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Mitigating Parametric Instabilities with Mechanical Dampers in Current and Future Gravitational Wave Detectors

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To enhance the sensitivity of gravitational wave detectors, it is crucial to reduce noise within the 10 Hz to 10 kHz frequency range. One effective method is to decrease shot noise by increasing the laser power. This allows for the achievement of noise specifications expected for the upcoming observation runs of the Advanced Virgo and Advanced LIGO detectors, as well as for third generation detectors. However, employing a high power laser may result in undesirable effects known as Parametric Instabilities, impacting the instrument's efficiency. This phenomenon occurs when the high power light stored in an optical cavity is scattered into high-order optical modes by the thermally excited acoustic modes of one of the cavity mirrors. Because of the radiation pressure, the optical modes can further drive the mechanical mode inducing its exponential growth. To mitigate the effect, a system has been developed to prevent the triggering of instabilities. Small oscillators resonating at the critical frequencies and with a low quality factor are attached to the lateral surface of the mirrors. Due to the coupling effect between the damper's mode and the mirror's mode, the quality factor of the mirror's mode is reduced, thus allowing for the reduction of the risk of triggering instabilities. We present the latest results of various types of dampers tested on a suspended small fused silica substrate placed in a vacuum chamber at room temperature, as part of the effort to set up dampers for the Advanced Virgo interferometer.

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PoS(PIC2024)036

1. Introduction to Gravitational Waves

The fabric of space-time can ripple like the surface of a pond hit by a stone. These distortions, known as gravitational waves (GWs) and predicted by Einstein's theory of General Relativity [1], occur when massive and asymmetric objects accelerate and travel across the universe at the speed of light. Cosmic events such as black holes and/or neutron star binary mergers, supernovae explosions and pulsars generate these waves. Additionally, a background of weaker and unresolved signals contributes to the GW spectrum.

GWs are observed in the frequency range from 10 Hz to 1 kHz using advanced modified Michelson laser interferometers: Virgo [2] in Italy, Hanford and Livingston LIGO [3] in the United States, and KAGRA in Japan [4]. After three observing runs, Virgo and LIGO confirmed 90 gravitational wave detections [5–7].

Achieving the sensitivity needed for GW detection requires minimising noise from various sources. This makes it possible to observe more distant phenomena, increasing the volume of the observed universe and thus raising the detection rate of GW sources. Seismic noise limits low-frequency sensitivity, while thermal noise from mirrors and suspensions as well as radiation pressure noise affect mid-range frequencies, and shot noise becomes the dominant limiting factor at higher frequencies.

Increasing laser power helps reduce shot noise but introduces a nonlinear optomechanical phenomenon known as parametric instability (PI). PI can compromise the efficiency of the interferometric instrument, setting an upper limit on the optical power that can be used in a GW detector. As a result, the sensitivity cannot be improved beyond a certain point.

The problem of PI affects not only existing detectors but also next-generation observatories such as the Einstein Telescope [8, 9] and the Cosmic Explorer [10].

2. Introduction to Parametric Instabilities

When a thermal transient or other type of disturbance excites a mirror mechanical mode of frequency ω_m, this vibrating mirror may scatter the cavity fundamental mode of frequency ω_0 into two sideband modes $\omega_0 \pm \omega_m$ [11].

If the difference between the frequency of the fundamental mode of the cavity ω_0 and the frequency of a higher optical mode ω_1 is identical to the frequency of the mechanical mode $\omega_m = \omega_0 - \omega_1$, and if the higher optical and mechanical modes overlap spatially, then the radiation pressure (determined by the coupling between the cavity fundamental mode and the scattered light) will excite the mechanical mode of the mirror. In other words, energy from the fundamental mode transfers to the mechanical mode, creating an instability.

Therefore, parametric instabilities occur because of a nonlinear coupling between the cavity mirror's mechanical modes and the cavity's higher optical modes.

Assuming that only one mechanical mode of a mirror contributes to the PI and there is no cross-correlation between the mechanical modes, it is possible to define the parametric gain R_m for each mechanical mode, which describes the conditions under which a PI may occur [12]:

$$R_m = \frac{4Q_1 Q_m P}{LMc\omega_m^2} \frac{\Lambda}{1 + (\Delta\omega_{0m}/\delta_1)^2}$$

PoS(PIC2024)036

It depends on the following parameters: the optical quality factor Q_1, the quality factor Q_m and resonance frequency ω_m of the mirror mechanical mode, the circulating laser power in the cavity P, the arm length L, the mass of the mirror M, the speed of light c, the spatial overlapping parameter Λ, the optical mode linewidth δ_1. $\Delta\omega_{0m} = |\omega_0 - \omega_1| - \omega_m$, and $\frac{\Lambda}{1+(\Delta\omega_{0m}/\delta_1)^2}$ is called optical gain. Λ and the optical gain are estimated by simulations.

The amplitude of the mechanical mode follows an exponential law $e^{\frac{t}{\tau_{\rm PI}}}$ where $\tau_{\rm PI} = \frac{2Q_m}{\omega_m(R_m-1)}$. If $R_m < 1$, then $\tau_{\rm PI} < 0$, indicating a decay in the mode amplitude; if $R_m = 1$, then $\tau_{\rm PI} = \infty$, implying stationary behaviour; if $R_m > 1$, then $\tau_{\rm PI} > 0$, the displacement caused by the radiation pressure is greater than the oscillations of the mirror, and the amplitude of the mechanical mode increases exponentially, making the cavity unstable.

Each upgrade aims to enhance the sensitivity of a GW detector. This involves increasing the laser power (to reduce shot noise) and the mirrors' quality factor (to minimise thermal noise). As a result, the large amount of laser power stored in the cavities (over 100 kW) and the high quality factor of the mechanical modes of the optics (higher than 10^7) lead to parametric instabilities, which prevent interferometers from operating at high power, limiting their duty cycles.

3. Observation Runs

The values of the radius of curvature (RoC) of the end mirrors influence the parametric gain: a change in them can trigger or damp an instability.

During O3, the RoCs of the end mirrors, chosen to optimise the interferometer's performance, facilitated the generation of the first PI observed in Virgo: a high-frequency mode at 155 kHz coupled with the TEM01 optical mode. This PI was mitigated by adjusting the temperature of the end mirrors to find the optimal RoCs that damped the PI. This approach worked because the PIs density was low. The Advanced Virgo Thermal Compensation System (TCS) [13], which uses wavefront sensors and actuators to correct mirror imperfections and reduce thermal gradients in the optics, enabled this adjustment. A non-contact wire surrounding the mirror heats its outer edge, changing its RoC. This adjustment shifts the problematic higher optical mode frequency, increasing its separation from the mechanical mode.

In O4, the mechanical modes remain unchanged because the mirrors were not replaced. However, the addition of a new optical cavity (signal recycling) changes the frequencies of the optical modes, leading to new values of the parametric gains and new PIs. Simulations suggest that the PI density is low, so TCS may still help damp these instabilities.

For O5, both the input and end mirrors will be replaced. This change is expected to increase the number of instabilities and the PI-free areas will be much smaller. Adjusting the mirror RoCs using TCS, as in O3 and O4, may no longer be sufficient, so alternative methods will be needed to damp these instabilities.

4. Passive Dampers

These instabilities can be damped using passive dampers, which reduce the quality factor (Q) of those mirror mechanical modes that can potentially produce instability (critical modes).

PoS(PIC2024)036

These are small oscillators with high dissipation (low quality factor), mechanically coupled to the mirror at the critical frequencies. The damper resonant frequency must be equal to that of the mirror critical mode. When damper and mirror are in resonance with each other, they exchange energy, which is dissipated by the more dissipative oscillator and consequently the mechanical mode quality factor is lowered [14].

The proposed damper, shown in Figure 1 (top left), has a mushroom-like shape and consists of three stacked parts. The base is a fused silica cylinder bonded to the mirror using Hydroxide-Catalysis Bonding (HCB) [15–17]. Above it, a small highly dissipative cylinder made of PEEK provides damping. Finally, the top part is a load mass composed of a heavy material (e.g., tungsten or steel), which can be modified so that the damper frequency is as close as possible to that of the critical mode.

The damper must be highly dissipative but without significantly affecting the modes near the Virgo detection band and the mirror total losses, as this may worsen the mirror thermal noise and reduce the interferometer's sensitivity.

5. Experimental Setup and Preliminary Results

The first damper prototype at 15 kHz is currently under test, and a first setup for its characterisation has been built. The damper (Figure 1, bottom left) is glued to a fused silica disc suspended at three points along the nodal circumference where vibrations do not occur for its first drum mode [18]. The mechanical drum mode of the mirror is excited using a mini-shaker. After turning off the excitation, the mode ring down is monitored with a small piezoelectric sensor bonded to the mirror's surface. The system is in a vacuum at a pressure of $\sim 10^{-4}$ mbar.

The quality factor is measured by analysing the ring-down decay time τ obtained from an exponential fit to the data at the resonance frequency ν_0 of the mirror's drum mode. The corresponding quality factor is then estimated as $Q = \pi\nu_0\tau$.

The measured quality factor is related to the mechanical losses, expressed by the loss angles ϕ_i of each component of the system by the formula: $Q^{-1} = \phi_{tot} = \sum_i \phi_i$. The adopted three-point suspension ensures that the main contributors to the drum mode are the losses of the silica disk and the damper elements.

The first measurements were conducted on a fused silica mirror (diameter of 100.0 mm and thickness of 10.0 mm), selecting the drum mode (~8900 Hz). The drum mode quality factor was first measured without any damper on the mirror. Then, the PEEK cylinder, with a diameter of 2.0 mm and height of 0.9 mm, was directly bonded to the mirror with epoxy glue, and the quality factor was measured again. The process was repeated with the steel component (diameter of 5.0 mm and height of 1.1 mm) epoxy-bonded to the top of the PEEK component. We did not glue the silica base (diameter of 5.0 mm and height of 2.0 mm) as we were mainly interested in estimating the losses of the PEEK cylinder, the most dissipative element. The losses of the fused silica component and the bonding glue HCB are known [17] and we were not interested in them at this stage.

The plot of the quality factor for these three configurations shows a 20% reduction in the drum mode's quality factor when the damper was attached to the fused silica disc (Figure 1, right).

The analysis is in progress to extrapolate the losses of the damper parts in order to predict the reduction of the quality factor of the critical modes for the masses.

PoS(PIC2024)036

An upgraded setup is now being developed employing an optical interferometric readout to prevent any direct contact with the mirror. Measurements are scheduled to begin soon.

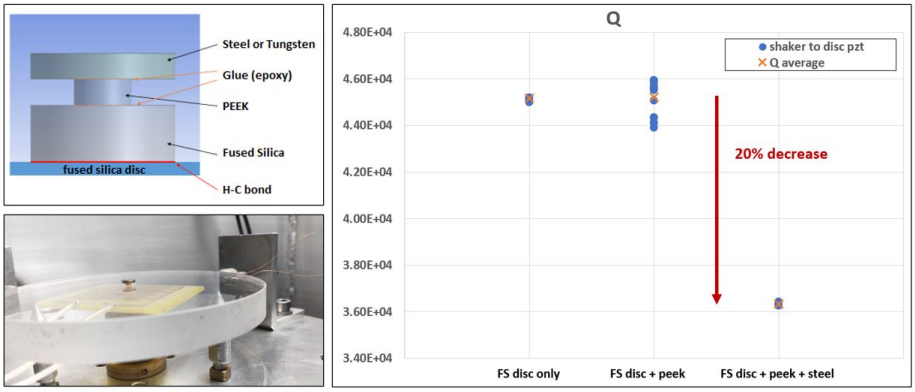

Figure 1: Top left: schematic diagram of the damper. Bottom left: damper bonded to the fused silica disc. Right: experimental data.

6. Conclusion

Increasing laser power is essential for improving the sensitivity of gravitational wave detectors at high frequencies, but it also raises the risk of parametric instabilities due to the interaction between cavity optical modes and high-Q mirror mechanical modes. Simulations and preliminary experimental results suggest that passive dampers can reduce instabilities by lowering the quality factor of critical mechanical modes. The next steps also include the completion of the design for another type of damper focused on another critical frequency zone of 60 kHz. These efforts ensure that passive dampers are ready for implementation in Virgo during the fifth observation run O5.

References

[1] A. Einstein, *Die Grundlage der allgemeinen Relativitätstheorie*, *Annalen der Physik* **354** (1916) .

[2] F. Acernese et al., *Advanced Virgo: a second-generation interferometric gravitational wave detector*, *Classical and Quantum Gravity* **32** (2014) .

[3] The LIGO Scientific Collaboration, J. Aasi et al., *Advanced LIGO*, *Classical and Quantum Gravity* **32** (2015) .

[4] K. Somiya (for the KAGRA Collaboration), *Detector configuration of KAGRA - the Japanese cryogenic gravitational-wave detector*, *Classical and Quantum Gravity* **29** (2012) .

[5] B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), *GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs*, *Physical Review X* **9** (2019) .

PoS(PIC2024)036

[6] R. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), *GWTC-2: Compact Binary Coalescences Observed by LIGO and Virgo during the First Half of the Third Observing Run*, *Physical Review X* **11** (2021) .

[7] R. Abbott et al. (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration), *GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo during the Second Part of the Third Observing Run*, *Physical Review X* **13** (2023) .

[8] ET Science Team, *Einstein gravitational wave Telescope conceptual design study*, *ET-0106C-10* (2011) .

[9] ET Steering Committee, *Design Report Update 2020 for the Einstein Telescope*, *ET-0007C-20* (2020) .

[10] E. D. Hall, *Cosmic Explorer: A Next-Generation Ground-Based Gravitational-Wave Observatory*, *Galaxies* **10** (2022) .

[11] D. E. Cohen et al., *Toward optomechanical parametric instability prediction in ground-based gravitational wave detectors*, *Applied Optics* **60** (2021) .

[12] V. B. Braginsky et al., *Parametric oscillatory instability in Fabry–Perot interferometer*, *Physics Letters A* **287** (2001) .

[13] A. Rocchi et al., *Thermal effects and their compensation in Advanced Virgo*, *Journal of Physics: Conference Series* **363** (2012) .

[14] P. Rapagnani, *Development and Test at $T = 4.2$ K of a Capacitive Resonant Transducer for Cryogenic Gravitational-Wave Antennas.*, *Il Nuovo Cimento C* **5** (1982) .

[15] D.-H. Gwo, *Ultra precision and reliable bonding method*, *U.S. Patent* **US 6284085 B1** (2001) .

[16] D.-H. Gwo, *Hydroxide-catalyzed bonding*, *U.S. Patent* **US 6548176 B1** (2003) .

[17] A. A. van Veggel and C. J. Killow, *Hydroxide catalysis bonding for astronomical instruments*, *Advanced Optical Technologies* **3** (2014) .

[18] E. Majorana et al., *Test facility for resonance transducers of cryogenic gravitational wave antennas*, *Measurement Science and Technology* **3** (1992) .

PoS(PIC2024)036