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Suppression of LIGO mirror vibrational mode Q's

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There is some concern that parametric instabilities due to coupling of optical cavity modes and acoustic mirror modes could occur in AdvLIGO. Likelihood of this occurring depends strongly on the mechanical Q's of the acoustic mirror modes. In this experiment we investigate the possibility of suppressing these Q's by placing copper ringbands around LIGO mirrors. Measurements are made at the Thermal Noise Interferometer, which is used to measure coating thermal noise in AdvLIGO mirror prototypes. Initial results indicate that Q's are indeed suppressed, although more research is necessary to confirm this. Also observed are undesirable vibrations that cover up coating thermal noise. Further work to design ringbands that do not exhibit this characteristic is in progress.

I. BACKGROUND

Advanced LIGO is expected to be an order of magnitude more sensitive to gravitational waves than the current Hanford and Livingston interferometers.[1] In order to accomplish this feat, current noise sources must be minimized. One such source of noise is coating thermal noise. The Thermal Noise Interferometer (TNI) was constructed with the measurement of this noise source in mind. The TNI consists of two parallel high finesse Fabry-Perot cavities, with length of approximately 1 cm. These two cavities are commonly referred to as the north arm cavity (NAC) and the south arm cavity (SAC). A diagram of the setup is shown in Fig. 1. The cavities are locked to the laser's TEM_{00} mode using the Pound-Drever-Hall technique.[2] The interferometer is seismically isolated and sealed in a vacuum chamber, and the mirrors are hung from steel wires as pendulums, similar to LIGO but on a much smaller scale. The thermal noise is measured as equivalent length noise by recording the error signals from the cavity servos. A block diagram of this servo can be seen in Fig. 2.

Recently, efforts at the TNI have focused on reducing Q's of acoustic mirror modes. This is motivated by the fact that parametric instabilities due to the coupling of high Q mechanical mirror modes and optical cavity modes may be a concern for AdvLIGO.[3] This is accomplished by placing ring dampers around the circumference of the mirrors, with the goal that thermal noise is still the dominant source of noise in the frequency range from 500 Hz to 10 kHz.[4] The first ring dampers used were made of buna rubber, and these were found to be very effective at damping mirror vibration. However, mechanical modes of these rings were found to contribute significantly to the total noise floor in the frequency region where thermal noise previously dominated. In an attempt to reduce this undesirable effect, the rubber rings were replaced with a thin layer of kapton tape. Unfortunately, while the tape didn't add to the noise floor, it also wasn't effective at damping mirror Q's.

These results lead to the current work with copper ring dampers (see Fig. 3), which are predicted to have an effect somewhere between those of the rubber and kapton tape rings. The rings are only placed around SAC's output mirror, while NAC is treated as a control. The rings currently being used are split in one spot and tightened around the mirror with a screw for expediency, with plans for the more difficult placement of solid rings in progress.

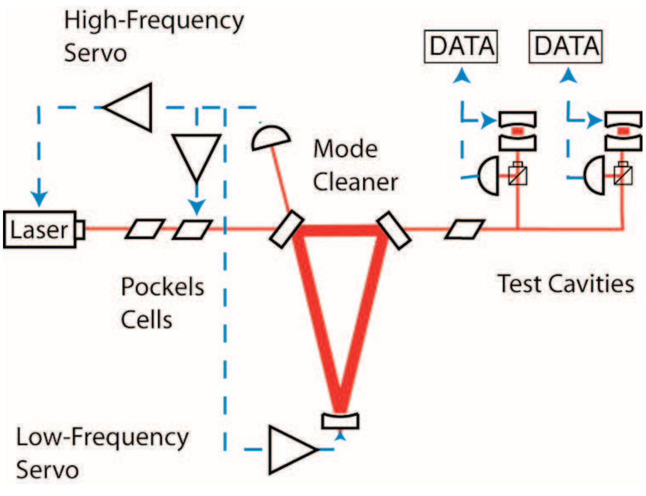

FIG. 1: A schematic of the TNI.

II. PARAMETRIC INSTABILITY

The possibility of parametric instability in an optical cavity has recently been analyzed[3] and later observed in both micro-cavities[5] and suspended mirror cavities.[6] The existence of acoustic vibrations (ω_m) in the cavity mirror induces Stokes (ω_1) and Anti-Stokes (ω_{1a}) optical sidebands within the cavity, centered around the carrier optical mode (ω_0). These modes are related as

$$\omega_1 = \omega_0 - \omega_m \tag{1}$$

$$\omega_{1a} = \omega_0 + \omega_m \tag{2}$$

If either of these optical modes are resonant in the Fabry-Perot cavity, the force on the mirror due to radiation pressure will then oscillate at ω_m, since radiation pressure

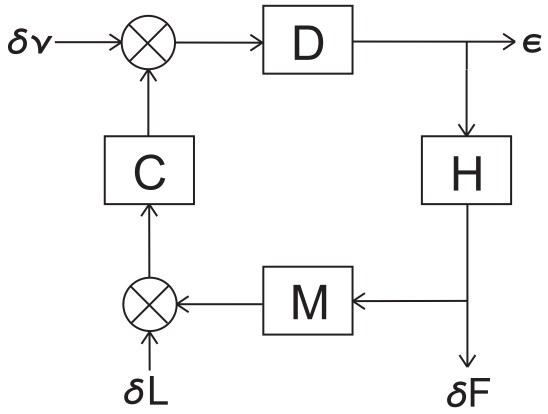

FIG. 2: A block diagram of the servo loop. D is the Pound-Drever-Hall discriminant in V/MHz, H is the electronic transfer function in V/V, M is the mirror response transfer function in μm/V, C is a conversion between cavity length and frequency in MHz/μm, $\delta\nu$ is an inserted frequency fluctuation for mirror response calibration, ϵ is the measured error signal, δF is the feedback to the mirror's magnetic actuators, and δL is the cavity length noise. With knowledge of all of the transfer functions the error signal can be converted to length noise.

is proportional to the square of the sum of the electric field. Essentially, the Stokes or Anti-Stokes mode "beats" with the carrier mode at their difference in frequency. If the optical and acoustic modes are treated as coupled oscillators, one can obtain an instability factor[3]

$$R \approx \frac{2PQ_m}{McL\omega_m^2}\left(\frac{Q_1\Lambda_1}{1+\Delta\omega_1^2/\delta_1^2} - \frac{Q_{1a}\Lambda_{1a}}{1+\Delta\omega_{1a}^2/\delta_{1a}^2}\right) > 1 \quad (3)$$

where the first term in the parentheses is an instability term dependent on the Stokes mode and the second is a damping term dependent on the Anti-Stokes mode, and where P and Q_m are the power circulating in the cavity and the quality factor of the acoustic mirror mode, respectively. Note that the likelihood of instability scales directly with circulating power and Q factors. This is why parametric instability is a potential problem for Advanced LIGO, since the circulating power is expected to be 830 kW, as opposed to 10-50 kW in initial LIGO. This project focuses on lowering Q_m, which effectively lowers R, and thus reduces the possibility of parametric instability.

III. RESULTS

As expected, the copper ring dampers are very effective in damping the Q's of acoustic mirror vibrations in SAC's output mirror. In past ring damping experiments, the resultant Q's have been measured quantitatively by inserting band limited white noise into the cavity feedback loop to excite the acoustic modes. However, we were unable to excite any of these modes, which is evidence that the Q's are indeed very low. Also, normally several notch filters are needed in order to maintain lock, because otherwise electronic feedback at acoustic mode frequencies will cause the mirrors to ring up and break lock. After the rings were in place, the notch filters were no longer necessary to easily initiate and maintain lock in SAC.

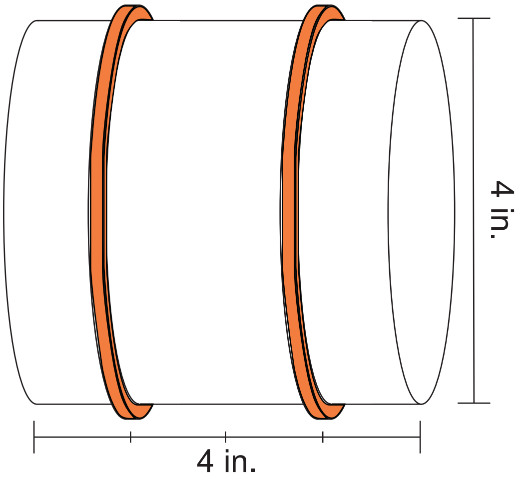

FIG. 3: The copper ring dampers are placed 1" away from the center of mass on either side, in order that the center of mass is preserved. The rectangular cross-section of each ring is 5 mm wide and 3 mm deep.

Unfortunately, the rings have introduced several vibrational modes of their own in the 1 to 10 kHz range (Figs. 4 and 5). The noise floor also seems to have been raised slightly. At this point in the project, these modes are believed to be a consequence of the screw used to tighten the split ring around the mirror. Further investigations will be conducted with uniform rings in order to confirm the origins of these undesirable noise sources. These rings will be machined so that their inner radius is the same or slightly smaller than the radius of the mirror. They will be thermally expanded to fit around the mirror and then allowed to cool in place.

IV. CONCLUSION

Preliminary work to suppress acoustic mirror modes, in light of possible parametric instabilities, shows promise. The question remains whether the ring damper approach can be utilized without sacrificing instrument sensitivity. Future results obtained using uniform copper rings will determine more completely the effectiveness of this approach.

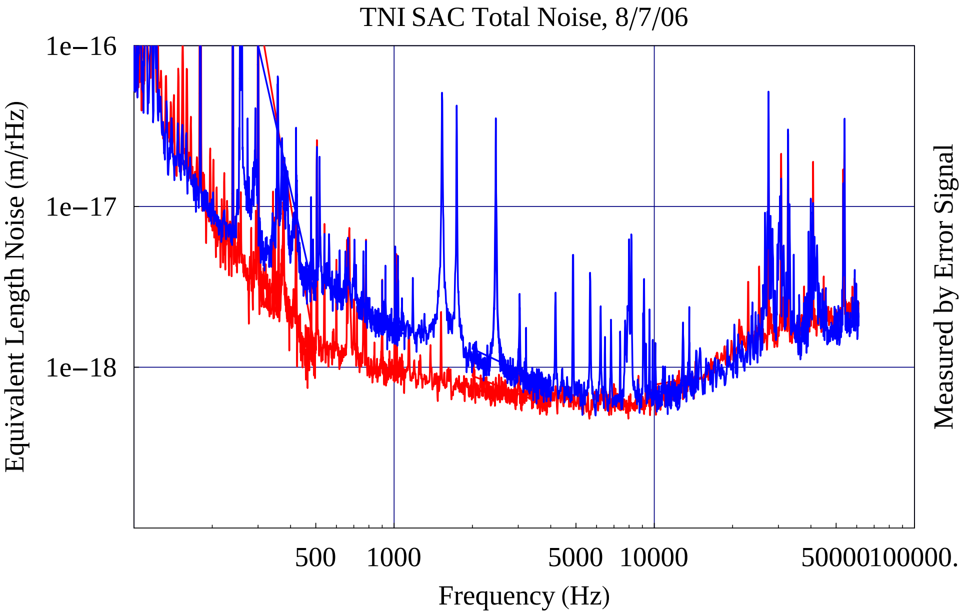

FIG. 4: A plot of SAC's equivalent length noise as measured from the feedback error signal. The red and blue curves are data taken before and after the rings were placed on SAC's output mirror, respectively. Note the broad peaks in the more recent data.

V. METHODS

A. Designing the Rings

The copper rings were designed to have fundamental shear wave modes well outside the thermal noise region. The speed v of shear waves in a material with shear modulus G and volume density ρ is given by

$$v = \sqrt{\frac{G}{\rho}} \tag{4}$$

Thus the frequencies of vibration f in this situation are given by

$$f_n = \frac{2n-1}{4d}\sqrt{\frac{G}{\rho}} \tag{5}$$

where d is the thickness of the ring, which is the outer radius subtracted by the inner radius. For a copper ring with a thickness of 3 mm, the fundamental frequency is approximately 190 kHz, well outside the region of interest.

B. TNI Alignment

There are actually three optical resonant cavities in the TNI. The first of these is the mode cleaner, which stabilizes the laser frequency and allows spatial conditioning of the beam into the TEM_{00} mode. These purposes are accomplished by locking the cavity to the laser at low frequencies and the laser to the cavity at high frequencies. The other two cavities are the north and south arm cavities, which are locked to the beam that is transmitted from the mode cleaner. Their purpose is to allow measurements concerning the mirrors that make up these two cavities.

All three of the cavities have what is called a cavity axis, defined by the position and face curvature of the mirrors forming each cavity. Resonance of axisymmetric laser beam modes (such as the TEM_{00} mode) is only possible in such a cavity when the laser beam overlaps the cavity axis. Thus alignment consists of directing the input beam onto the cavity axis. The closer the beam is to the cavity axis, the higher the visibility of the cavity will be (the percentage of light input that gets transmitted). For our purposes, we desired to have 80% visibility out of the mode cleaner and 90% visibility out of each arm cavity. At the expense of plenty of time and effort, a visibility of over 95% can be achieved in the mode cleaner, but the only effect of this is a slight increase in laser power to the arm cavities.[7]

After the desired visibilities were met, we closed the vacuum chamber that contains all three optical cavities. Some realignment was then necessary due to the introduction of the chamber windows into the optical system. Once the cavity visibilities were again up to satisfactory levels, the system was ready for data collection.

C. Mirror Response Calibration

Placing the rings around the output mirror of SAC results in a slight change in the mirror's response to feedback through the magnetic actuators fixed on the output side of the mirror. Since we need to know this response in order to produce accurate length noise data, this response needed to be recalibrated.

Calibration is performed by inserting a known laser frequency fluctuation $\delta\nu$ into the servo loop through the mode cleaner while the cavity to be calibrated is in lock. Then the mirror response transfer function M reduces to

$$M \approx \frac{\delta\nu}{\delta FC} \qquad (6)$$

at measurements well below the unity gain frequency, as can be seen from Fig. 2.

D. Common Mode Rejection

Since both cavities are locked to the same beam, which is split equidistant from the two cavities, the laser frequency noise is common to both. Thus, this noise can be mostly removed simply by subtracting one error signal from the error. Where individually the noise floor in each cavity begins to rise due to this noise source at slightly less than 10 kHz (see Figs. 4 and 5), the noise floor continues to decline when common mode rejection is utilized (Fig. 6). This results in a better visualization of the peaks which represent mirror body modes, allowing a better understanding of the effect the ring dampers are having on these modes.

Acknowledgments

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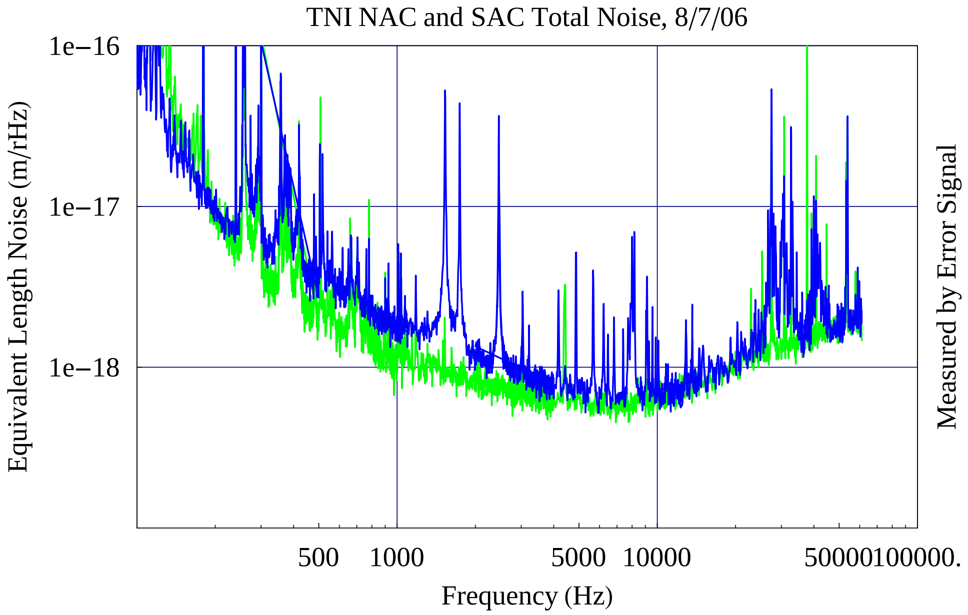

FIG. 5: A comparison between the north (green) and south (blue) arm cavities. SAC's output mirror has rings in place, while NAC's does not. These data were taken were taken with both cavities in lock at the same time.

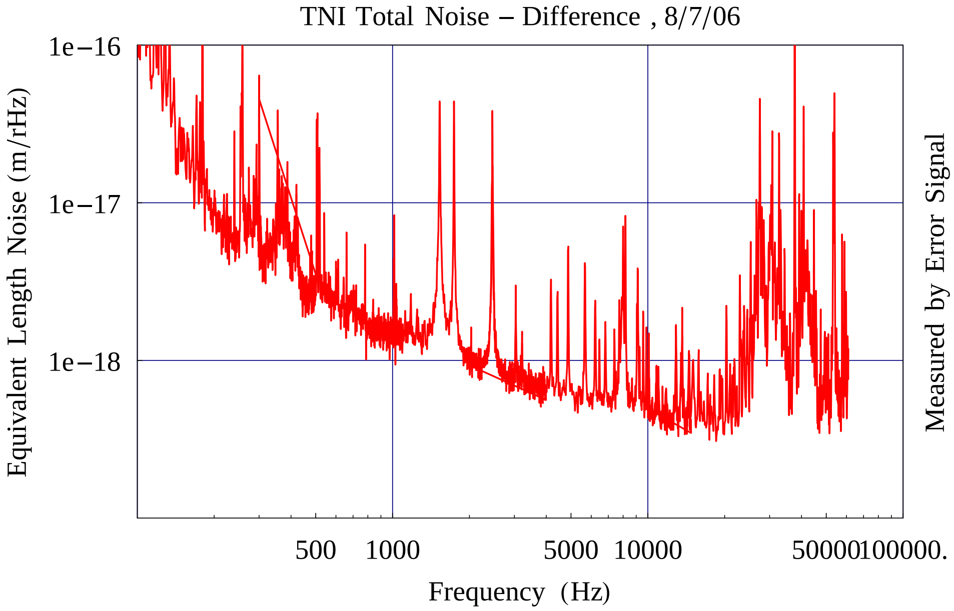

FIG. 6: Data taken by subtracting the error signal from one cavity from the other, called common mode rejection. This allows removal of most of the laser frequency noise, which otherwise dominates at higher frequencies.