Proposed Research Program on Thermal Noise

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Rationale

Thermal noise is expected to be one of the most important noise terms in LIGO receivers. It is likely to dominate in a frequency band as wide as as decade or more, in the vicinity of 100 Hz.

No prototype interferometer has yet been limited by thermal noise. This is because we need to make progress against other noise sources as well. By the time we have interferometers sensitive enough to see thermal noise, we will wish we could be making shot noise limited measurements of gravitational waves, not studying thermal noise. We ought to try to learn as much as possible now about ways to minimize thermal noise.

The situation is slightly different for seismic noise. There, what we design is a filter which attenuates the ambient spectrum. Under the assumption that the system is linear, we can drive our filter with noise much larger than ambient to measure its response. Thus, we don't need a sensor of LIGO-class sensitivity to test the vibration isolation system.

Thermal noise is, by contrast, a noise which drives the test mass itself. There is no input to scale up. We need high sensitivity to see the noise itself.

One possibility is to construct special low mass oscillators which would respond more visibly to the thermal noise. So far, I have not been able to come up with a scheme that improves the situation enough to make it worth the trouble.

Fortunately, there is an indirect measurement which should tell us what we most need to know. The fluctuation-dissipation theorem links the random motion that we call thermal noise to the magnitude of the mechanical losses in the suspension system. It is these losses which are amenable to measurement. They can be determined by measuring the damping time of resonances in samples of candidate suspension materials.

Program

The work to be done divides naturally into a preliminary phase and a possible subsequent advanced phase.

The preliminary phase consists of setting up the equipment necessary to perform the loss measurements, debugging it, and compiling a catalog of loss spectra (loss as a function of frequency) for candidate suspension materials.

I propose that the basic measurement consist of measuring the damping of normal modes in samples of dimensions appropriate to LIGO pendulums, hanging vertically, held by a clamp at one end. It seems most straightforward to me to test materials most nearly in the form that we intend to use them. That way, there is a smaller chance that some unsuspected scaling will cause different losses than we extrapolated from our measurements.

The use of a clamp, as opposed to some other way of suspending the sample, is the most controversial aspect of this proposed scheme. The worry is that the clamp will introduce losses not characteristic of the material under test. This worry is legitimate, but I nevertheless think that use of a clamp is the right choice. Firstly, the same worry is important for any suspension scheme. Secondly, we use clamps when we construct pendulums. Finally, I think that the spurious losses should be small, since the samples are compliant and light while the structure will be stiff and massive. Still, this needs to be examined more closely both by calculation and by experiment. A clever clamp design may be needed to minimize rubbing, or to properly hold brittle materials such as fused quartz or sapphire.

When the system has been built and debugged, we should test a number of different materials, including tungsten, sapphire, and fused quartz. Because it is likely that damping depends on poorly controlled factors, such as impurities or defects, a number of samples of each material should be measured, if possible from several different manufacturers. We will also need to check whether factors within our control, such as cleanliness or surface treatment, make a difference to the damping. It will also be valuable to compare the loss in pieces with the same cross-sectional area but different shape. Flat ribbons typically will reduce the total amount of loss, but for loss mechanisms which involve diffusion across the flexing member (such as thermoelastic dissipation), the change in frequency scale with thickness could negate this advantage.

I would consider this phase successful if at its end we had believable measurements for the losses in the materials we are likely to use for pendulums in the LIGO. This would let us predict the thermal noise with a much greater degree of confidence than we can now.

We will need to verify that the losses that we measure are not degraded by the tension which is applied to the suspension member when it is used in an actual pendulum.

At the end of the preliminary phase, we ought to consider whether it appeared likely that more detailed research might lead to lower levels of loss. If there is reason for optimism, then we could embark on a longer term effort which would involve diagnostic measurements to try to identify the most important loss mechanisms. The ultimate goal would be to find ways to manufacture suspension materials, or to treat them after manufacturing, in order to reduce the amount of loss at frequencies of interest.

Resources

I will confine the discussion of the resources required to the preliminary phase of the proposed research plan.

Only modest equipment is needed for the measurements. A diffusion-pumped bell jar, available in the MIT lab, is sufficient vacuum equipment. Some machining is required to construct the test jig itself. Exciting the resonant modes can be done electrostatically, with sensing performed optically with shadow detectors. The necessary equipment is either already available or can be built without undue effort. The test instruments needed are a storage scope, a spectrum analyzer, and (if we're lucky) a chart recorder. These can be shared with other experimental work in the lab.

We will need to acquire a number of samples of the materials to be tested.

This project should fully occupy a graduate student, with supervision by a senior scientist. Joe Kovalik has expressed interest in the work. At the beginning, and sporadically thereafter, some machining assistance will be required.

A major review of the state of the work should probably be scheduled for mid-August. That is a reasonable target to set for completing the preliminary phase. In any event, my sheduled departure for six months at JILA makes the end of the summer a natural time to take stock.