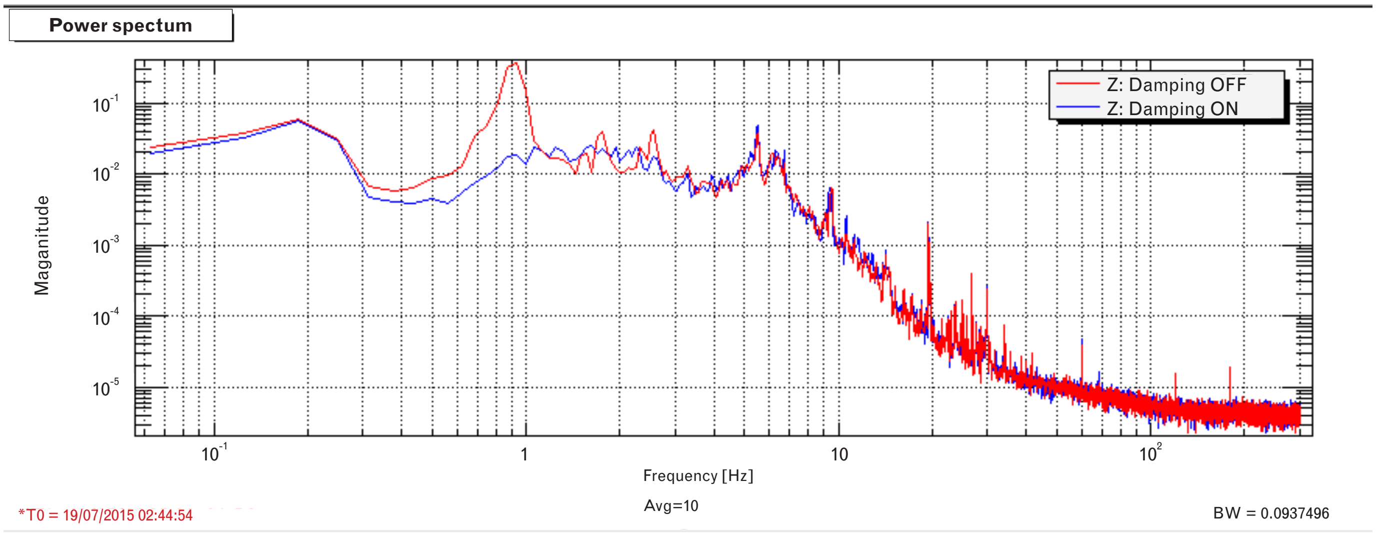

Figure 12: Spectrum of Z motion: Before and after damping

The peak around 1 Hz, as seen in Figure 7, has now disappeared. The damping system has therefore fulfilled the first of the requirements, of reducing the height of the peak.

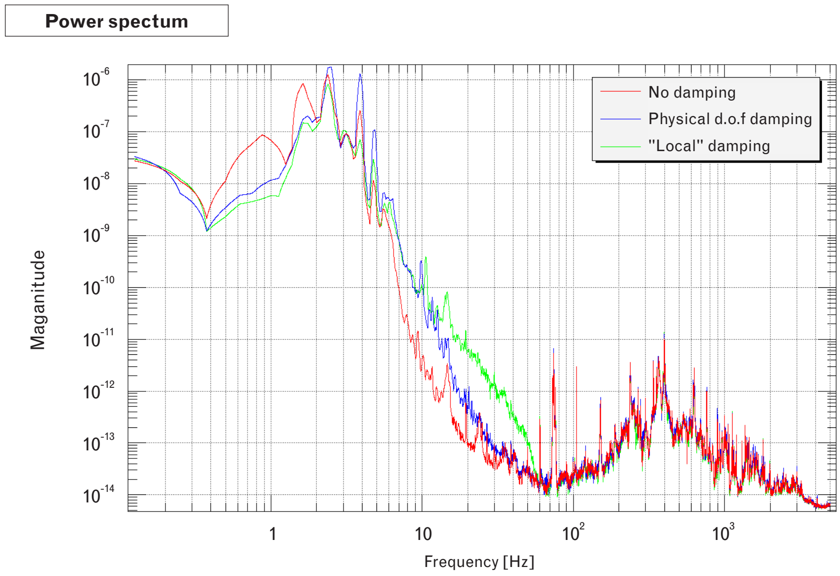

Figure 13: Spectrum of Michelson differential signal

This figure shows that the damping system has not introduced too much noise in the 10s of Hz range of frequencies, which is important, because Crackling noise is expected to be detected in this range of frequencies.

taken independently, due to linearity. We modeled the suspension system on the Mathematica-based SUspension Model CONstructor (SUMCON), built by scientists at KAGRA (another experiment aiming to detect gravitational waves). The transfer functions were then extracted from the suspended breadboard. The Z-Z transfer function is shown in Figure 8. The experimentally measured transfer functions were fit using the vectfit3 function in MATLAB [4]. Figure 9 shows the Z-Z transfer function after fitting. The experimental results match with the analytical predictions. With the vector fitting of measured transfer functions, we have information about the poles and zeros of the transfer function, and can use this information to design a compensator, or damping filter, and complete the feedback loop. The transfer function consists of two poles (in most cases, around 1 Hz), and motion at these frequencies (Q) is to be reduced with a damping filter. The damping noise in the 10's of Hz regime must be low as possible, since this is the range of interest in detection of Crackling noise. To design the filter, it is necessary to add one or two complex pole pairs, in order to roll of the compensator for frequencies well above the region with high motion. In this case, this means that the roll off must begin after a few Hz. However, with faster roll off, the unity gain frequency changes such that the Phase Margin drops, and having a good Phase Margin and Gain Margin is essential for the loop to remain stable: thus, there is a tradeoff with stability versus roll off in this filter design. (For the moment, the reader can imagine Phase and Gain Margins to be some measures of stability of a loop. A detailed discussion of these parameters can be found in any Control Systems text.) MATLAB's SISO (Single Input Single Output) was used to design these filters. This is an approximation, because to use SISO the assumption that the six degrees of freedom are decoupled, which is not the case: the suspended breadboard is "suspended," not "free," and this will result in coupling of some degrees of freedom. Transforming to physical degrees of freedom makes SISO a good approximation, because X and Y are decoupled. Figure 10 shows an example of the Open Loop Editor and Analysis plots of SISO, for the Z-Z transfer function. Figure 11 shows the filter design for the Z-Z transfer function. Q is reduced in the poles. Results: How effective is the damping filter? Upon implementing the filters through the computer interface and adjusting magnitudes and signs of the gains, the feedback damping loops were in action and worked as expected. Figure 12 shows the spectrum of motion along the Z direction, plotting the spectrum before and after damping. The striking feature of this plot is the reduction of Q of the peaks, which indicates the damping system is working as expected. Also, at the higher magnitude at some frequencies, which is too much noise. Thankfully, the new filter damping system gives much better results, improving the sensitivity by an order of magnitude. Though it may appear from the plot that the undamped case looks better, in the undamped case, it is likely that the Michelson would unlock due to spurious horizontal motion of the setup! When damped, this complication is taken care of, though the sensitivity is slightly compromised.

Conclusion: What did we learn, and what is next?

In this paper, a control system that was designed to damp the motion of the suspended optics breadboard of Crackle2 was described. Using shadow sensor signals of OSEMs, motion of the breadboard was sensed and reconstructed into physical degrees of freedom. The coils of the OSEMs were used to drive the breadboard along the degrees of freedom. After characterizing the mechanical response of the system by measuring transfer functions of actuation to motion, feedback damping was achieved by approximating the breadboard as a SISO system with six degrees of freedom. A filter was designed for each degree of freedom, and this filter was able to reduce the Q of the poles. Finally, the spectrum of the Michelson signal indicated that there was improvement from the "local" damping system, though the undamped case still had better sensitivity. The damping system described in this paper is being used in the Crackling noise detection experiment currently. An interesting extension to this work would be to mount additional OSEM's on the breadboard, as opposed to the ones used in the current setup that are mounted outside the breadboard, and use them as inertial sensors to detect motion in six degrees of freedom more accurately.

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