LIGO SURF Project Proposal:
Modeling of Gravitational Wave Detector Suspensions

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Introduction/Background

The experimental apparatus that the advanced LIGO team used to make the first direct observation of gravitational waves is based on a Michelson interferometer. The miniscule perturbations of space-time predicted by Albert Einstein in this theory of general relativity result in very slight shifts in the lengths of the interferometer arms, and thus have a measurable effect on the interference pattern produced by the recombined laser beams. However, the magnitude of this shift is so tiny that it has taken decades of efforts in noise reduction to make the detection possible. Much of the seismic vibrations of the Earth are able to be filtered out of the signal by suspending the mirrors at the end of the chambers by fibers, designed as a quadruple pendulum in such a way that the resonant frequencies of the pendulum are well out of the range of the frequencies that we are trying to detect. Another significant source of noise comes from mechanical and thermo-elastic loss within the test mass and fiber material, and in order to effectively deal with these noise sources, a very accurate and precise model of the thermal activity of the system is required. To create these models, the LIGO team uses finite element analysis software in order to take into account for all the specific parameters of the suspension system, such as internal friction, non-uniform shapes, spatially varying material properties, temperature distributions and heat flow. With an accurate model of the thermal noise, the detectors can be designed to optimize the sensitivity of the experiment. The advanced LIGO project successfully modeled a monolithic fused silica glass structure consisting of a 40 kg test mass fused to silica fibers which in turn are fused to a fused silica penultimate mass, and designed the detectors to concentrate thermal energy close to resonances and thus reducing off-resonance thermal noise in the measurement band. The next generation of the LIGO detectors will be cryogenically cooled to reduce even more of the thermal noise, but this requires research into new materials to be used for the interferometer and a complete redesign of the mirror suspensions. My project will focus on using finite element analysis to model crystalline materials such as sapphire and silicon, to guide the design of the upgraded mirror suspensions. If successful, these new models will result in further reduced contributions of thermal noise and thus improve the sensitivity and range of the LIGO detectors.

Objectives

The objective of my project is to improve the range and sensitivity of the LIGO detectors, so that we can measure more of the space-time perturbations associated with extreme astronomical events such as coalescing binary black holes, neutron stars, and supernova explosions. To do this, I will be investigating the performance of new crystalline materials to gain the best understanding of the thermal noise in mirror suspensions. The development work will require considerations of new geometries of the test masses and ribbons/fibers, strength testing, and mechanical losses in silicon, sapphire, and fused silica/silicon hybrid materials. It is hoped that when working with silicon as opposed to fused silica, there will be a significant performance improvement by changing the geometry of fibers with a circular cross section to ribbons with a rectangular cross section. Also the means by which the fibers are bonded to the masses will require research and testing. The advanced LIGO detectors used intermediate "ears" fused to the masses, which the fibers were welded to, but new methods will also be investigated and modeled.

Approach

The main tool that I will use to model the thermal noise in the LIGO systems is software called ANSYS that is often used for finite element analysis. I intend to begin investigating very basic models that allow me to make consistency checks with analytical models and can be checked with experimental measurements. This way I will become familiar with FEA techniques and much of the modeling that has already been done by LIGO. From this, I can build up sections of the model piece by piece, moving towards an accurate and precise model of the experiment. Eventually, a fully model of the final stage of a cryogenically cooled mirror suspension will allow for the design of improved detectors, and thus a more sensitive and reliable experiment.

Project Schedule

The research program that will fund my project is about ten weeks long. During the first couple weeks, I will begin the investigation of basic models in order to calibrate the consistency of the FEA models with experimental data and analytical models. By the third week, I hope to have a firm grasp of the LIGO suspension models and begin realistic testing of silicon and sapphire materials. Throughout the next few weeks, I hope to analyze fundamental differences between the silica fibers and crystalline ribbons, and find evidence of a significant improvement in thermal noise reduction. I will also be researching new methods of bonding the masses to the ribbons, and producing finite element models of the thermal noise within these bonds. At this point, I will also need to consider how material properties are affected at cryogenically cooled temperatures. Hopefully by the sixth week, I will begin considering how to adjust various parameters of the system in order to optimize the thermal noise reductions, and adjusting my finite element models accordingly. Hopefully, the modeling work will be done in parallel with physical testing of new crystalline materials, so I will have access to experimental data with which to compare my models. By the end of the project, I hope to have a complete model of the thermal noise in the cryogenically cooled suspension system, ready to be built for the next generation of LIGO detectors and adequately prepared for the most sensitive experimental measurements ever made.

References

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