Determining the Effect of Acoustic Coupling on Advanced LIGO

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Abstract

Advanced LIGO is built to be extremely sensitive to movements of the test mass as small as 10-20 $1 \times 10^{-20} \frac{m}{\sqrt{Hz}}$, which allows many signals other than gravitational waves to be detected by the system. Pressure created by external sound can alter the differential arm movement measurement by creating Doppler shifts, intensity fluctuations, and scattering in the laser beam. To determine the areas affected by external sound, we inject acoustic noise in the laser and vacuum equipment area. On a smaller scale, vibrating a horizontal access module or beam splitter chamber with a shaker tests the effect of sound on single chambers. To calculate the scale at which these vibrations affect the differential arm movement signal as well as the effect of other environmental injections, a Python program was written. This program analyzes ambient background noise signals as well as injections with coupling functions and outputs a file with the estimated differential arm movement effect for each calculated frequency. By calculating the effect of acoustic coupling and other environmental signals with this program, the calculation process will be streamlined and calculation error will be reduced.

1 Introduction

The Laser Interferometer Gravitational Wave Observatory, or LIGO, was built to serve a collaboration of scientists with a common goal: to detect gravitational waves. These waves can be produced when certain cosmic events occur, as predicted by Albert Einstein's theory of general relativity.

In order to detect these waves, both LIGO setups, one in Hanford, WA and one in Livingston, LA, consist of two perpendicular 4 km long arms with a mirror, called a test mass, at the end of each. Laser light splits and moves through vacuum in the beam tubes of both arms, reflects off the test mass, and recombines at the same time. The hypothesis is that even a small gravitational wave will stretch space in the direction of one arm, and compress it in the other arm's direction, therefore making the beams return to the recombination spot at separate times. [1]

Since the Advanced LIGO set up was designed to be extremely sensitive to movements of the test mass as low as $1\times10^{-20}\frac{m}{\sqrt{Hz}}$, many signals other than those created by gravitational waves can be detected by the system. Some factors that can affect the output of the system include acoustic noise, external magnetic fields, and tilt caused by wind surrounding the observatory.

In order to detect these environmental signals, a Physical Environmental Monitoring (PEM) System setup is used at each interferometer. This system includes microphones, magnetometers, seismometers, and various other sensors. The goal of the PEM system is to understand how the environment affects the signal in the interferometer and how these effects will affect the eventual detection of a clear gravitational wave.

2 Problem

One PEM injection that can be used is testing for acoustic coupling. Acoustic coupling can occur within the interferometer when external noise shakes any part of the optical or vacuum systems. When sound travels, it creates a change in pressure in the air and these pressure fluctuations can affect the Differential Arm Movement(DARM) output by creating noise. This noise can be created in three different situations, the first being when the pressure fluctuation shakes the vacuum chamber walls and the small fraction of scattered light that bounces off the wall and returns to the beam is modulated. Noise in DARM can also occur when pressure fluctuations shake external parts of the seismic isolation system and the vibrations travel through the system and shake the mirrors, and accordingly, shaking the laser beam that hits those optics. Lastly, mirrors and optics directly in the air can be shook by pressure fluctuations, which also produces noise in DARM.

In order to understand the effect of environmental signals on the interferometer, the PEM team conducts injections of environmental signals. An example an injection consists of placing a solenoid that produces a magnetic field in the area of the vacuum chambers and looking at the difference in the Differential Arm Movement (DARM) signal. With these injections, the goal is to determine the estimated ambient background level of this signal on DARM. In the calculation linearity is assumed, so if an injected peak has an order of magnitude difference of 5, then the ambient background level is 5 orders of magnitude under the point in DARM at that frequency.

During initial LIGO, a script was developed to do this calculation, but new advanced LIGO data for PEM injections had largely been calculated by hand,a tedious and time consuming approach. Therefore, a program to calculate the ambient background estimates for PEM injections in advanced LIGO was necessary.

3 Results

3.1 Ambient Background Estimates Program

A Python program was developed in order to calculate the estimated ambient background for PEM injections. The program accepted input text files with data from LIGO's Diagnostic Test Tools (DTT) program. At least one ambient signal and the DARM injection spectrum and their respective references, which are taken immediately prior to the injection, are required as inputs to the program. The program can accept data from up to seven different signals. The calculation done by the program only calculates estimates for signals and DARM spectrum using certain thresholds above their references. These thresholds can be changed within the program, but during preliminary tests, a threshold of 10 for the environmental signal and a threshold of 1.5 for the DARM spectrum worked accurately. If the environmental signal is above threshold but the DARM spectrum is not, an estimate of the ambient background?s upper limit is calculated. The program outputs three text files, one with the factor of coupling for each frequency, one with the ambient background estimate for each frequency, and one with upper limit estimates.

The program also has the capacity to add two signals in quadrature, which is ideal for accelerometer data that is represented as one file for movement in the horizontal direction and one file for movement in the vertical direction. After the ambient background estimates have been made, the program has the capacity to compare data from multiple sensors during the same injection with the choice of outputting the maximum, minimum, or median estimate at each frequency. These options enable the flexibility that analyzing data from multiple types of environmental sensors requires.

3.2 Acoustic Coupling Studies

Shaker tests were conducted on all horizontal access modules (HAMs) and beam splitting chambers(BSCs) in the corner station laser and vacuum equipment area (LVEA). A comparison was conducted between all HAMs to see which had the largest effects of acoustic coupling. A ranking was created based on the average of the ten highest ambient background estimates for the HAM. All estimates were created by the ambient background estimating program.

Large effects of acoustic coupling occured in HAM 2 and HAM 6, which rank at the top of the most affected. As shown in Figures 2 and 6, respectively, the average highest ambient background estimates for these two were around $1 \times 10^{-20} \frac{m}{\sqrt{Hz}}$, which is within the DARM limiting region. HAM 5 had the next highest ranking in the effects of acoustic coupling. Figure 5 shows that the average high ambient background estimates were between $1 \times 10^{-20} \frac{m}{\sqrt{Hz}}$ and $1 \times 10^{-21} \frac{m}{\sqrt{Hz}}$. These estimates are still close to limiting DARM. HAM 4 follows HAM 5 in the ranking with its average high estimates around $1 \times 10^{-21} \frac{m}{\sqrt{Hz}}$, as shown in figure 4. HAMs 1 and 3, however, did not show any significant change in DARM throughout the injections. Figures 1 and 3 show the similarities in DARM for each of these HAMs.

Each HAM is made of two tables, held together by three flexures and blade springs, as shown in Figure 7. After examining acoustic injection data from HAM 6, it was hypothesized that some acoustic coupling within the HAM could be caused by the flexures and blade springs vibrating at their natural frequencies. Therefore, when the horizontal access module was open for repairs, the effect of flexure movement was tested. Temporary flexure damping materials were created using Viton lined paperclips encased in Class A compatible covers. The flexures were plucked with and without these damping materials and the movement was measured using the accelerometers within the HAM. A comparison of the movement for each flexure with and without the clamps is shown in Figure 7. The clamps significantly lowered the peak between 750 and 755 Hz.

4 Conclusions

As shown from the acoustic injections, HAM 2 and HAM 6 both have high levels of acoustic coupling followed by HAM 5 and HAM 4. Identifying the causes for acoustic coupling and developing approaches to limit it in each of these HAMs is necessary. Flexure damping studies could be used to determine whether those resonances are a cause, but since each HAM is composed of different internal optics, the cause could be different for each individual HAM.

Loudspeaker injections should also be conducted in both end stations, and at LIGO Livingston as well to see if acoustic coupling effects the interferometer signal in those places as well. If so, additional acoustic coupling studies should be conducted. The data from shaking the BSCs in the Hanford corner station need to be analyzed using the ambient background program to see if there is acoustic coupling in those chambers.

Based on the results of the flexure damping studies, further research into the best way to damp the flexure and blade spring is currently underway to develop a change in HAM 6 that will limit acoustic coupling.

The implementation of the ambient background estimate program should provide more information on the environmental effects on the interferometer and enable easier data analysis during PEM injections.

5 Methods

5.1 PEM Injections

Injections were normally prepared prior to the time of injection by placing a shaker on the chamber and setting up the signal generator, attenuators, and amplifier on the PEM cart. When the interferometer was in lock, a background measurement was first taken using the Diagnostic Test Tools software and the results were saved. Next, the shaker was plugged in to the attenuators on the amplifier and a sweep was set on the signal generator over a specified set of frequencies. While this sweep was run, data was taken using Diagnostic Test Tools again and saved. This was repeated over a range of sets of frequencies for each chamber.

6 Figures

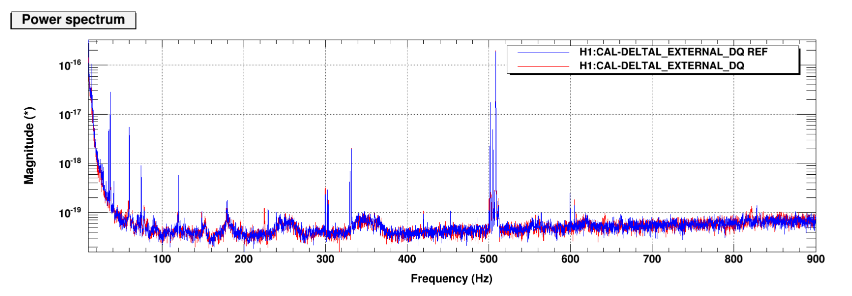

Figure 1: DARM and background DARM signals for HAM 1 during shake test.

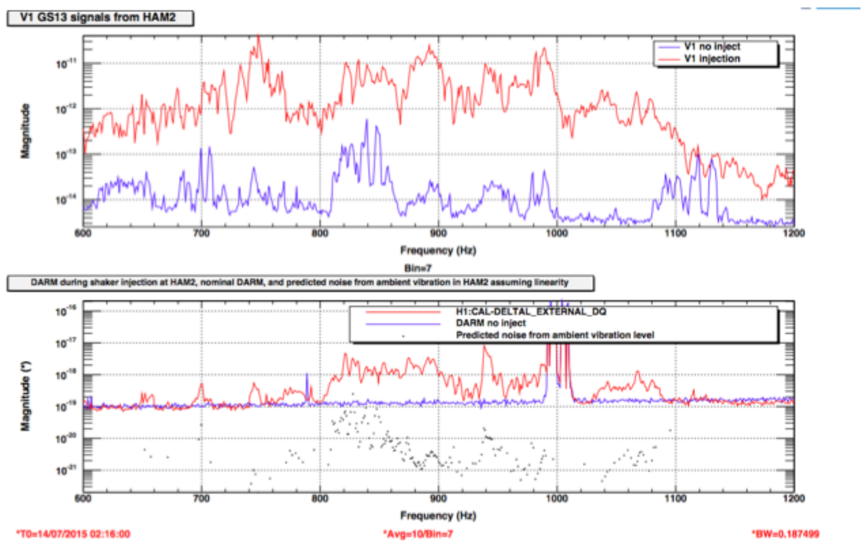

Figure 2: Accelerometer signals, DARM, and ambient background estimates for HAM 2 during shake test.

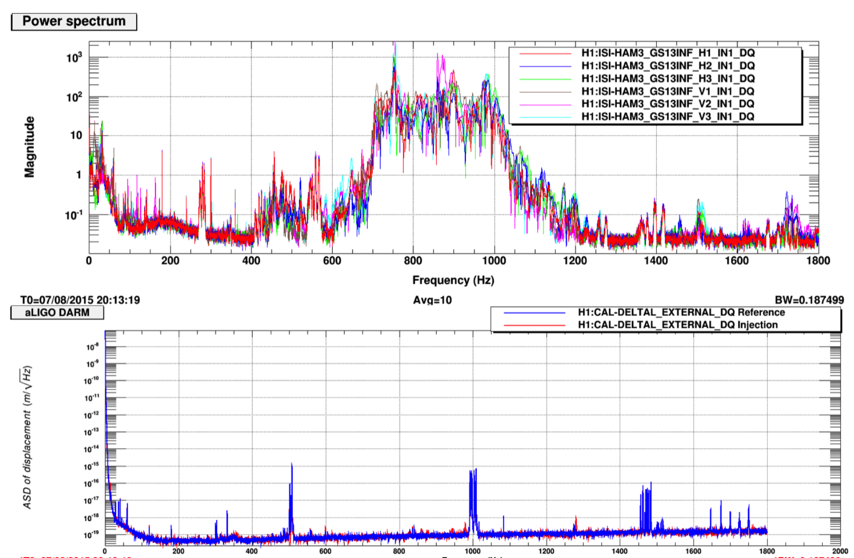

Figure 3: Accelerometer signals, DARM, and ambient background estimates for HAM 3 during shake test.

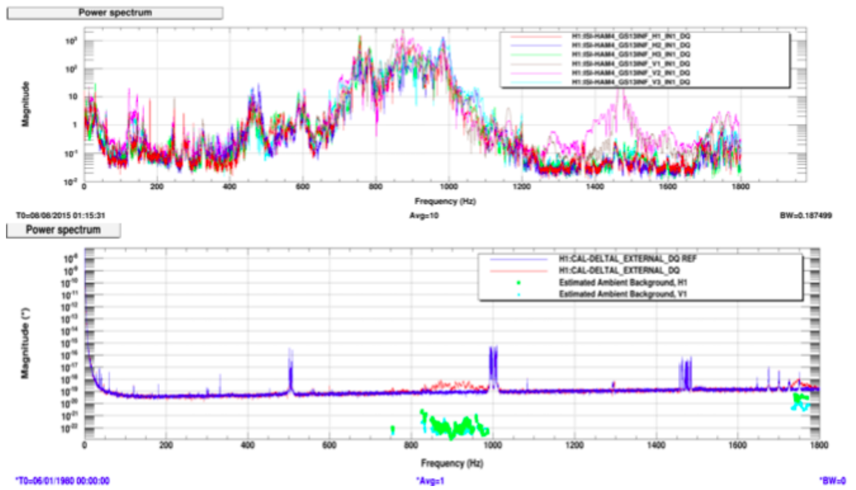

Figure 4: Accelerometer signals, DARM, and ambient background estimates for HAM 4 during shake test.

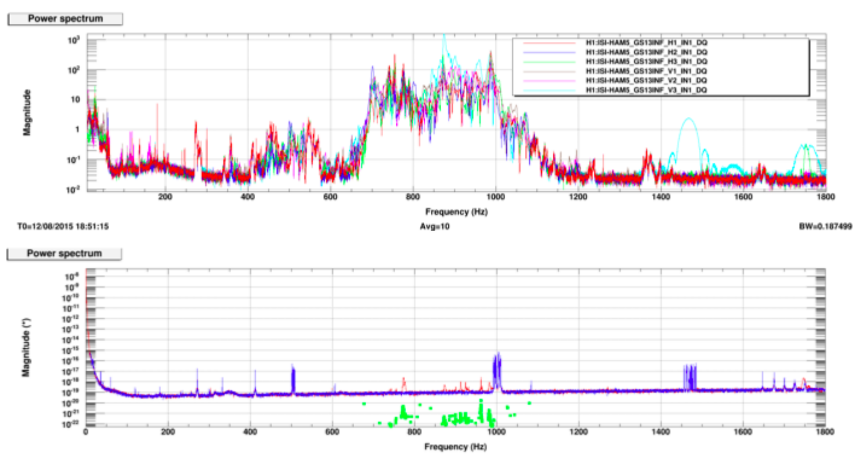

Figure 5: Accelerometer signals, DARM, and ambient background estimates for HAM 5 during shake test.

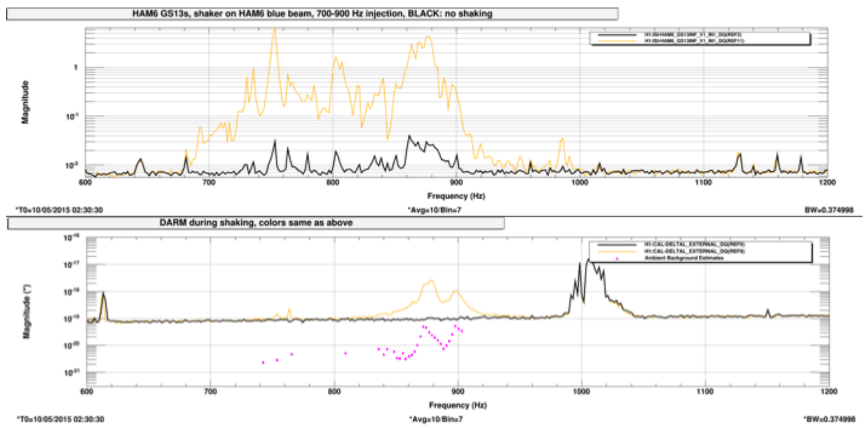

Figure 6: Accelerometer signals, DARM, and ambient background estimates for HAM 6 during shake test.

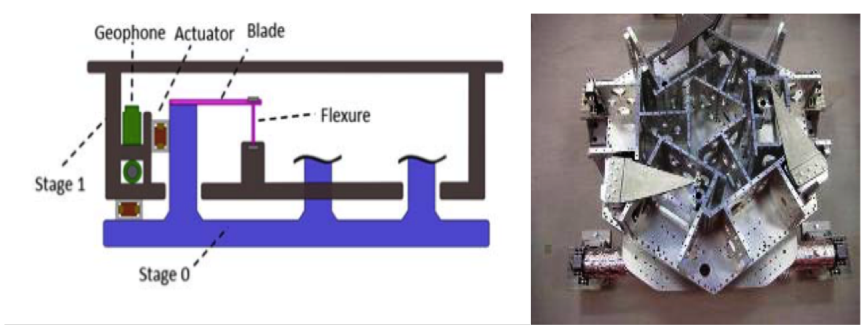

Figure 7: The layout a horizontal access module from a side-view sketch and a picture from above.[3][4]

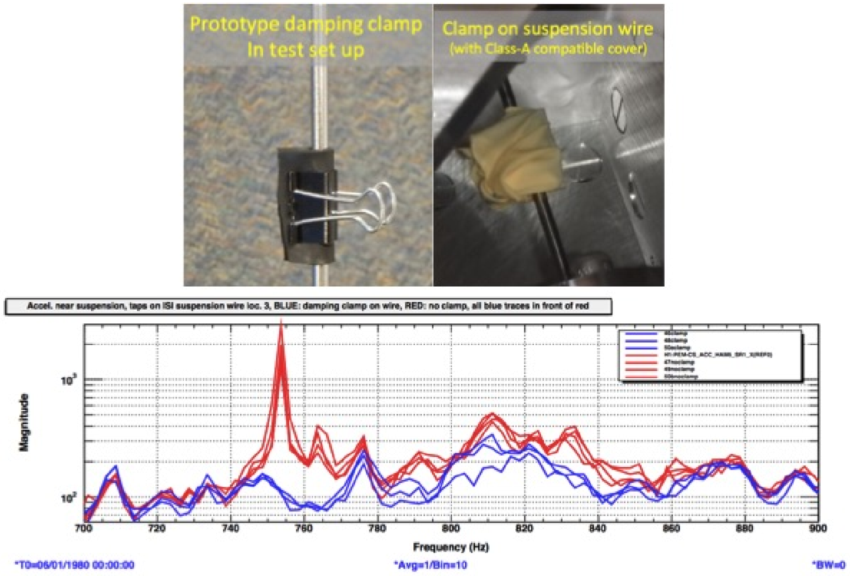

Figure 8: The design of the Viton lined damping clamp, the viton-lined clamp in use, and the accelerometer signals for plucking the flexures with and without clamps.[2]

7 References

References

[1] "LIGO Overview" *LIGO Hanford Observatory* 2010. Web. 06 July 2015

[2] Robert Schofield. "High acoustic coupling likely due to HAM6 ISI blade spring and suspension wire resonances; wire damping demonstrated". 25 June 2015. *aLog*.

[3] F. Matichard et al. ?Conceptual representation of the HAM-ISI?, *http://arxiv.org/pdf/1502.06300.pdf*

[4] LIGO. *https://www.advancedligo.mit.edu/sei.html*

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