The Development of Passive Dampers for Parametric Instabilities in Advanced Virgo and 3rd Generation Interferometers

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Abstract

The sensitivity of interferometers is affected by multiple noise sources, it is important to identify these sources and produce methods to reduce them as much as possible. Parametric instabilities are due to the interaction between the optical modes of the cavity arms and the mechanical modes of the mirrors of the interferometer with very high quality factors and high light power (hundred of kW). They cause an increase in the mirror's oscillation, leading to a reduction in the interferometer's sensitivity and reliability. They can represent a crucial limit to the detector’s performance, reducing its ability to detect and analyze gravitational waves. Thus, the focus will be the development and testing of dampers for the parametric instabilities to dampen these oscillations at the critical frequencies and consequently ensure the stability of the detector. Passive dampers can be applied directly to all interferometer test masses to reduce the quality factors of their mechanical modes associated with parametric instabilities. Mechanical mode dampers act on all instabilities simultaneously without requiring further tuning or intervention. During this laboratory experience with the Virgo Rome 1 group, I worked on the mode excitation and detection system. I also collected initial measurements of the mode quality factors using a small fused silica substrate in a vacuum chamber at room temperature. This analysis focuses on the drum mode, which is identified around a frequency of 9000 Hz. To measure the quality factor, Q, of the mirror, the ring-down technique is used.

Introduction

Advanced Virgo, located in Cascina (Pisa), is a Michelson interferometer with Fabry-Perot cavities designed to detect gravitational waves in the 10 Hz to 10 kHz frequency range. A laser beam is directed toward a half-reflecting beam splitter, which splits the beam light into two perpendicular beams. These beams travel down into the interferometer arms and are reflected off the end mirrors towards the beam splitter due to a coating on the mirrors. The recombination of the two beams creates interferences used to detect gravitational waves.

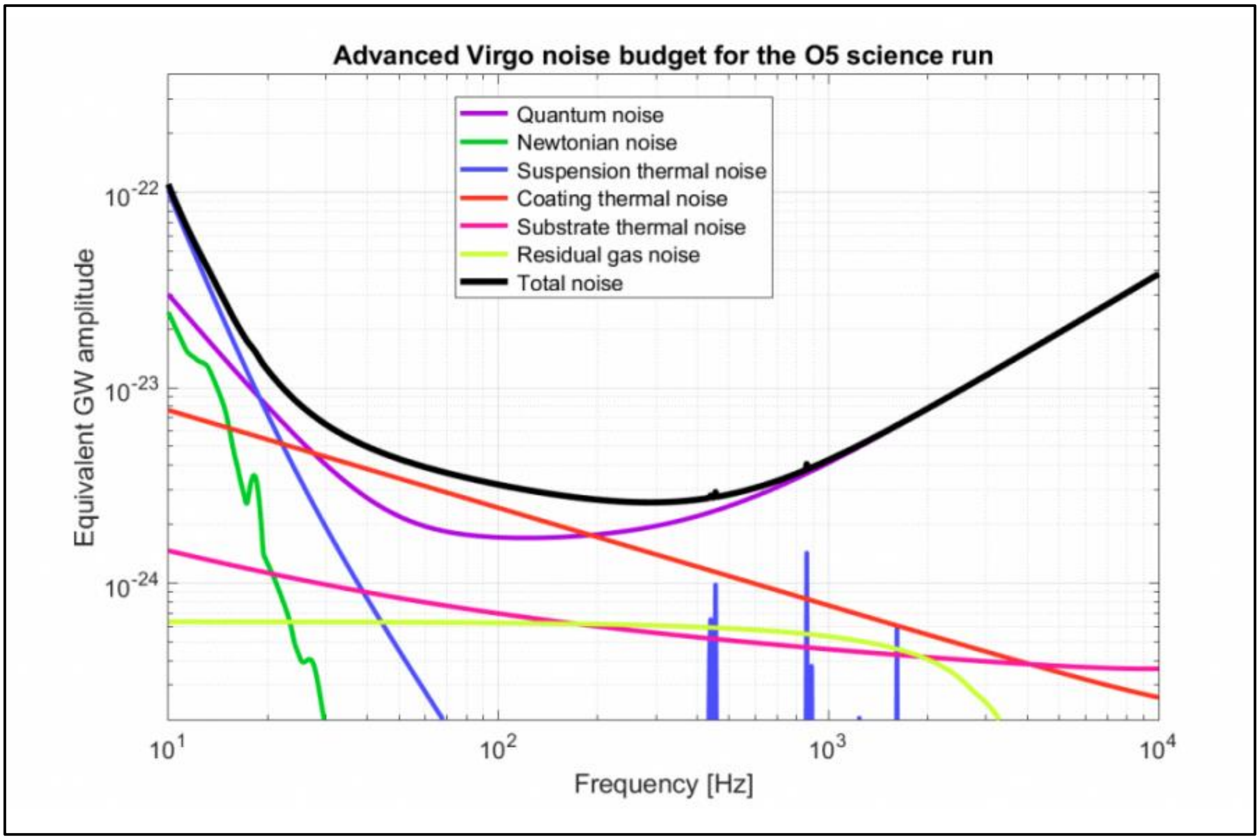

Figure 1 - Noise Sources Affecting the Advanced Virgo [1]

The sensitivity of interferometers is affected by multiple noise sources, which is why it is important to identify these sources and produce methods to reduce them as much as possible. Noise sources for Virgo depend on the frequency of operations. For less than 3 Hz, seismic noise or noise from ground and human movement affects the detectors. Michelson interferometers use an inverted pendulum design to suspend the mirrors, which reduces seismic noise, or noise from ground movement. For frequencies between 3 Hz and 300 Hz, thermal noise, or noise from the thermal agitation of the molecules in the detector's components, such as the mirror's coating is dominant. For more than 200 Hz, shot noise, or noise from the quantum effects of the laser light due to photons being excited.

Parametric instabilities are due to the interaction between the optical modes of the cavity arms and the mechanical modes of the mirrors of the interferometer. They cause an increase in the oscillation of the mirror, leading to reduction in the sensitivity and reliability of the interferometer. They can represent a crucial limit to the detector's performance, reducing its ability to detect and analyze gravitational waves. The high optical power in the cavity and high mechanical quality factor (slow dampening) of the optics Q lead to parametric instabilities.

The quality factor, Q, is a critical parameter of damped harmonic oscillators that quantifies how effectively the energy is stored and dissipated. It provides valuable insights into oscillatory systems' overall performance and efficiency, indicating their susceptibility to damping forces and ability to maintain energy during oscillation cycles. The higher the Q, the smaller the energy losses of the mirror are for the same amount of maximum energy stored. Energy conservation is important because it illustrates how energy is preserved during oscillations and helps identify areas for improvement in oscillatory system designs. Furthermore, the Q-value can be used to determine a system's susceptibility to external excitations as its natural frequency.

The parametric gain can be used to analyze parametric instabilities. The parametric gain equations are:

$$R_m = \frac{4Q_l Q_m P}{LMc\omega_m^2} \frac{\Lambda}{\left[1 + \left(\frac{\Delta\omega_{om}}{\delta_l}\right)^2\right]},$$

$$\Delta\omega_{om} = |\omega_0 - \omega_l| - \omega_m.$$

Where Q_m is the mechanical quality factor, P is the laser power, Q_l is the optical quality factor, Λ represents the spatial overlap between the mechanical and optical modes, L is the arm length, M is the mass of the mirror and δ_l is the optical mode linewidth.

The amplitude of the mechanical mode follows an exponential law given by $e^{-\frac{t}{\tau_{pi}}}$, where:

$$\tau_{pi} = \frac{2Q_m}{\omega_m(R_m - 1)}.$$

Based on the value of R_m, the following can be said regarding parametric instabilities:

- If $R_m < 1$, then $\tau_{pi} < 0$, indicating a decay of the mode amplitude and signifying the lack of parametric instabilities.
- If $R_m = 1$, then $\tau_{pi} = 0$, indicating stationary behavior.
- If $R_m > 1$, then $\tau_{pi} > 0$, indicating exponential growth and the presence of parametric instabilities.

Thus, the focus will be the development and testing of dampers for the parametric instabilities to dampen these oscillations at the critical frequencies and consequently ensure the stability of the detector. The optomechanical parametric instabilities are driven by three modes: the fundamental optical mode, the higher order mode, and the mechanical mode. These are the mode of the source beam, the parasitic eigenmodes with frequencies higher than that of the fundamental mode of the resonant radio-frequency cavities, and the mode of the mirrors, respectively. An optomechanical parametric instability can occur if the optical beat note, or the frequency difference between the two optical mode frequencies, is near the mechanical mode frequency, such that the mechanical mode is driven. Hence, we need to evaluate the optical modes of the advanced Virgo's arm cavities and the mechanical modes of its mirrors.

There are two motivations for this project. One, optomechanical parametric instabilities are a power-proportional phenomenon and the power will continue increasing to improve the detector's sensitivity. Two, since the characteristic detection time of gravitational wave events lasts, at most, a few tens of seconds, one must try not to encounter any instability. Gravitational waves test Einstein's equations, such as space-time bends and curves due to the distribution of matter and energy but have small amplitudes. This highlights the need to reduce noise for detection.

Passive dampers can be applied directly to all interferometer test masses to reduce the quality factors of their mechanical modes associated with parametric instabilities. These dampers are small oscillators characterized by high dissipation, or a low-quality factor, at the specific critical frequencies and attached to the mirrors. The resonance frequency of the damper must be close to that of the mechanical mode of the mirror to dampen. Resonance occurs when a system is excited by an external force with a frequency matching its natural frequency, which leads to a significant increase in the oscillation amplitude, but damping can reduce resonance by causing the amplitude to decay gradually. When these two oscillators, the damper and the mirror, are in resonance, they exchange energy, which is dissipated by the more dissipative oscillator, which is the damper. This reduces the Q of the mechanical mode. Mechanical mode dampers act on all instabilities simultaneously without requiring further tuning or intervention.

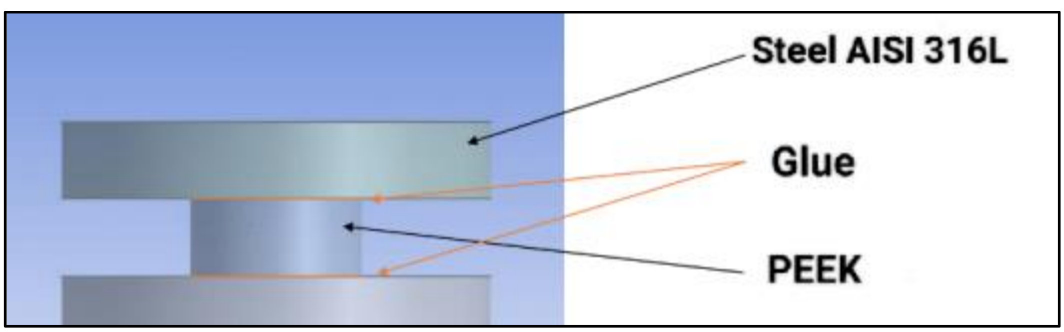

Figure 2 - Structure of Passive Damper, Modified from [2]

The damper used in Advanced Virgo is composed of a silica base bonded directly upon the mirror, a PEEK, and a steel cylinder. During my laboratory experience with the Virgo Rome 1 group, I measured the drum mode quality factors using a small fused silica substrate and a simple damper with PEEK and steel cylinder only in a vacuum chamber at room temperature.

This analysis focuses on the drum mode, which is identified around a frequency of 9000 Hz. This mode is characterized by nodal diameters symmetrical with respect to the optical axis. The drum mode exhibits symmetric radial expansion and contraction of the mirror surface, like the motion of a vibrating drumhead. This mode presents a single peak because of the center symmetry of the disk rather than its axial symmetry. It represents the peak with the strongest signal because the disk's three cylindrical support points are positioned on the nodal circumference of this mode, thereby maximizing its oscillations.

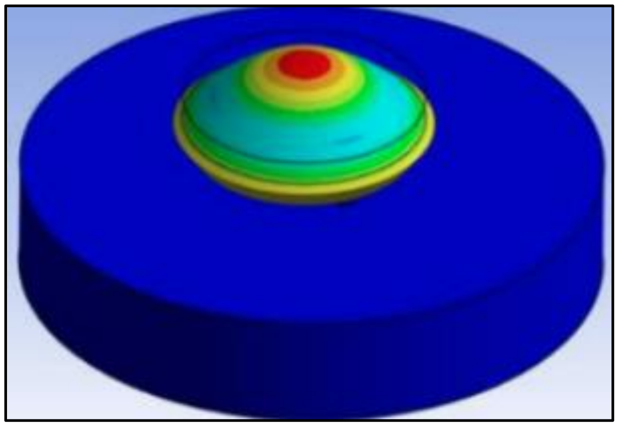

Figure 3 - Drum Mode Illustration [2]

To measure the quality factor, Q, of the mirror, the ring-down technique is used. The quality factor of a mechanical mode of pulsation ω_0 is linked to its characteristic decay time τ through the following relation:

$$Q = \frac{\omega_0 \tau}{2}$$

The equation of motion is based on the time evolution of every mechanical mode being able to be treated as a one-dimensional harmonic oscillator of frequency ν_0 and effective mass m_{eff} that is excited by an external force of amplitude F_0.

$$m_{eff}\ddot{x} + \beta\dot{x} + k\,x = 0$$

Where β is the forcing term.
When allowed to decay, the oscillation amplitude is:

$$x(t) = A_0\, e^{-\frac{t}{\tau}} \sin(\omega_0 t + \phi_0)$$

Where A_0 and ϕ_0 are constants determined by the initial conditions and $\tau = \frac{\beta}{2m_{eff}}$. The amplitude of the damped oscillations can be determined using the following equation:

$$A(t) = A_0\, e^{\frac{t}{\tau}}$$

In an interval of time τ the system undergoes a number of oscillations equal to $N = \frac{\tau}{T}$, where $T = \frac{2\pi}{\omega_0}$ is the period of the oscillation. If one considers $\nu_0 = \frac{\omega_0}{2\pi}$, which is related to the number of oscillations the system undergoes before its amplitude is reduced by a factor 1/e, the final expression for the quality factor is found to be:

$$Q = \pi \nu_0 \tau$$

Methods

The methods for this project are a mixture of hardware experimental setup and software analysis. The quality factor, Q, of the drum mode of a fused silica disk with a diameter of 10 cm will be measured by calculating the decay time via a spectrum analyzer. A silica disk is used to simulate Virgo's mirror, with the sample employed in two different configurations: one with a small and large PEEK cylinder mounted and one without. The damper is at the center of the disk to detect the drum mode. The disk rests on three cones positioned around its nodal circumference, as this arrangement prevents interference with the drum mode signal.

The excitation method utilized a capacitive comb placed under the fused silica disk. A comb circuit is an electronic circuit characterized by a frequency response that exhibits a pattern of equally spaced peaks, resembling a comb. The Q value of the mirror is not altered since there is no direct contact between the excitor and the sample.

The system is excited with a periodic chirp spanning 400 Hz at a frequency of 9000 Hz via the spectrum analyzer. After identifying the potential resonance peaks, the system is excited with a sinusoidal signal spanning 12.5 Hz at the determined frequency to increase the resolution. After 24 seconds, the input source is disconnected to confirm that the system decays exponentially. The decay characteristic time τ is determined via linear fit by applying the logarithm to the exponential decay. The quality factor Q is estimated using the frequency used via the equation $Q = \pi v_0 \tau$.

The detection of the disk's vibrations is performed using a laser, which simulates an interferometer. The laser beam is positioned closer to the edge of the disk since it is the area in which the greatest vibrations occur.

Figure 4 - Vacuum Chamber

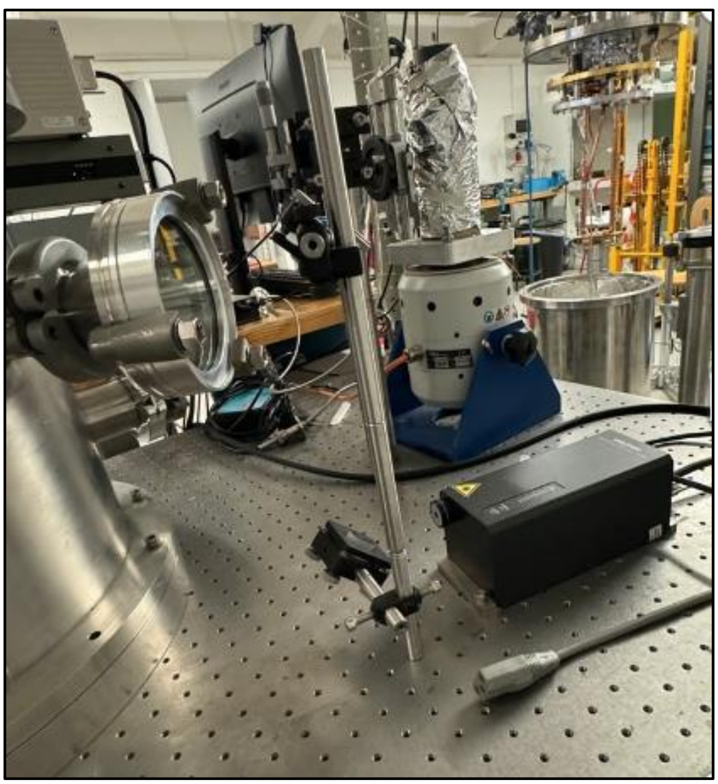

Figure 5 - Laser Setup

The experimental setup includes many components, the first of which is a vacuum created using a rotary vane pump and a turbomolecular pump. This is done to minimize external interferences caused by air particles. Second, as mentioned, a silica disk with a flat surface is used to model a Virgo mirror. Third, a passive damper with two components, a PEEK support and a steel top, which is used to reduce the quality factor of the mechanical modes associated with parametric instabilities. PEEK is high-performance and highly dissipative thermoplastic polymer. Other components of the setup include an aluminum support, 3 cones, a spectrum analyzer, an amplifier, a preamplifier, and an oscilloscope.

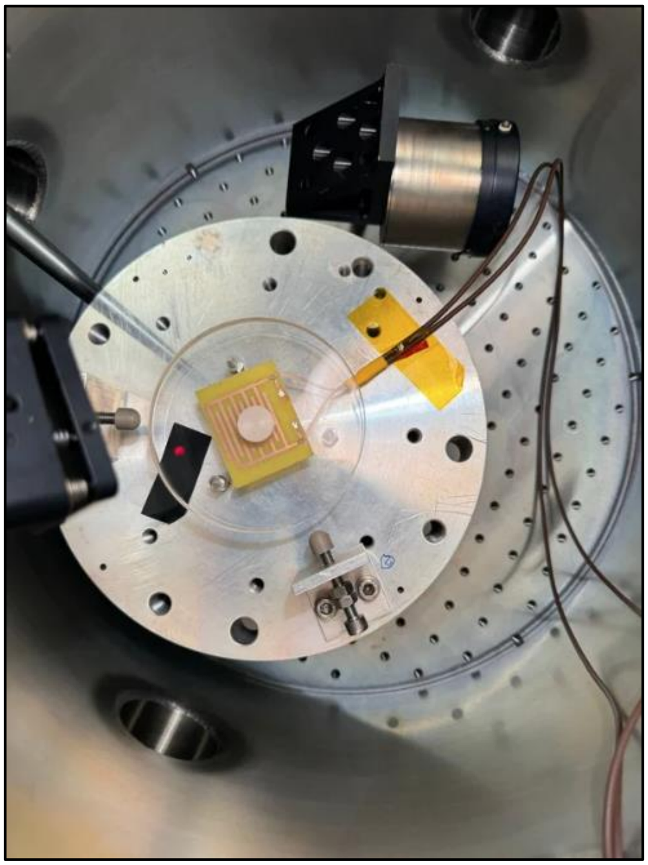

Figure 6 – Large PEEK Component Placed on Fused Silica Disk Inside Vacuum Chamber

The input voltage was selected to be 1.3995 V due to the use of the amplifier TREK-5/80 that provides an output signal of V_{out} = 1000*V_{in}, which amplifies the input voltage of the comb. Thus, this input voltage was set to prevent the comb from burning out or any other component being damaged.

The laser source used is an Onosokki LV 9002 He-Ne laser, which is positioned outside the chamber. The incoming beam is directed to the edge of silica disk by reflecting it off three mirrors, two outside the chamber and one inside. As the laser replicates an interferometer, it is essential to align the outgoing and incoming beams. This is done by adjusting the vertical apparatus that holds the two outside mirrors.

The signal emitted by the laser is cleaned of noise and then amplified through a pre-amplifier before being visualized by the spectrum analyzer. The spectrum analyzer used is the Agilent-35670A, which generates the input signal and visualizes the output signal. This instrument reveals the incoming signal in both the time and frequency domains, which are visualized simultaneously, allowing for the evaluation of the peaks and decay of the mode in real-time.

Results & Analysis

Results were obtained for two comparisons: the fused silica without and with a small peek cylinder, and the fused silica disk without and with a large peek cylinder. The goal was to determine the effect the peak cylinder had on the mirror's quality factor at the drum modes. The drum mode frequency and Q may vary based on the position of the fused silica disk. Therefore, maintaining the same position is important for comparison to be viable. Additionally, taking the measurements at similar pressures helped ensure consistent environmental conditions, reducing the factors affecting differences. The frequency of the drum mode was measured for all sets of data collection, and for each measurements, the exponential decay was linearized by taking the logarithm to estimate the decay time, τ, and the quality factor, Q. The excited drum mode found is in the frequency range expected, ranging from 8936.625 to 8992. All measurements were taken using a span of 12.5 Hz.

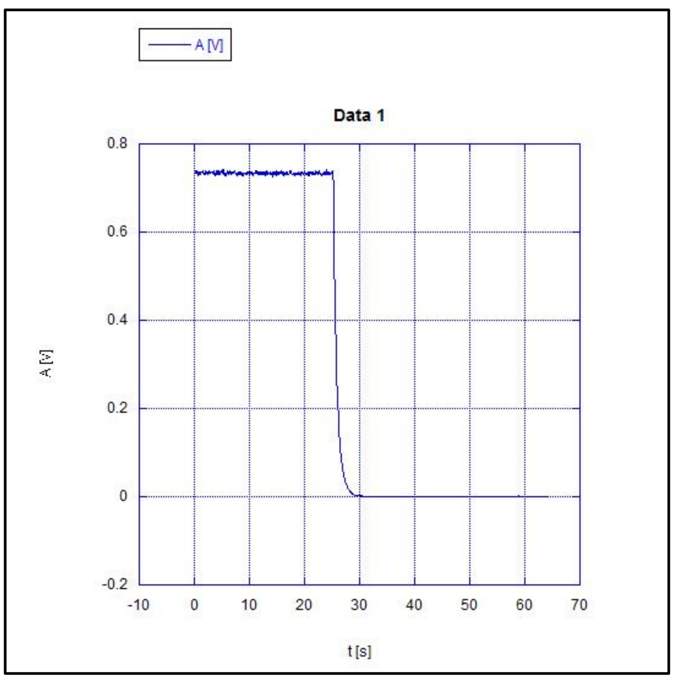

Figure 7 - Example Exponential Decay

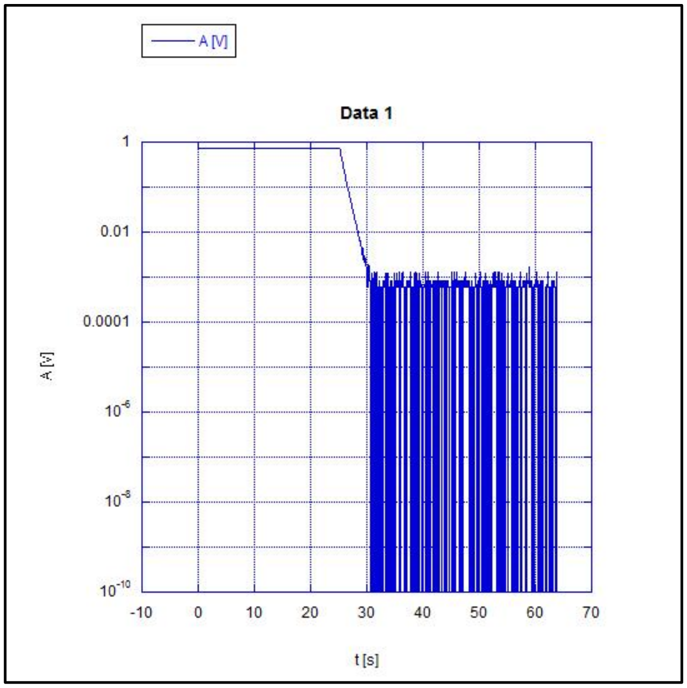

Figure 8 - Example Logarithmic Decay

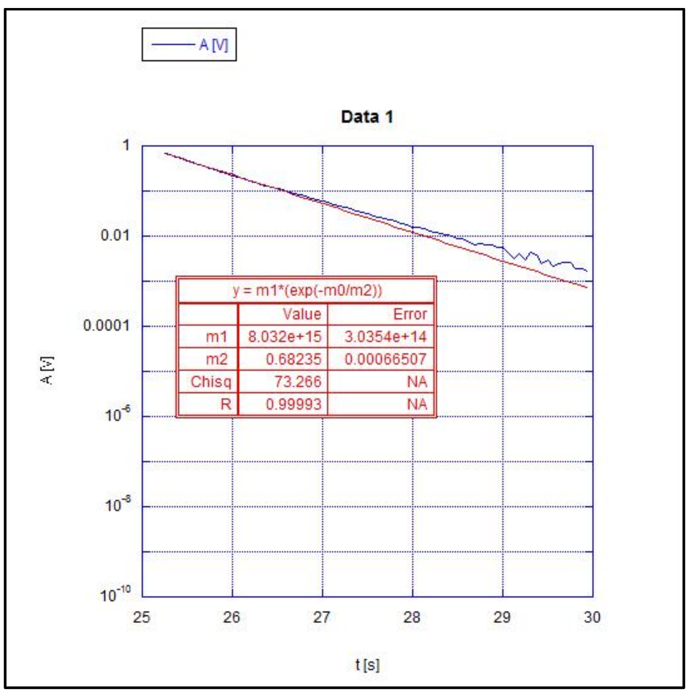

Figure 9 - Example Linear Fit

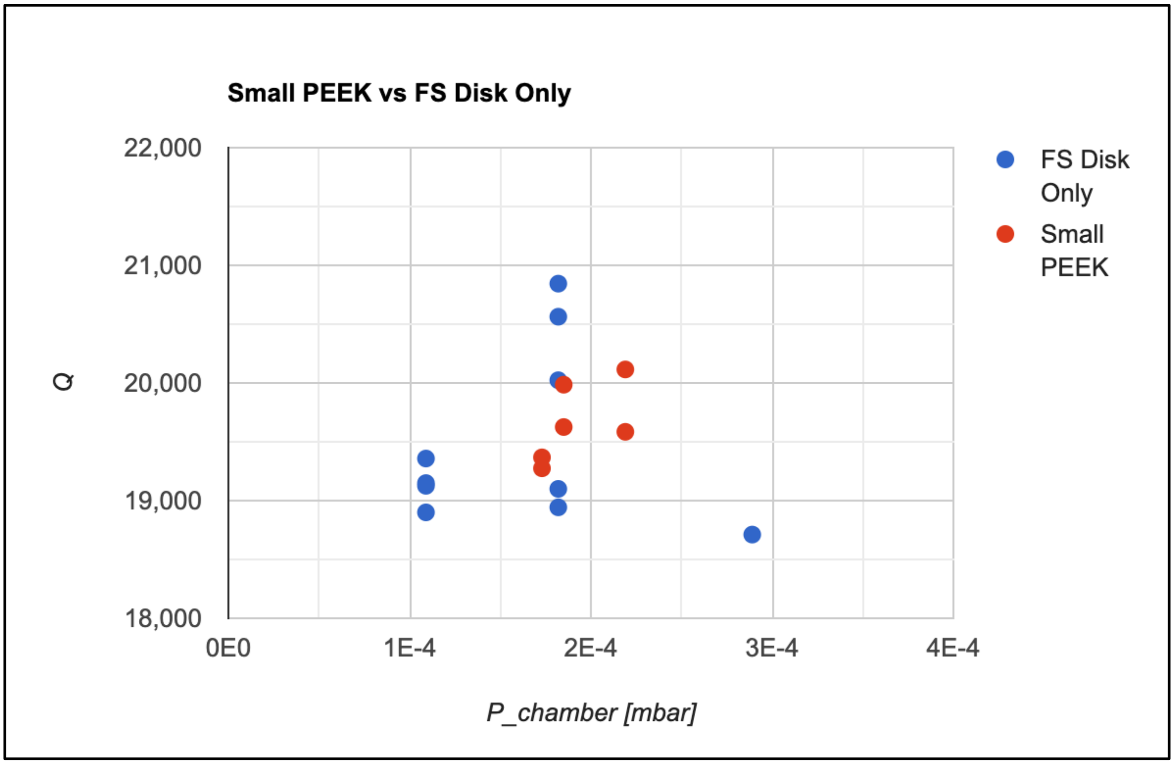

Figure 10 - Small PEEK vs Fused Silica Disk Q Comparison

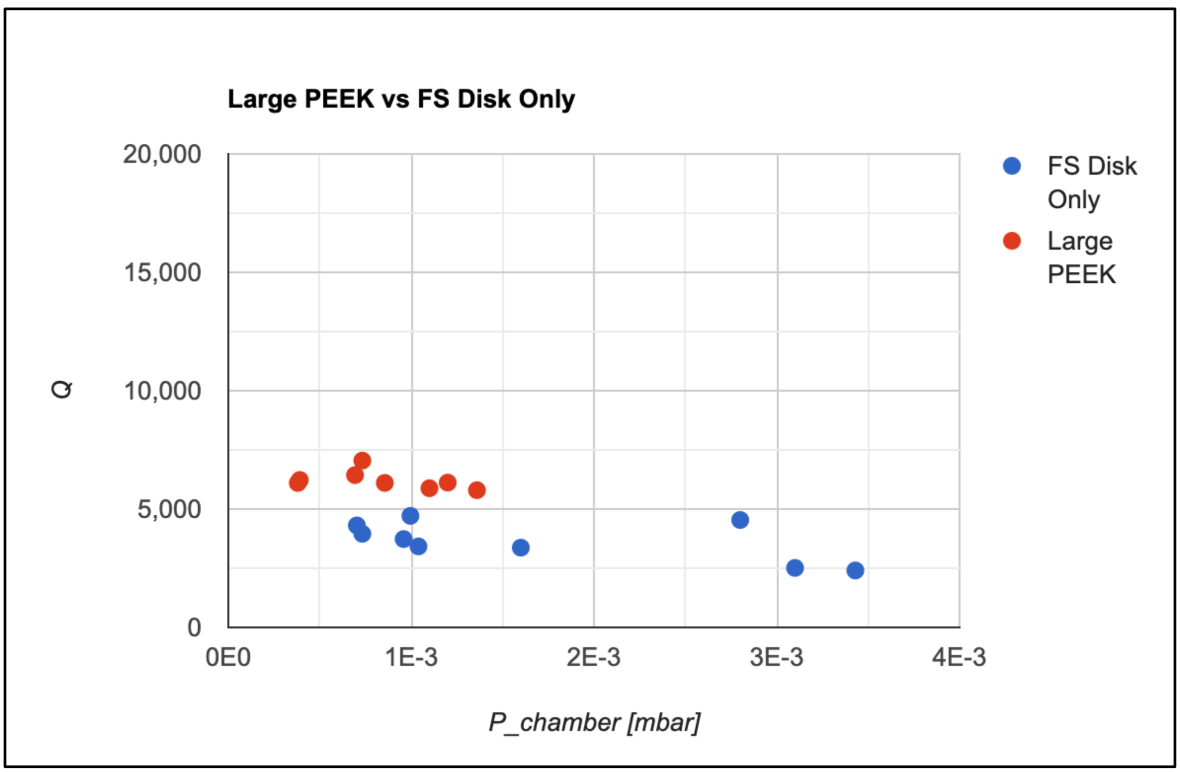

Figure 11 - Large PEEK vs Fused Silica Disk Q Comparison

P_chamber [mbar]	Frequency, v [Hz	tau [s]	Q = pi*v*tau
2.89E-04	8991	0.66244	18711.32
1.82E-04	8991.3	0.72798	20563.25
1.82E-04	8991.3	0.67617	19099.78
1.82E-04	8991.3	0.73793	20844.31
1.82E-04	8991.3	0.67062	18943.00
1.82E-04	8991.3	0.70887	20023.45
1.09E-04	8992	0.67786	19149.00
1.09E-04	8992	0.66905	18900.13
1.09E-04	8992	0.67704	19125.84
1.09E-04	8992	0.68525	19357.77
2.18E-03	8992	0.7483	21138.88
2.18E-03	8992	0.72111	20370.78
2.18E-03	8992	0.78111	22065.73
2.19E-04	8991.3125	0.69334	19584.80
2.19E-04	8991.3125	0.71211	20115.00
1.85E-04	8991.4375	0.69477	19625.47
1.85E-04	8991.4375	0.70751	19985.34
1.73E-04	8991.4375	0.68564	19367.57
1.73E-04	8991.4375	0.68235	19274.64

Table 1 – Values for Figure 10

P_chamber [mbar]	Frequency, v [Hz]	tau [s]	Q = pi*v*tau
3.43E-03	8975.6875	0.085325	2405.99
3.10E-03	8975.6875	0.089167	2514.33
2.80E-03	8975.6875	0.16096	4538.74
1.60E-03	8979.6875	0.11945	3369.75
1.04E-03	8979.8125	0.12134	3423.11
9.96E-04	8979.8125	0.16708	4713.48
9.59E-04	8979.8125	0.13231	3732.59
7.33E-04	8979.8125	0.14019	3954.89
7.03E-04	8979.8125	0.15276	4309.50
1.36E-03	8936.625	0.2065	5797.54
1.20E-03	8936.625	0.21788	6117.03
1.10E-03	8936.625	0.20943	5879.80
8.56E-04	8936.625	0.21746	6105.24
7.33E-04	8936.625	0.25105	7048.29
6.93E-04	8936.625	0.22918	6434.28
3.91E-04	8936.75	0.2219	6229.98
3.80E-04	8936.75	0.21737	6102.80

Table 2 – Values for Figure 11

It can be observed that the frequencies stayed consistent for the first set of measurements despite changes in pressure, staying around 8992 Hz. On the other hand, the second set of measurements for the large PEEK had more variance in the frequency values, staying around 8975.6875, 8979.8125, and 8936. Factors affecting the frequency will be discussed in more detail in the discussions section. It can be observed in figures 10 and 11 that the tau and Q values varied for all measurements but stayed relatively consistent for each data set.

For the first set of measurements with the fused silica disk only, the tau values ranged from 0.66244 s to 0.73793 s and averaged 0.689321 s, while the Q values ranged from 18,711.32 to 20,844.31. For the set of measurements with the small PEEK cylinder added, the tau values ranged from 0.68235 s to 0.78111, and averaged 0.71403 s, while the Q values ranged from 19,274.64 to 22,065.73. Comparing data values at the similar pressures of 1.82E-04 for the disk only and 1.85E-04 with the small PEEK, the average Q values were 19,894.76 and 19,805.41. There are no significant differences between the data for the fused silica disk alone and the data when a PEEK cylinder is attached.

For the second set of measurements with the fused disk only, the tau values ranged from 0.085325 s to 0.16708 s, and averaged 0.12984 s, while the Q values ranged from 2,405.99 to 4,713.48. For the set of measurements with the large PEEK cylinder added to the disk, the tau values ranged from 0.2065 s to 0.25105 s, and averaged 0.22135 s, while the Q values ranged from 5,797.54 to 7,048.29. Again, comparing values at the same pressure of 7.33E-04, the Q factor for the data considering the PEEK attached to the disk is higher compared to the data considering only the disk, with their respective values being 7,048.29 and 3,954.89. A higher Q factor indicates that the system has a greater capacity to maintain the oscillating energy for a longer period, reducing energy losses.

These results need to be repeated to demonstrate reproducibility and compared with ongoing Ansys simulations.

Discussion & Progress and Challenges

Measurements were performed to calculate the Q of the drum mode for a fused silica disk, both with and without a small and large PEEK cylinder. Additionally, procedures important to operating the setup were learned. These include closing and opening the vacuum chamber, adjusting the laser setup, finding the drum mode frequency, using the ring-down technique to observe the decay behavior of the sample, and calculating the tau and Q values of the measurements.

The oscillations of the disk are extremely sensitive to variations in its positioning on the three support cones, as even a slight misalignment from its nodal circumference can lead to significant changes in the Q value.

Some challenges included finding the correct position of the disk after it has been removed, as it takes many attempts since there is no way to take proper measurements of the Q value in the air. Additionally, the chamber must be closed, and the pressure must be adequately adjusted for each repositioning attempt to allow for accurate Q value measurements, which can take an extensive amount of time. Furthermore, multiple issues occurred with the setup. The vacuum chamber had to be opened on various occasions and data sets had to be discarded due to our inability to recreate the conditions, mainly the exact position of the silica disk. Incidents include the disk having to be removed due to the capacitive comb being burnt, the disk being moved due to the incorrect opening of the chamber, the chamber being opened by unknown personnel, and the chamber being hit by an object, affecting the disk's position. A possible reason for the discrepancy in Q may be that the sample was subjected to some damage. This damage could explain that difference, but further measurements need to be taken to confirm this.

In order to simplify the sample positioning, the support system can be changed to a hemispherical support device, where the silica disk would be placed in the center. Gravity and friction would ensure that the disk will not slip if placed directly in the center. This would reduce the difficulty of aligning the disk, as having to align an object on a single surface is much easier than three.

Conclusion & Future Directions

The aim of this study was to test one of the three components of the damper, specifically the PEEK part, for a fused silica disk, which simulates the Virgo detector's mirrors, by measuring its decay time, tau, and estimating its quality factor, Q. The disk was excited using a capacitive comb located under the disk, and only the drum mode was considered. For each measurements, the tau was derived by a linear fit of the logarithm of the exponential decay in the time domain. Using the relation $Q = \pi v_0 \tau$, the quality factor was estimated. It was found that the PEEK components increased the tau and Q.

Next steps should include verifying whether damage to the disk significantly influences the Q value and exploring new methods for disk positioning that improve the ability to easily center the disk with minimal error. One proposed method is the use of a hemispherical support device that simplifies the alignment process and improves data collection for the butterfly modes. Also, testing the other potential components of the damper and comparing the disk and the completed damper are necessary.

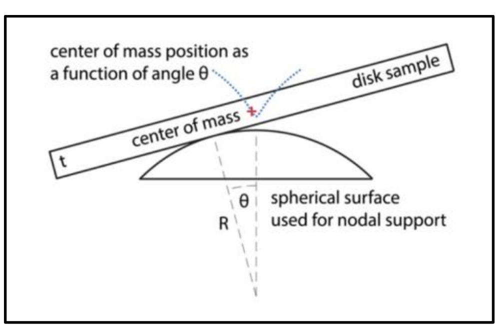

Figure 12 - Hemispherical Support Device [3]

In conclusion, training was completed to use the vacuum chamber setup and estimate the Q value of various setups. It was demonstrated that the PEEK components exhibit the undesired behavior of increasing the Q factor.

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References:

[1] Virgo sensitivity, https://www.virgo-gw.eu/science/detector/sensitivity/.

[2] Reduction of parametric instabilities in Virgo Adv+ Phase 2 by dynamical dampers, Audrey Couineaux, V. Mangano, P. Rapagnani, P. Puppo, LVK Toyama, September, 11th, 2023.

[3] A high throughput instrument to measure mechanical losses in thin film coatings, Vajente, G and Ananyeva, A and Billingsley, G and Gustafson, E and Heptonstall, A and Sanchez, E and Torrie, C, Review of Scientific Instruments.

[4] Mitigating Virgo Parametric Instabilities with Mechanical Dampers, Report for 'Physics Laboratory II' course, students: Niola Alessandro, Quintavalle Anna Lea, Scuderi Margherita, Valletta Andrea; tutors: Dr Mangano Valentina, Dr Puppo Paola, Prof. Rapagnani Piero.

[5] Virgo_PI: Characterization of Passive Damper for the Parametric Instabilities of Advanced Virgo Presentation, Dr. Paola Puppo, Prof. Piero Rapagnani, Dr. Valentina Mangano.

[6] Reduction of Parametric Instabilities in Virgo AdV+ Phase 2 By Dynamical Dampers Presentation, Audrey Couineaux, V. Mangano, P. Rapagnani, P. Puppo, LVK Toyama, September, 11th, 2023.